Quality Assurance for Lithium-Ion Batteries Using EIS

Whitepaper

Executive Summary

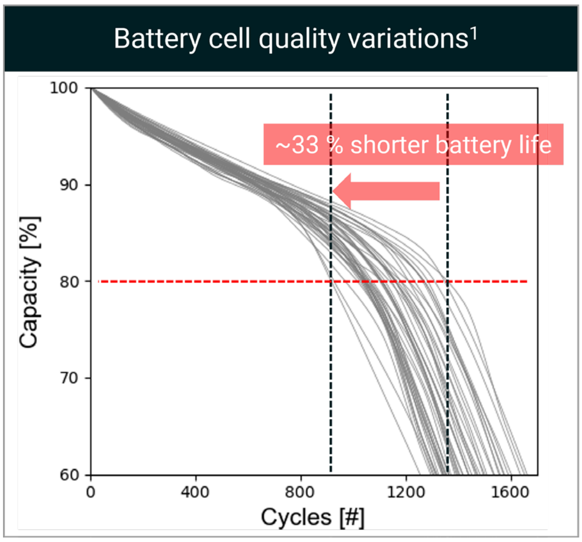
Lithium-ion batteries are developing into a widely used technology in the field of electromobility, defense and stationary energy storage owing to their high energy density and low associated costs. However, recent incidents such as rapid failure of battery packs, fire-safety issues and damage to battery packs by fast-charging have harmed brand reputations of cell manufacturers and OEMs. Majority of such incidents are a result of poor cell quality and ineffective quality-detection methods adopted as the industry standard. Real-time electrochemical impedance spectroscopy (RT-EIS) by far supersedes the existing quality-detection methods in the most important metrics - speed, accuracy, robustness and operational costs. Combined with the power of intelligent algorithms, machine-learning and digital twin modelling, the impedance data of batteries can be automatically analyzed to effectively assess the quality of lithium-ion batteries and predict the electrical, thermal and aging behaviour of cells. When RT-EIS is further integrated into a standardized and scalable quality assurance system, cell manufacturers and OEMs can ensure the safety of their battery systems and reduce the warranty and maintenance costs, thereby maintaining a stellar brand reputation and smooth operation of a profitable business model.

Introduction: Varying Cell Qualities

Rising global concerns for climate change and the need to shift to renewable energy sources have shown that batteries are becoming an intricate part of our existing and future infrastructure in all sectors including power systems, transport, defense and agriculture. However, in large systems such as electric vehicles, aircrafts and maritime as well as grid energy storage, battery packs are the most expensive component and are critical for safe and reliable system operation.

As electrochemical systems, batteries suffer from both energy and power fade inevitably during usage and storage, which are reflected by the capacity loss and resistance increase. Apart from the capacity fade, power fade may also cause critical performance degradation in some applications, e.g. heavy duty vehicles, trains, and aircraft. Even for electric passenger vehicles, increasing attention is paid to the negative implications of the power degradation with respect to internal resistance increase on fast charging and thermal management. The battery cells with identical capacity fade may have entirely different capacity end-of-life due to the difference in power fade, vice versa.

Due to their complex chemical and mechanical composition, battery cells can never be manufactured in constant quality. At the same time, battery-powered products usually have very precise demands on the performance and service life of each individual cell used. Varying cell qualities not only affect the performance, but also the safety of battery-powered products. An accurate prediction of the performance degradation of each battery cell in the battery pack is of crucial importance for both first- and second-life applications, as the lifetime of the whole pack is determined by the worst cell. The safety issue of only one cell can even cause a thermal runaway of the whole battery system. Thus, it is imperative that high-quality cells are selected at the very beginning of the chain of pack design to avoid pack-replacement or repair costs and downtime and to ensure proper warranty assignment, maximum customer satisfaction and a stellar brand reputation.



