EXPERIMENTAL INVESTIGATION OF THERMAL RUNAWAY IN LITHIUM-ION BATTERIES: IMPLICATIONS FOR TUNNEL SAFETY AND STRUCTURAL INTEGRITY

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ABSTRACT

The increasing use of lithium-ion batteries (LIBs) in electric vehicles and energy storage systems raises new safety concerns, particularly in confined environments such as road tunnels. This study presents an experimental investigation into thermal runaway (TR) events in LIBs triggered by mechanical, thermal, and electrical abuse conditions. The work focuses on characterising temperature and pressure evolution, gas emissions, and the effects of battery fires on surrounding structural materials, specifically concrete, representative of tunnel linings. Abuse tests, including nail penetration, overheating, and external short circuits, were conducted using an Accelerating Rate Calorimeter (ARC). The maximum temperature, pressure and released gases were monitored. Pre- and post-mortem computed tomography analyses provided insight into internal cell degradation and structural changes. Importantly, TR events in proximity to cement mortar samples revealed their thermal damage, leading to microstructure degradation (mostly microcrack network development) after repeated exposure. The results show that thermal runaway of cells can rapidly propagate in confined spaces, developing flammable gases, toxic substances and thermal loads capable of compromising tunnel structures. Cells triggered at higher ambient temperatures are more reactive, reaching higher peak temperatures and pressures during TR. The state of health (SOH) of cells influences the severity of TR, with degraded cells producing less intense but still dangerous reactions. Overheating tests demonstrated a critical delay window (~350 s) enabled by safety valve activation, crucial for mitigation in real tunnel scenarios. For external short circuit, no thermal runaway occurred for different SOC states. These findings contribute to a better understanding of LIB behaviour under critical conditions and support the development of safety strategies, emergency response plans, and structural containment systems for tunnels. The data will serve as a basis for future risk assessments and engineering models aimed at improving resilience to battery-induced fires in underground infrastructure.

Keywords: Thermal runaway; lithium-ion battery; nail penetration; overheating; tunnel safety; structural degradation.

1. INTRODUCTION

The global energy transition and decarbonization goals have accelerated the deployment of lithium-ion batteries (LIBs) for both electric vehicles (EVs) and stationary energy storage systems. These technologies are crucial for managing the intermittency of renewable energy sources and reducing greenhouse gas emissions from the electricity (32.3%) and transport (15.5%) sectors [1]. In 2024, global battery demand reached 1 TWh, with electric vehicles accounting for over 85% of this total; the most rapid growth was observed in electric trucks (+75%) [2]. However, the widespread use of LIBs introduces critical safety challenges, primarily related to thermal runaway (TR)—a rapid, self-sustained temperature rise caused by exothermic reactions within the cell. TR can lead to fires, explosions, and the release of toxic and flammable gases, posing risks in confined environments such as tunnels or enclosed transport systems. This aspect is increasingly felt at the level of risk management, due to the increase of electric vehicles, especially considering large vehicles (electric buses or trucks), for these vehicles the impacts can be extensive and experimental studies are scarce. Mechanistically, TR initiates when internal heat generation exceeds dissipation, leading to SEI and separator degradation at temperatures between 70–130 °C, followed by cathode decomposition and gas release above 150 °C, and full electrolyte breakdown near 200–300 °C [3], [4], [5]. These reactions may be triggered by mechanical, thermal, or electrical abuse—each capable of producing internal short circuits (IC) that start runaway reactions [6]. Existing safety standards, such as SAE J2464 (2009), require testing across four system levels—cell, module, pack, and vehicle—but this study focuses specifically on cell-level abuse behaviour [7]. Typical abuse mechanisms include:

- Mechanical: impact, crush, or penetration tests (e.g., nail tests).
- Thermal: overheating or exposure to extreme temperatures.
- Electrical: short circuits and overcharge conditions

This research aims to provide a comprehensive experimental investigation of LIB thermal runaway under realistic conditions, including interactions with structural materials such as concrete, which are critical for assessing safety in tunnel infrastructures. The work explores TR triggered by mechanical, thermal, and electrical abuse, analyzing thermal, pressure, and gas-emission profiles to develop improved safety models and mitigation strategies.

