DETECTION OF ELECTRICAL ABUSE IN EV LIB CELLS

Mandlaenkosi Mthetwa[1], Ethan Kohrt[1], Nenad Nenadic[1]
[1]Rochester Institute of Technology, 1 Lomb Memorial Dr, Rochester, NY 14623

Primary Topic Area: Innovative Remanufacturing Technologies
Secondary Topic Area: Building a Sustainable Circular Economy for Materials & Products

Abstract

In addition to the need for accelerated estimation of the state of health (SOH)—specifically, the remaining capacity—of electric vehicle (EV) lithium-ion battery (LIB) modules at the end of life (EOL) in their primary applications, successful repurposing of these modules for secondary, less demanding uses requires the ability to detect prior abuse that could lead to thermal runaway (TR). Detecting abuse is more critical than estimating capacity fade, as the testing process may trigger TR in a previously abused module during capacity evaluation. Among the three mechanisms of TR—thermal, mechanical, and electrical—electrical abuse is the most difficult to detect retrospectively. This manuscript reviews the state of the art in detecting and empirically testing for TR, and presents an empirical study investigating electrical tests for identifying prior electrical abuse. Experiments were conducted at the cell level to minimize the risk of energy release during TR, as the tests were designed to push the cells to the edge of failure. Cells from the same module were extracted and divided into two groups: one subjected to overcharge, and the other to overdischarge. Both groups were subsequently evaluated within normal operating voltage ranges. The primary approach in this study was to analyze the transient voltage response during rest periods following pulsed charging. This method was chosen because rest periods allow the cell to stabilize, revealing subtle electrochemical changes that may indicate prior abuse. Multiple rest periods were incorporated intentionally, as used modules—especially those with a history of abuse—can arrive at varying states of charge (SOC). Each rest period corresponded to a different SOC level, enabling the detection of anomalies across a broader operating range. Furthermore, this design increases the likelihood of identifying abuse-related signatures that may only manifest under specific SOC conditions.

Keywords: electric vehicles, lithium-ion batteries, second-life batteries, transient response, abuse, thermal runaway

Introduction and Motivation

Climate change mitigation has driven policy adoption across many sectors, with transportation leading efforts to cut emissions. Falling lithium-ion battery costs—dropping from US$732 to US$152 per kWh in the past decade [1]—have accelerated electric vehicle (EV) adoption, especially in developed countries [2], [3].

Despite these advances, battery safety remains critical. Performance issues have led to recalls and fire incidents worldwide, including EV and HEV fires in China (2016) and the U.S. (2008, 2011) [4], [5], [6]. Improving battery safety is essential to boost consumer confidence and EV adoption. Original equipment manufacturers (OEMs) must meet safety standards through rigorous testing, yet failures still occur [7]. Battery safety remains a critical concern in retired EV batteries, as they often serve in secondary applications, but they are sometimes marketed as new, creating expectations for reliability.

A single cell's thermal runaway (TR) can ignite an entire pack, making TR risk assessment vital for both first- and second life battery (SLB) uses. TR typically results from mechanical, electrical, or thermal stress [8]. Chemistry also affects thermal resistance, a topic explored later. Detecting conditions that precede thermal runaway (TR)—such as thermal onset—is key to prevention [9]. Mechanical stress is easy to identify, and extreme thermal stress is rare in normal operation. Electrical stress, however, plays a major role during battery use and repurposing. Charge and discharge currents vary widely, making their impact critical for predicting retired battery performance.

This study focuses on TR initiation under electrical stress in lithium-ion batteries. The goal is to review how electrical stress can reveal TR precursors at the cell, module, or pack level. The following sections examine stress factors, with emphasis on electrical stress.

Review of Related Work

TR is a leading cause of EV battery fires. TR occurs when exothermic reactions inside a cell escalate, generating extreme heat that can ignite adjacent cells [10]. Separator failure typically initiates TR by creating an internal short circuit, which triggers these reactions. A battery cell comprises an anode, cathode, electrolyte, and separator. When the separator is compromised, direct contact between electrodes induces heat-producing reactions that may lead to TR. Preventing such failures is critical for safety.

EV batteries are generally replaced when capacity falls to 80%, as range becomes inadequate [11]. Circular economy strategies increasingly repurpose these batteries for less-demanding applications. By 2030, roughly 1000 GWh of retired EV batteries will be available for reuse [12]. These batteries are often marketed as new, making thermal performance assessment essential, especially since prior degradation can affect safety.

Repurposing costs vary by level: US$29/kWh for packs, US$55/kWh for modules, and US$69/kWh for cells [13]. Testing typically occurs at the module level due to cell-level disassembly challenges. Initial screening uses electrochemical impedance spectroscopy (EIS) and transient analysis, which are faster and cheaper than full capacity tests. Modules failing these tests are redirected to low-end uses, while those passing undergo capacity testing for high-end applications; unsuitable units are recycled [12].

