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Thermal Runaway and Fire Characteristics of Lithium-Ion Batteries Triggered by Nail Penetration

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The 15th International Association for Fire Safety Science (IAFSS) Symposium - La Rochelle, France

Research motivation & objectives

- **Thermal runaway** (TR) and fire behavior of **Lithium-ion battery** (LIB) cells and small modules under **mechanical abuse condition** was investigated using Accelerated Rate Calorimeter (ARC).
- The integration of **phase change materials** (PCMs), **thermally conductive barriers** (e.g. boron nitride and graphene nanoplatelets), and **biochar-enhanced PCMs** derived from food waste and wastewater digestate at cell level under **normal cycling condition and abuse condition** (nail penetration) was assessed as a passive thermal management and mitigation strategy.
- Key parameters including **cell surface temperature**, **temperature rate** and **peak temperature**, **pressure and pressure rate** inside the chamber, as well as **exhaust gas concentrations** (CO and CO2) were measured.
- **Inter-cell TR propagation** in small modules subjected to nail penetration was studied.

Test set-up & experimental procedure

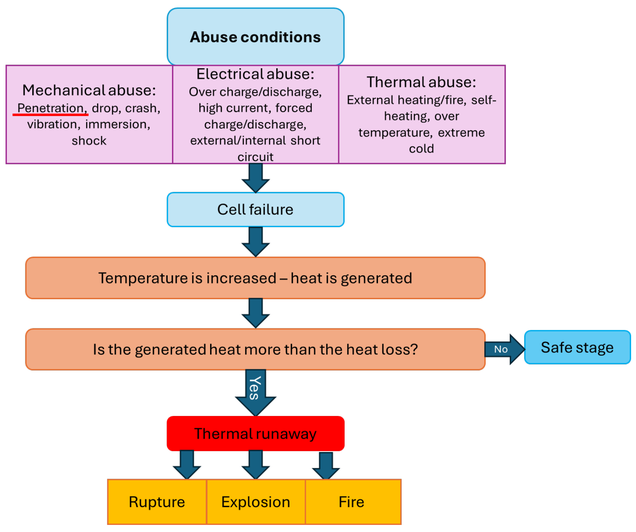


Figure 1. Cell failure due to abuse conditions leading to TR

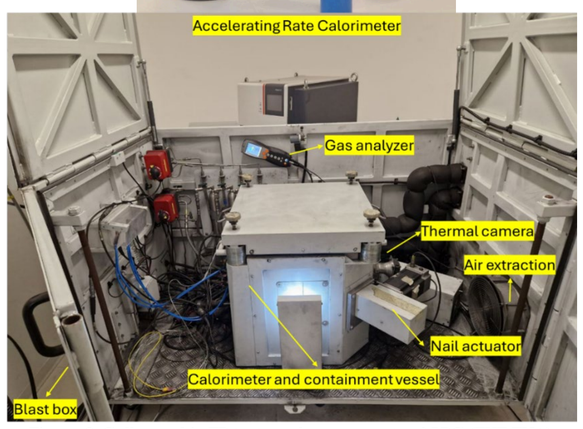


Figure 2. Cells used in TR tests and components of ARC (THT EV+)

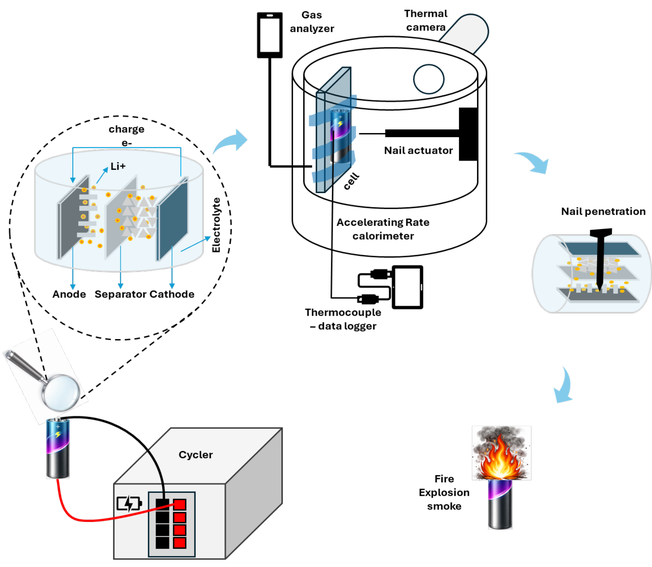


Figure 3. The procedure of nail penetration tests

As shown in Fig. 1, **nail penetration** was selected to trigger TR among different abuse conditions. The test setup included an **ARC** and an external gas analyzer (Fig. 2). **Cylindrical NMC and LFP cells** (1.1–4.9 Ah, 100% SOC, CC–CV mode) and **3-cell parallel modules** were subjected to nail penetration to investigate TR and **inter-cell propagation** (Fig. 3).

