

Lithium-ion battery fires: Understanding risks and containment

BY STUART “KIPP” LAU



On average, two lithium-ion battery thermal runaway events occur every week, mostly while aircraft are in cruise.

Lithium-ion battery fires are an increasing risk for aviation, with more incidents and greater severity in recent years. The threat of these fires exists on any flight at any time. Uncontained, these fires can lead to a catastrophic loss of an aircraft in minutes. Although passengers may not recognize these dangers, the industry is actively working on improved mitigation and containment strategies.

Underwriters Laboratories' Thermal Runaway Incident Program (TRIP)—a voluntary program that tracks and trends lithium battery incidents—indicates that the risk of a lithium-ion battery fire is at its highest point in five years of data collection. On average, there are two lithium-ion

battery thermal runaway events per week; over half of those events occur during the cruise phase of flight, often the furthest point from a suitable airport.

Thermal runaway is defined as a phenomenon where the lithium-ion battery enters an uncontrollable, self-heating state. In addition to extreme heat, fire, and smoke, experts are now concerned with the vapors that release harmful toxins.

TRIP surveys suggest that the average passenger brings four rechargeable devices onboard and often (one in five passengers) packs rechargeable batteries in their checked luggage. Half of all Americans, according to the surveys, know nothing about the dangers of lithium batteries.

Once alerted to the risks, passengers show high levels of concern.

Industry experts understand the growing risk of lithium-ion batteries traveling onboard aircraft and are concerned that operators are ill-equipped to handle an in-flight event. Lithium Battery Air Safety Advisory Committee chairman Bob Brown said, “After six years of expert analysis, our committee reached a clear finding: lithium battery fires can outpace traditional firefighting methods rapidly, and most aircraft are not equipped with containment tools proven to manage these events under real-world conditions.”

The frequency of these events is troubling, Brown added. “Industry data shows more than two lithium battery events



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occur worldwide every week, and the trend continues upward. More concerning is that most aircraft do not carry containment systems capable of controlling these events once they escalate.”

A hidden danger of a lithium-ion battery going into thermal runaway is the toxins released in confined spaces. “The thermal runaway vapors are definitely not conventional ‘smoke’ as they contain toxic and flammable components,” Batt-Tek Consulting’s George Brilmyer explained. “In a confined space such as a bedroom or aircraft, the toxins can reach dangerous concentrations that may do permanent damage to your eyes and lungs, per National Institute for Occupational Safety and Health (NIOSH) and the Acute Exposure Guideline Level-1 (AEG1-1) safety specifications.”

THE STAGE FOR THERMAL RUNAWAYS

In general, lithium-ion batteries are rechargeable batteries that employ a Nobel-prize-worthy electrochemical process (intercalation) to store energy. Lithium-ion batteries are widely used in many consumer products because they offer higher specific energy, greater energy density and efficiency, and longer cycle and calendar life compared to other rechargeable batteries. In the three decades since its introduction, the volumetric energy density increased threefold, while cost decreased tenfold. Higher-capacity lithium-ion batteries contain multiple cells. As an example, a battery for a large electric vehicle may contain 4,000 to 6,000 cells.

As described, lithium-ion batteries store a lot of energy. Damaged, overheated, overcharged, or otherwise in distress, Brilmyer added, “the battery goes into thermal runaway and delivers all of its energy through a spontaneous and self-sustaining chemical thermal degradation reaction.” Lithium-ion batteries in failure will overheat, smoke, emit toxic fumes, and eventually explode or catch on fire.

Brilmyer, in his paper “The Hidden Dangers of Vapor Toxicity in Li-ion Battery Fires,” describes the five stages of the thermal runaway process and extrapolates published vapor concentration data to describe the dangers of these toxic vapors in confined spaces. Understanding each stage of the thermal runaway will provide insight into managing a potential battery fire or an actual battery fire.

As described, a thermal runaway is a multistep chemical reaction: 1) Onset; 2) Escalation; 3) Runaway; 4) Propagation; and 5) Aftermath.

Onset is the first stage where an “event” initiates cell overheating. Examples of these initiation events may include the cell being damaged by crushing, puncturing, overcharging, or internal damage related to a manufacturing defect. In this stage, the cell begins to overheat (internal temperature rises), and the protective layer on the carbon or graphite anode begins to decompose.