TR-inducing stresses

TR is induced by three types of stresses: mechanical, thermal, and electrical stress, as shown in Figure 1.

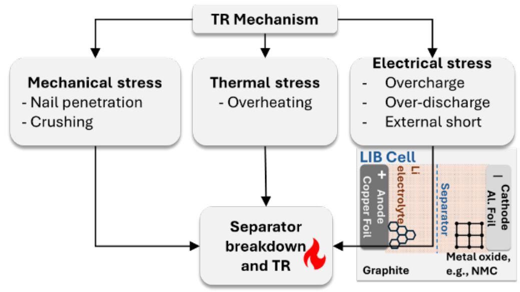


Figure 1: TR mechanisms and simplified LIB cell

Mechanical stress refers to physical damage to a cell, such as nail penetration, crushing, or accidental dropping of a cell, module, or pack [18]. Nail penetration compromises the separator and creates an internal short circuit that can initiate TR [19]. Crushing can cause similar separator damage and can also trigger TR, as shown in prior studies [19], [20]. Robust cell and pack enclosures are therefore essential to prevent mechanical damage and reduce associated risks [21]. Because mechanical damage typically affects the exterior of the battery, it is usually identifiable through visual inspection. As a result, detecting mechanical stress during EV battery repurposing is generally straightforward.

Thermal stress results from high-temperature storage or exposure to heat, cold, burns, or radiation. TR occurs when external heat degrades the separator inside a cell, creating a conductive path between the anode and cathode and leading to an internal short circuit [16]. At low temperatures, the electrolyte begins to solidify, restricting electron mobility. This restriction increases the cell's internal resistance and raises its temperature, which can initiate TR [17]. At high temperatures, the energy threshold for internal reactions may be reached, triggering a sequence of exothermic reactions that culminate in TR. Such reactions at both temperature extremes can pose significant hazards. Retired EV batteries may have experienced thermal stress during their first life, leading to internal degradation that could more readily trigger TR and affect performance. Therefore, maintaining battery cells near room temperature is essential to mitigate these risks.

Electrical stress arises during cell operation and is driven by conditions such as overcharging, over-discharging, and external short circuits [16], [22]. It is more difficult to detect than mechanical or thermal stress because it depends on internal cell behavior that can only be observed during operation. As the cell functions, its state of charge (SOC) continually changes. SOC represents the amount of charge in the cell relative to its capacity and is expressed as a percentage between fully discharged and fully charged conditions. Internal characteristics such as impedance vary with SOC and also evolve with degradation. These changes are particularly significant in retired EV batteries, where internal conditions often vary widely from cell to cell. As degradation progresses, variation within the pack increases, making parameters such as internal impedance especially important to monitor. Elevated impedance causes greater internal heating, and this heating can initiate TR.

Overcharging occurs when SOC $> 100\%$, potentially reaching dangerously high levels and causing TR. The same risk applies to overdischarging, where discharging below the specified threshold can also lead to TR. Therefore, monitoring overcharging and overdischarging situations is essential to detect early signs of TR and prevent this hazardous occurrence.

Table 1 TR onset SOC values for various chemistries

Chemistry	TR SOC (%)	Source
NMC-111	180%	[22]
LFP	127%	[16]
NMC-811	133%	[16]
NMC-622	139%	[16]
NMC-111	156%	[16]
LFP	Lower stability implied	[16]

In current literature, there is a predominance of experimental overcharging of cells, with various studies focusing on cells of different chemistries and charge and discharge currents [16], [22]. The researchers observed that the voltage during overcharge increases to a certain point before plateauing and eventually rising again when TR occurs. Reported TR thresholds differ significantly across studies. Yuan et al. [22] identify TR onset for nickel-manganese-cobalt (NMC)-111 at 180% SOC, while Wang et al. [16] report notably lower thresholds—127% for lithium-iron-phosphate (LFP), 133% for NMC-811, 139% for NMC-622, and 156% for NMC-111. Additional findings suggest LFP may exhibit lower thermal stability than often assumed. These discrepancies underscore the strong influence of manufacturing differences and experimental conditions on TR behavior. To our knowledge, no studies have examined overdischarge or external short circuits as direct pathways to TR. Accordingly, a portion of our experimental effort focused on deep-discharge testing.