In addition, **charge-discharge cycling** and nail penetration tests were performed on LIBs wrapped with **PCM composites**, including **pure PCM**, **BN-**, **GNP-**, and **biochar-enhanced PCMs**, to evaluate their thermal management and **TR mitigation** performance.

Results & discussion – TR in LIBs without PCMs

The temperature evolution and temperature rise after triggering cells in single cell and module tests are represented in Figs 5 & 6. No TR was observed in **1.1 Ah LFP** cell. In contrast, NMC cells with **3.4 Ah** & **4.9 Ah** exhibited TR, reaching peak temperatures of **770 °C and 900 °C**. In module tests, TR propagation occurred only in one the tests of **3 x 3.4 Ah NMC** Modules. Fig. 4 shows some of the cells after TR tests.

Figure 4. Damaged cells and modules after TR tests

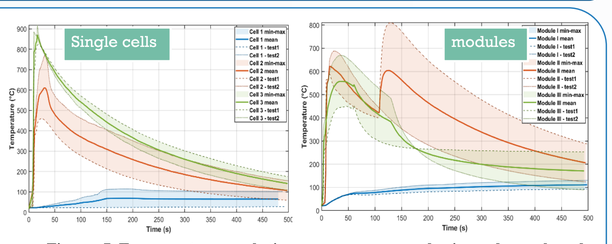


Figure 5. Temperature evolution, mean curve and min and max bands

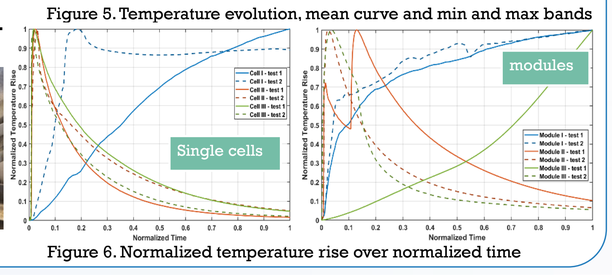


Figure 6. Normalized temperature rise over normalized time

Results & discussion – TR in LIBs with PCMs

Table 1 summarizes the values measured during ARC TR tests for different cells and modules, including **peak temperature**, **pressure, and gas emissions**. The maximum temperature rate exceeded **600 °C/s** for the 21700 cell, while the 1.1 Ah LFP cell remained below **3 °C/s**, insufficient to trigger TR. Gas emission trends (CO and Oxygen) for single cell tests are shown in Fig. 6. The 4.9 Ah NMC cell produced **peak CO concentrations** of ~7000 ppm, whereas the LFP cell generated negligible CO. Thermal camera snapshots of the 4.9 Ah NMC cell during TR are shown in Fig. 7. After nail penetration, local temperature rise and **exothermic reactions** initiated TR, followed by jet and smoke ejection and sustained combustion. **Pressure evolution** inside the vessel is presented in Fig. 8, with a maximum pressure of 2.18 bar recorded during the first module test.

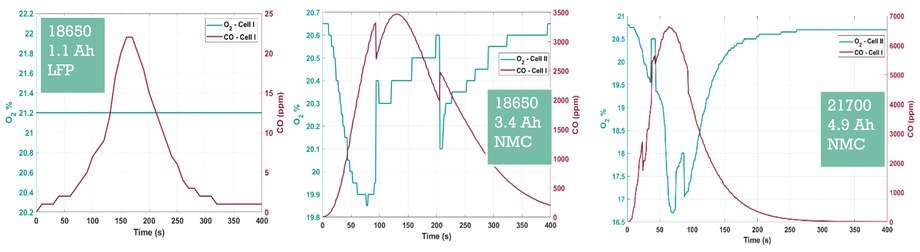


Figure 6. Gas emission variation (CO and O2 average values)

Table 1. Values measured during mechanical abuse testing (without PCM)

	18650 1.1 Ah	18650 3.4 Ah	21700 4.9 Ah	18650 3 x 1.1 Ah	18650 3 x 3.4 Ah	21700 3 x 4.9 Ah
Maximum Temperature (°C)	114.9	770.6	918.5	170.8	810.7	669.5
Maximum Temperature Rate (°C/s)	2.81	323.22	614.50	4.67	562.04	352.54
Maximum Pressure (bar)	2.05	1.98	2.10	2.18	1.48	1.90
Maximum Pressure Rate (bar/s)	0.37	1.07	1.12	0.66	0.32	0.89
Maximum CO (ppm)	32	3470	6642	35	16718	16555
Minimum O_2 (%)	21.1	19.9	16.7	20.5	16.0	12.1
Maximum NO (ppm)	0	6	36	0	26	106
Maximum CO_2 (%)	0	1	4	0	4	3
Cell mass before test (g)	39.5	50	68.5	3x39.5	3x50	3x68.5
Avg mass after test (g)	38.5	29	35.5	114.5	78	172

