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Insight

Lithium-ion Battery Fire Safety

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The fire dynamics of LFP and NMC/LMO chemistries are compared by analysing Heat Release Rate (HRR) data to demonstrate how safety features vary with scale. The analysis shows a performance crossover: LFP can display a higher peak HRR at smaller scales, while NMC/LMO becomes more intense at larger scales. Additionally, the difference between peak power and total energy release is important, as LFP's lower peak HRR can be balanced by a longer burn duration. Safety is an emergent property of the engineered system, requiring a design approach that prioritises resilience over mere prevention.

The selection of a lithium-ion battery chemistry for any given application involves a trade-off between performance, cost, and safety. The most common cathode types, Lithium Iron Phosphate (LFP) and Lithium Nickel Manganese Cobalt Oxide (NMC), or Lithium Manganese Oxide (LMO), exhibit different risk profiles. The safety of a particular chemistry is frequently evaluated based on its thermal runaway severity, the volume and composition of vented off-gas, and the challenges associated with fire suppression. Although these factors are critical for assessing the hazards associated with failure events, they do not entirely characterise the likelihood of fire occurrence due to the complexities inherent in real-world battery systems, as well as operational and environmental factors that contribute to battery fires.

Nevertheless, to quantify the potential fire hazard, engineers depend on the Heat Release Rate (HRR) metric. Although fires can be characterised by numerous attributes, including temperature and heat flux, the HRR signifies the fire's power. It serves as the most pivotal variable for predicting its intensity and development, and it facilitates the prediction of other essential parameters such as smoke generation, toxicity, and temperature. Through the analysis of HRR, designers can develop practical fire barriers, suppression systems, and safety protocols.

This article exclusively concentrates on the fire intensity produced by battery thermal runaway, without addressing the probability of thermal runaway initiation or spontaneous off-gas ignition. Through the analysis of comprehensive test data obtained from a broad spectrum of cell, module, and pack-level experiments conducted at 80%-100% SOC, the article elucidates the differing fire behaviours of LFP and NMC/LMO chemistries, occasionally involving the intentional ignition of vented gases to facilitate combustion during experimental procedures.

The Heat Release Data

Naturally, the peak heat release rate during thermal runaway generally increases with system capacity. However, as shown in Fig. 1, the scaling relationship is chemistry-dependent, resulting in a performance crossover between the trend lines of the LFP and NMC/LMO systems at different scales, although a larger dataset would be needed to confirm this trend statistically.

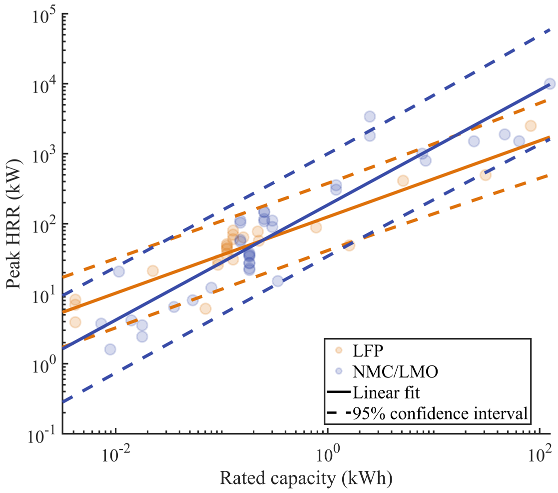

Figure 1: *Peak heat release rate.*

Specifically, at the scale of a single cell or a small module (<0.2 kWh), where components tend to fail in near-unison, LFP chemistries can exhibit a higher peak HRR than their NMC/LMO counterparts. This behaviour is attributed to the composition of the vented off-gas; compared to NMC/LMO cells, LFP thermal runaway can produce significantly higher concentrations of hydrogen, a fuel characterised by a substantially higher gravimetric energy density and laminar flame speed compared to hydrocarbon gases. Conversely, in larger systems (10 kWh – 100 kWh), the higher energy density of NMC/LMO chemistries, combined with oxygen release from the cathode structure during decomposition, facilitates more energetic and rapid cell-to-cell propagation, resulting in a greater overall system-level HRR.