Early indicators of potential TR include gas release from the cell [23], [24], [25]. Studies on LFP cells subjected to overcharging at different current levels (corresponding to 0.25C, 0.33C, 0.5C, 0.75C, and 1C) have identified four distinct stages of TR, including an initial gas-generation stage that may support early detection and prevention strategies [23], [25]. These experiments also show that increasing the charging current raises the likelihood of rapid TR onset [23], a trend consistent with other observations on NMC LIBs [24], [25]. Higher charging currents accelerate electron transport within the cell; for retired EV batteries, which typically exhibit increased internal resistance due to aging, this acceleration further elevates the risk of heat generation. Consequently, assigning SLBs to applications with lower current demands (preferably below the manufacturer's original specifications) is recommended. Furthermore, because impedance can vary significantly among retired cells, grouping batteries with similar impedance characteristics can improve both safety and operational performance. Batteries with higher impedance should be deployed in less demanding applications, whereas lower-impedance units can support comparatively higher loads. Table 2 summarizes the relationship between overcharge C-rate and thermal runaway (TR) behavior in lithium-ion cells, synthesized from experimental gas detection data [23] and electrochemical-thermal modeling [25].

Table 2: Cathode chemistry influence on thermal runaway behavior in lithium-ion cells

Overcharge C-rate [C]	Onset SOC [%]	Side Reactions Begin SOC [%]	Gas-Generating Reactions (in sequence)	Gas Species Detected
0.25	No TR up to 180	Not reported	Electrolyte oxidation occurs but insufficient heat for TR	H_2 only (limited)
0.33	167.4	≈ 120	(1) Li + electrolyte → H_2; (2) Electrolyte oxidation → CO_2/VOC; (3) SEI decomposition	H_2 → VOC → CO
0.50	167.0	≈ 120	(1) Li + electrolyte → H_2; (2) Electrolyte oxidation → CO_2/VOC; (3) SEI decomposition	H_2 → VOC → CO
0.75	Not reported	≈ 120	(1) Li + electrolyte → H_2; (2) Electrolyte oxidation → CO_2/VOC; (3) SEI decomposition	H_2 → VOC → CO
1.00	165.2	≈ 114	(1) Li + electrolyte → H_2; (2) Electrolyte oxidation → CO_2/VOC	H_2 → VOC → CO

The internal resistance of a battery depends on its state of charge, temperature, and degree of degradation [26]. As cells age, their internal resistances gradually diverge. During an external short circuit, where the cathode and anode are connected through a path of extremely low resistance, a large current flows between them, leading to rapid heating and potentially triggering TR. Yuan et al. report that a cell's internal resistance can increase by a factor of five to seven during TR, illustrating the strong influence of temperature on internal electrochemical reactions [22]. Spinner et al. have proposed that this increase in internal resistance may be used with electrochemical impedance spectroscopy (EIS) to detect the onset of TR [27], since resistance rises as TR becomes more likely. Variations in the internal impedance of retired EV batteries may therefore influence the severity of TR.

Factors that affect TR

In addition to external stresses, TR is influenced by several internal factors, including cathode chemistry, state of charge, temperature, and cell geometry (pouch, cylindrical, or prismatic) [16], [23], [28]. These factors affect both the likelihood of TR and the maximum temperature reached during the event.

Table 3: Cathode chemistry influence on thermal runaway behavior in lithium-ion cells

Factor	**Details**
Cathode chemistry	LFP, NMC (111, 622, 811), LTO, LMO, LCO
Stability Ranking (most → least)	LTO > LFP > NMC > LMO > LCO
Effect of Nickel Content	Higher Ni NMC → reduced thermal stability
Safety in Industry Practice	LFP (adopted in Tesla EVs)
Dominant End-of-Life EV Chemistry	NMC needs careful thermal evaluation before repurposing
SOC & TR Severity	Higher SOC → more stored energy → more severe TR
Key Implication	Thermal stability vs. capacity fade must be understood for safe second-use

Battery chemistry is a critical factor influencing TR. The cathode material defines the cell chemistry, with common variants including LFP, NMC, lithium titanate oxide (LTO), lithium manganese oxide (LMO), and lithium cobalt oxide (LCO). As summarized in Table 3, thermal stability varies significantly across chemistries, with the general ranking from most to least stable being LTO, LFP, NMC, LMO, and LCO [16]. Compositional differences within the same chemistry can also alter thermal behavior — for example, higher nickel content in NMC variants is associated with reduced stability [16]. In industry practice, LFP is often regarded as one of the safer chemistries, a trend reflected in its recent adoption in Tesla vehicles [29]. Because most EV packs reaching end of life today are NMC-based, careful evaluation of their thermal behavior is necessary before repurposing, as their thermal capability may limit suitability for certain second-use applications. Therefore, understanding thermal stability in relation to capacity fade remains of paramount importance for safe second-use deployment.