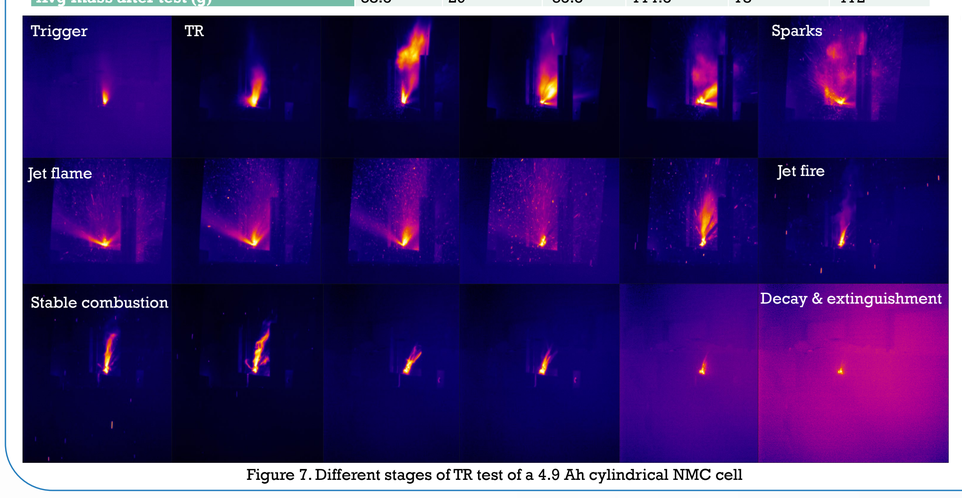


Figure 7. Different stages of TR test of a 4.9 Ah cylindrical NMC cell

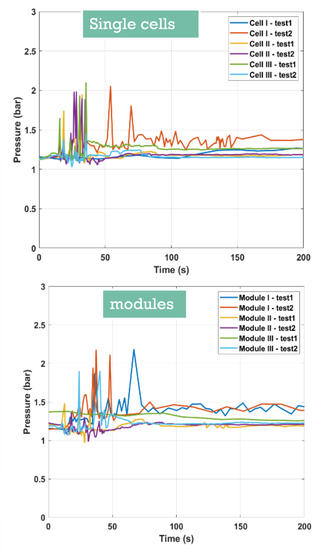


Figure 8. Pressure variation inside the vessel during TR tests

Results & discussion – TR in LIBs with PCMs

A wide range of innovative **PCM composites** using nanomaterials and additives was used to study their **thermal management capabilities** under normal and abuse conditions. The list of materials is summarized in Tab. 2. Their thermal conductivity, latent heat, melting temperature, thermal stability, degradation behavior, and heat release rate were characterized prior to the main cycling and nail penetration tests using a hot disk analyzer, differential scanning calorimetry (DSC), thermogravimetric analysis (TGA), and cone calorimetry, respectively.

Charge-discharge cycling tests were performed on batteries wrapped with PCM-based composites (Fig. 9) at 0.5C, 1C, and 1.5C rates. Thermocouples attached to the battery surface and PCM materials recorded temperature variations to evaluate **thermal dissipation performance**. Selected results for GNP1.5, GNP30, and pure PCM are shown in Fig. 10, where GNP1.5 exhibited superior thermal management performance. However, the BN additive was selected for its flame resistance and electrical insulation properties, helping maintain circuit safety in the event of PCM leakage. Nail penetration tests were performed to assess the capability of different materials to **control TR**. Fig. 11 shows the temperature evolution during TR tests. In many scenarios, PCM-based composites were able to affect TR and fire events by reducing the **severity of TR** and **peak temperatures**. It should be noted that although the addition of nanomaterials improved the leakage resistance of the composites, complete prevention of PCM leakage can only be achieved through **macro-encapsulation** approaches.