2. DATA AND METHODS

2.1. Experimental Setup

Tests were conducted using a Thermal Hazard Technology EV+ Accelerating Rate Calorimeter (ARC), equipped with thermocouples, pressure transducers, and a vent gas analysis system, see Figure 1.

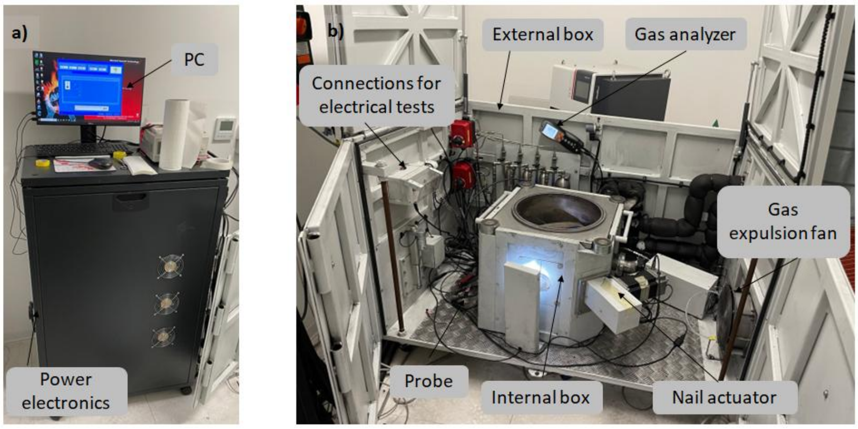


Figure 1: Thermal Hazard Technology EV+ Accelerating Rate Calorimeter (ARC): a) power electronics, b) testing tool.

Mechanical (nail penetration), thermal (overheating), and electrical (external short circuit) abuse conditions were applied to commercial cylindrical LIB cells (LG INR18650 M29 and Samsung INR21700-50E), see Table 1.

Table 1: cells tested datasheet.

Parameters	**LG 18650**	**Samsung 21700**
Technology	Li-$NiMnCoO_2$	Li-$NiMnCoO_2$
Nominal Capacity	2850 mAh	4900 mAh
Nominal Voltage	3.67 V	3.6 V
Charging Voltage	4.2 V	4.2 V
Charging Current	0.5C (1375 mA)	0.5C (2450 mA)
Max Charge Current	1C (2750 mA)	1C (4900 mA)
Max Discharge Current	10 A	14.7 A
Weight	45 g	69 g

Environmental temperature and state of charge (SOC) were systematically varied. Gas emissions (CO_2, CO, NO_x, O_2) were monitored using a Testo 330 gas analyser. Concrete samples representative of tunnel linings were placed in proximity to cells to observe flame and pressure effects, see Figure 2. Scanning electron microscopy (SEM/EDS) were used to assess internal cell damage and concrete microstructure degradation.

