SCENARIO-BASED SAFETY ASSESSMENT OF THERMAL RUNAWAY IN EVTOL BATTERY APPLICATIONS

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Abstract

Recent battery research shows new approaches for module-level strategies to prevent thermal runaway propagation through the use of thermal barriers and advanced heat dissipation methods. Since evidence for failure mechanisms and propagation processes is still new and limited, we propose a scenario-based safety assessment in this paper, ranging from very conservative to progressive assumptions. The focus of the analysis is on the interaction of the two protection technologies to investigate whether the battery system can potentially meet the safety targets for manned eVTOL and UAV use cases. The analysis shows that even under the most conservative scenario, UAV safety targets could be met with a moderate mass penalty, but a further reduction of the failure probability for manned aircraft increases the mass penalty to a greater extent.

1. NOTATION

Acronyms:

BTMS	Battery Therm. Management Sys.
eVTOL	elec. Vertical Takeoff and Landing
FHA	Functional Hazard Assessment
TIF	Time Improvement Factor
TR	Thermal Runaway
TRP	Thermal Runaway Propagation
UAM	Urban Air Mobility
UAV	Unmanned Aerial Vehicle
VFS	Vertical Flight Society

2. INTRODUCTION

While a multitude of research efforts on Urban Air Mobility concentrate on vehicle performance and design, safety and certification aspects are lagging behind. However, it remains a critical factor in achieving acceptable safety levels for battery electric or hydrogen-hybrid concepts. A variety of new manned and unmanned eVTOL use cases have recently been proposed. Garrow et al. (Ref. 1) highlight the strong research interest in distributed electric propulsion and battery advancements, while work in the safety domain is still underrepresented. Due to the inherent safety challenges associated with the use of lithium-ion batteries, a structured assessment according to well-known standards (e.g. SAE ARP4761) is an essential certification step (Ref. 2). To assess whether certification thresholds can be met for specific eVTOL use cases, we use the results of a Functional Hazard Assessment (FHA) for a battery system in conjunction with a scenario-based safety analysis for battery Thermal Runaway (TR). Recent advances in research on thermal runaway protection methods for batteries help to create four different scenarios describing the propagation of a thermal runaway event, together with a corresponding detection and passivation strategy. The aim of these scenarios is to investigate and develop comprehensive methods to prevent Thermal Runaway Propagation (TRP) within battery modules or across the entire battery system. Another aspect of this scenario analysis is to understand how the detection of TR affects the effectiveness of prevention, and, in turn, how the time available for detection affects the likelihood of successful detection and subsequent prevention of TRP.

3. CREATING A SCENARIO ANALYSIS FOR THERMAL RUNAWAY PROPAGATON

As a basis for a structured definition of the four scenarios leading to TR and for the quantification of their respective failure mechanisms using state-of-the-art safety assessment methods, an overview of current developments in cell- and system-level protection measures is first given. Subsequently, the scenarios including their assumptions are discussed.

3.1. Previous Work

The use of lithium-ion batteries plays a crucial role in the electrification of Urban Air Mobility (UAM). However, the prevalent concern is a TR, a critical failure that dominates certification aspects. This phenomenon is an unstable exothermic behavior that may lead to battery fire, smoke and possible explosion (Ref. 3, Ref. 4). It has been found that critical TR failure in one cell alone can trigger neighboring cells. According to Ref. 5, the majority of the heat flux (≈ 90%) transfers through the module shell, emphasizing the need to address mitigation strategies at the module level. In recent years, researchers have published more work on TR detection and mitigation at the module level, focusing primarily on preventing TRP through a combination of thermal insulation and enhanced heat dissipation. Thermal insulation pads (thermal barriers) prevent heat transfer between adjacent cells, while heat dissipation mechanisms, typically liquid cooling systems, remove excess heat from the battery system, preventing overheating and reducing the risk of TRP. (Ref. 6, Ref. 7, Ref. 8) In addition, recent research has shown that certain novel phase change materials have the ability to prevent thermal runaway propagation on their own, without the need for additional assistance. This is due to their higher conductivity before phase change, which implies higher heat absorption during the phase change process, and lower thermal conductivity after phase change, which acts as thermal insulation. (Ref. 9, Ref. 10, Ref. 11) Furthermore, while the primary function of liquid cooling systems used in Battery Thermal Management Systems (BTMS) is to maintain the battery temperature within the normal operating range rather than to prevent thermal runaway (TRP) per se; the literature suggests that some novel liquid cooling systems can prevent TRP alone, without the need to use them in combination with other TRP prevention mechanisms. These mini-channel cooling systems accomplish this by maintaining the temperature of cells adjacent to the triggered cell below the critical threshold for initiating thermal runaway. (Ref. 3, Ref. 12, Ref. 13) TR detection systems are also vital in detecting anomalies during a thermal runaway event so that appropriate action can be taken to mitigate its effects and prevent further escalation. This typically involves the use of various sensors, including gas sensors, voltage sensors, and surface temperature sensors, the effectiveness of which is critical in providing early warning and enabling rapid response. (Ref. 14, Ref. 15)

