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DATA DESCRIPTOR

Multi-modal thermal runaway dataset of fresh and aged lithium-ion battery cells and modules

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This study provides a multi-modal thermal runaway (TR) dataset for pristine and aged lithium-ion battery cells and modules. The novel specialized experimental frameworks, including an airtight canister and force measurement testbench, were designed to capture thermal and mechanical dynamics during TR. Rigorous uncertainty analysis validated the reliability of the experimental setup and dataset. The dataset comprises synchronized temperature, pressure, and force evolution data across nickel-manganese-cobalt (NMC) cylindrical, pouch cells and pouch modules for fresh and aged state of health (SOH). This multi-modal dataset characterizes SOH-dependent TR kinetics by integrating internal peak pressure, venting timing, and intervals from venting to peak expansion force. Consequently, this new dataset enables the systematic parametrization of SOH-informed TR models across scales from cell to modules, facilitating high-fidelity design-enabling solutions for real-world applications by providing critical metrics for the optimization degradation-informed mitigation protocols for lithium-ion battery systems.

Background & Summary

The proliferation of lithium-ion batteries (LIBs) in diverse applications, from mobile devices to electric vehicles (EV) and energy storage systems (ESS), has increased the importance of thermal runaway (TR) safety¹. TR is an uncontrollable and explosive process the mitigation of which is complicated by the chain reactions that occurs during TR^{2–7}. Extensive experimental research on TR across various LIBs has been conducted to reveal the mechanism of TR and provide insights for robust design and safety management. Specifically, accelerated rate calorimetry quantifies the exothermic heat released from individual cell components by determining the total amount of heat generated from the anode, cathode, and electrolyte⁸ based on specific thermal stability thresholds and decomposition temperatures. The previous experimental studies further demonstrate that TR characteristic is quantitatively governed by cell electrochemistry, including state of charge (SOC), and cathode material, which determines the total amount of heat generated by the individual cell components^{9–12}. These datasets provide valuable foundational datasets for estimating kinematic parameters required to model LIB TR^{13,14}. Specifically, extensive research on modeling TR has been conducted to build digital twins of LIBs, where experimental data are essential for identifying model parameters and validating predictive capability¹³. Coupled electrochemical–thermal models have emerged as powerful tools for resolving internal temperature dynamics across different battery components under varying ambient conditions, providing deeper insight into heat generation and transport mechanisms within the cell¹⁵. Moreover, gas generation represents a critical hazard indicator during TR, involving toxic species and acting as a direct precursor to explosion risk¹⁶. Consequently, additional multiphysics phenomena, including pressure buildup, gas venting, and flame dynamics, have been integrated by incorporating the PDEs of ideal gas behavior and Navier–Stokes equations, enabling multimodal predictions of heat transfer, gas evolution, and pressure rise that are difficult to measure simultaneously in experiments. The reliability of these modeling approaches, however, fundamentally depends on the availability of high-quality, multi-modal experimental datasets capturing the coupled thermal, pressure, and force evolution

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across diverse cell chemistries, configurations, and aging conditions, underscoring the value of the dataset presented in this study.

However, the previous research remained predominantly confined to the analysis of thermal evolution during TR owing to the complexity of TR phenomena. Note that the systematic TR experiments remain constrained by the inherent risks of destructive fire testing and the necessity for specialized infrastructure to control explosive failure. The extreme nonlinearity and explosive heat release during TR further create formidable experimental challenges, including sensor detachment, signal instability, and violent material ejection. These complications impeded the accumulation of comprehensive, high-volume and reliable TR datasets. Consequently, the current research transitions toward multi-modal signals acquisition focused on gas generation and pressure evolution during TR to address the analytical gap in thermal observation and the nonlinearity of TR^{17,18}. Specifically, current research utilized airtight chambers equipped with pressure transducers to quantify gas generation and internal pressure evolution during TR^{19,20}. The gas and pressure datasets revealed that internal gas generation occurs throughout the cascading exothermic decomposition reactions of cell components during TR, with the gases accumulating inside the cell prior to being ejected externally only after the venting event. These measurements therefore provide critical diagnostic indicators of the underlying internal reactions and the hazardous gas species generated throughout the TR process^{21,22}. These various gas species are generated inside the cell as a direct consequence of the cascading decomposition reactions during TR, resulting in pressure and force peaks that coincide largely with the temperature peak when the most violent exothermic reactions occur. The peak magnitudes of pressure and force provide useful metrics for optimizing casing robustness and material endurance across module and pack designs, as well as for guiding the dimensioning of the rupture opening in prismatic and cylindrical cells. Furthermore, quantifying the expansive forces exerted between cells informs the structural requirements for resilient containment systems and mechanical mitigation strategies. Consequently, these synchronized multi-modal datasets provide critical hazard indicators for TR characterization and early detection, facilitating a deeper understanding of internal reaction kinetics during TR.

Decades of LIB application show degradation emerges to represent a primary safety concern for practical, long-term LIB operation. The degradation modifies internal electrochemistry alongside TR kinetics, altering the resultant safety hazards^{23,24}. However, previous multi-modal TR datasets are limited to LIBs at fresh SOH due to the lengthy timescales required for cell degradation^{1,25}. The current research shows that the solid electrolyte interphase (SEI) intensifies the structural degradation of electrode during the degradation of LIBs at room temperature, which further accelerates internal side reactions²⁶. Accordingly, experimental observations show that LIBs aged at the room temperature accelerated TR peak compared with fresh cells^{27–29}, although the extent and direction of this effect strongly depend on cathode chemistry, SOC, aging type, and trigger method³⁰. In practical applications, however, the degradation of LIBs is directly dependent upon ambient temperatures, which dictates the trajectory of electrochemical degradation mechanisms across high and low temperature regimes. Specifically, the datasets regarding the low-temperature degradation reveal that the Li plating on the anode surface, which is the predominant degradation mechanism³¹, compromises the thermal stability of the cell. During the internal temperature elevation, the reaction between metallic Li and the electrolyte becomes the primary source of self-heating, thereby accelerating the TR onset. This dataset shows that residual metallic Li accelerates TR³² by lowering the onset temperature of TR for the aged LIB. By contrast, the datasets regarding the high-temperature degradation reveal the primary degradation pathway shifts toward the loss of lithium inventory (LLI), suggesting a more rapid depletion of reactive electrolyte components, which reduces the inventory available for exothermic reactions during TR^{33,34}. Consequently, the dataset at high-temperature degradation revealed the delayed TR onset relative to the fresh cells³⁵. However, the multi-modal TR datasets capable of capturing these complex failure kinetics across diverse SOH levels are limited due to the immense experimental burden and time required for aging protocols.

Beyond the TR characterization of individual cells, experimental research on TR propagation within module and pack scale has also increased recently. Note that the LIBs are expanded within the scale of module and pack for real-world applications such as EV and ESS. However, TR hazards intensify at the module and pack scale, which is attributed to the accumulation of uncontrollable and explosive heat released from multiple LIBs³⁶. These catastrophic hazards necessitate robust safety characterization and validation of TR propagation. Accordingly, recent TR dataset with the TR propagation within module and pack has increased to address the demand for empirical validation. Specifically, datasets of TR propagation with module and pack scale reveal that after the onset of TR within a trigger cell, the propagation spread throughout in a fast and destructive way, which highlights the importance of safe configuration to mitigate the propagation, and the early detection to mitigate the trigger of TR. Furthermore, module-level TR dataset revealed the highly sensitive expansion force characteristics enable reliable TR detection, ensuring the velocity and robustness of the early TR rapid detection in both pouch³⁷ and prismatic cell formats³⁸. Nevertheless, the substantial infrastructure demands large-scale destructive testing, and high financial costs limit the availability of module and pack datasets. Resource limitations further impede the implementation of multi-modal monitoring in larger assemblies. Furthermore, these datasets regarding module and pack are limited to fresh SOH, which lacks the analysis of TR propagation dependency on electrochemical degradation in aged systems.