Cell geometry influences heat dissipation and, consequently, thermal stability, with cylindrical, pouch, and prismatic formats exhibiting distinct thermal behaviors [34]. Research shows that cells enclosed in metal casings provide greater thermal stability than those without such casings, as the metal housing can better withstand the internal pressure generated during TR [35]. As a result, pouch cells generally demonstrate lower stability compared with prismatic and cylindrical types [35]. Most retired EV batteries entering second-use markets are cylindrical or prismatic. Prismatic cells, in particular, offer high volumetric efficiency because their rectangular shape allows tightly packed arrangements without the void spaces inherent to cylindrical formats, contributing to their prevalence among retired cells. Since incoming retired batteries predominantly adopt geometries that are inherently more thermally stable than pouch cells, geometry is expected to play a limited role in influencing thermal performance during repurposing.

The capacity of a cell represents the maximum amount of energy it can store, and higher-capacity cells can release more energy during TR, leading to more severe outcomes than lower-capacity cells [36]. Surface area may also influence this behavior, since larger surface areas dissipate heat more effectively than smaller ones [34]. Consequently, the effect of capacity is partly governed by cell geometry. Although retired EV batteries exhibit reduced usable capacity due to degradation, system design is typically based on meeting a predetermined capacity requirement. When retired cells are used, additional volume must be installed to achieve the required capacity, increasing the overall system size. This larger system volume heightens the potential for TR propagation, underscoring the importance of understanding TR mechanisms when integrating retired EV batteries into second-use applications.

Onsets of TR and detection techniques

Before TR occurs, battery cells often exhibit early signs that can be detected in advance. Identifying these indicators is essential for determining when to disconnect circuits and implement appropriate safety measures. The three primary detection approaches involve monitoring temperature, gas generation, and internal resistance.

Temperature is a key precursor to TR, making it important to establish threshold values that signal its onset. Although different experimental conditions lead to variations in reported results, several studies examining multiple chemistries have shown that during overdischarge, the cell voltage initially rises and then begins to decline as both external and internal temperatures increase simultaneously [16], [22]. This inflection point marks the beginning of TR. While the precise temperature associated with this behavior varies with cell chemistry, recognizing this transition is critical for improving operational safety.

Chemical reactions occurring prior to TR also generate gases, and early detection of these gases can provide valuable warning before failure progresses. Because batteries contain diverse chemical species, the composition of released gases depends on the specific internal reactions taking place. Gas evolution leads to swelling of the cell, and different gases appear at different temperatures, including hydrogen, hydrogen fluoride, carbon dioxide, carbon monoxide, ethene, methane, and oxygen [34]. Initial gas release typically occurs between 80 and 120 °C, coinciding with decomposition of the solid electrolyte interphase [34]. Selecting sensors capable of detecting these gases at early stages is therefore important for preventing fire propagation within a battery pack.

Gas formation also causes pressure build-up, leading to measurable expansion of the cell. This expansion can serve as an additional indicator of the onset of TR, and some manufacturers have developed pressure sensors for integration into battery packs to monitor this behavior and reduce TR risk [37].

Internal resistance provides another means of detecting the conditions leading to TR. As TR approaches, short-circuit behavior within the cell causes measurable changes in internal resistance. Monitoring this behavior can help predict imminent failure. Although state of charge itself affects resistance, electrochemical impedance spectroscopy (EIS) can track internal resistance with high sensitivity. Several studies have proposed methods for performing EIS while the battery is operating, enabling real-time monitoring [27], [38]. However, such systems may be costly and bulky, adding complexity to the design, and in-operation EIS may interfere with system functionality if not carefully managed.

Voltage and current deviations beyond manufacturer-specified safe operating limits also indicate risk of TR. The battery management system (BMS) is responsible for shutting down the circuit when the predefined voltage limits are exceeded [14]. Ensuring that threshold values are appropriately defined and enforced is critical to maintaining safety. In cases where the BMS fails and a cell enters an unsafe operating region, additional technologies such as internal fuses can provide a final layer of protection by interrupting current flow and mitigating TR risk and OEMs have started producing cells with a built-in mechanism or internal fuse that triggers to safeguard the cells [15].

Thermal Runaway models

Battery models vary based on the required level of accuracy, typically falling into categories such as physical, semi-empirical, and empirical models [39]. Each type has its advantages and disadvantages, including the potential complexity of details that may not be easily determined. Simple models are often effective for understanding the behavior of a battery system.

Equivalent circuit models (ECMs) are commonly used to represent battery behavior, predicting factors such as current, voltage, etc., that may impact system functionality. Since electrical stress can be easily modeled by an equivalent circuit due to parameters related to the flow of electricity, using these models will help ensure that electrical stress, even in retired batteries, can be modeled easily, reducing the possibility of TR occurring.

