



Lifetime Investigation of Lithium-Ion Cells

**Evaluation of a Novel Aging Concept Using
Non-Invasive Battery Analytics Methods**

Authors: Bernhard Vietz, David Frey

Table of Contents

1. Introduction

2. Lithium-Ion Cells

2.1 Electrochemical Structure	3
2.2 Aging of Lithium-Ion Cells	3 – 4

3. Novel Test Concept

3.1 Parameter Cycling	4
3.2 Experimental Setup and Test Cases	5 – 6

4. Measurement Data Analysis

4.1 Data Science	6
4.2 Non-Invasive Test and Analysis Methods	6 – 7

5. Results and Interpretation

5.1 Cell Parameters	8
5.2 Aging Mechanisms	8 – 9

6. Summary

7. References

Note on the source text:

This whitepaper contains verbatim passages from the bachelor's thesis of one of the authors, which was created as part of these investigations:

Frey, D. (2025): Lifetime Investigation of Lithium-Ion Cells – Evaluation of a Novel Aging Concept Using Non-Invasive Battery Analytics Methods, Bachelor's thesis, Technische Hochschule Ingolstadt.

The passages are used with the author's consent.

1. Introduction

Lithium-ion cells form the backbone of energy storage in electromobility and are a central component of modern electric vehicles. Their high energy and power density, as well as their advanced level of development, make them the preferred technology in both the consumer and automotive sectors. Important factors in this context are the service life and reliability of vehicle batteries, which will play a decisive role in the economic efficiency and everyday usability of future mobility solutions. In order to better understand and predict the aging behavior of these energy storage systems under realistic operating conditions, robust testing procedures and comprehensive analysis concepts are of central importance.

2. Lithium-Ion Cells

2.1 Electrochemical Structure

A lithium-ion cell consists of a negative and a positive electrode, which are separated by a separator and immersed in an electrolyte. The two electrodes contain the active material of the cell, whereby various material pairings are used in practice. The positive electrode frequently consists of metal oxides such as manganese (Mn), cobalt (Co), and nickel (Ni) combined with oxygen, or combinations thereof. Other common material classes include lithium nickel cobalt aluminum oxide (NCA) and lithium iron phosphate (LFP). For the anode material, carbon compounds in the form of parallel graphene layers with a hexagonal structure, also referred to as graphite, are predominantly used today. During operation of the cell, lithium ions can

pass through the separator and migrate back and forth between the electrodes. In this process, intercalation and deintercalation of Li^+ occur within the host lattices of the active materials. The lithium ions release electrons, which can subsequently flow through the two current collectors of the cell via an externally closed electrical circuit (Fig. 1).

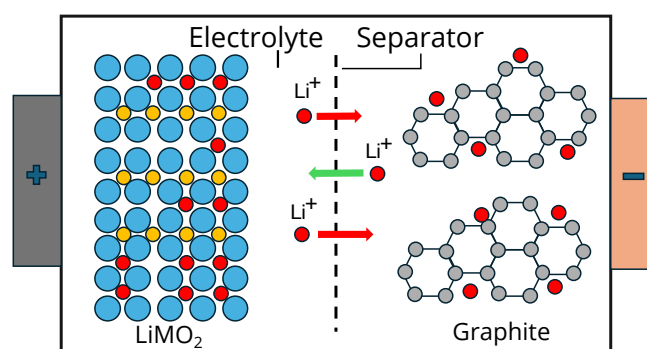


Figure 1: Schematic representation of the operating principle of a lithium-ion cell.

2.2 Aging of Lithium-Ion Cells

Like other electrochemical storage systems, lithium-ion batteries are also subject to various aging processes that limit their service life. In this context, the term aging describes the entirety of electrochemical, mechanical, and chemical processes within the cell that, over time and with increasing cycle numbers, lead to deterioration of the battery parameters of the cell. Different stress factors can act on the system boundary of a cell. They can trigger a wide variety of aging mechanisms within the cell, which can be classified into the aging modes loss of active material (LAM) and loss of cyclable lithium ions (LLI). Ultimately, all conceivable aging mechanisms lead to two possible aging effects: loss of cell capacity and increase in internal resistance. In principle,

aging of a lithium-ion cell is divided into cyclic aging and calendar aging (Fig. 2).