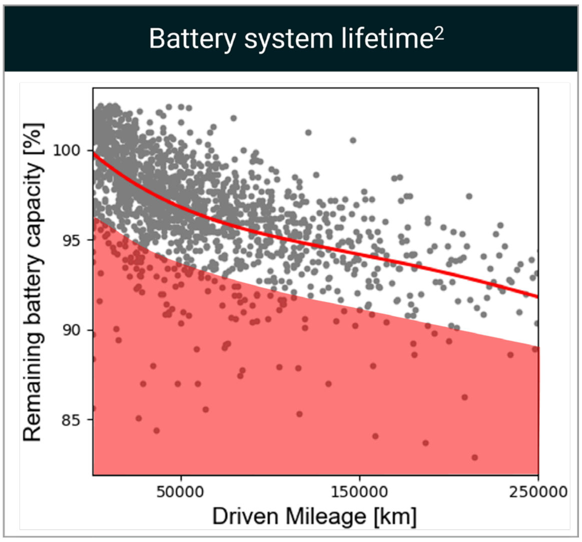


Figure 1: Effect of weak battery cells on battery system lifetime

As seen in figure 1, production-induced inhomogeneities can result in significant deviations in the lifetime of battery cells even though they exhibit similar behavior at the beginning-of-life (BOL). When assembled to battery modules and packs, these quality deviations are carried over. The example of Tesla EVs on the right shows how many vehicles' driving ranges fade significantly after a very short time, due to just a few inferior cells jeopardizing whole battery systems. These vehicles fail to meet their lifetime warranty resulting in added costs and tarnished brand reputation for the OEM.

1 Data source: T. Baumhöfer et al. / Journal of Power Sources 247 (2014) 332e338
2 Data source: https://electrek.co/2018/04/14/tesla-battery-degradation-data/ and own modifications

Background: State-of-the-Art for Battery Testing

Different technologies have been adopted on production lines to gauge the electrical performance of lithium-ion cells. Electrical methods can directly assess the electrical properties of batteries, which is the primary focus of businesses who wish to maximize the power delivering capability, voltage levels and the remaining lifetime of batteries. Additionally, such methods can detect the presence of mechanical faults and issues caused within cells during production processes. Among the most common methods used are open-circuit voltage (OCV), 1kHz resistance, pulse-resistance as well as initial cell capacity measurements and self-discharge tests. A comparison has been drawn against the key metrics of assessment - speed, robustness, cost, lifetime estimation and accuracy of performance assessment.

1kHz resistance measurement

The measurement of the cell's AC internal resistance at 1kHz is a widespread quality assessment technique. This is due to its high relevance in the determination of the State of Health (SOH) of lead-acid batteries, which are typically used to crank internal-combustion engines. A 1kHz AC sinusoidal current mimics a part of the cranking procedure, thereby making the 1kHz resistance a reliable attribute for quality assessment of lead-acid batteries. However, its variation within a production lot of lithium-ion cells is insufficient for differentiating good and bad cells.

Open circuit voltage measurement

OCV is defined as the variation of the equilibrium voltage of a cell with its state of charge (SOC). It is dependent on the individual electrode potentials of the anode and the cathode within a cell under no-load conditions. As OCV constitutes only a single voltage measurement, it is not a reliable indicator of the estimated lifetime and performance of cells. A significantly low OCV may be a sign of high self-discharge of a cell, but could also be induced by inaccuracies in setting the SOC of cells in different production batches during the cell formation process.

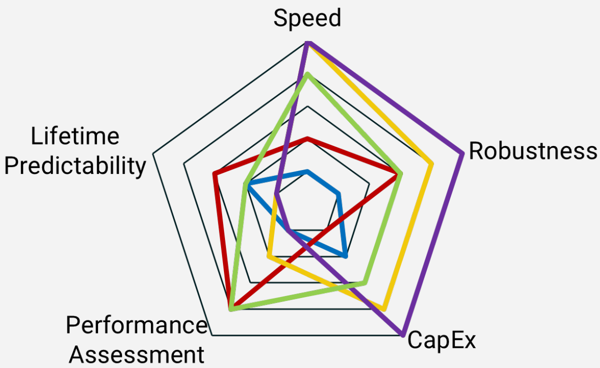


Figure 2: Battery assessment methods in comparison

Capacity test

Initial capacity tests determine the available discharge capacity of cells at the beginning-of-life (BOL). However, it is not a sufficient determinant of cell quality due to its weak correlation with the degradation trajectory, and in turn, the end-of-life (EOL) of cells. High-current discharge of cells also limits the accuracy of performance assessment owing to cell-discharge under conditions different from the actual application and time-limitation that will allow screening of randomly sampled cells instead of each incoming cell.