ECM development requires substantial data, yet the battery industry's limited data availability makes model construction challenging. Furthermore, conducting thermal-runaway (TR) experiments is hazardous due to the extreme heat generation and requires specialized equipment. To date, the literature has not presented a model that uses a simple equivalent circuit to predict the onset of TR, underscoring the need for such work to advance battery safety.

Technology Approach

The approach, building on our previous work [40], [41], involved generating empirical data, applying the phenomenological ECM to model the transient response of LIBs, and developing inference methods. The ECM was a double-exponential model [42] with an open-circuit voltage V_{oc}, internal resistance R_B and two polarization layers, $R_{p_1}C_{p_1}$ and $R_{p_2}C_{p_2}$, as depicted in Figure 2.

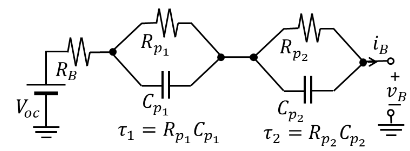


Figure 2: ECM with two polarization layers

Electrical cell-abuse experiments were conducted on individual LIB cells rather than EV LIB modules to minimize potential damage from thermal runaway. The overcharge and overdischarge tests are considered separately. The experiments prioritized electrical abuse conditions because, unlike mechanical or thermal abuse, these events often produce minimal externally observable damage, making their detection, characterization, and diagnosis significantly more challenging. Yet, to support early and accurate decisions during remanufacturing, a rapid and reliable electrical test is needed to identify cells that may have experienced prior abuse and determine whether they should be redirected to the recycling stream.

The objective of the study was to alternate controlled cell abuse, either overcharge or overdischarge, with characterization performed within the normal operating range in order to assess whether prior abuse could be inferred from the characterization data, particularly from a single transient that can be captured within minutes.

Overdischarge experiments

Our review of prior work revealed a gap in empirical studies on electrical abuse in the form of deep discharge. To address this, we designed a straightforward experiment to examine capacity fade and to assess whether a prior deep-discharge event can be detected after the cell returns to its normal operating range, using information extracted from the transient data.

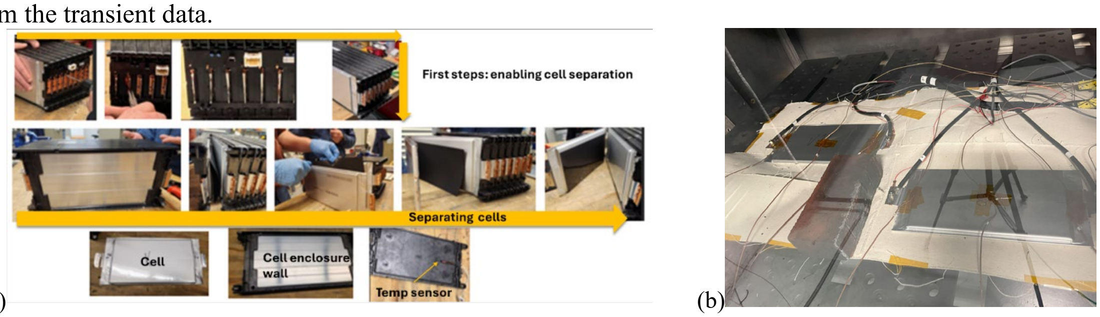
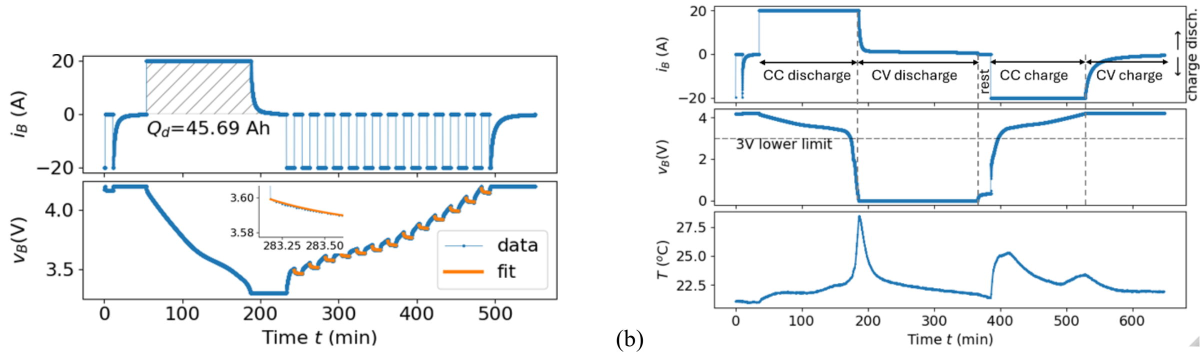
(a)  (b)

Figure 3: (a) Disassembly of a module into cell (b) Two cells undergoing deep discharge test cycles.