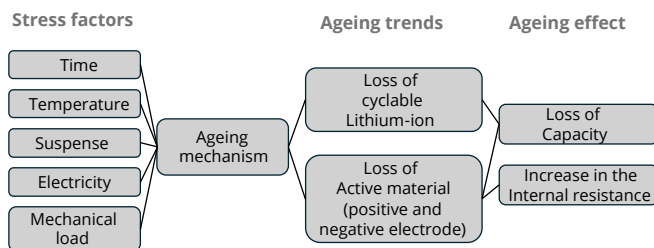


Figure 2: Chain of effects of different stress factors and aging mechanisms.



Calendar Aging

Time-dependent aging of the lithium-ion cell in the unloaded state. It mainly plays a role during storage of battery cells. Chemical processes, for example in the context of self-discharge, also occur here.

Cyclic Aging

Includes all aging processes that may arise from dynamic loading during operation of the cell. It depends, among other things, on the number of cycles, charging and discharging current rates, and temperature.

3. Novel Test Concept

3.1 Parameter Cycling

As part of the investigations conducted by the Mobility Technology Center (MTC), long-term tests on lithium-ion cells were carried out at intech GmbH over a period of several months. For the design of the test cases and test architec-

ture, a novel approach, the so-called parameter cycling, was established for conducting aging tests in order to obtain the best possible measurement points within the parameter space. Instead of using mixed cycling to cover many relevant stress factors and aging mechanisms of a cell through one test scenario, the design of several individual test cases is intended to specifically address individual influencing factors and their effect on the intensity and speed of cell aging. This parameter cycling approach therefore aims to break down the aging behavior of lithium-ion cells as effectively as possible according to the individual aging mechanisms rather than across a single operating point. (Fig. 3).

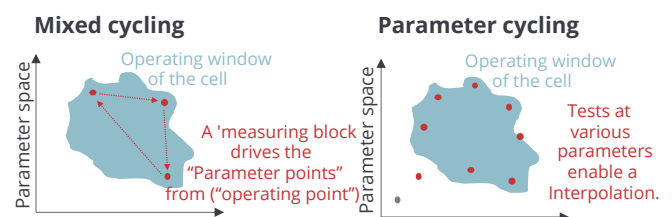


Figure 3: Comparison of the testing strategies of mixed cycling (left) and parameter cycling (right), simplified representation.

Parameter cycling is intended to enable more comprehensive predictions through interpolation of the individual test parameters. Depending on the number "n" of previously defined test parameters, an n-dimensional parameter space becomes available for linking individual stress factors. Using various mathematical and physical modeling approaches, the real effect paths of the stress factors can be approximated (Fig. 4a und b).

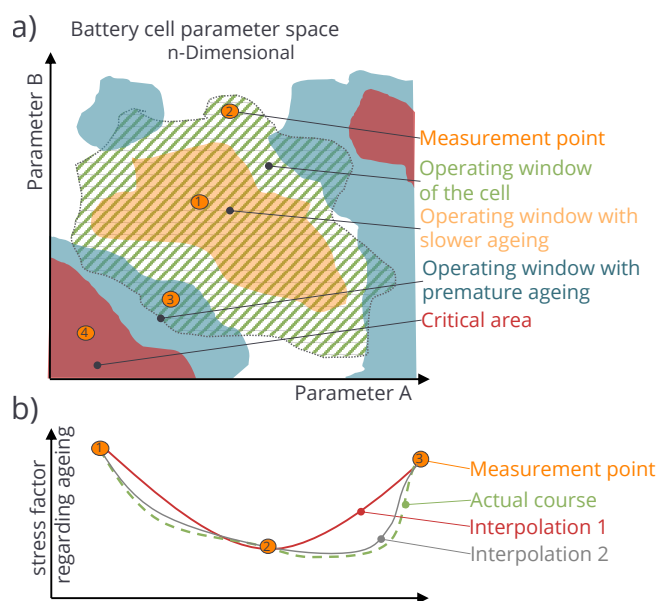


Figure 4: (a) Schematic representation of the parameter space with input parameters A and B. (b) Exemplary description of possible modeling approaches.