Self discharge test

Self-discharge rate is the loss in the SOC due to internal reactions between the electrodes of a cell. It is determined by taking multiple OCV measurements over time. Although self-discharge of a cell is correlated to some degree to cell quality, the tests can last up to several weeks, since new lithium-ion cells have an average self-discharge rate between 0.5-3% per month. The dependency on temperature is an added complexity, since different batches of cells stored for several weeks can have a huge impact in terms of floating temperatures at different points of time unless constant storage temperature is ensured.

Pulse resistance measurement

Pulse resistance tests determine the DC internal resistance (DC-IR) of cells. Current pulses (0.5C to 1C) are applied to cells for typically less than 1 minute to obtain the voltage used to calculate the DC-IR. Problematically, the large current applied for such a duration inflicts differences between the true and measured resistance values. Additionally, cells with higher DC-IR heat up more than others, resulting in non-uniform deviations in measured DC-IR. This blurs fine differences between the measurements that are crucial to qualitatively segregate cells.

New Method: Real-Time Electrochemical Impedance Spectroscopy

Impedance is defined as the resulting opposition to the flow of current offered by a circuit's resistance and reactance. The impedance of a battery has significant influence on its future performance and can be considered as the battery's fingerprint. Among the various widely used methods, electrochemical impedance spectroscopy (EIS) can provide the battery impedance for a wide range of frequencies. Based on the measured impedance data, the values of the elements of the equivalent-circuit model of batteries have a direct correlation with the real-time performance, and after processing, potentially, the remaining lifetime of batteries. However, classical EIS measurement also involves some challenges when it comes to consistency and time effort.

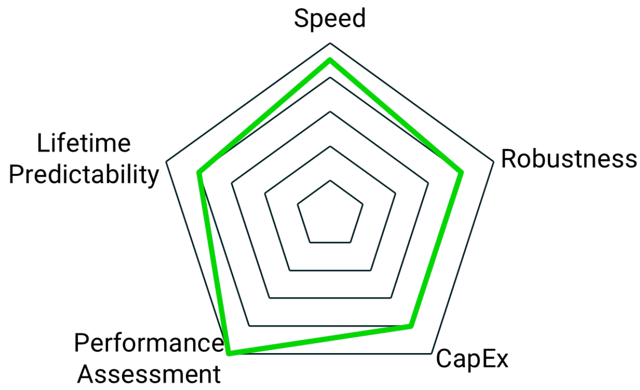


Figure 3: RT-EIS battery assessment overview

While reaching near-perfect precision and accuracy, the classic technology takes several minutes for a singe cell. Safion's real-time EIS (RT-EIS) method uses superimposed excitation to measure up to 32 impedance points simultaneously. This reduces the measurement time from minutes to seconds, enabling a high throughput. Special hardware components and a strict measurement procedure can ensure a consistently high accuracy.