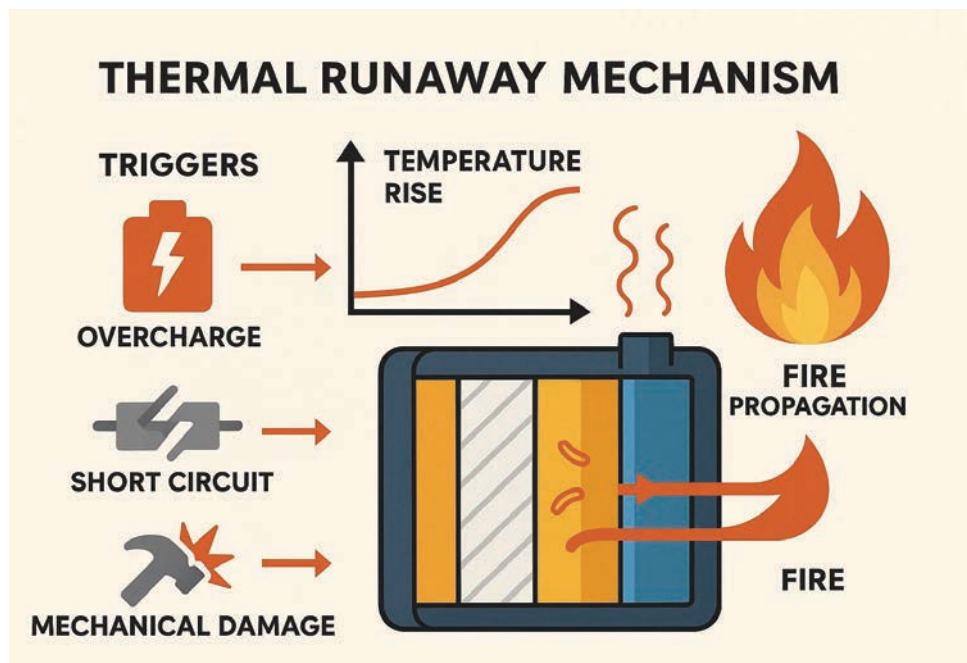
Escalation is the second stage where cell self-heating takes control of the reaction. The unprotected anode releases heat and flammable vapors as it attacks the electrolyte. The cell temperature continues

to increase; throughout this stage, there is the possibility of internal shorting. Also, during this stage, the internal pressure of the cell begins to climb, and cells begin to bulge. At this point, there is no turning back since the thermal runaway is well underway.

Full runaway is the third stage, where the cell demonstrates the features of a runaway reaction (the cathode releases its oxygen). Large quantities of vapors are now released through the safety vent or the rupture of the case. These vapors are toxic and typically flammable; flames and fires are only seen about 50% of the time.

Propagation is the fourth stage, where—in devices that use multi-cell batteries (tablets, laptops, power banks, et cetera)—a “domino effect” begins. The thermal runaway of one cell begins to propagate to neighboring cells, starting a cascading effect that travels from one cell to the next. During this stage, the heat and thermal runaway quickly spread through the whole battery module or pack.

Aftermath is the fifth and final stage of a thermal runaway. Often thought of as the “reignition” step, larger batteries with



Thermal-runaway of a lithium-ion battery is a multi-step chemical reaction that can start when a battery is crushed, punctured, or overcharged, or has been harmed by a manufacturing defect.

multiple cells may take hours or days to conclude the propagation. Generally, this stage will continue until all cells have released their energy.

TOXIC VAPORS

As highlighted, the thermal runaway is a chemical reaction that is almost unstoppable. According to Brilmyer, “Inside the lithium-ion cell, the high-power anode and cathode may spontaneously react with each other, or the electrolyte, to deliver massive amounts of heat and toxins. Unlike most other batteries, the solvent and electrolyte in the lithium-ion battery is flammable, and that is the crux of the lithium-ion thermal runaway problem.”