3.2 Experimental Setup and Test Cases

Two types of lithium-ion pouch cells from the manufacturers LG Chem (nominal capacity 78 Ah) and SK Innovation (nominal capacity 55.6 Ah) with NMC/graphite electrode composition were investigated. In total, 40 cells were tested at three different temperature levels: room temperature (RT = 25 °C), low temperature (LT = 15 °C), and high temperature (HT = 35 °C). Both cyclic and calendar aging were taken into account.

Each test case was developed individually in order to represent a specific operating point within the parameter space. The objective was to sufficiently test all operationally relevant aging mechanisms as well as user-oriented load cases in the context of electromobility. The long-term tests were implemented on three identical test benches consisting of a cell tester, climate chamber, and recirculating chiller.

Cell testers from the LBT21 product series by Arbin Instruments were used, featuring a usable voltage range of 0 to 5 V and a maximum current of 300 A. The climate chambers (ACS DM1200) with a volume of approximately 1 m³ enabled stable thermal test conditions at different temperature levels. Active cooling of the cells was realized through liquid cooling using recirculating chillers (Julabo FL) with a flow rate of 4 to 6 l/min. (Fig. 5).

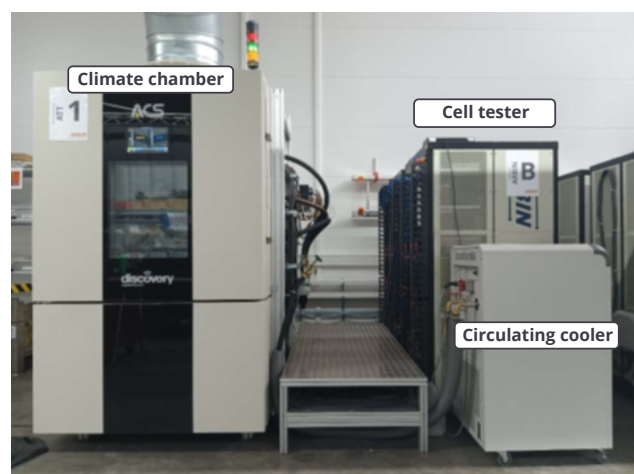


Figure 5: Test bench setup.

The electrical contacting and mechanical compression of the tested cells were implemented through an in-house design by in-tech GmbH. Via a modular cell compression fixture, the two current collectors of the test cells are contacted through copper busbars and connected to the power terminals of the cell testers through external screw connection points. For corresponding measurement accuracy according to standards, contact points for four-wire voltage measurement are provided. The cell is subsequently clamped between two laminate plates in order to prevent excessive volume changes of the cells during testing. Through integrated internal coolant channels and contact surfaces made of copper and aluminum, active cooling and therefore

targeted heat flows can be enabled in addition to the passive cooling of the climate chamber. The objective of active liquid cooling was to reproduce real systems and environmental conditions for battery modules as accurately as possible with regard to thermal management in electromobility applications. (Fig. 6).

new evaluation routines. This way of working accelerated development and facilitated documentation of the analysis processes. Extensions to the evaluation routines, such as monitoring Coulombic efficiency over the cycles or additional functions, can therefore be integrated easily.