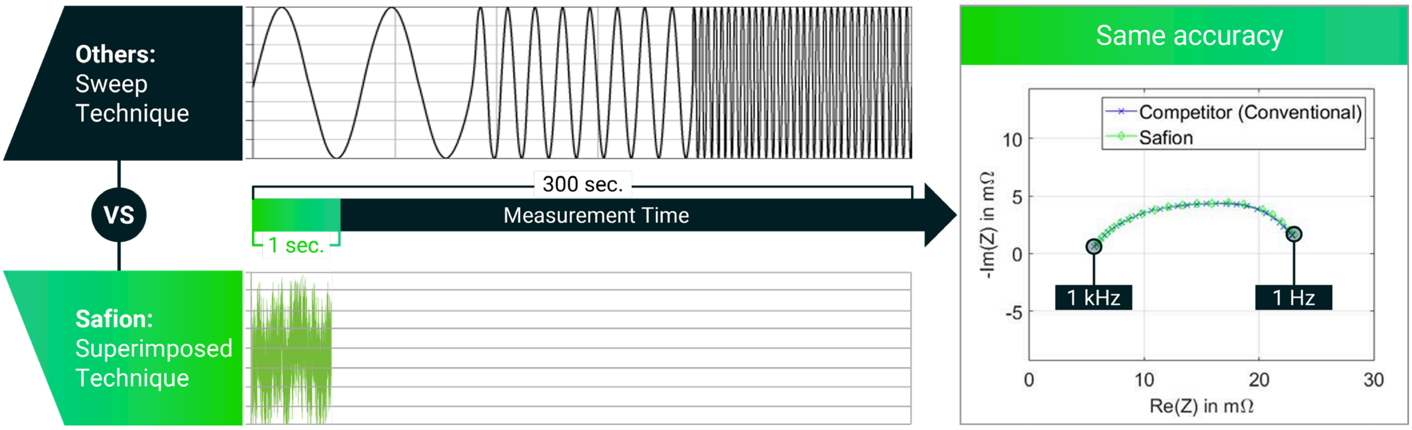


Figure 4: Superimposed RT-EIS measurement technique

Essentials for EIS Measurements

An impedance spectrum of a cell is a set of impedances obtained at different AC frequencies. Typically, an impedance spectrum is expressed as a complex quantity with real and imaginary parts and is therefore best represented in the form of Nyquist plots. EIS measurements are highly sensitive to temperature, SOC as well as hardware-related faults. To obtain an accurate and reproducible impedance spectrum of each cell inspected, being wary of the quality and layout of hardware components as well as possible sources of error is essential. Hardware-related aspects such as contacting heads to cell terminals, lengths of cables for the application of current and measurement of corresponding cell voltage, cable routing and their electrical and electromagnetic insulation are most prone to introduce measurement errors. Furthermore, device calibration and the choice of current amplitude and frequencies play an important role in EIS measurements. Finally, since EIS measurements are highly sensitive to temperature, arrangements should be made to record and store temperature data along with the impedance data. This necessitates incorporating additional hardware to measure temperature and techniques to prevent the creeping of measurement errors.

Analyzing EIS Spectra to Assess Battery Quality

If RT-EIS techniques are implemented and essentials for EIS measurement are ensured, it is possible to swiftly obtain reproducible impedance spectra of cells. However, production environments require the transformation of mere EIS measurements into a reliable, consistent and automated quality assessment solution. This is important for all OEMs whose primary focus lies on the high throughput of their production lines to meet the fast-growing demand for LIB products while at the same time minimizing the costs incurred due to incorrect warranty assignments.