3.2. Scenario framework

Based on the principles outlined, it is clear that TRP mitigation can be achieved through the synergistic use of thermal barrier and liquid cooling methods. Additionally, the integration of redundant TRP prevention strategies that include both thermal barrier and liquid cooling mechanisms holds promise for increasing the effectiveness of TRP mitigation, thereby further reducing the likelihood of its occurrence. While qualitative studies have demonstrated the potential to prevent thermal runaway, it is imperative to substantiate these findings with systematic and quantitative analysis and to validate the effectiveness and reliability of the proposed strategies. To achieve this, we develop a comprehensive TRP prevention system configuration encompassing all possible combinations of available prevention strategies. This configuration also integrates the critical role of thermal runaway detection in order to employ all the safety mechanisms. It further enables the use of active (liquid cooling system) and passive (thermal barrier) thermal runaway mitigation strategies.

3.3. Scenario definition

Considering the high degree of uncertainty in the safety assessment, four scenarios are introduced to discuss the variety of potential failure mechanisms and propagation processes. The role of heat dissipation along with thermal protection provides the basis for the analysis, which is then extended to include the need for detection to initiate the cooling scheme. The scenarios can therefore be outlined as follows, in ascending order of progressiveness (Table 1):

Sc.	Failure mechanism for TRP mitigation	Detection	No. of Ref.
1	Thermal protection and cooling required	dependent	5
2	Thermal protection or cooling required	dependent	2
3	Thermal protection and cooling required	independent	-
4	Thermal protection or cooling required	independent	-

Table 1: Scenario definition with role of detection and number of references showing evidence

Six distinct thermal barrier materials with varying thicknesses are selected for further quantitative analysis. These materials include aerogel (A) (Ref. 16,17,19), composite phase change material (P1) (Ref. 8), fibre-reinforced hydrogel (H1) (Ref. 9, Ref. 10), fire-retardant phase change material (P2) (Ref. 18), a combination of aramid fiber and hydrogel (H2) (Ref. 11), and hollow glass microsphere plates (HMP) (Ref. 20). Table 2 provides a detailed overview of the materials used in this study, where the notation H1/1 refers to the material H1 with a thickness of 1 mm. This nomenclature is used throughout the table. The materials are chosen based on experimental data derived from TRP tests conducted on electric vehicle (eV) batteries, which are equivalent in capacity to those used in eVTOL aircraft.

In this work, we analyze the design of a *Lift+Cruise* aircraft capable of performing a five-minute hover, with the remaining energy for flight provided by a fuel cell system. In all four scenarios, the battery system is considered to consist of two additional strings, i.e. three parallel strings. This design ensures that the failure of a single string can be tolerated without a loss of functionality. In addition, two different types of redundant liquid cooling systems are used. A direct cooling system is used for scenarios 1 and 3, while a mini-channel cooling system is used for scenarios 2 and 4.