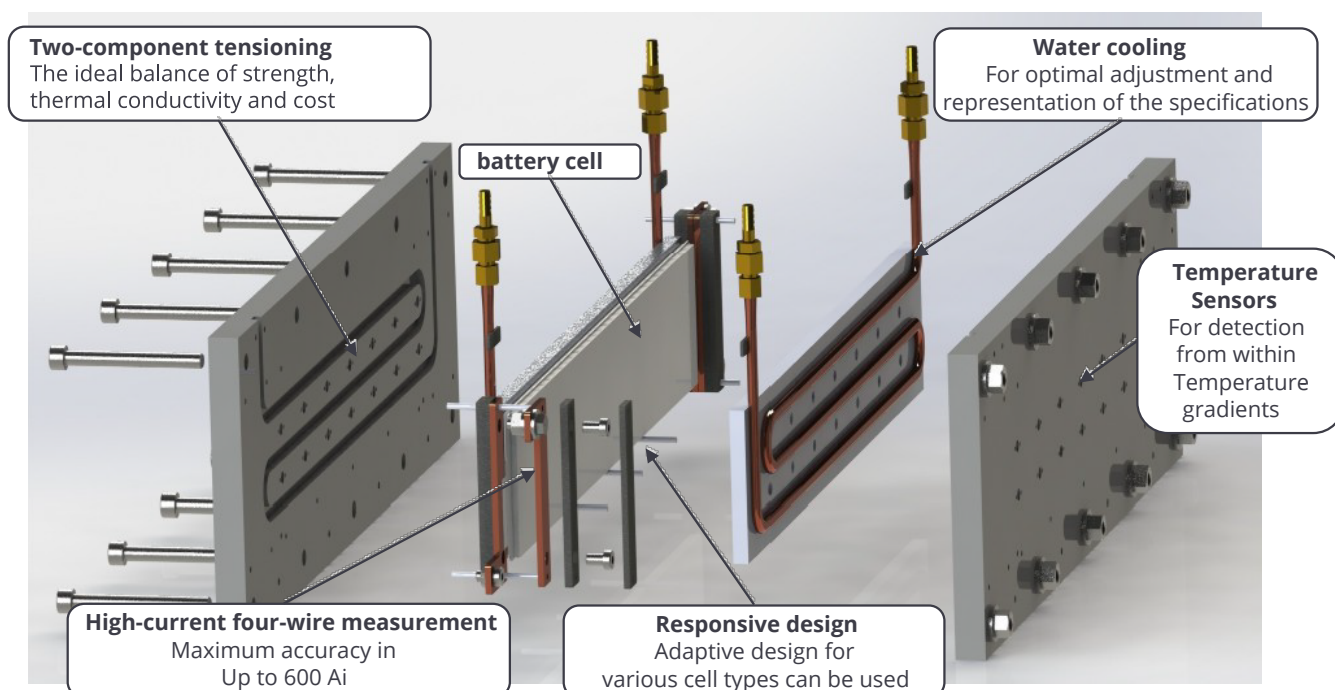


Figure 6: Structure of the cell compression fixtures with contacting and liquid cooling.

4. Measurement Data Analysis

4.1 Data Science

Python was used for evaluating the measurement data from the MTC long-term tests on lithium-ion cells. The combination of NumPy, pandas, SciPy, and matplotlib enabled efficient data preparation, analysis, and visualization of large measurement datasets. Through the use of Jupyter notebooks, the analysis process could be designed iteratively and transparently, which was particularly advantageous when validating intermediate results and developing

Automated data analyses during runtime additionally enable rapid determination of the current condition for monitoring the actual state.

4.2 Non-Invasive Test and Analysis Methods

Evaluation of the MTC long-term measurements was carried out exclusively using non-invasive methods of battery analytics. In contrast to invasive methods, which render a battery cell unusable for further operation, these analysis methods allow non-destructive, cost-effective, and reliable evaluation of cell aging over the entire service life.

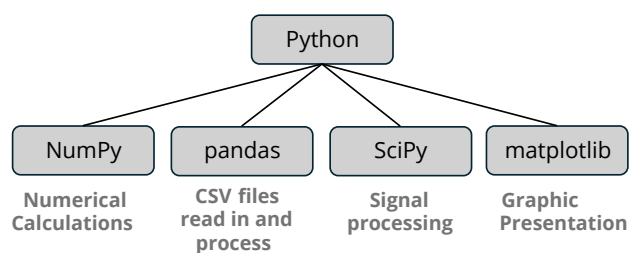


Figure 7: Representation of the Python libraries used within the scope of data processing.