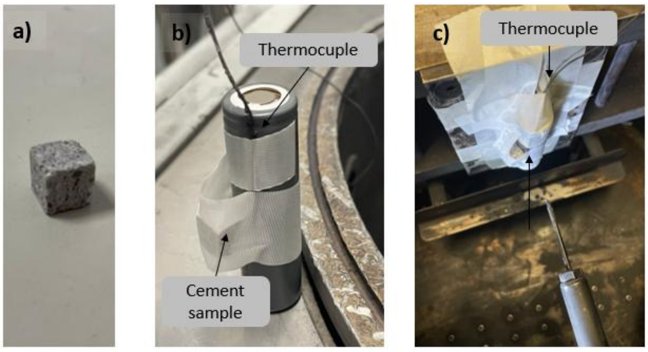


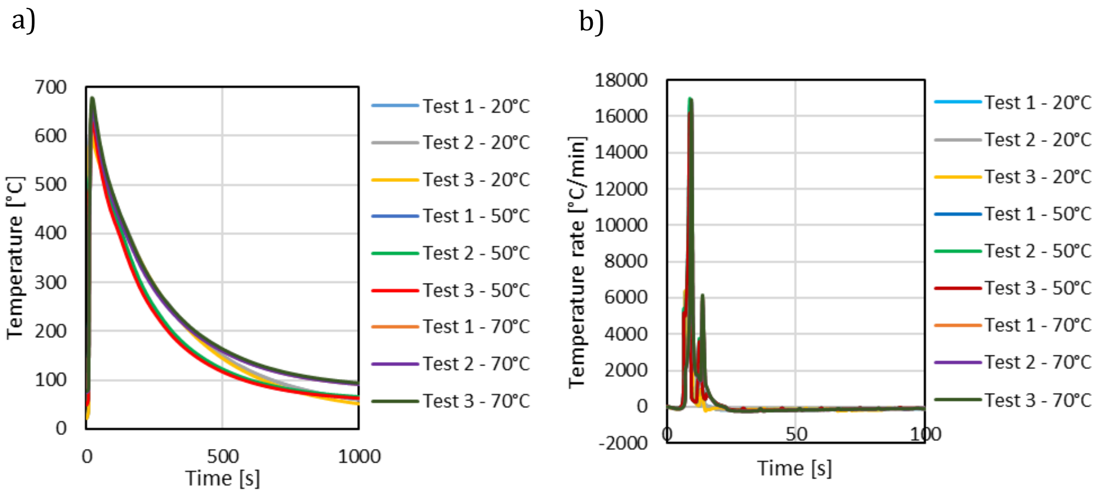
Figure 2: a) cement mortar sample, b) positioning of the concrete sample in contact with the surface and with the thermocouple, c) experimental setup in the THT instrument.

3. RESULTS AND DISCUSSION

Thermal runaway occurred during nail penetration and overheating tests, but not under external short-circuit conditions.

Mechanical abuse – nail penetration

Cells triggered at 70 °C ambient temperature exhibited more severe TR, with peak temperatures exceeding 660 °C and pressures above 2.3 bar, see Figure 3. Higher ambient temperatures increased reaction rates and gas production, primarily CO_2 and CO, see Table 2.



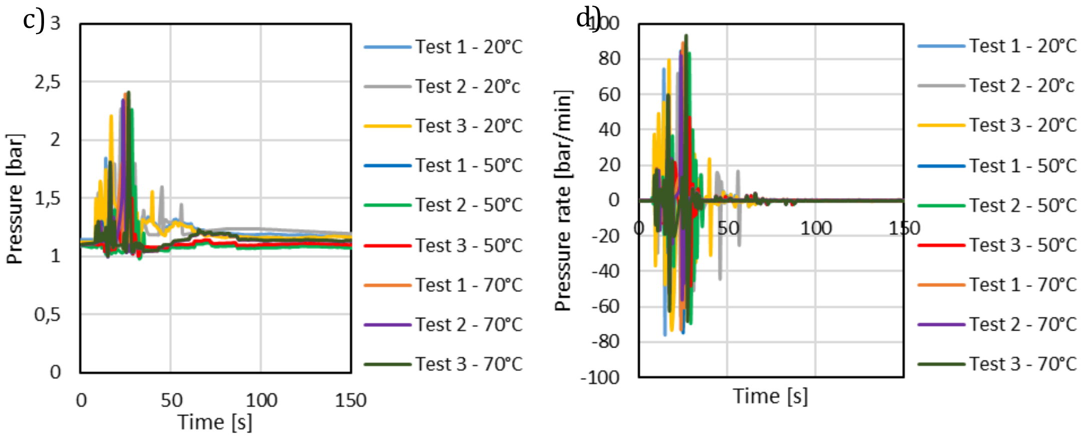


Figure 2: a) Temperature profile during TR for nail penetration tests, b) Temperature growth rate during TR for nail penetration tests, c) pressure profile during TR for nail penetration tests, d) pressure rate of temperature tests for nail penetration tests.

Table 2: Average key values of gas analysis.

Room temperature [°C]	**CO_2 max [%]**	**O_2 min [%]**	**ppm(v) CO max**	**ppm(v) NO max**
20	3.6	16.1	12359.7	23.3
50	4.0	15.1	14374.9	35.1
70	4.4	14.8	16553.7	50.8

In tests involving concrete samples, it was observed that the thermal runaway triggered by the nail penetration caused progressive degradation of the concrete matrix. After repeated TR events, microcracks developed in the concrete, particularly in the cement matrix, leading to structural damage. The extent of degradation was directly proportional to the number of TR events, with samples exposed to multiple battery explosions showing widening cracks and increased porosity, up to 8 µm wide and the incorporation of metallic inclusions from cell materials, see Figure 4-7.