A set of nine NMC cells, extracted from the same EV LIB module, underwent three or four abuse cycles as described above. Figure 3a illustrates the disassembly of a module into individual cells. The top, middle, and bottom rows depict, respectively, the initial steps for separating sub-frames that contain the cells, the process of cell separation, and the resulting separated cells with two frame walls. Figure 3b displays two cells in the safety chamber, undergoing a test.



(a) (b)

Figure 4: (a) Characterization profile (b) deep discharge profile

Testing consisted of alternating characterization and deep-discharge cycles, beginning and ending with a characterization step. The characterization procedure, shown in Figure 4a, started with a fully charged cell that was discharged using a constant-current phase followed by a constant-voltage phase to ensure repeatability. Note that the current was defined as positive during discharge and negative during charge, consistent with the conventional reference direction indicated in the ECM in Figure 2. This full discharge cycle provided an estimate of the cell capacity.

After the discharge, the cell was recharged using a pulsed-current profile with a 50 percent duty cycle and a 20-minute period. The pulsed charges generated transient responses at different states of charge. The ECM fit these transients extremely well, as illustrated in the inset of Figure 4a. Because the ECM parameters depend on SOC, each transient corresponded to a distinct ECM, and the resulting parameter sets were used to infer prior abuse events.

In the deep-discharge profile, cells were discharged well below the lower operating limit of 3 V; they were driven to 0 V using a constant-current phase and held at 0 V under constant-voltage control for nearly three hours, then rested for 20 minutes and recharged using a CC–CV protocol, as shown in Figure 4b.

Overcharge experiments

The overcharge testing consisted of alternating the characterization and overcharge profiles. The characterization profile was the same as the one used in deep discharge tests (see Figure 4a).

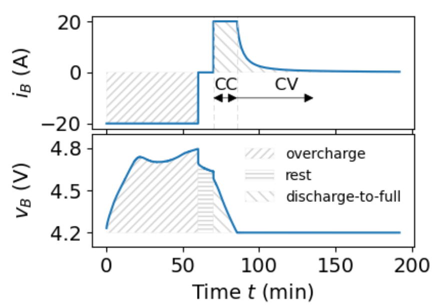


Figure 5: Overcharge profile

The overcharge profile, shown in Figure 5, consisted of charging at CC above 4.2 V for sixty minutes or until the voltage reached 5 V. The voltage never reached 5 V; instead, after rising to approximately 4.75 V, it slightly declined and slowly moved through a minimum before resuming its rise at a much lower rate. This voltage behavior had been observed in prior studies [16][22] and was associated with the TR. However, the cells in our experiments did not experience TR, even after being subjected to multiple overcharges. After a ten-minute rest, a CC discharge at the same current reduced the voltage back to 4.2 V. To improve the repeatability of the subsequent characterization test, a CV discharge followed the CC discharge. The shading in the plots indicate overcharge, rest, and discharge back to full (4.2 V). The current subplot also indicates CC and CV ranges.

Discussion

The study investigated whether the abuse cycles caused measurable damage to the cells, as reflected in capacity fade, and whether such prior abuse could be detected using a quick transient at different SOC levels.

Figure 6a shows capacity at baseline and after up to four deep-discharge abuse cycles. The first two cells exhibited slower degradation than the remaining seven cells. We observed that the cells subjected to the stress of deep discharge continued to degrade after the abuse cycles, regardless of whether they remained connected to the equipment or were simply stored on a shelf (see Figure 6b). It is possible that even before the abuse, shelfed cells experienced degradation, which would explain the faster degradation on Cell 3-9.

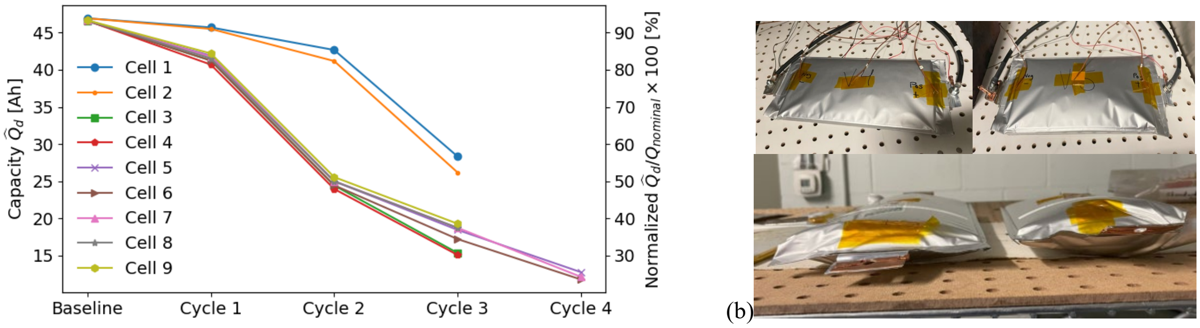


Figure 6: (a) Capacity fade as the function of abuse cycles (b) Cells after abuse continue to degrade on the shelf.