Parameter Test

By conducting the so-called **Reference Parameter Test (RPT)**, the battery parameters at the time of testing can be experimentally determined. The RPT represents a standardized testing procedure. It consists of a sequence of complete charging and discharging phases followed by short current pulses. From the results, important quantities such as actual capacity and internal resistance can be derived from the cell behavior, which are subsequently required for determining the State of Health (SoH) of a battery cell (Fig. 8).

Differential Voltage Analysis (DVA) and Incremental Capacity Analysis (ICA)

The methods of DVA and ICA are based on differential evaluation of voltage curves from charging and discharging processes of lithium-ion cells under constant current. Depending on the chemical composition (e.g., LiFePO4 or LiNiMnCo) and proportional distribution (e.g., NMC333 or NMC622) of the electrode materials, these exhibit a voltage signature characteristic for the cell type. Through so-called OCV or pOCV measurement, the voltage characteristic of a lithium-ion cell can be represented particularly well.

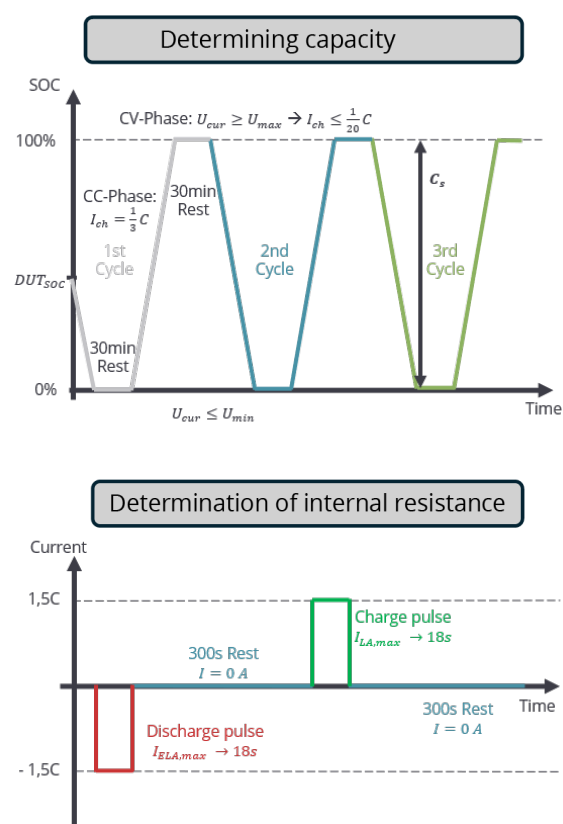


Figure 8: Sequence of the Reference Parameter Test (RPT).



OCV (Open-Circuit-Voltage)

The open-circuit voltage of a battery is described by the term Open-Circuit Voltage (OCV). It refers to the equilibrium state of the cell voltage in the current-free state. An approximation (pOCV) can be achieved through charging/discharging at very low current rates.

Aging of a lithium-ion cell leads to a lasting and progressive change of the OCV curve. However, these changes are often difficult to recognize with the naked eye. Through numerical differentiation of the voltage curves, these slight changes can be visualized and analyzed in amplified form.

Differential Voltage Analysis describes the derivative of voltage U with respect to charge Q . **Incremental Capacity Analysis**, with the derivative of charge Q with respect to voltage U , represents the reciprocal value of DVA. Both calculation methods therefore provide different approaches for representing the existing voltage signature of a lithium-ion cell. This enables the best possible condition assessment of the cell through complementary use of both analysis approaches (Fig. 9).

The extrema of DVA and ICA represent thermodynamic states within the lithium-ion cell, which can be assigned to phase transitions within the active materials of the positive and negative electrodes. A change in the extrema enables reliable analysis of the aging characteristics.