Figure 3: Effects of explosions on concrete samples.

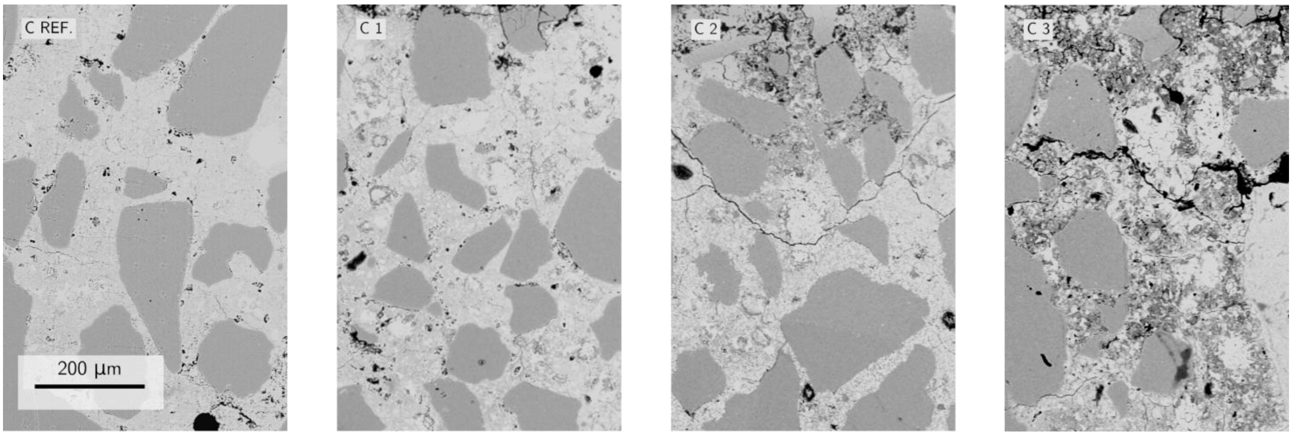


Figure 4: SEM micrographs of the samples after exposure to TR.