To address the limitations of the existing TR datasets, this study constructed a comprehensive TR dataset comprising multi-modal measurements for fresh and aged batteries across cell to module. The dataset is structured into distinct categories for fresh and aged SOH across cylindrical and pouch cells and modules. This study implemented high-temperature aging protocols for individual cells to achieve uniform SOH levels within both cell and module scales, enabling a precise evaluation of degradation impacts on subsequent TR behavior. The aged batteries represent the condition of batteries during prolong field operation in real-world applications. Consequently, the TR dataset of fresh and aged batteries enables a comprehensive evaluation of SOH-dependent TR hazards throughout the operation lifecycle of LIB systems. The multi-modal datasets

further enable a detailed characterization of TR hazards across the sequential stages of the TR process. In Stage 1, the internal pressure exceeds the structural threshold of the cell casing, resulting in an instantaneous release of gases and ejecta followed by a sharp pressure drop, with the venting pressure indicating the onset of the cascading exothermic reactions. In Stage 2, the cell reaches its TR peak, driven by the catastrophic exothermic decomposition of the cathode material and its reaction with the organic electrolyte, with the peak temperature and peak pressure representing the most violent stage of the chain reaction. These measurements support the optimization of thermal design and management of battery systems. The main contributions of this study can be summarized as follows:

- This study developed the novel multi-modal TR experimental testbeds: an airtight canister for measuring temperature and pressure evolution in cylindrical cells and a specialized force measurement testbench for measuring temperature and mechanical force evolution in pouch cells and modules. The degradation experiments were conducted to reach target SOH levels prior to TR tests, and an uncertainty analysis was conducted on the experimental testbeds and resulting multi-modal datasets to confirm the reliability of the measurements.
- This study constructed a multi-modal TR dataset for fresh cylindrical cells, pouch cells, and pouch module. These multi-modal datasets enable the systematic characterization of TR hazards associated with gas generation by identifying mechanical responses—specifically the force monitored during venting and peak evolution in a closed cabinet—to be a distinct indicator for the early detection of TR hazards and critical factors for practical optimization.
- A new multi-modal TR dataset for aged cells was constructed for both cylindrical and pouch cells. This dataset enables a quantification of how degradation influences TR hazards through comparison with fresh cell datasets. Furthermore, this dataset is useful for parameter estimation for SOH-dependent TR models, which further enables the optimization of thermal safety design and management across the operational lifecycle in real-world applications.
- A new multi-modal dataset for aged pouch modules was constructed, integrating synchronized temperature and force measurement. This dataset enables the analysis of direct correlations between degradation and TR propagation behavior. Specifically, the dataset reveals the variations in venting and subsequent propagation across SOH ranges, which support the optimization of TR mitigation strategies and parameterization of models for battery modules and pack systems throughout the operational lifecycle.

The remainder of the paper is organized as follows: the Methods section discusses the development of degradation experiment testbed and the novel multi-modal TR experimental testbeds, including the configurations for the airtight canister and the force measurement testbench. The Data Records section describes the data repository, and the structure and format of the dataset. Finally, the Technical Validation section provides analysis of the synchronized multi-modal measurements, incorporating the uncertainty analysis to confirm the reliability of the dataset, and also investigates the influence of degradation on TR propagation.

Methods

This section describes the experimental framework developed to characterize the TR behavior of LIBs using distinct aging protocols. The methodology involved a sequential two-phase process: (1) degradation and (2) TR experiments (Fig. 1). First, degradation experiments were conducted on two NMC battery shapes—2170 cells and pouch cells—to reach the target SOH for comparative analysis (Fig. 1(a)). Distinct cycling profiles were established and applied to each battery type according to the specifications to ensure a robust and safe testing environment. The ambient temperature during the degradation experiments was varied for comparative analysis. In this phase, test specimens with various SOH levels were prepared by controlling the electrochemical and thermal stress factors during the cycling process. Second, TR was triggered using specialized test zigs customized for each battery geometry (Fig. 1(b)). The experimental testbed integrated a heating controller, data acquisition (DAQ) system, and exhaust hoods to ensure rigorous safety standards during the fire tests. This setup enabled the systematic quantification of TR parameters, providing a comprehensive dataset on the thermal stability of LIBs at SOH 100% and 86%.

Degradation experimental setup. Degradation experiments were conducted on two NMC batteries, 2170 and pouch, to systematically evaluate the impact of high-temperature degradation on TR characteristics (Table 1). The degradation experimental setup integrated a battery cycler (M4300K, MACCOR, USA), bi-directional DC power supplies (IT6012C-300-150, ITECH, Taiwan, ITM3901C-10-170, ITECH, Taiwan), and an environmental chamber (Jeiotech LCH-11-2C, Korea). These systems provide a versatile operational range, with a voltage range of 0–170 V and a maximum current of up to 300 A (Fig. 1(a)). Environmental chambers were maintained at a constant ambient temperature to provide both reference and high-temperature conditions. Specifically, the degradation experiments for reference data were conducted at a constant temperature of 25 °C, while the high-temperature degradation experiments were conducted at 40 and 45 °C for the 2170 and pouch cells, respectively. Note that a 40 °C ambient setpoint was maintained for the 2170 cells to prevent the polylactic acid (PLA) casing, which is used for electrode connectivity, from reaching its glass transition temperature (60 °C). This temperature limit was attributed to the increase in battery surface temperature, which increased by approximately 10 °C during the cycling process, resulting in PLA structural softening. The observed temperature rise resulted from the combined effect of the elevated ambient temperature and the restricted convective cooling at the cell surface caused by the compact PLA casing configuration, ultimately leading to PLA structural softening if the threshold was exceeded. By contrast, the pouch cells employed aluminum connectors with higher thermal stability, allowing for a higher ambient setpoint of 45 °C. Additionally, cycling protocols were established based

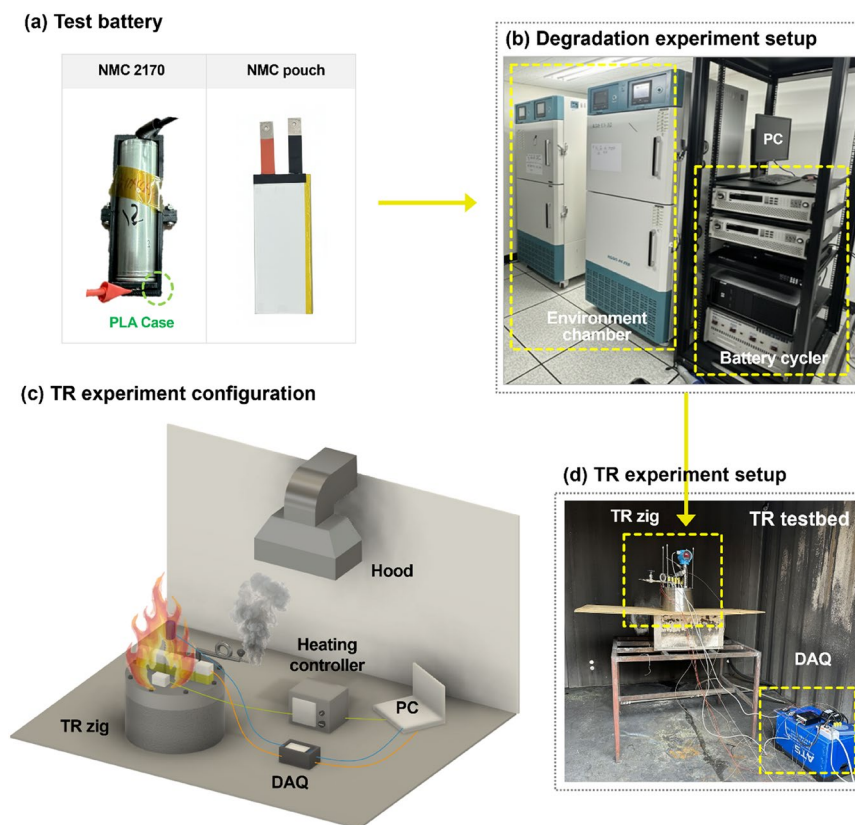


Fig. 1 Overall framework of the LIB TR experiments across various aging protocols: (a) test batteries, (b) degradation experimental setup, (c) schematic of the TR experiments, (d) TR experimental setup.