Through intermediate measurements, changes within the cell over time and/or cycles can also be visualized.

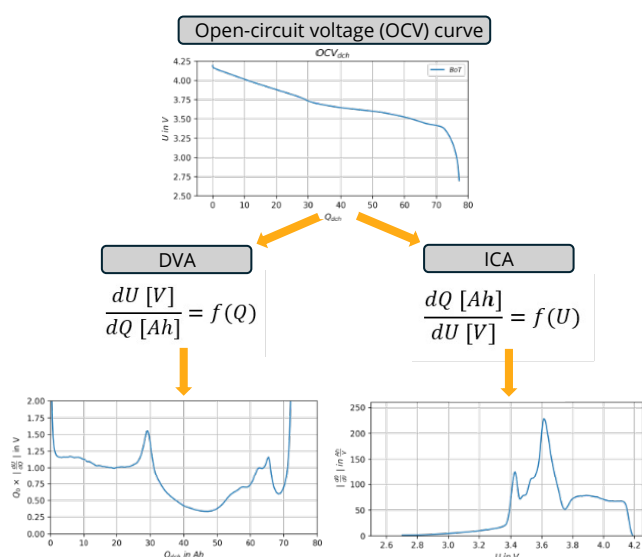


Figure 9: Calculation of differential voltage analysis and incremental capacity analysis from the open-circuit voltage curve (OCV) of a lithium-ion cell.

5. Results and Interpretation

A comprehensive evaluation of all test cases was carried out using the described non-invasive testing and analysis methods. By repeatedly conducting parameter tests (RPT) over the entire testing period, a meaningful representation of aging progressions could be achieved. For improved comparability, the total charge throughput of the two tested cell types was converted into equivalent full cycles.

In the analysis of aging modes and aging mechanisms using DVA and ICA, the two cell states before the beginning and after completion of the long-term tests were taken into account.

5.1 Cell Parameters

The test cells at high temperature were cycled over a testing period of 107 days. The aging behavior shows the expected deviations in the capacity behavior of the cells due to the individual design of the test cases. This indicates good coverage of the parameter space within the framework of parameter cycling (Fig. 10).

5.2 Aging Mechanisms

Based on the states of the lithium-ion cells before and after testing, extensive conclusions about the existing aging mechanisms can be drawn through changes in the characteristic features of Differential Voltage Analysis and Incremental Capacity Analysis. Taking scientific evaluation approaches into account, the observed changes can indicate loss of active material (LAM) at the negative electrode (NE) and positive electrode (PE), as well as loss of cyclable lithium ions (LLI). The different signal progression of the LG and SKI cell types is also clearly recognizable in both

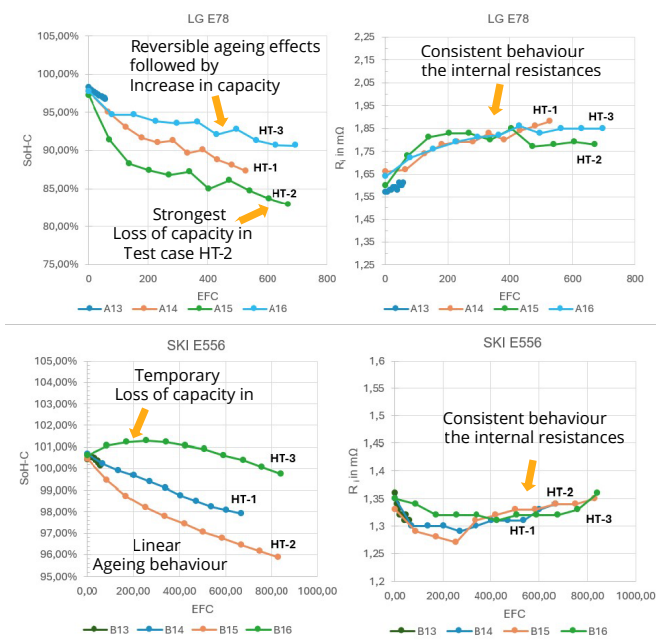


Figure 10: Representation of the cell parameters capacity (left) and internal resistance (right) for cyclic aging of LG cells (top) and SKI cells (bottom).