The characterization cycle produced transient data within the normal operating range, which served to extract model parameters as a function of SOC. The most sensitive parameters were the battery's internal resistance R_B and the resistances associated with the polarization layers R_{p_1} and R_{p_2}, which exhibits a shorter time constant. Both resistances increased significantly after the second and subsequent abuse cycles, but showed no notable change after the first cycle, as illustrated in Figure 7a and Figure 7b. The colors signify the cell. Different markers signify the different levels of SOC. The lines correspond to the mean values. The graphs indicate that R_B and layers R_{p_1}, on average, increase with the abuse cycles.

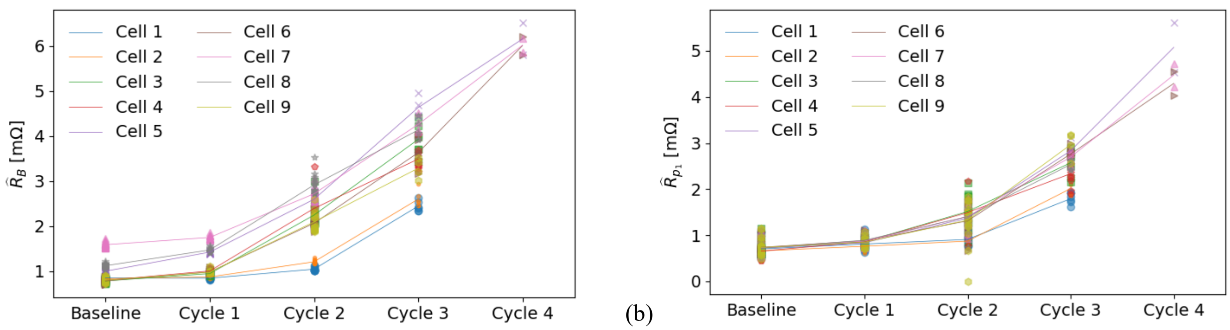


Figure 7: ECM parameters change after abuse cycles (a) internal resistance (b) polarization resistance.

The analysis of the overcharge experiment follows the same approach as the over-discharge case. Figure 8a presents the capacity evolution of the two cells subjected to overcharge-abuse cycles (see Figure 5 for the overcharge profile). Both cells exhibited an abrupt and substantial capacity loss after the first abuse cycle, followed by a plateau and a modest partial recovery in subsequent cycles.

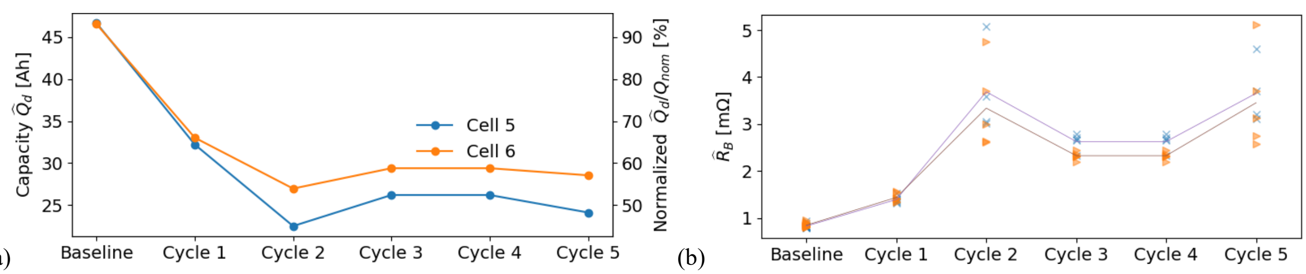


Figure 8 Internal resistance as a function of the capacity fade (overcharge).

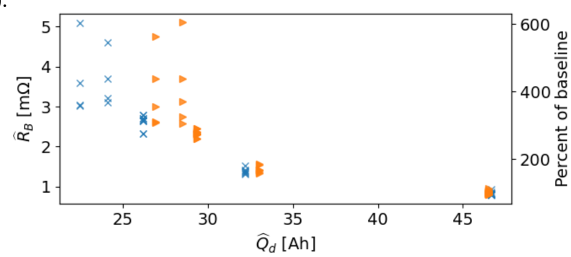


Figure 9 Internal resistance vs. capacity

Figure 8b shows the evolution of internal resistance across the same sequence of overcharge-abuse cycles, and its trend closely parallels the capacity behavior. Both cells experienced an immediate, pronounced rise in resistance after the first overcharge event, indicating that most electrochemical damage occurred early in the experiment. After this initial jump, resistance growth stabilized, suggesting that subsequent overcharge cycles introduced only incremental degradation. This alignment between resistance increase and capacity fade supports the conclusion that the first overcharge cycle imposed the most severe stress on the cells. Figure 9 further illustrates this relationship by plotting the estimated capacity against the estimated internal resistance for both cells, revealing a clear coupling: as resistance increases, capacity systematically decreases. This joint evolution highlights the interconnected degradation mechanisms triggered by electrical abuse and underscores the diagnostic value of these parameters for identifying prior overcharge events.