Model	NMC 2170	NMC pouch
Ambient temperature	40 °C	45 °C
SOH	86%	86%
Cycle protocol	1	2

Table 1. Degradation experimental condition.

Model	INR21700-50E	CTS
Type	Cylindrical	Pouch
Dimension	2170	60 × 60 × 12 mm
Positive electrode	NMC	NMC
Negative electrode	Graphite	Graphite
Nominal capacity	4.9 Ah	10 Ah
Nominal voltage	3.6 V	3.7 V
Maximum voltage	4.2 V	4.2 V
Cut-off voltage	2.5 V	3.0 V
Maximum charge C-rate	1 C	1.5 C
Operating temperature	−20~60 °C	−20~45 °C

Table 2. LIB specifications.

on the specifications of each battery type (Table 2) to reach the target SOH levels systematically. Specifically, the NMC 2170 cells were aged to 86% SOH using Protocol 1, which consisted of a constant-current constant-voltage (CCCV) charge to 4.2 V at 0.3 C, followed by a 10-min relaxation, and a constant-current (CC) discharge to 2.5 V at 0.3 C with a subsequent 10-min relaxation (Fig. 2(a)). To accelerate the NMC pouch cell degradation to 86% SOH, Protocol 2 incorporated four repetitive CC charge pulses at 1.5 C until reaching 20% SOC, followed by a 1.0 C CCCV full charge. A 1-minute relaxation period was introduced between each pulse to mitigate localized

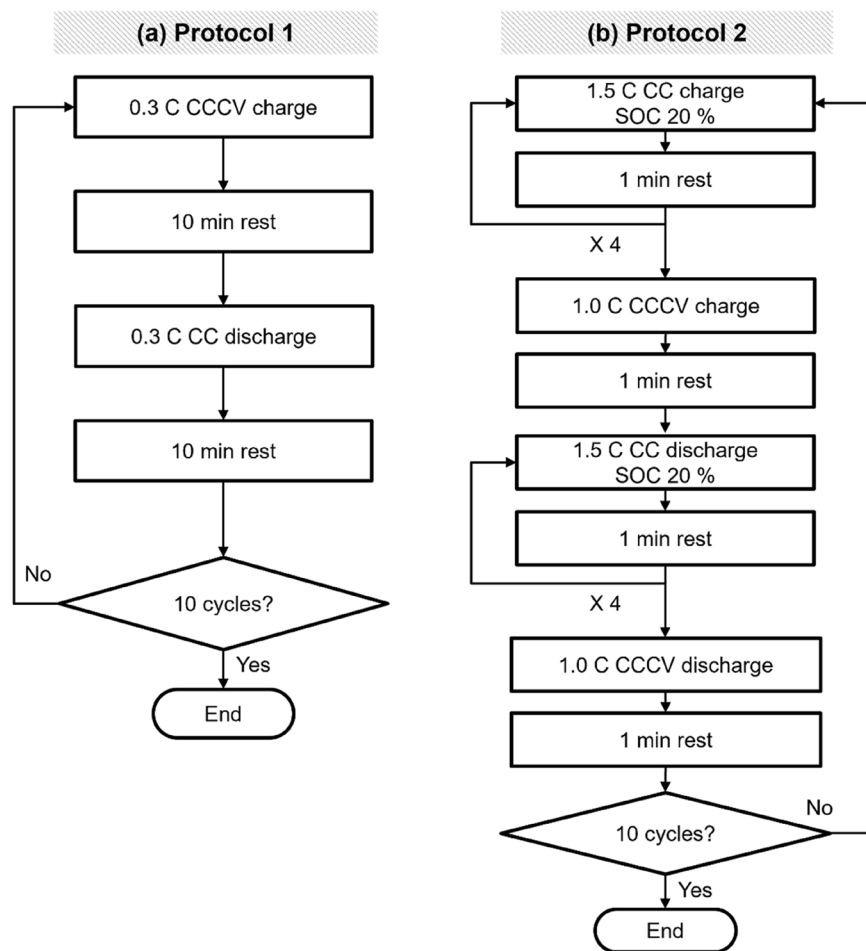


Fig. 2 (a) Protocol 1 for the NMC 2170 cell; (b) Protocol 2 for the NMC pouch cell.

polarization and lithium plating effects at the elevated charging rate, thereby ensuring reproducible accelerated aging without inducing immediate cell failure. Note that Protocol 2 was designed as an accelerated degradation procedure, specifically developed to compress the year-long high-temperature degradation timescale into a feasible experimental duration³⁹. The discharge sequence followed a profile consisting of four CC pulses at 1.5 C down to 20% SOC and concluded with a 1.0 C CCCV full discharge; 1-min relaxation periods were maintained between all steps (Fig. 2(b)).

TR test apparatus. In this study, TR experiments were conducted on LIBs using two systemically designed test zigs (Fig. 1(b)), a force measurement bench and an airtight canister. First, a force measurement test bench was designed to measure the temperature and force evolution during TR of the NMC pouch cell and module (Fig. 3(a)). The module consists of four NMC pouch cells in each row, as shown in Fig. 3(c). The force measurement test bench comprised two end plates and two middle plates made of AL 6063 (Fig. 3(b)). The structural integrity of the assembly was maintained by fixing the end plates with bolts and nuts at each of the four corners. A load cell (Omega LCKD-1000, USA) with a 4448-N capacity was integrated into the end plate to quantify the pressure induced by thermal swelling and gas generation during TR. The middle plates effectively transmitted the internal expansion forces to the load cell, which was attributed to the much greater equivalent stiffness of the middle plates compared to that of the LIB. This high stiffness ratio further ensured a homogeneous pressure distribution across the battery surface during measurement. Mica boards were positioned between the middle plates and the battery heater assembly as insulators. These boards mitigated heat dissipation into the aluminum plates, ensuring that the thermal energy from the heating film was directed entirely toward the test specimen to trigger the TR event. Measurement uncertainty was evaluated using the root sum square method⁴⁰, considering the accuracy of the thermocouple, load cell, and DAQ. The total uncertainty (95% confidence level; $k = 2$) was calculated to be $\pm 1.6^\circ\text{C}$ for temperature and $\pm 88\text{ N}$ for load cell. This uncertainty is reasonable considering the temperature and force measurement ranges during the TRP of LIBs.

Second, an airtight canister was designed to measure the temperature and pressure evolution during the TR of the NMC 2170 cell. In this study, we designed an airtight high-pressure canister (Fig. 4(a)) to measure both the temperature and pressure attributed to gas generation during TR. The designed airtight canister comprises a body, head, and cap made of aluminum, which can endure high temperatures and pressures during TR (Fig. 4(b)). The cap was designed to install cylindrical cells with three holes on the top and side to release the ejected electrolyte