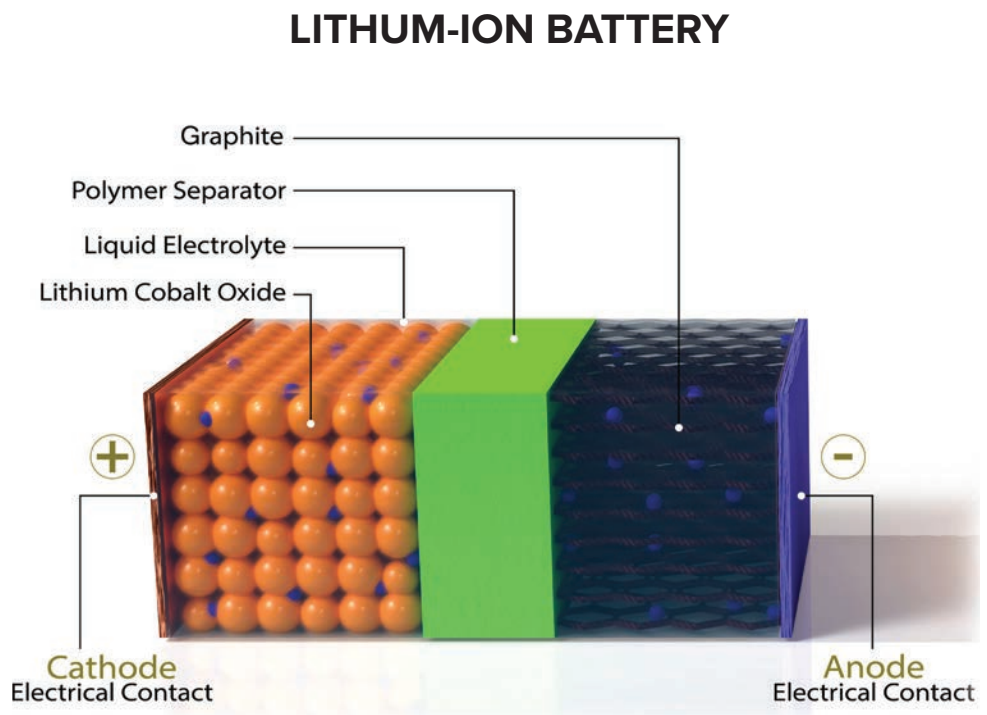
Of importance, there is no set timeline between each stage of a thermal runaway; it is volatile and unpredictable. According to Brilmyer, “should the cell experience any significant amount of heat—either internal or external—one or more of these stages may spontaneously set the entire process into action.” Thus, for the flight crew, early recognition and action are paramount.

Brilmyer further lists the chemical compounds that have been identified in the vapors emitted from a lithium-ion cell during a thermal runaway and the concentration of these compounds pre-ignition and post-ignition.

Of the compounds identified, they are either highly toxic, flammable, or explosive.

Common compounds include carbon monoxide (CO) and carbon dioxide (CO₂). Others such as hydrogen fluoride (HF) and phosphoryl fluoride (POF₃)—along with some ultra-fine metal oxides—are very hazardous; have higher concentrations during pre-ignition; are extremely corrosive to lungs, eyes, and skin; and can be fatal or cause long-term health effects in higher doses. HF is heavier than air and will collect near the floor.

According to Brilmyer, “At the top of this list of toxins is HF, which is the biggest immediate risk to human health—flames



or no flames. The NIOSH-identified immediate danger to health and life level of HF is only 6 ppm (during a thermal runaway—pre-ignition HF is measured at 20 to 200 ppm).” In a confined space such as an aircraft, this is extremely dangerous.

A thermal runaway is hazardous at any stage. Pre-ignition, there are high concentrations of toxins. Post-ignition, there are flames, explosions, and extreme heat. As described, any lithium-ion battery that is compromised (damaged, distressed, or overheated) has the potential to enter the irreversible stages of a thermal runaway—volatile, unpredictable, and unstoppable—and an operator must have a swift plan to mitigate and contain this risk.

CONTAINMENT PLAN

“Government testing conducted by Transport Canada highlights a reality every professional pilot should understand,” noted the Lithium Battery Air Safety Advisory Committee’s Brown. “Once a lithium-ion battery event progresses beyond approximately 19 minutes, it can become operationally uncontrollable using traditional onboard firefighting tools.”

Brown continued: “At that point, heat output can overwhelm handheld extinguishers, toxic smoke and flammable vapors increase rapidly, and crew workload rises sharply as visibility and systems degrade. Diversion timelines compress quickly, often leaving crews with fewer viable options. The operational lesson is straightforward: early and effective containment matters. Delay can allow a manageable event to become a serious, aircraft-threatening emergency.”