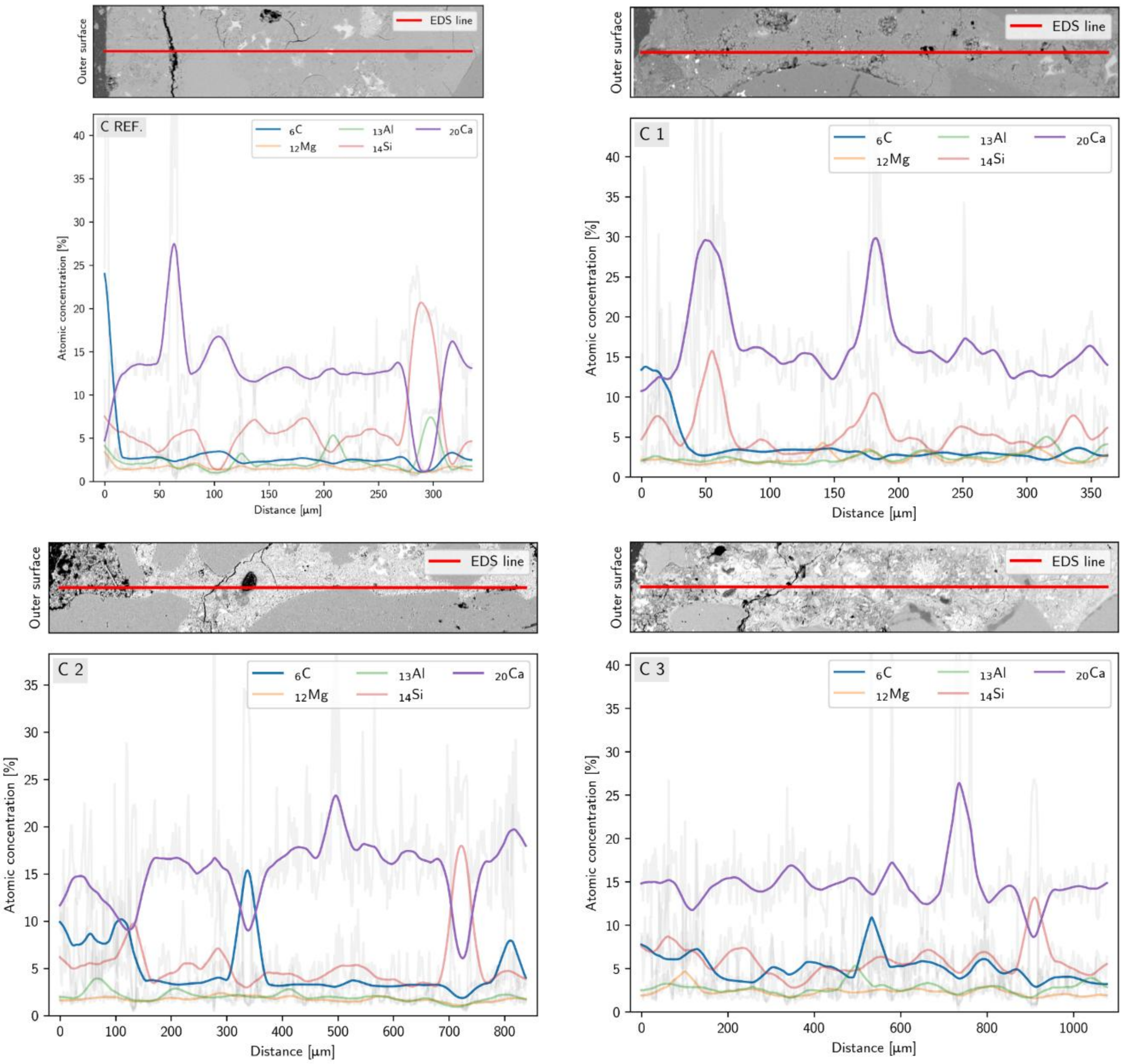


Figure 5: Changes in elemental composition of concrete samples in the vicinity of the surface subjected to cell explosions: a) reference sample, b) sample C 1 – after one cycle, c) sample C 2 – after two cycles and d) sample C 3 – after 3 cycles.

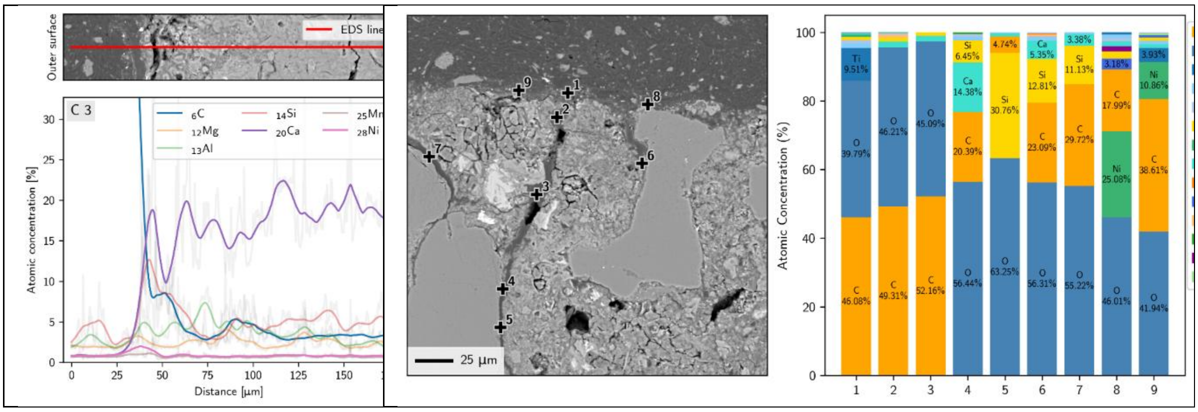


Figure 6: Combustion product penetration into concrete samples: elemental composition in concrete degradation zone, locations of spot measurements and measured atomic concentrations at selected points of concrete sample C 3.

The presence of nickel, cobalt, and manganese within the concrete samples was not uniform but concentrated in specific regions, particularly at the interfaces between the cracks and degraded matrix areas, confirming that these metallic elements originated from the battery cell and migrated into the concrete due to the thermal runaway reactions. This finding is critical for understanding the long-term impact of battery fires on the structural integrity of tunnel linings and other concrete infrastructure exposed to battery-induced fires.