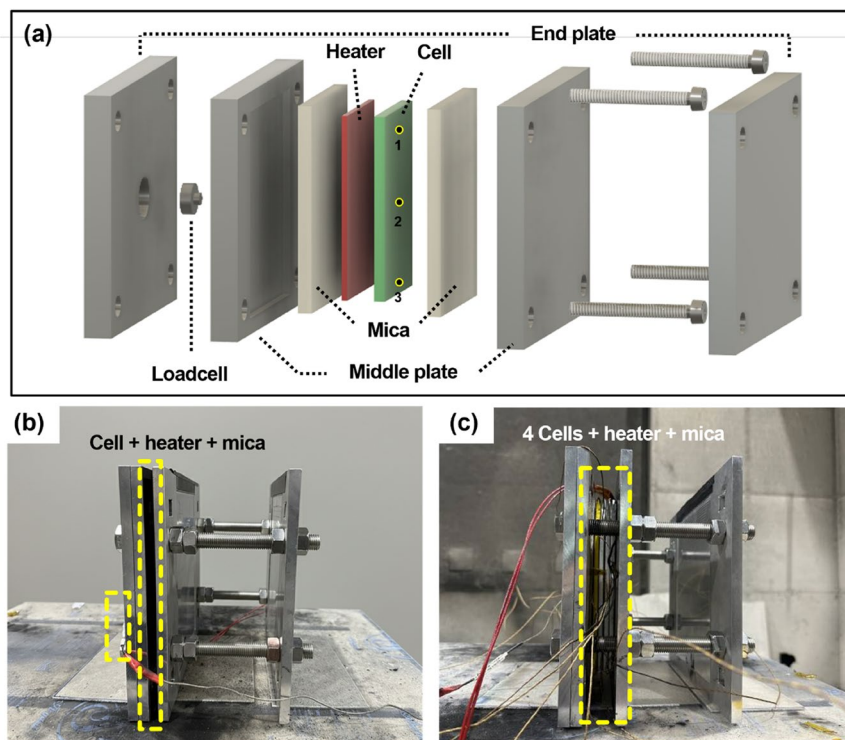


Fig. 3 (a) Configuration of force measurement testbench during TR; (b) Pouch cell-level test zig; (c) Pouch module-level test zig.

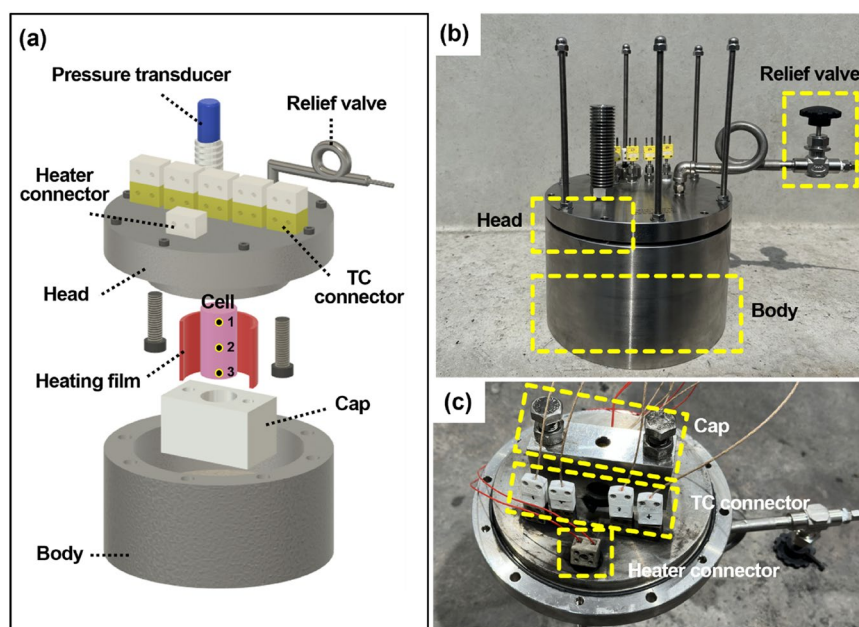


Fig. 4 (a) Airtight TR test zig configuration; (b) Integrated airtight zig setup; (c) Internal view of the head of the TR test zig.

and gas generated after venting. The cap was also designed to be bolted to the head to fix the cylindrical cell and prevent detachment of the heating pad and thermocouples from the cell surface during TR. Ceramic-designed thermocouple connectors were installed inside the head and connected to the exterior of the head (Fig. 4(c)). Note that ceramic connectors were employed owing to their high-temperature resistance characteristics, as ceramic connectors can endure temperatures above 2000 °C. Three K-type thermocouples were affixed to the bottom, center, and top surfaces of the cell, and the three measurements were spatially averaged to derive a single

representative surface temperature. To preserve the integrity of the measured TR dynamics, no digital filtering or smoothing was applied to the raw signals. An additional thermocouple was attached to the center of the cell to provide temperature feedback to the heating controller. A pressure transducer (PA-21Y, KELLER, Switzerland) with a 3-MPa measurement range was deployed on the head with a cooling element to protect the pressure transducer from elevated temperatures during TR. The temperature and pressure measurements were collected using a DAQ system (GL860, GRAPHTEC, Japan) with a 10-Hz frequency integrated with a computer, ensuring that all measurement channels were inherently synchronized within the same acquisition framework. A relief valve was also installed on the head to ensure safety, considering the potential hazard of a high-pressure-induced explosion or rupture of the canister. The measurement uncertainty was evaluated using the root sum square method⁴⁰, considering the thermocouple, pressure transducer, and DAQ accuracy. The total uncertainty (95% confidence level; $k=2$) was calculated to be $\pm 1.6^\circ\text{C}$ for temperature and $\pm 0.06\text{ MPa}$ for pressure. This uncertainty is reasonable considering the measurement ranges of temperature and pressure during the TRP of LIBs.

For both the force measurement test bench and airtight canister, TR was triggered using a constant heating profile controlled by a heating controller (LL50A, YOKOGAWA, Japan) supplied by a DC power supply. The custom-designed heating films utilized wound elements to ensure uniform thermal coverage across cell surfaces. A heating rate of $5.5^\circ\text{C}/\text{min}$ was applied, consistent with the $5\text{--}8^\circ\text{C}/\text{min}$ range specified in the UL9540A standard⁴¹, and maintained until the peak temperature was reached. It is worth noting that TR can be triggered by three primary categories of abuse conditions in practical applications: electrical, mechanical, and thermal abuse¹. Among these, thermal abuse represents the most fundamental triggering mechanism, as electrical and mechanical abuses ultimately converge to a thermal abuse pathway, beyond which the cascading exothermic reactions become largely independent of the original trigger³. The constant heating rate protocol therefore serves as a foundational baseline for TR modeling by isolating the intrinsic thermal response of the cell from trigger-specific variability, with the selected $5.5^\circ\text{C}/\text{min}$ ramp closely approximating the heat input experienced during thermal propagation within a battery pack. The present dataset is consequently most relevant for TR propagation modeling and thermal abuse safety assessment. To ensure experimental reliability, three pre-requisite experiments were conducted for temperature, pressure, and force measurements. First, thermal validation was performed by ramping the heating pad to 200°C , where the observed linear heating rate and precise temperature tracking confirmed the system capacity to maintain controlled thermal input. Second, the pressure measurement capabilities and airtightness were verified by injecting compressed air into the canister in the 1–3-MPa range. The canister maintained an effective internal volume of 0.002829 m^3 after accounting for internal fixtures and was initially set to atmospheric pressure to simulate realistic battery pack conditions. The high correlation between the injected pressure and sensor output confirmed the sealing performance of the airtight canister. Finally, force measurement accuracy was established by applying known masses to the test rig. The load cell successfully captured the resulting force evolution, thus demonstrating the structural robustness and measurement precision of the experimental setup.

Data Record

The dataset is publicly available for download from the Open Science Framework (OSF) at <https://doi.org/10.17605/OSF.IO/C2HNQ> of comma-separated values (.csv)⁴². The “Dataset_TR” repository is organized into a hierarchical structure to facilitate the systematic analysis of TR at the two representative SOH levels of 100% and 86%. The root directory is branched into two primary categories: “Cell” for individual battery characterization and “Module” for module testing. To evaluate the impact of degradation, both the Cell and Module directories are further bifurcated into “Fresh cell” and “Aged cell” subfolders. Within these categories, data are partitioned into folders for the NMC 2170 and NMC pouch.

All experimental results were recorded as comma-separated values (.csv) files to ensure cross-platform compatibility and ease of post-processing. For the NMC 2170 cell folders, the files consist of “Temperature.csv” and “Pressure.csv,” containing synchronized time-series data for cell surface temperature ($^\circ\text{C}$) and internal canister pressure (kPa), respectively. By contrast, the NMC pouch folders—at both the cell and module levels—feature “Temperature.csv” and “Force.csv” files, which represent the thermal transients ($^\circ\text{C}$) and expansion force (N) evolution during TR. Each .csv file includes a “Test_time(s)” column as the primary temporal reference, along the respective physical measurement. This systematic organization allows for direct, side-by-side comparisons of TR characteristics between fresh and aged cells by navigating the parallel “Fresh” and “Aged” paths. The dataset folder structure is illustrated in Fig. 5.