Engaged with government and industry, Brown has extensively researched battery fires for nearly two decades. “Aircraft fire protection systems were never designed to manage prolonged, chemically driven lithium-ion battery failures,” he said, further explaining that, unlike conventional Class A or B fires, thermal runaways are self-sustaining, prone to re-ignition, and capable of producing large volumes of toxic and flammable gases. In fact, ISO3941:2026 has just been issued and classifies lithium-ion battery fires as “Class L,” a totally new fire class. But ISO has yet to map a “Class L” fire extinguisher.

According to Brown, here is the crux: many of the containment bags and systems developed in the past 15 years are not effective at containing lithium-ion battery fires. “Data from airline SMS programs, Underwriters Laboratories’ TRIP surveys, and testing conducted by the FAA and EASA consistently show that many commonly used containment bags leak smoke and fine particulate matter, lose structural integrity over time, and fail to manage sustained heat or repeated re-ignition,” he said.

Brown further stressed, “Compounding this risk is a critical regulatory fact pilots should clearly understand. There is no FAA certification or approval pathway for lithium battery fire containment bags. Claims of ‘FAA-approved’ equipment are marketing language, not safety standards. In practice, labels and assumptions do not guarantee performance when it matters most.”

In fact, FAA emphasized this point when issuing AC 120-80B, Firefighting of General and High-Energy In-Flight Fires, on March 16, 2023. Guidance in the advisory circular stated, “Manufacturers may have stated in their advertisement and marketing videos

that their products are ‘FAA-certified,’ ‘successfully tested by the FAA,’ or ‘meet FAA standards.’ However, the Fire Safety Branch of the FAA William J. Hughes Technical Center and the Aircraft Certification Service emphasize that no FAA test standards exist for these containment products, nor does the FAA have a mechanism to approve these products.”

Underwriters Laboratories (UL) developed UL 5800 to become the first comprehensive aviation safety standard created specifically to address lithium-ion battery fires. Unlike short-duration flame tests, UL 5800 requires demonstrated performance under realistic, energized battery conditions. According to this standard, to earn the “UL” stamp of approval, a compliant system must contain heat, flames, smoke, and toxic emissions continuously for six hours, even with batteries capable of propagation and re-ignition.

Involved in much of the UL 5800 testing, Brown said, “That six-hour requirement is not arbitrary. It reflects how lithium battery events behave in flight. Operationally, UL 5800-compliant systems are designed to buy time—time to divert safely, time to manage crew workload, and time to

prevent smoke and fumes from incapacitating the cockpit or cabin.”

Likewise, regulator momentum is accelerating. “Regulators and industry bodies are rapidly aligning around this risk,” he said. “After publishing test data demonstrating how commonly used fire bags fail, the FAA issued SAFO 25002 directing operators to reassess lithium battery fire risks, emergency equipment, and onboard mitigation capability. EASA testing has reached similar conclusions regarding smoke leakage and containment shortcomings.”

Brown continued, “UL 5800-compliant containment devices became the committee’s top recommendation for aircraft. Testing by the FAA and EASA validated the importance of having a certified safety standard. The industry consensus is shifting away from improvised or unverified solutions and toward certified performance-based mitigation strategies.”

As specified in SAFO 25002, operators should, at a minimum, accomplish the following:

Assess onboard safety equipment, such as fire extinguishers, water sources, and fire containment products, to ensure they have the capability to mitigate fires from lithium batteries; evaluate aircraft components, emergency equipment, and passenger items that may become involved in a thermal runaway event; and review procedures that minimize the potential for smoke inhalation by passengers and crew members.

The threat of lithium-ion battery fires is real, frequent, and unforgiving of delay. According to Brown, “Testing shows a lithium-ion battery fire can rapidly overwhelm traditional firefighting methods, while no regulatory safety net ensures that onboard containment tools will perform as expected.”

While UL 5800 changes that, operators must also employ a comprehensive plan that develops a strategy to mitigate the battery fire threat for crew members and passengers alike. ■



Lithium-ion battery fire events remain highly dangerous when they occur in a confined space such as an aircraft cabin or cockpit, and it’s important for operators to develop mitigation measures.