Figure 9. LIB cell inside PCM composite container during cycling tests

Table 2. Summary of the PCM composites used in this study

Acronym	Material
PCM	Phase Change Material
BN	Boron Nitride
GNP	Graphene Nanoplatelets
FW400-PCM	Biochar derived from food waste
DW400-PCM	Biochar derived from pyrolyzed digestate from a wastewater treatment plant
FLG240	Carbon nanomaterial
E17PP	Carbon nanomaterial

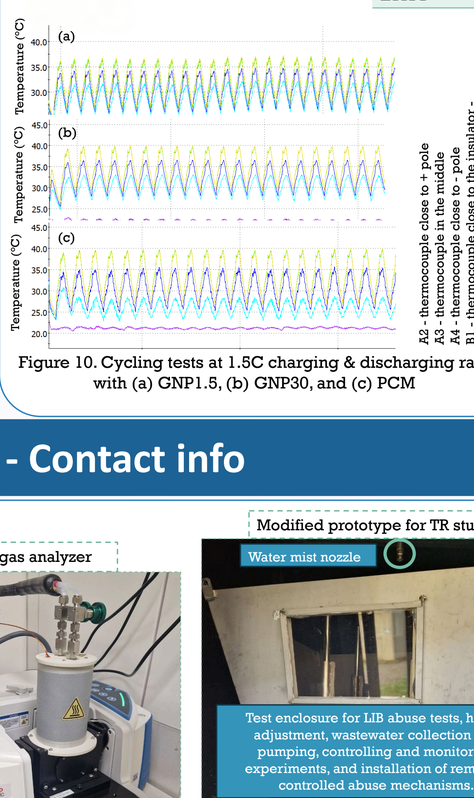


Figure 10. Cycling tests at 1.5C charging & discharging rate with (a) GNP1.5, (b) GNP30, and (c) PCM

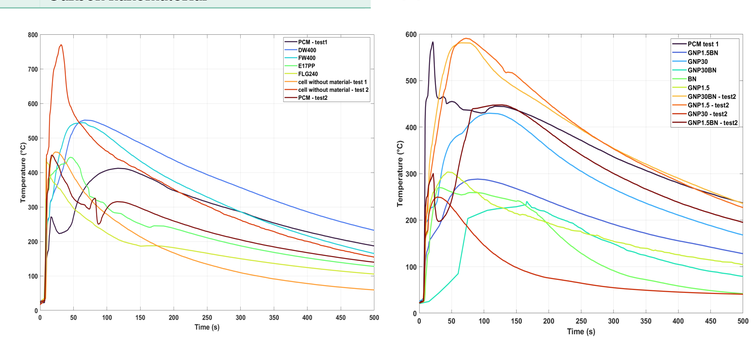


Figure 11. Cell surface temperature during nail penetration tests with & without PCM composites

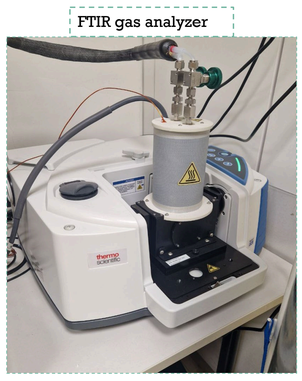
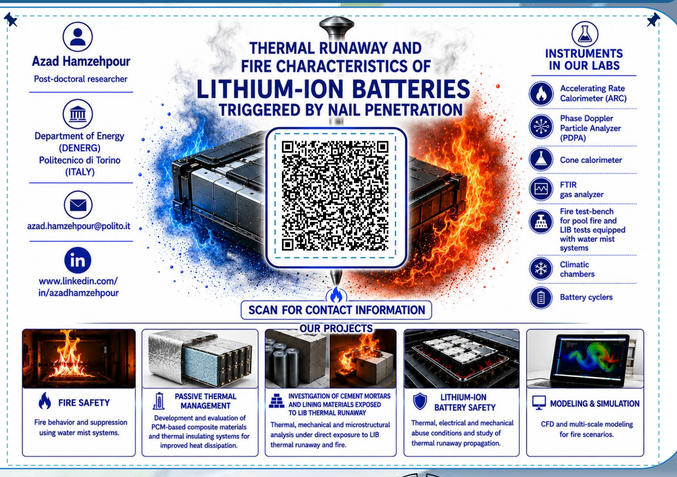
Future works - Contact info

Research on progress:

- ❑ The application of active fire protection systems (water mist systems with and without fire extinguishing agents) for LIB fires is being investigated.
- ❑ Microstructural and micromechanical changes in cement-based materials, used in tunnel linings, after being exposed to LIB TR as well as water mist are being studied.
- ❑ Post-combustion gas emissions from LIBs subjected to mechanically induced and thermal abuse conditions are being analyzed using an FTIR gas analyzer.
- ❑ Analysis of water runoffs in terms of contamination after activation of water mist and post-mortem analysis will be conducted for LIB abuse tests.
- ❑ The capacity of LIB cells and modules subjected to mechanical, thermal, and electrical abuse conditions will be increased eventually up to 150 Ah.
- ❑ The impact of the distance between water mist nozzle and LIB fire will be investigated.

Acknowledgement:
This project (eFITNESS - electricity Flexibility dIstrict heaTiNg bidirEctional SubStation) is funded by Ministero dell'Ambiente e della Sicurezza Energetica (DM n. 386 del 17 novembre 2023).

FTIR gas analyzer



Modified prototype for TR study