This fundamental difference in propagation mechanism directly correlates with distinct temporal fire dynamics. The superior thermal stability of LFP signifies that it necessitates greater time and energy input to initiate thermal runaway. This inherent resistance, coupled with a less energetic, heat-transfer-driven propagation, results in a more gradual escalation of the fire – notwithstanding the fact that the off-gas from a cell possesses the potential for more en-

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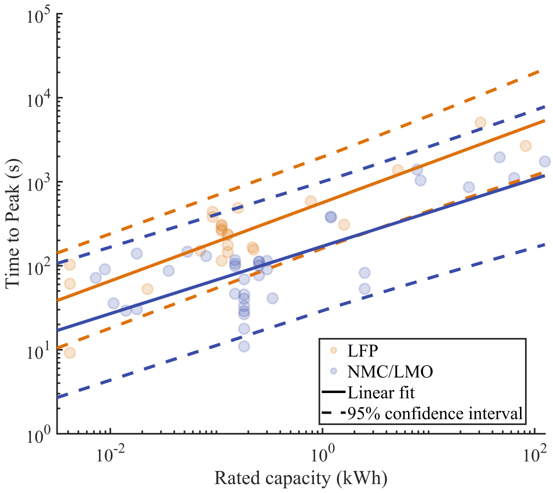

Figure 2: *Time to peak HRR.*

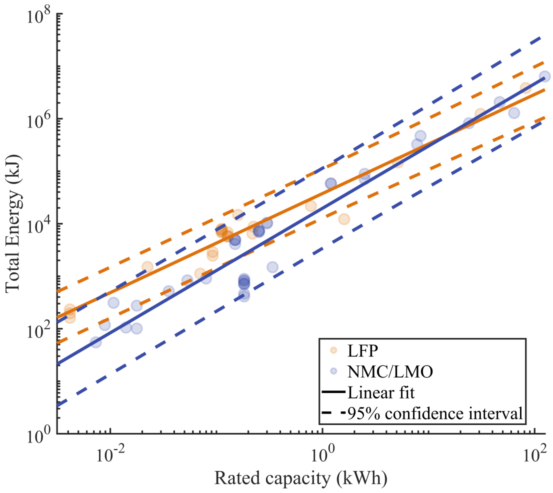

Figure 3: *Total energy released.*

ergetic combustion. Consequently, as system capacity increases, LFP batteries consistently require more time to attain their peak heat release rate, as illustrated in Fig. 2.

Although the peak power (HRR) of an LFP fire is lower at larger scales, the total energy released over the event's full duration reveals a more complex picture (Fig. 3). The extended combustion characteristic of LFP fires can lead to a more thorough consumption of available fuels, such as the electrolyte and plastic components. Consequently, an LFP battery fire can produce a greater cumulative heat release than a comparable NMC/LMO system, especially in systems with a capacity below 10 kWh.

Engineering for Resilience

The data indicates a pivotal aspect in the safety evaluation of LFP and NMC/LMO batteries: the characterisation of "safer" is wholly contingent upon the system scale and the particular fire property being assessed. At smaller scales, LFP's hydrogen-rich off-gas may lead to a fire exhibiting greater peak intensity (HRR), whereas its extended combustion duration can result in a higher total energy discharge. Conversely, at larger scales, NMC's energy density and the cell-to-cell propagation mechanism generate a fire with a significantly elevated peak HRR. This dichotomy does not advocate for one chemistry over the other; rather, it highlights the perilous oversimplification that has frequently pervaded safety discourses. There exists no singular "safest" chemistry; instead, there is a dynamic hazard profile that necessitates a more sophisticated and nuanced approach to risk evaluation.

This understanding fundamentally shifts the engineering objective from merely preventing thermal runaway to designing systems that are resilient in the event of failure. The factors influencing the probability of a fire are distinct from those determining its ultimate consequences. While the selection of chemistry impacts the severity of outcomes, it is the comprehensive system design that governs resilience. Engineering for resilience entails acknowledging that failures are possible and emphasising containment measures. This includes the implementation of robust thermal barriers, effective off-gas management, and suppression systems specifically tailored to the unique fire dynamics—whether it involves the high peak power characteristic of a large NMC fire or the sustained, high-energy combustion typical of an LFP fire. This highlights a critical point: one cannot assess a system's fire risk solely based on the data sheet of a cell.

Ultimately, the fire hazard of a lithium-ion battery is not a static property of its chemistry but a dynamic behaviour that evolves with the engineered system. The perceived safety advantage of LFP—lower peak HRR at the pack level—is counterbalanced by different hazards at other scales. For engineers, this means moving beyond a simplistic "LFP vs. NMC" debate. Proper safety is an emergent property of the entire system, integrating the cell chemistry, mechanical design, and safety controls. It requires a holistic approach: understanding the specific failure dynamics dictated by the chosen components and scale, and engineering a resilient system equipped to manage, contain, and mitigate the consequences of a fire, regardless of its origin.

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Web: www.bugryniecconsulting.com
E-mail: info@bugryniecconsulting.com

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