Thermal abuse - Overheating

The overheating thermal abuse tests provided crucial insights into the behavior of lithium-ion cells under extreme thermal stress. A key finding was the rate of temperature increase, which was alarmingly fast, with some cells heating from 130 °C to over 1300 °C in just 1.8 seconds, see Figure 8. This rapid escalation results to the high reactivity of the cells when exposed to prolonged heat, compounded by reduced heat dissipation in an already-heated environment. As shown in previous studies, the combination of reduced cooling capacity and accelerated reaction kinetics at high temperatures makes thermal runaway more severe [8]. The pressure profiles observed in these tests also highlighted the importance of safety mechanisms, as gases released during TR caused significant pressure buildup inside the cell, peaking at 1.47 bar under the most extreme conditions, see Figure 9. The safety valve’s role in relieving pressure helped mitigate some of the immediate risks associated with explosion or fire propagation, but it was evident that the reaction would continue to escalate once the valve had been triggered.

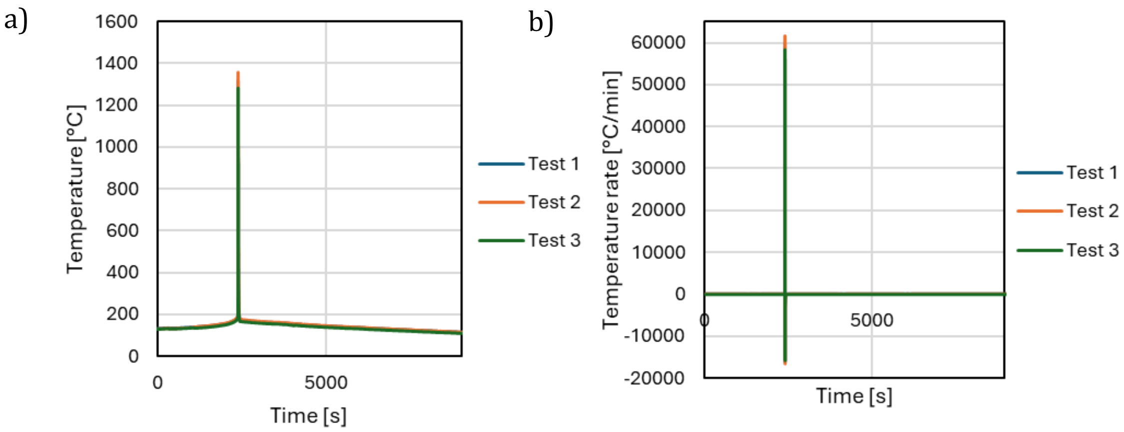


Figure 7: a) temperature profile of the cell during the overheating test,
b) temperature gradient profile of the cell during the overheating test.