The sharp capacity loss after the first abuse cycle was substantial and accompanied by a corresponding rise in internal resistance. These resistance estimates were derived from short-duration signal transients—less than ten minutes of data—demonstrating that even brief observations can capture significant degradation after a single overcharge event. This capability aligns with earlier findings reported in [40], reinforcing the sensitivity of transient-based parameter estimation for detecting early-stage damage.

Conclusion & Recommendations.

The literature shows that ensuring lithium-ion battery safety remains a significant challenge as the field rapidly evolves with new chemistries and rising deployment. As EV batteries move into second-life use, understanding safety across both life cycles becomes increasingly important. Battery behavior is complex and driven by multiple interacting factors, making performance modeling essential. ECMs can capture parameter variations with state of charge, and extending them to include thermal effects from electrical stress would provide deeper insights into safety and performance.

Most TR onset criteria were developed for new batteries, and their applicability to retired EV batteries is uncertain. Degradation may shift pressure thresholds and other precursors, underscoring the need for experiments on aged cells and updated data sheets defining safe operating limits. Data scarcity remains a major obstacle; while public databases now offer free cycling data [43], they rarely include TR information, especially under electrical abuse. Increasing access to such data is crucial given the high cost and risks of TR testing.

Emerging technologies continue to target TR mitigation while improving performance. Graphite anodes influence dendrite formation and TR likelihood [44], and ongoing work explores alternative materials and additives. Significant investments focus on next-generation anodes—niobium tungsten oxide, lithium metal, and silicon [45], [46], [47]—with some studies suggesting that fully silicon anodes can increase energy density and reduce charging time [48], benefiting transportation applications through longer range and shorter charging periods.

Our empirical study indicates that ECM parameters can reliably identify prior abuse of sufficient severity well before TR, enabling safer testing of used or potentially compromised EV modules. Addressing current research gaps will help reduce TR risk and support stakeholders working to optimize the performance and safety of retired EV batteries.

In summary, TR is initiated by mechanical, electrical, or thermal stress. High temperatures driving thermal stress are uncommon during normal operation, while mechanical damage is often visible in retired batteries. This review therefore emphasizes TR initiation under electrical stress. BMS failures can cause voltage excursions beyond manufacturer limits, leading to overcharge or overdischarge and potentially triggering TR. Understanding these mechanisms is especially important for retired batteries, where TR onset remains poorly characterized and contributes to consumer concerns over fire risk.

Predictive TR models are essential but are limited by insufficient data sharing and collaboration. Some manufacturers likely possess TR data on degraded cells that could benefit the broader community. Existing prevention strategies may apply only to specific battery types or conditions, and their relevance to retired EV batteries is unclear. Sensor-based monitoring adds cost and bulk, making financial support important for companies handling repurposed batteries. As volumes rise, OEMs should provide datasets defining safe voltage, current, and temperature ranges to reduce electrical stress during second-life operation. Reliable detection of prior abuse—enabled by ECM parameters extracted during brief transients—will be a key element in ensuring the safe testing and reuse of EV LIBs.

Acknowledgments

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Advanced Manufacturing Office Award Number DE-EE0007897 awarded to the REMADE Institute, a division of Sustainable Manufacturing Innovation Alliance Corp. In addition, RIT received funding, in part, from New York State Empire State Development under Grant #AC118 that supported the work on this project. The views expressed herein do not necessarily represent the views of the U.S. Department of Energy or the United States Government or New York State.

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About the Authors

Mandlaenkosi Mthetwa is a Battery Engineer working on silicon anodes and lithium-ion systems. He holds a bachelor's in Electrical Engineering and an MSc in Sustainable Systems from RIT. His work covers emerging battery technologies, second life batteries, sustainability and energy access.

Ethan Kohrt received his M.S. in Computer Science from Northwestern University in 2022. In 2023 he joined the Golisano Institute for Sustainability where he is currently a Data Science Engineer.

Nenad Nenadic is a Research Associate Professor at RIT. He received a Ph.D in Electrical and Computer Engineering from the University of Rochester in 2001. His research interests include sensors, battery systems, automation, and machine learning.