6. Summary

The investigations carried out show that targeted cycling for addressing individual parameters in combination with non-invasive analysis methods enables differentiated evaluation of the aging mechanisms of lithium-ion cells. Through targeted variation of individual stress factors, specific influences on cell aging could be identified and quantified. The methods used, particularly Differential Voltage Analysis and Incremental Capacity Analysis, allow non-destructive and continuous monitoring of cell condition over the entire life cycle. The findings obtained make an important contribution to optimizing testing strategies and developing longer-lasting battery systems for electromobility.

DVA and ICA. This can be explained by the different nickel contents in the positive electrode of the two cell types (Fig. 11).

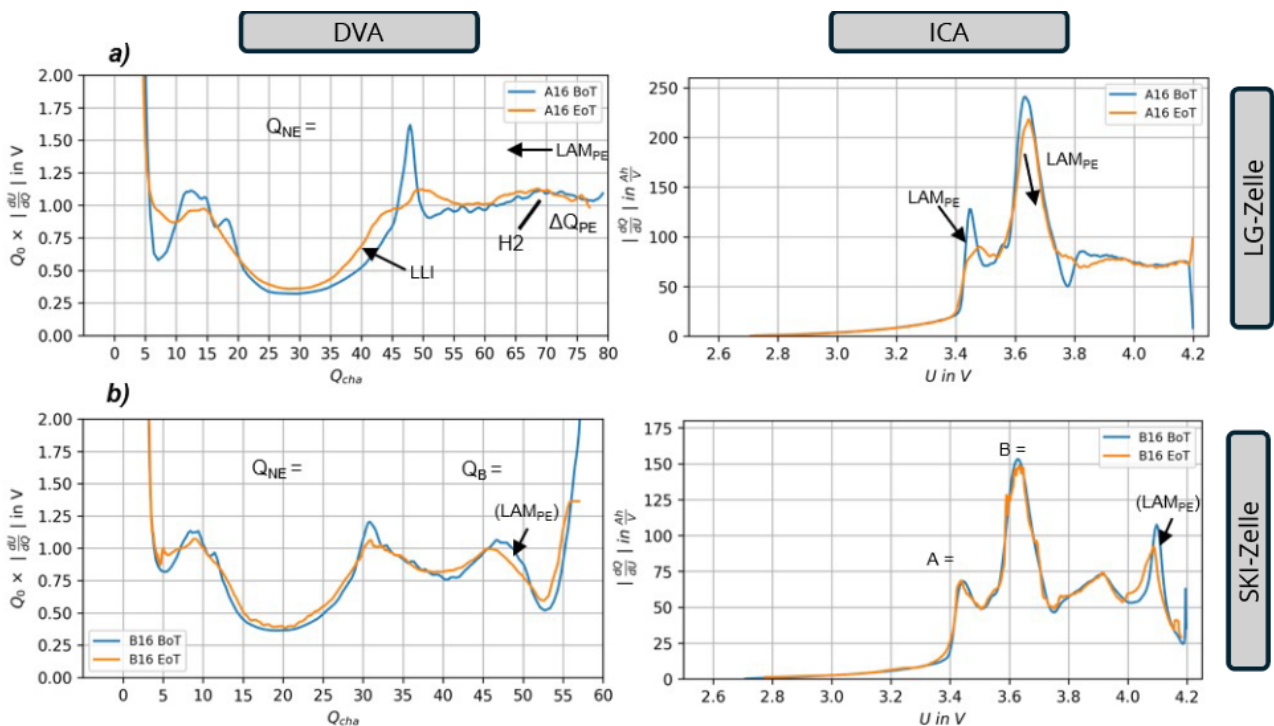


Figure 11: Graphical representation of DVA and ICA with the identified aging characteristics of a parameter cycling test case at high temperature (35 °C).