A critical aspect that warrants discussion is the probability of detection and the Time Improvement Factors (TIFs) for all materials. We define the TIF parameter in equation (1) as:

$$TIF = \frac{t_b}{t_{nb}} \qquad (1)$$

where:

t_b: average time of TRP (time between the onset of TR and onset of TR of the adjacent cell)

t_{nb}: average time of TRP without protection

This parameter serves as a critical indicator of the available response time before a triggered thermal runaway event propagates to the adjacent cell.

The TIF also forms the basis for calculating the probability of detection for each material. As seen in Figure 1, the likelihood of battery thermal runaway (or loss of the protection) is directly influenced by the probability of an undetected thermal runaway which can lead to a failed cooling system activation. Due to the lack of available data, we assume that the material with the highest TIF (H1/2) provides the highest probability of detection. In this case, it is the minimum detection probability (99.99%) required to ensure a probability of battery thermal runaway of $\leq 1 \cdot 10^{-9}$, as shown in Figure 1. This is the quantitative requirement for a failure condition having a 'catastrophic' safety effect on the aircraft (Ref. 2). The detection probabilities for other materials are calculated by linear interpolation between the baseline and the highest detection probability, using the TIF values as the independent variable on the x-axis. However, the following qualified assumptions are made to compute detection probabilities for all materials:

- The detection probability can be improved if more time is available for detection.
- The detection probability increases linearly with the available detection time.
- The configurations developed for all scenarios are simplified architectures that do not account for all secondary effects and dependencies.

Scenario 1 and 3			
Material	TIF (-)	Det. Prob. (%)	Mass Increase per Cell (Barrier + Cooling) (%)
H1/1	3.6	93.0	16.5
H1/2	12.0	99.9	18.8
A/1	4.6	93.8	14.6
P1/3	2.0	91.7	16.4
HMP/1.5	4.0	93.3	14.5
HMP/2	5.0	94.1	14.6

Scenario 2 and 4			
H1/3			29.1
H2/1.9			26.4
H2/2.9	∞	n.a.	28.2
P2/3			24.9
HMP/3			22.8

Table 2: TIF, detection probability, and mass increase for various materials in different scenarios

3.4. Safety targets and FHA

Defining the quantitative requirements for certification is an essential step for the safety assessment. The basic process includes a System Functional Hazard Assessment (System FHA) for the battery system of various eVTOL use cases. The methodology and the results of this initial assessment were published at the VFS Forum 79 (Ref. 21). Since a complete TR – due to its uncontained nature – can be described as an 'out of control' event, its classification is assessed as 'catastrophic' for all considered use cases.

3.5. Safety assessment and FTA

According to ARP4761, the demonstration of quantitative compliance is typically achieved through the use of a Markov or Fault Tree Analysis (FTA). A stochastic Markov process offers the advantage of a higher computational complexity when using a numerical solver to evaluate all discrete probability states of the system (Ref. 22). However, for the scenario analysis in this paper, an FTA provides benefits due to its graphical nature and intuitive understanding. The top event created from the System FHA can be linked to individual intermediate and basic events. We assume random failures with a constant failure rate λ, which leads to exponentially modeled component failure probabilities according to equation (2):

$$P_{f,fm}(t) = 1 - e^{-\lambda} \qquad (2)$$

The most commonly used logical gates in an FTA are the *'or'* gate and the '*and*' gate. While the '*and*' gate models events that must all to occur to trigger the (unwanted) top event, the *'or'* gate covers failure mechanisms where a single event is sufficient to lead to the top event. For this work, a number of qualified assumptions are required to construct the fault trees in order to account for the uncertainties resulting from the limited evidence on the failure mechanisms:

- The failure probabilities of the different thermal barriers are assumed to be identical and are modeled with the same probability as the cell failures.
- The failure probabilities of the cooling system (mini-channel or liquid cooling) are assumed to be equal.