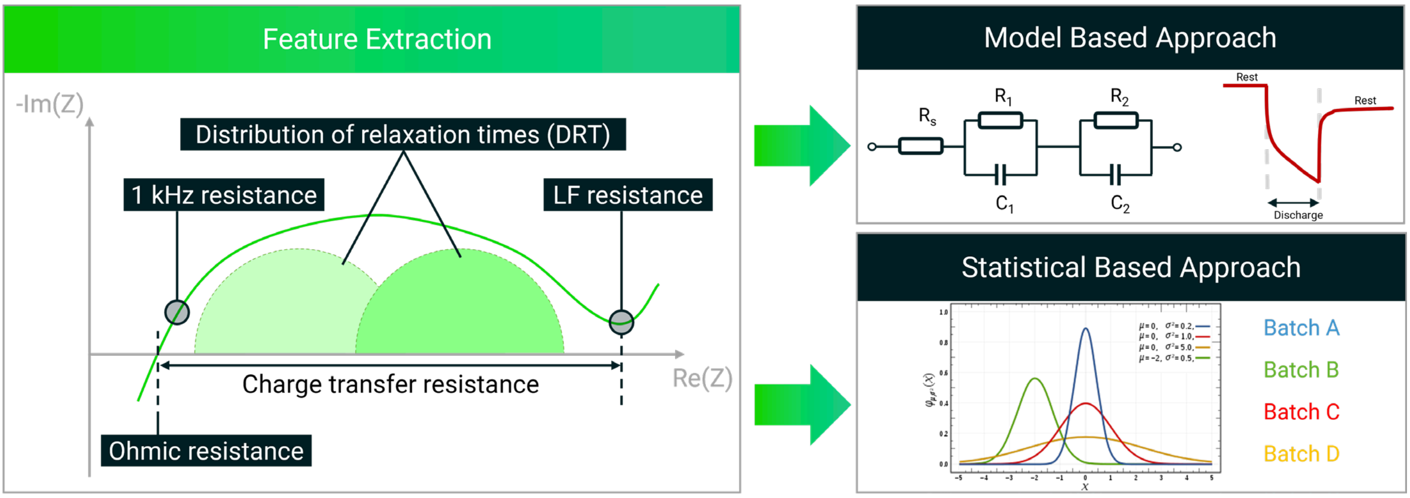


Figure 5: Battery quality assessment process from EIS data

Feature extraction

The first step is defining the quality criteria that form a basis for the segregation of high- and low-quality cells. The raw impedance spectrum of a cell is complex for direct analysis and can be non-intuitive and incomprehensible to users without sufficient domain knowledge. Hence, the impedance spectrum should be simplified into independent features that can help clearly distinguish between qualitatively different cells. These features directly correlate with important quality metrics such as the ohmic resistance of cell materials, resistance offered by the cell under operation and power losses under different application conditions. Furthermore, these features can be incorporated into a digital twin of the cell that can serve as a basis for a deeper insight into its electrochemical and thermal dynamics.

Model Based Approach (Digital Twin)

By bridging the physical and the virtual world, the digital twin allows the monitoring and deep understanding of the internal states of the batteries by modeling the battery behavior based on the data. With the measured impedance data, the parameters of the battery model can be identified and the battery dynamics can be modeled in the cloud. With the battery diagnostic algorithms, the battery digital twin can not only show the data measured by sensors in battery packs but also visualize the internal state of each battery cell accurately as a result of an accurate parameter identification based on the impedance data.

Statistical Based Approach

Not only the capacity data but also the impedance data of battery cells in different production batches show significant variations between cells, leading to the performance variances in deliverable energy and power. As the worst battery cell usually determines the performance of the battery module, the large variation will lead to the energy and power fade of the whole system. Therefore, it is necessary to analyze the production variations statistically before the integration of the battery cells from different batches into the battery system. The monitoring of the production variances based on the impedance data will also provide a statistical way for the long term evaluation of the supplier quality.

Power loss calculation / heat generation assessment

The impedance of a battery has a direct correlation with its power ability. The impedance growth directly has an influence on both charging and discharging power of a battery cell and reduces the maximum power that can be delivered by the battery. With a higher initial impedance, the battery cell will generate more heat during operation under the same load profile. The generated heat will further increase the cell temperature and lead to a higher rate of impedance growth and therefore further accelerate the degradation. Therefore, the impedance data can be used as important information for the estimation and prediction of the power loss.

Lifetime prediction

The values of the elements of the battery model obtained from the analysis of impedance data has a direct correlation with the real-time performance, and after processing, potentially, the remaining lifetime of batteries. Power fade and capacity fade will accelerate each other and together reduce the lifetime of the battery cell and lead to the degradation in performance. Aging tests can also be carried out in the laboratory to understand the cyclic and calendric aging behavior of the battery cells. By analyzing the correlations between the impedance data of the battery cells at the begin of life with the cyclic aging data, the lifetime of the battery cells can be predicted based on the impedance data, even at the early phase of the battery life, using machine learning models.

Quality Assurance System for Incoming Cell Inspection

A quality assurance (QA) system should consider several aspects that determine its efficacy. Three key features crucial for the assessment and handling of incoming cells within a production environment are:

– 100% testing

This implies that each cell entering the inspection line should be evaluated. The importance of 100% testing has been iterated previously – a single inferior cell leads to sub-par functioning of an entire battery module or pack. Therefore, a contacting system is needed that is capable of processing a high number of cells within a short duration.

– Automatic quality assessment and grading

The quality assurance system should have the provision of requirement- or statistics-based cell grading. The requirement-based grading focuses on the application for which the cells would be used. The cells can be segregated based on the set of features of the impedance spectrum relevant to the performance of the cells in different applications, e.g., aviation, e-cigarettes, electric vehicles, etc. statistical based quality acceptance allows the QA system to grade cells from production batches of cells and place them under different categories. This allows the selection of uniform-quality cells for customer applications.

– Complete traceability

It is of paramount importance to put in place an additional system for complete traceability of cells. This is especially helpful in handling of warranty claims of battery packs that underperform in terms of lifetime. The cells from battery packs that prematurely reached end-of-life can be traced back to the initial reports which can be instrumental in diagnosing unexpected cell-characteristics. This diagnosis can then be used to fine-tune the QA system to detect such anomalies or changes.