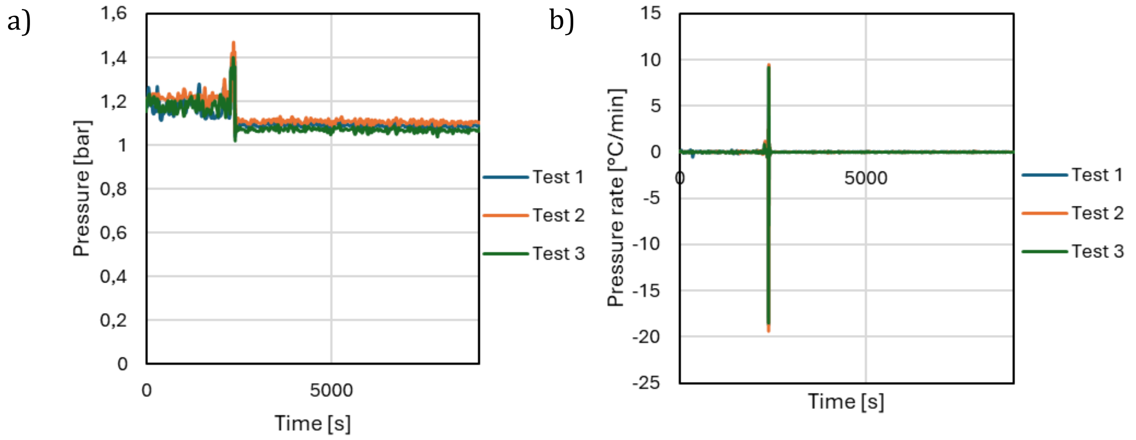
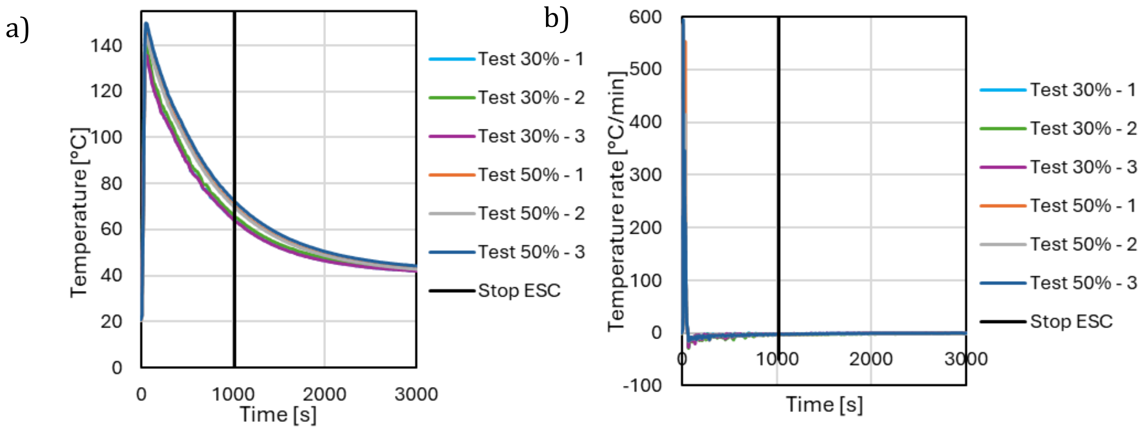


Figure 8: a) pressure profile during the overheating test,
b) pressure gradient profile during the overheating test.

Electrical abuse - External Short Circuit

During the ESC tests, the cells exhibited an increase in temperature; however, the rise was not sufficient to trigger TR. The maximum temperatures reached were relatively moderate, and temperature gradients remained within manageable levels. At both 30% and 50% states of charge (SOC), the temperature increase was slower compared to tests involving nail penetration or overheating, where the cells experienced rapid and extreme thermal escalation, see Figure 10. This indicates that external short circuits under these conditions do not generate the intense thermal reactions that lead to TR, likely due to the thermal protection mechanisms built into the cells, such as PTC (Positive Temperature Coefficient) thermistors and Current Interrupt Devices (CID).



c)

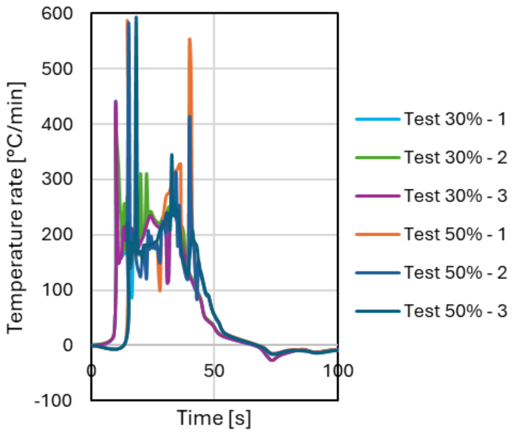


Figure 9: a) ESC test temperature profiles on 21700 cells at different SOCs,
b) ESC temperature gradient profiles on 21700 cells at different SOCs,
c) Temperature gradient profiles in the early stages of ESC on 21700 cells at different SOCs.

4. CONCLUSIONS

The experimental study revealed the critical parameters influencing lithium-ion battery thermal runaway under realistic conditions. TR events generate intense heat, pressure, and toxic gases that can compromise tunnel structures. Mechanical and thermal abuses were identified as dominant triggers, while electrical short-circuiting was mitigated by cell safety mechanisms. Concrete materials experienced cumulative degradation after repeated exposures, underlining the need for fire-resistant designs. The observed 300–350 s safety valve delay offers a crucial opportunity for emergency response in confined environments. These results provide a foundational dataset for developing safety models, risk mitigation measures, and structural protection strategies in underground applications.

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