3.6. Example: Scenario 1

Four scenarios are discussed in this paper. Figure 1 shows the failure mechanism of scenario 1 based on the aforementioned considerations in a Fault Tree. For the sake of clarity, we briefly summarize the main aspects:

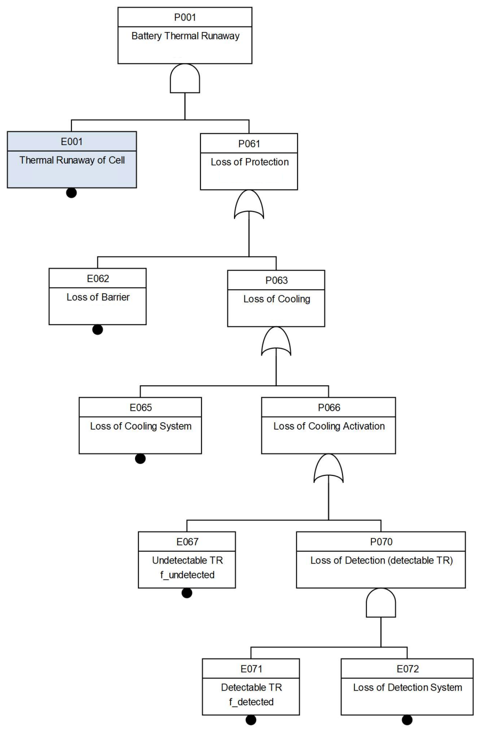

Figure 1: Fault Tree of scenario 1; TR protection depends on the combination of proper cooling system function (by detection) and barrier effect

- *Loss of Cooling Activation (Detection):* Detecting thermally unstable behavior is modeled with the probability 1-$f_{undetected}$, which is set to 0.9 for the baseline architecture and increased by the barrier materials as described above. In addition, a redundant design of the detection system can provide a sufficiently low probability of failure for false alarm protection.

- *Loss of Protection*: If a TR is successfully detected, the cooling system is required to increase the flow rate to improve the temperature control of the adjacent cell (Ref. 6). Thus, either a failure of the thermal barrier or a loss of the (redundant) cooling system will still result in a TRP.

Scenario 2 differs from the described fault tree in a slight modification of the mechanism at the '*Loss of Protection'* event. The affected *'or'* gate is replaced with an *'and'* gate to account for the sufficiency of one of the two mitigations. Scenarios 3 and 4 describe failure mechanisms where the liquid cooling system control is independent of the detection scheme after a *runaway* event in a single cell. Thus, Scenario 4 stands for the most optimistic propagation process, as it requires neither detection-based monitoring nor both of the introduced mitigations.

4. RESULTS

The sizing process was conducted using a cell mass model and an aircraft sizing code by Ng and Datta (Ref. 23). As shown in Table 3, the configuration analyzed is a *Lift+Cruise* concept with a battery sized to sustain a hover phase of 5 minutes. Further sizing related parameters are depicted as well.

Characteristic	Value
Payload weight	360 kg
Configuration	Lift+Cruise
Hover period	5 min
Cruise period (*fuel cell*)	1 h
Motor efficiency	0.9
Battery type	Lithium-Ion
Number of cells in series	108
Number of cells in parallel	3

Table 3: Use case characteristics of aircraft and battery sizing

Figure 2 shows the relationship between the probability of battery TR and the corresponding absolute battery mass for all four scenarios. Scenario 1 warrants particular attention due to its lower degree of progressiveness and is supported by more substantial qualitative evidence than the other three scenarios. As a result, the data points for the various thermal barrier materials are fully represented in scenario 1, demonstrating the potential for the heaviest material to meet both safety targets. Only the material with the lowest mass penalty is shown for the remaining scenarios. This decision is based on the assumption of equal failure probabilities for all thermal barriers and the liquid cooling system in these scenarios.

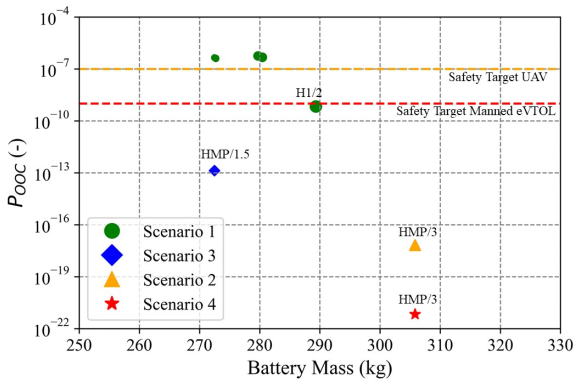

Figure 2: P_{OOC} vs. mass plot for scenarios 1-4 considering all potential barrier materials for scenario 1 and the lightest option for scenarios 2-4
(info: yellow dashed line: safety target UAV; red dashed line: safety target manned VTOL; data point size indicates the relative battery mass changes within the various materials of scenario 1)