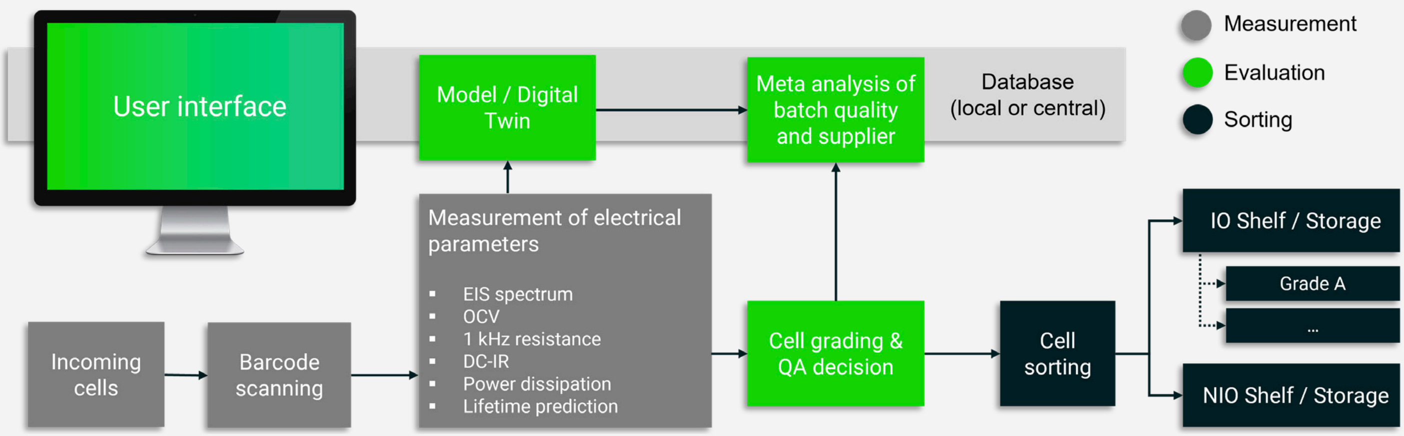


Figure 6: Ideal process for incoming cell inspection and battery quality assurance

Figure 6 shows an ideal process for quality assessment of incoming cells operated and monitored via a digital user interface. The beginning of the line is the measurement phase in which the cell is documented, the measurement signal is generated and the raw data is captured. In the following evaluation phase the raw data is processed, cells are graded and the decision is made to accept or reject it based on predefined thresholds. Additionally, the measured data is stored and modeled within a database as well as compared to already measured cells to perform a meta-analysis of the supplier and cell quality. Finally, in the sorting phase, the cells processed during the evaluation phase are segregated and assigned to be put into 'In Order (IO)' or 'Not In Order (NIO)' shelves.

Conclusion

With the growing global demand for lithium-ion batteries and the increasing number of players in cell-manufacturing and battery systems development, there exists in parallel a growing necessity for accurate inspection of cell quality. Electrochemical impedance spectroscopy (EIS) provides detailed insights into lithium-ion batteries more than the current industry standard of quality assessment. If the laboratory-based technique is modified into a real-time solution for production lines, EIS can be leveraged for obtaining high accuracy and short measurement time in cell inspection. The quality assessment solution should be able to automate all intermediate processes such as feature extraction from raw measurement data, creation of digital twins of cells and intermediate data analysis and storage of all data for every cell, providing complete traceability at every stage. The output of this solution can comprise of the cell quality, heat generation and remaining lifetime. This guarantees that only the cells having high and uniform quality are used in field applications and in turn, allows OEMs to ensure safety of their products, assign proper warranties and maintain their brand reputations.

About Safion

Safion is a leading provider for quality assessment and diagnosis of prototype and commercial lithium-ion batteries. We supply stand-alone and fully integrated production line systems for quality, safety and performance controlling as well as supplier assessment in the fastest, most accurate and most cost-effective way. This enables customers along the whole battery value chain to achieve significant technological performance improvements as well as cost and resource savings.

As developer of the Real-Time-EIS technology, Safion is in the forefront of battery quality assurance and provider of the first process-oriented solution for precise industrial cell screening. At the heart of these solutions is the ExaMight, Safion’s turn-key solution with scaling options from low to high throughput.

Schedule a demonstration!

You would like to see how to assess battery cells with Real-Time EIS live in action? Our team will be happy to show you through all functionalities of the ExaMight quality assurance system and answer your questions. Get in touch with us to schedule a web or in-person demonstration.

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