Technical Validation

This section presents the reliability and validity of the experimental framework and dataset used in this study by analyzing the uncertainty and accuracy of the acquired data. A total of 8 thermal runaway experiments were conducted, comprising 6 cell-level tests (2 NMC pouch cells at 100% SOH, 2 NMC 2170 cells at 100% SOH, and 2 NMC 2170 cells at 86% SOH) and 2 module-level tests (1 NMC pouch module at 100% SOH and 1 NMC pouch module at 76% SOH). Owing to the multi-modal nature of the measurements capturing temperature, pressure, and force evolution simultaneously during TR, the success of each channel was independently assessed: a measurement was classified as successful when the acquired signal exhibited a continuous and physically consistent evolution with a well-defined peak aligned with the TR dynamics, whereas a measurement was classified as failed when the data acquisition was disrupted by sensor detachment, load cell malfunction, or noise interruption resulting in incomplete or non-physical signals. Based on this criterion, all 8 experiments were successfully recorded for temperature measurements, while 2 cases exhibited pressure or force sensor malfunctions, which were excluded from the published dataset to preserve the reliability of the retained data. First, an uncertainty analysis of the repeatability of the TR experiments for fresh cells was conducted on the force measurement test bench. Second, an uncertainty analysis regarding the repeatability of the TR experiments for fresh cells was conducted for the airtight canister. Following this baseline validation, the repeatability of the TR

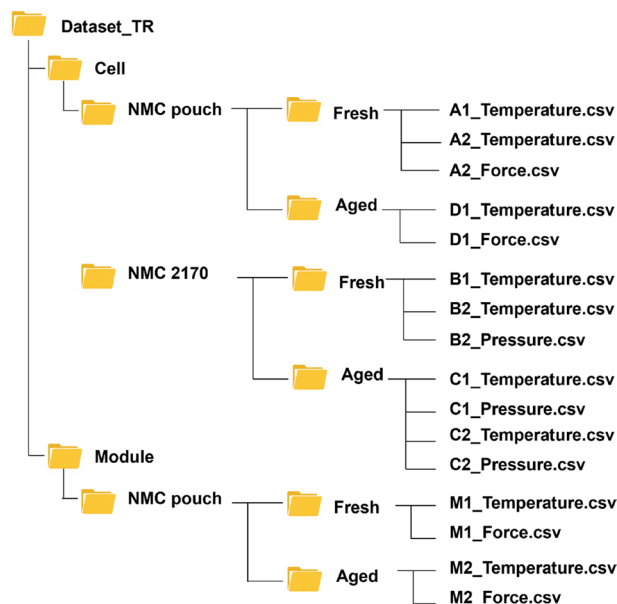


Fig. 5 Dataset folder structure.

experiments for the aged cells was analyzed to verify the consistency of both the electrochemical degradation process and the subsequent TR characteristics. Finally, the practical utility of the force measurement test bench is demonstrated via TRP characterization in both fresh and aged NMC pouch cells. The information provided in this section confirms that the dataset provides a robust and precise experimental setup for LIBs throughout the lifecycles, which is useful for parameterization of TR model over the entire lifecycle.

Uncertainty analysis of the force testbed. The reliability of the TR datasets acquired for the NMC pouch cells with the force measurement testbed was confirmed through high-consistency repeatability metrics and accuracy via validation against existing literature. The two characteristic TR metrics, the Stage-2 peak temperature and Stage-1 venting pressure, were analyzed for statistical comparison. Specifically, the Stage-1 venting point represents the TR onset when the exothermic reaction inside the cell is triggered by SEI and anode decomposition²⁹. As illustrated in Fig. 6(a), the venting point is not discernible through temperature evolution alone; however, the venting point can be explicitly captured by the force (proportional to pressure, see Eq. 3) evolution in Fig. 6(b). In stage 1, the internal pressure exceeds the structural threshold of the cell casing, resulting in an instantaneous release of the generated gases and ejecta, followed by a sharp, characteristic pressure drop. The Stage-2 maximum temperature represents the TR peak when the cell reaches its highest thermal intensity and heat generation rate. This stage was primarily driven by the catastrophic exothermic decomposition of the cathode material and its subsequent chemical reaction with the organic electrolyte⁴³. These two metrics are the most critical in TR characterization, which represent the chain reaction of cell components and differ from cell types that have different cell component materials and electrochemical structures. It is worth noting that the highly nonlinear and hazardous nature of TR experiments and the significant temporal requirements for degradation—requiring approximately six months to reach the target SOH levels—impose substantial experimental challenges. Consequently, identical TR tests were repeated twice for each experimental condition. It should be noted that the sample size is inherently limited due to several experimental constraints, including the time-intensive nature of battery degradation experiments spanning over a year, the substantial infrastructure requirements associated with large-scale destructive testing, and the high financial costs of conducting fire and explosion experiments, all of which significantly restrict the availability of module-level datasets. Consequently, the ability to fully demonstrate repeatability and reproducibility is limited by the small sample size. To address this limitation, the acquired data were supplemented by comparative analysis with reference datasets, thereby verifying the reproducibility of the observed phenomena despite the inherent constraints of destructive testing.

First, the precision across the force measurement testbed was evaluated by comparing the temperature evolution of two repeated TR tests conducted on the NMC pouch cells at 100% SOH and 100% SOC, as illustrated in Fig. 6(a). Specifically, the precision of the acquired data via designed force testbed is quantified through two metrics: the relative percent difference (RPD) and Pearson correlation coefficient (γ). The peak TR temperature deviation observed for the NMC pouch cells (707 and 669 °C) was assessed via RPD, which is calculated as follows:

$$RPD = \frac{|X_1 - X_2|}{(X_1 + X_2)/2} \times 100\%, \quad (1)$$

where X_1 and X_2 are the peak temperatures of cells A1 and A2, respectively (Fig. 6(a)). The calculated RPD (5.6%) remains well below the 10% threshold typically accepted for high-energy destructive testing⁴¹. Furthermore, the kinetic and temporal similarity of the TR evolution was also verified using γ , which is calculated as follows:

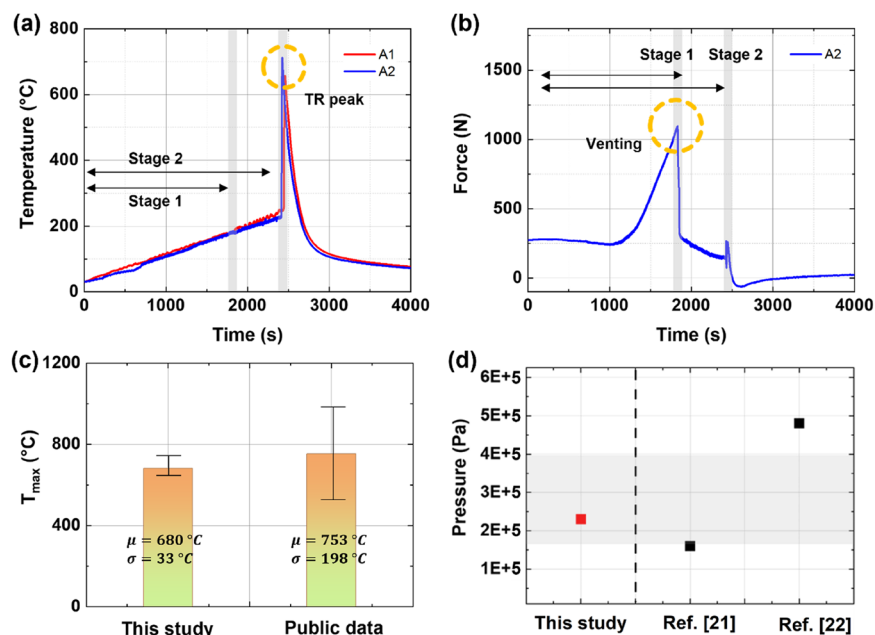


Fig. 6 (a) Temperature evolution of a fresh NMC pouch cell during TR; (b) Force evolution of a fresh NMC pouch cell during TR; (c) Statistical analysis of the peak temperature against reference data; (d) Comparison of the venting pressure with the reference data.

$$\gamma = \frac{\sum (t_i - \bar{t})(T_i - \bar{T})}{\sqrt{\sum (t_i - \bar{t})^2 \sum (T_i - \bar{T})^2}}, \quad (2)$$

where T and T represent the time and temperature evolution of the two cells, respectively. The calculated $\gamma = 0.8$ indicates a strong correlation in the TR kinetics, confirming that the dataset is reproducible.