7. References

1. Barai, A. et al. (2019) „A comparison of methodologies for the non-invasive characterisation of commercial Li-Ion cells“, *Progress in Energy and Combustion Science*, no. 72, S. 1 – 31 [Online]. Available at <https://doi.org/10.1016/j.pecs.2019.01.001>
2. Bilfinger, P. et al. (2024) „Battery pack diagnostics for electric vehicles: Transfer of differential voltage and incremental capacity analysis from cell to vehicle level“, *eTransportation*, no. 22, S. 1 – 14 [Online]. Available at <https://doi.org/10.1016/j.etrans.2024.-100356>
3. Birkel, C. et al. (2017) “Degradation diagnostics for lithium ion cells“, *Journal of Power Sources*, no 341, S.373–386 [Online]. Available at <https://dx.doi.org/10.1016/j.jpowsour.2016.12.011>
4. Börger, A. and Wenzel, H. (2023) *Batteries: Fundamentals, Systems, Applications*, Weinheim, WILEY-VCH
5. Dubarry, M. und Anseán, D. (2022) „Best practices for incremental capacity analysis“, *Frontiers in Energy Research*, vol. 10, S. 1 – 18 [Online]. Available at <https://doi.org/10.3389/fenrg.2022.1023555>
6. Ehsan, R., Kerstin, S. and Moritz, V. (2015) *Compendium: Lithium-ion batteries: Fundamentals, characteristics, laws and standards* [Online], Frankfurt am Main, VDE Association for Electrical Engineering and Electronics. Available at: https://www.digitale-technologien.de/DT/Redaktion/DE/Downloads/Publikation/IKT-EM/ikt2-komp-lithium-ionen.pdf?__blob=publicationFile&v=4 (Retrieved on 13 June 2025)
7. Fath, J. (2021) *Modelling of lithium-ion batteries for life-cycle prediction with particular consideration of the anode overhang effect*, PhD thesis, Karlsruhe, Karlsruhe Institute of Technology [Online]. Available at <https://publikationen.bibliothek.kit.edu/1000139455> (Accessed on 26 June 2025).
8. Frey, D. (2025) *Study of the service life of lithium-ion cells – Evaluation of a novel ageing concept using non-invasive battery analysis methods*, Bachelor’s thesis, Ingolstadt, Ingolstadt University of Applied Sciences ¹
9. Gewalt, T. (2021) *Accelerated ageing characterisation of lithium-ion cells in automotive applications*, PhD thesis, Munich, Technical University of Munich [Online]. Available at <https://nbn-resolving.org/urn:nbn:de:hbv:91-diss-20211221-1600181-1-5> (Retrieved on 23 June 2025).
10. Holze, R. and Wu, Y. (2020) “Why do lithium-ion batteries age?” DOI: 10.1002/ciuz.201900044
11. ISO (2018) *ISO 12405-4:2018-07: Electrically propelled road vehicles: Test specification for lithium-ion traction battery packs and systems*, Berlin, DIN Media.
12. Kohs, A. (2022) *Battery model for predicting the health status of lithium-ion batteries*, Wiesbaden, Springer
13. Korthauer, R. (ed.) (2013) *Handbook of Lithium-Ion Batteries*, Berlin, Springer
14. Schreiber, M. et al. (2025) „Understanding lithium-ion battery degradation in vehicle applications: Insights from realistic and accelerated aging tests using Volkswagen ID.3 pouch cells“, *Journal of Energy Storage*, no 112, S. 1 – 16 [Online]. Available at <https://doi.org/10.14459/2024mp1748915>

¹Some passages have been taken from this paper, which was written as part of this research

Contact

Should you have any questions, please do not hesitate to contact us at sales@in-tech.com.

Contact Persons

Thomas Utzinger

Technical Director

E-Mail: thomas.utzinger@in-tech.com

Bernhard Vietz

Expert for Battery Testing and Battery Laboratories

E-Mail: bernhard.vietz@in-tech.com

David Frey

Test Engineer

E-Mail: david.frey@in-tech.com