ABSTRACT

Lithium-ion batteries are a cornerstone technology in the transition toward sustainable mobility and renewable energy integration, yet their safety remains a significant challenge. Chief among safety hazards is *thermal runaway* – a self-accelerating, exothermic reaction sequence that can result in fire, explosion, and toxic emissions. This dissertation investigates the degradation processes of modern materials used in Rechargeable Energy Storage Systems for electric vehicles and stationary Battery Energy Storage Systems under conditions of fire exposure and/or mechanical overloads. The work identifies critical limitations in current regulatory fire testing procedures, particularly the UNECE R100.03 open-flame external fire test, which exhibits high variability, qualitative pass/fail criteria, limited diagnostic capability, and safety hazards to personnel and the environment.

A comprehensive literature review is combined with experimental, numerical, and statistical analyses to evaluate the thermal, mechanical, and electrochemical failure mechanisms of lithium-ion batteries, the influence of cell chemistry and architecture, and the efficacy of passive and active safety measures. A detailed examination of current global standards reveals inconsistencies in sensor placement, environmental control, and acceptance criteria. Using open-flame fire resistance testing as a core study, this thesis demonstrates how uncontrolled environmental variables (e.g., wind, flame impingement patterns) lead to poor repeatability between laboratories.

To address these issues, an alternative, quantitatively grounded methodology is developed by adapting the ISO 834-1 / EN 1363-1 furnace-based fire resistance standard, widely applied in structural fire engineering – to the evaluation of lithium-ion battery enclosures. This approach offers tightly controlled and reproducible thermal exposure, improved safety, and enhanced diagnostic value through rigorous sensor instrumentation and continuous data acquisition. Comparative analyses show that furnace-based testing significantly reduces measurement uncertainty and yields rich datasets on heat transfer, structural degradation, and propagation thresholds, thus enabling better-informed safety engineering decisions.

Complementing this methodological advance, a Thermal Runaway Emissions Aftertreatment System (TREAS) is designed and validated to mitigate the release of hazardous gases during testing, aligning with emerging environmental and occupational safety requirements. The combined methodology – controlled thermal exposure with integrated emissions management-provides a robust framework for both scientific investigation and regulatory compliance.

The outcomes of this research contribute a repeatable, data-rich fire testing protocol for battery energy storage systems, offering actionable recommendations for standards development, improved enclosure design, and enhanced public safety. By bridging fire science, battery engineering, and standardisation practice, this thesis supports the safe and reliable deployment of high-energy battery systems in next-generation transport and energy infrastructures.