In scenario 1, even with moderate mass penalties, most materials achieve only minimal improvements in failure probability. Only H1/2 results in a comparatively significant reduction of failure probability, although it incurs a mass increase of almost 20 kg. For this material, the contribution of undetectable thermal runaway to the overall probability of battery thermal runaway is comparatively less significant. This is due to the fact that H1/2 offers the highest probability of TR detection, which in turn results in the lowest probability of battery thermal runaway. In scenarios 2 and 4, implementing redundant protection systems (thermal barrier and liquid cooling system) significantly reduces the probability of battery TR. Scenario 4 illustrates the impact of the cooling system's independence from the TR detection system. In comparison to scenario 2, where the cooling performance depends on the state of detection, this scenario results in an even lower probability of battery TR. Scenario 3 achieves the lowest mass penalty among the four scenarios while satisfying the safety criteria for UAVs and eVTOLs despite the lack of redundant protection systems. This advantage can be attributed to the detection-independent cooling system, which differs from that in scenario 1, and the use of a lighter liquid cooling system compared to scenarios 2 and 4. Overall, scenario 4, followed by scenarios 2 and 3, offers the most favorable outcome in terms of battery TR probability. Nevertheless, the mini-channel cooling system utilized in scenarios 2 and 4 incurs a higher mass penalty than the direct cooling system used in scenarios 1 and 3.

It should be noted that further experimental evaluation of the liquid cooling system is necessary to ensure the plausibility of scenarios 2 and 4. In addition, the potential indirect mass penalty from increased power requirements and the complex geometry needed for higher flow rates during a TR event warrants further investigation.

5. CONCLUSIONS AND OUTLOOK

The paper presents a structured approach to the quantitative safety assessment of Li-ion batteries with TRP prevention strategies, with the objective of meeting the certification thresholds for specific use cases. Based on recent advances in thermal runaway protection techniques, four scenarios were formulated and analyzed to prevent TRP. This investigation highlights the effectiveness of integrating thermal barriers and cooling systems for TR detection and prevention of TRP within a battery module. The findings presented allow us to draw the following key conclusions:

- Scenario 1 currently appears to be the most plausible failure mechanism, supported by substantial evidence. However, undetected thermal runaway remains a critical factor in determining the probability of battery thermal runaway. Among the materials evaluated, H1/2 might provide the highest probability of detecting TR. As a result, this material is a candidate for a potential certification for UAV battery systems as it has the lowest TR probability. Nonetheless, further research is needed to investigate the performance of H1/2 in conjunction with different TR detection mechanisms to validate its effectiveness in enhancing TR detection.
- Using the HMP/1.5 material for scenario 3 meets the certification targets for both UAV and eVTOL applications while incurring the lowest mass penalty. However, further research is necessary to examine the performance of the liquid cooling system to respond to temperature variations in the absence of a TR detection mechanism.
- Scenarios 2 and 4 could not only ensure certification for UAV as well as eVTOL applications, but also significantly reduce the probability of battery TR. However, even with the lightest material, HMP/3, these scenarios result in considerably greater mass penalties due to the use of heavier mini-channel cooling compared to direct cooling used in scenarios 1 and 3.
- Additional experimental investigation is required to verify the viability of implementing mini-channel cooling for scenarios 2 and 4 in terms of achieving coolant flow rates that will prevent TRP.
- The current assumption that all thermal barriers are modeled with an identical failure rate has led to a focus solely on their mass penalties. Therefore, further experimental analysis is essential to determine the true failure probabilities of all barrier materials. This will facilitate the identification of the optimal barrier material by considering both mass and the probability of battery thermal runaway.
- Further research is needed to analyze the factors influencing the detection probability and its relationship with the available detection time.

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