Second, a statistical comparison with a comprehensive literature survey further verified the reliability and accuracy of the acquired TR datasets using the force measurement testbed (Fig. 6(c)). Specifically, the experimental maximum temperatures were validated against 20 experimental datasets^{2–12} to confirm that the data reside within the expected physical boundaries for the TR of the NMC pouch battery. Specifically, the confidence interval of the literature data exhibited a global mean μ of 753 °C and standard deviation σ of 198 °C. The high σ variability reflects the significant impact of the NMC chemistry ratio (e.g., NMC811 vs. NMC111) and the highly nonlinear TR characteristics that repeat the explosive results. Interestingly, the experimental results in this study reside within the 1σ range (356 to 1151 °C), confirming that the measured peak temperatures are highly representative of typical NMC TR behavior. Furthermore, the σ of the repeated tests was only 33 °C, which is approximately six times smaller than that in the literature (198 °C), highlighting the repeatability and reliability of the measurement testbed and acquired data.

Additionally, the reliability of the pressure measurement was verified by comparing the Stage-1 venting force with that of the reference studies, as shown in Fig. 6(d). Note that the force measurement was obtained exclusively from the A2 test owing to load cell malfunction during the A1 experiment. In the first trial, a slight non-uniformity of the preload resulted in localized destruction at the TR peak, resulting in an incomplete pressure dataset. Consequently, trial A2 utilized a lower, uniformly stabilized initial preload, which allowed for successful data acquisition. The surface-normalized force is measured quantitatively and compared with reference data that have different battery dimensions as follows:

$$P = \frac{F}{A}, \quad (3)$$

where P , F , and A represent pressure, force, and surface area of the cell, respectively. The venting force of 820 N measured in this study was converted to a surface-normalized pressure using Eq. (3) by using a pouch cell surface area of 3.6e-3 m², whereas the reference values (1.6e+5²¹ and 4.9e+5 Pa²²) were normalized by the respective surface area of 1.4e-2 m². Interestingly, as shown in Fig. 6(d), the measured venting pressure of 2.3e+5 Pa aligns within the range in the literature, confirming that the testbed accurately captures the force evolution attributed to gas generation during TR. Consequently, the designed force measurement test bench for the pouch cells precisely captured the temperature and force evolution during TR, further validating the reliability of the acquired data.

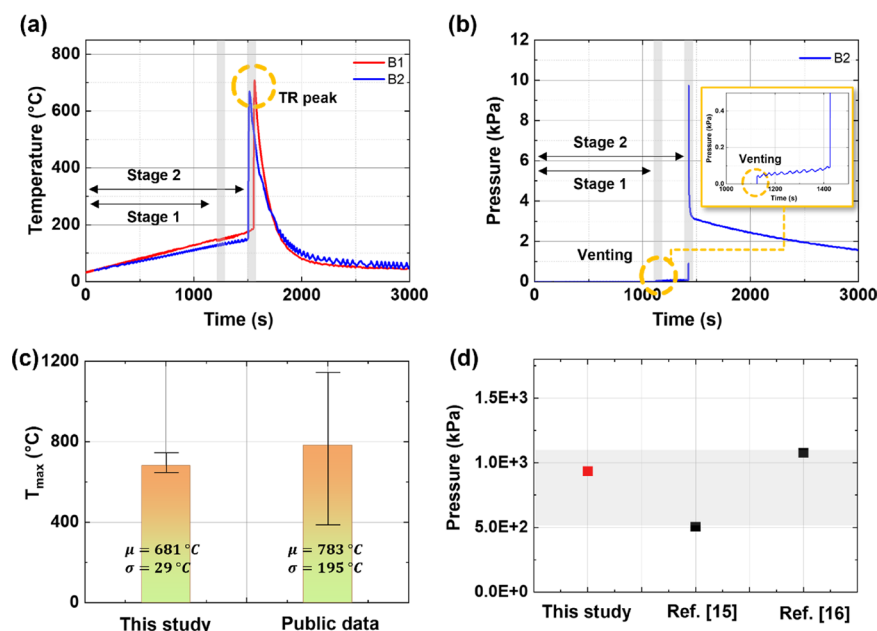


Fig. 7 (a) Temperature evolution of a fresh NMC 2170 cell during TR; (b) Pressure evolution of a fresh NMC 2170 cell during TR; (c) Statistical analysis of the peak temperature against reference data; (d) Comparison of the volume-normalized peak pressure with reference data.

Uncertainty analysis of the airtight canister. The reliability of the TR datasets acquired for the NMC 2170 cells with an airtight canister was validated through repeatability metrics and accuracy via validation against existing literature. First, precision across the airtight canister was evaluated by comparing the temperature evolution of two repeated TR tests conducted on NMC 2170 cells at 100% SOH and 100% SOC, as illustrated in Fig. 7(a). Specifically, the precision of the data acquired via the designed force testbed was quantified via RPD (Eq. (1)) and γ (Eq. (2)). The peak TR temperature deviation observed for the NMC pouch cells was assessed (661 and 702 °C), and the calculated RPD (6.9%) remains well below the 10% threshold typically accepted for high-energy destructive testing⁴⁴. Furthermore, the calculated $\gamma = 0.8$ indicates a strong correlation in the TR kinetics, confirming that the dataset is reproducible. Consequently, both the operational reliability and repeatability of temperature acquisition within the designed airtight canister were confirmed, thereby demonstrating the validity of the resulting TR datasets.

Second, a statistical comparison with a comprehensive literature survey verified the reliability of the acquired TR datasets (Fig. 7(c)). Specifically, the experimental maximum temperatures were validated against 20 experimental studies to confirm that the data resided within the expected physical boundaries for the TR of the NMC cylindrical battery^{4–14}. Specifically, the confidence interval of the literature data exhibited a global mean μ of 783 °C and standard deviation σ of 195 °C. Note that a slight deviation exists between the pouch and cylindrical cells. The NMC cathode remained identical across both shapes; however, the variations were attributed to inherent geometric differences, which resulted in disparities in the measurement uncertainty. Specifically, the curved surfaces of cylindrical cells present significant challenges in maintaining consistent contact with heating films and thermocouples. By contrast, the planar surface of the pouch cell enables stable sensor placement and uniform thermal contact. Furthermore, the cylindrical geometry was more prone to TC detachment during violent expansion during TR. Consequently, the distinct measurement noise associated with each geometry results in deviations in the experimental uncertainty. Remarkably, the TR experimental results for the NMC 2170 cells conducted in this study remained within the 1σ range (588 to 978 °C), validating that the measured peak temperatures are highly representative of TR for NMC cylindrical cells at 100% SOC.

Additionally, the pressure measurement was compared with that obtained from the literature, which measured the pressure evolution of airtight chambers within NMC cells during TR. This comparison aimed to validate the rationality of the pressure measurement within the expected physical range for a specific battery chemistry. It is worth noting that the pressure data was obtained exclusively from the second test (B2) due to a malfunction of the pressure transducer during the initial experiment (B1). In the first trial, a leakage microcurrent interfered with the pressure transducer signal, amplifying the noise during data acquisition. Consequently, for trial B2, rigorous grounding measures were implemented to eliminate electrical noise, enabling the successful acquisition of the peak pressure data. Note also that the peak pressure during Stage 2 was analyzed because the Stage-1 venting pressure was an inconsistent reference for comparative analysis. The pressure measurement sensitivity is inversely proportional to the control volume, and thereby, the Stage-1 venting pressure signals frequently fall below the detection threshold in the larger-volume setups of the existing literature. Furthermore, venting cap endurance thresholds have distinct manufacturer-specific specifications, making Stage-1 data highly dependent on individual cell designs rather than on universal TR kinetics. Moreover, the peak pressure is a primary safety concern, reflecting the kinetic energy of the gases evolved during TR. The peak pressure magnitude

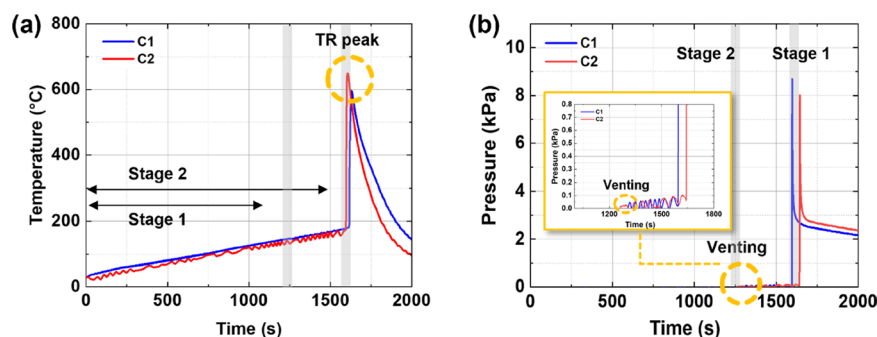


Fig. 8 (a) Temperature evolution of aged NMC 2170 cells during TR; (b) Pressure evolution of aged NMC 2170 cells during TR at 40 °C.

is the cumulative generation of various hazardous gas species during the sequential decomposition of cell components. The resulting internal pressure buildup within the cell during TR triggers catastrophic failures, including casing rupture, high-velocity ejection of materials, system-level propagation, and explosion. Consequently, the peak pressure in Stage 2 is an indispensable safety metric for TR. This measurement provides a reliable and standardized basis for confirming the accuracy of the testbed and the gas generation intensity of NMC batteries. The peak pressure of 900 kPa measured during Stage 2 was normalized relative to the 808,950 mm³ control volume of the airtight canister in this study. This volume-normalization procedure enables a quantitative comparison across disparate experimental setups from the literature. This method effectively accounted for variations in canister dimensions, ensuring the evaluation of gas generation intensity on a standardized scale. Interestingly, the volume-normalized peak pressure was consistent with that in the literature (Fig. 7(d)), confirming a reliable gas generation intensity assessment and pressure measurement accuracy for the NMC batteries. Consequently, the designed airtight canister for cylindrical cells precisely captured the temperature and pressure evolution during TR, further validating the reliability of the acquired data.

SOH analysis. Uncertainty analysis was further conducted on the TR datasets for the aged NMC 2170 cells to validate the reliability of both the degradation and TR experiments. Specifically, two NMC 2170 cells were cycled with the identical Protocol 1 at 40 °C until an SOH of 86% (Table 1) and conducted the same TR tests with the airtight canister by measuring the temperature and pressure evolution during TR. The precision of the degradation experiments was evaluated by comparing the temperature evolution of two repeated TR tests conducted on the NMC 2170 cells, as illustrated in Fig. 8(a). Notably, the RPD was calculated as 9.02%, which is higher than that of the fresh cell baseline but remains below the 10% threshold for experimental reliability. Additionally, the standard deviation (40 °C) is higher than that of the fresh cell variance (29 °C), whereas is five times smaller than that in the literature (196 °C). This precision was further validated by a Pearson correlation coefficient of 0.99, which confirmed that the underlying reaction kinetics were highly reproducible, while the uncertainty window was widened. The increased variance is attributed to degradation features such as nonuniform SEI layer growth and localized impedance variations. However, the uncertainty ranges remained within the standard deviation in the literature, confirming the reliability of both the degradation and TR experiments. Furthermore, the uncertainty analysis of the peak pressure was validated to confirm the reliability of the degradation and TR experiments presented in Fig. 8(b). Peak pressures of 8.68 and 8.00 kPa resulted in an RPD of 8.15%, which aligned closely with the 9.02% RPD observed in the temperature data, indicating pressure measurement repeatability coupled with the degradation experiments. The standard deviation (0.48 kPa) also confirmed the TR experimental precision with the airtight canister for pressure measurement during TR.

Utilizing the validated force measurement testbeds, two experiments were conducted on the NMC pouch cells to examine how high-temperature electrochemical aging influences subsequent TR characteristics: (1) NMC pouch cells were cycled with Protocol 2 at 45 °C until an SOH of 86% and triggered TR in a single-cell configuration; (2) identical cells were aged to 76% and triggered TR within module-array configurations.

First, Fig. 9 compares the temperature and force evolutions of NMC pouch cells at SOH 100% and 86%. Notably, a significant temporal divergence exists between the fresh and aged cells, characterized by two time-related metrics: time to vent t_{vent} and time duration from venting to peak t_{vtp} . The t_{vent} indicates a vital early-warning signal that is critical for safety management regarding the uncontrollable and explosive hazards of TR ignition and subsequent rapid propagation. Additionally, the t_{vtp} indicates the available evacuation time, which is another critical safety metric for protecting personnel and assets following an initial TR warning. Interestingly, Fig. 9(a,b) show that high-temperature degradation accelerates t_{vent} from 1812 s in the fresh cell to 1703 s in the aged cell in Stage 1, while simultaneously delaying t_{vtp} from 614 to 1037 s in Stage 2. This shift is attributed to the electrochemical variation caused by high-temperature cell degradation. Specifically, the faster t_{vent} is attributed to the SEI, which grows substantially thicker during high-temperature degradation³⁴. This thickened SEI is predominantly composed of oxygen-rich metastable lithium salts (e.g., Li₂CO₃), which are significantly less thermally stable than the pure graphite matrix of fresh cells. These oxygen-rich species are highly susceptible to early exothermic decomposition because oxidizers and organic residues reside directly at the anode interface, triggering self-heating at significantly lower temperatures³⁵. By contrast, t_{vtp} was delayed in aged cells, which is attributed to electrolyte depletion due to increased loss of active lithium (LLI) and internal

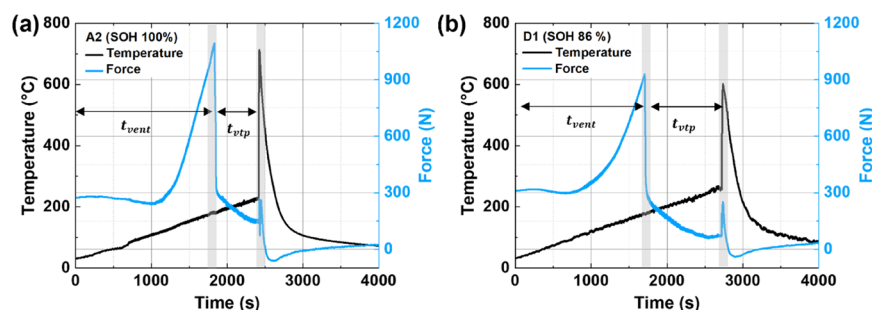


Fig. 9 (a) Temperature and force measurements for the NMC pouch cell (A2) with 100% SOH; (b) Temperature and force measurements for the aged cell (D1) with 86% SOH.

resistance³⁴. The continuous cycles of SEI decomposition and reformation in high-temperature-aged cells consume a significant fraction of the available electrolyte inside the cells. Furthermore, the cumulative LLI and increase in ohmic resistance further consumed the electrolyte, which desiccates the electrodes³⁴. Although post-mortem disassembly was not conducted in the present study due to resource limitations, previous studies have observed a dry jelly roll interior, where the electrodes were no longer sufficiently wet owing to electrolyte depletion³⁴. It is worth noting that the primary heat source during TR is the electrolyte, which results in severe depletion of the most violent TR stage³³. Consequently, high-temperature electrolyte depletion slowed the reaction kinetics, resulting in a delayed peak and longer time between vent and TR, t_{vtp} . These experimental datasets provide meaningful insights into the TR safety metrics, demonstrating the influence of degradation on the critical interval between early-warning signals and peak failure. It is worth noting that the TR models should account for SOH-dependent parameters, because aging influences TR kinetics and modifies the optimization of safety designs.

Second, Fig. 10(a,b) compare the temperature and force measurements of NMC pouch modules (consisting of four cells in row) with 100% and 76% SOH. Thermocouples were attached to the surface of each cell as follows: cell 1 (TC 1–3 on the heating film side and 4–6 on the other side), cell 2 (TC 7–9), cell 3 (TC 10 and 11), and cell 4 (TC 12–15). Both fresh and aged modules showed that TR propagated through all four cells following TR triggering by cell 1 (Fig. 10(e,f)). Consistent with the single-cell observations, high-temperature degradation induced significant temporal divergence in the TRP of the modules. Specifically, Fig. 10(c) shows that the fresh cell exhibits the first venting of cell 1 at $t_{vent,1} = 2137$ s. Consequently, the second venting of cell 2 resulted in the TRP of the entire module simultaneously. In Fig. 10(d), the aged module exhibits the first venting of cell 1 at $t_{vent,1} = 1569$ s and cell 2 at $t_{vent,2} = 2162$ s, after which the subsequent venting of cell 2 triggered TRP throughout the module, with all remaining cells sequentially undergoing TR. This accelerated first venting confirmed that SEI growth during degradation resulted in a faster $t_{vent,1}$. Furthermore, t_{vtp} for cell 1 increased from 478 s in the fresh module to 1039 s in the aged module. Consistent with the single-cell experiments, this extended venting interval demonstrates that electrolyte depletion during degradation slows the reaction kinetics, thereby delaying the onset of TRP in the aged module. Figure 10(e,f) show the module debris, where the TRP consumed all four cells within 40 s for both the fresh and aged modules. This rapid and uncontrollable combustion during the TRP further highlights the importance of t_{vent} and t_{vtp} , which serve as early-warning signals. Furthermore, the force data provided meaningful insights for identifying TR initiation before a catastrophic TRP occurred. The experimental dataset further provides critical insight into the TR characteristics associated with high-temperature degradation, providing the dataset for SOH-dependent parameter estimation of TR propagation models of modules and pack.

Summary. This study presented a comprehensive multi-modal TR dataset for fresh and aged LIB cells and modules, covering NMC pouch cells, NMC 2170 cylindrical cells, and NMC pouch modules at two representative SOH levels of 100% and 86%, acquired using two dedicated experimental testbeds: an airtight canister for the simultaneous measurement of temperature and pressure evolution in cylindrical cells, and a force measurement testbench for the simultaneous measurement of temperature and mechanical force evolution⁴⁵ in pouch cells and modules. The principal contribution of this dataset lies in its multi-modal and lifecycle-spanning nature, providing simultaneously acquired temperature, pressure, and mechanical force signals for both fresh and aged cells and modules, which remain rarely available in existing literature and provide a foundational reference for the development and validation of multi-physics TR models. However, the dataset has several limitations, as the number of repeated tests is constrained by the time-intensive nature of degradation experiments and the high cost of large-scale destructive testing, the SOH coverage is limited to two representative levels, and post-mortem chemical characterization was not conducted, such that the mechanistic interpretations rely on literature-supported explanations rather than direct validation. Future work will focus on extending the dataset to a broader range of SOH levels to enable comprehensive lifecycle characterization and TR model parameterization, developing an integrated multi-modal testing bench capable of simultaneously acquiring force, temperature, voltage, and current signals during both the aging process and the subsequent TR event, extending the testbeds to prismatic cell formats, and directly correlating the acquired multi-modal signals with multi-physics TR models to further enhance the fidelity, generality, and predictive applicability of the dataset.

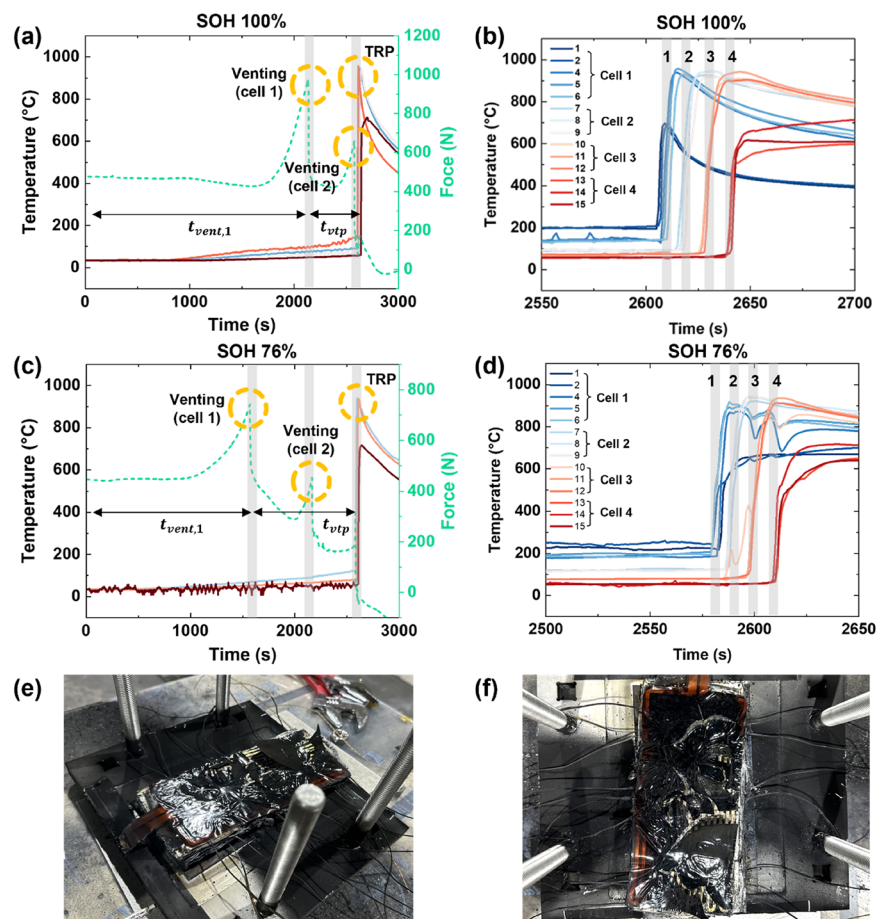


Fig. 10 (a) Temperature and pressure measurements of the NMC pouch module with 100% SOH; (b) Temperature and pressure measurements of the aged module with 86% SOH at 45 °C; (c) TRP of the NMC pouch module with 100% SOH; (d) TRP of the NMC pouch module with 76% SOH; (e) Debris of the fresh module; (f) Debris of the aged module.

Data availability

No datasets were generated or analysed during the current study.

Code availability

The custom scripts used to generate the plots in this study are provided in the data repository along with the dataset. The code used in this study is available upon reasonable request. The dataset and associated code are also available at the OSF repository: <https://doi.org/10.17605/OSF.IO/C2HNQ>.

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Author contributions

Eunji Kwak: Methodology, Formal analysis & investigation, Validation, and Writing—original draft preparation; Jinho Jeong: Methodology & Experiment; Jun Hyeong Kim: Experiment; Yeongjin Shin: Experiment; Moonwoo Park: Funding acquisition & Experiment; Ki-yong Oh: Conceptualization, Writing—review & editing, and Project administration

Competing interests

The authors declare no competing interests.

Additional information

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