Post-Fire Metallic Degradation Following Lithium-Ion Battery Thermal Runaway: Observational Evidence from Field Investigation and Destructive Testing

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Abstract

Lithium-ion battery (LiB) thermal runaway is known to release toxic gases, fluorine-containing compounds, metal-bearing particulate matter, and contaminated fire-suppression runoff. However, the potential for these residues to contribute to continuing metallic degradation after suppression has received limited attention in post-fire assessment, restoration, and insurance frameworks. This paper examines observations of metallic corrosion following LiB fire events through three complementary lines of inquiry: direct post-fire site investigation, laboratory observation of materials and equipment exposed to LiB fire residues, and controlled destructive testing in a sealed mobile research unit.

Across these settings, corrosion was observed on copper electrical components, galvanized steel enclosures, carbon-steel tools, stainless-steel instruments, laboratory surfaces, and metallic fittings. Observed effects included localized pitting, oxide formation, surface discolouration, increased electrical contact resistance, instrument drift, and progressive deterioration occurring over days to months following exposure. In a residential case study, corrosion patterns on electrical panel busbars corresponded to soot-exposure boundaries, while tools stored in the affected structure developed substantial visible corrosion within 1 week of the incident, which was not present the day after the event. Comparable degradation was subsequently documented in equipment and laboratory materials associated with post-fire investigations.

These observations are interpreted in relation to established LiB thermal-runaway chemistry, including hydrofluoric acid formation from $LiPF_6$ containing electrolytes, fluorine-bearing decomposition products from battery materials, potential contributions from hydrochloric and sulphur-containing species, and deposition of cathode-derived metal oxides. Although the observational design does not establish corrosion rates, prevalence, or definitive causal attribution, the convergent findings support a plausible pathway whereby deposited LiB fire residues remain chemically active within moisture-bearing surface films and promote ongoing degradation of metallic infrastructure. LiB-specific post-fire protocols should therefore incorporate chemical decontamination, HVAC assessment, electrical-system inspection, instrument recalibration, and evaluation of corrosion beyond visibly burned areas.

1. Introduction

Lithium-ion batteries (LiB) have become ubiquitous within our energy storage infrastructure, and while they provide many environmental benefits, we must be aware of the consequences of thermal runaway events, which can produce multiple hazards that include smoke, fire, explosions, toxic and flammable gases, particulates, and vapour clouds (Bugryniec et al., 2024). Gases from these events include hydrogen fluoride (HF), hydrogen chloride (HCl), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), and volatile organic compounds (Bugryniec et al., 2024; Hynynen et al., 2023; Koch et al., 2018; Sturk et al., 2019). Among soot and particulate matter, chemicals include polycyclic aromatic hydrocarbons, metals (including lithium, aluminum, cadmium, chromium, cobalt, copper, manganese, nickel, and zinc), and PFAS (Hynynen et al., 2023; Wang et al., 2023; Willstrand et al., 2025). The field has and continues to understand the associated emissions of various gases and particulate-bound pollutants through controlled thermal runaway events conducted in laboratory environments to replicate real-world scenarios (Shibu Nair et al., 2026).

Fire events associated with LiBs leave hazardous residues that persist after traditional fire suppression techniques. The controlled combustion of LiB fire events inside a modified waste truck demonstrated that the water runoff from extinguishing the fire included elevated levels of fluoride and metals (Al, Mn, Ni, Cu) that exceeded national freshwater protection guidelines in Auckland, New Zealand (Jalali et al., 2026). An evaluation of internal combustion engine vehicles (ICEV), battery electric vehicles (BEV), and large-scale battery tests performed in a fire hall equipped with a calorimeter hood found that the water used to extinguish the fires showed high toxicity in ecotoxicity tests (Quant et al., 2023). Microtox (EC_{50}, 15 min) showed high toxicity to ICEV, BEV, and batteries. Green algae (E_rC_{50}, 72 h) showed high toxicity for both the ICEV and the BEV (battery-only was not evaluated). Crustacean (EC_{50}, 48 h) demonstrated high toxicity for the ICEV and intermediate toxicity for the BEV (battery-only not tested). In addition, several metals and ions exceeded surface water guidelines, and PFAS levels ranged from 200 to 1400 ng/L, increasing with battery flushing (Quant et al., 2023). Additionally, runoff water has included carbonaceous species (e.g., soot) and solvents used in the battery electrolyte (Bordes et al., 2024).

The existing standards and regulatory frameworks in North America, including NFPA 1851, NFPA 2, NFPA 855, CSA standards, and provincial occupational health frameworks governing post-fire response and recovery, were developed before LiB fire-byproduct chemistry was characterized at the post-incident level. They address the acute hazards, including suppression, egress, and toxic gas exposure during active thermal runaway; however, the chronic hazard of ongoing chemical attack on infrastructure and equipment following suppression is not addressed in any current standard. In addition to this limitation, ongoing research on LiB fires focuses on the hazards generated during the fire event. It is unable to capture the long-term effects of combustion products, which may occur days, weeks, or months after fire suppression in real environments with humidity, residential and commercial ventilation systems, various metallic infrastructure, and a multitude of equipment carried by investigators.

In this paper, we explore the unaddressed hazard of post-event metallic corrosion associated with LiB fire events, as observed in laboratory-controlled experiments and during firefighting operations (R.N.), including as a Chemical, Biological, Radiological, Nuclear, and Explosive threats or events expert (R.N.). Unlike many conventional fire residues, compounds associated with LiB fires are not chemically inert after suppression, and they initiate and sustain corrosion of metals at ambient temperatures, driven by moisture, over timescales that may extend for months beyond the incident. We discuss the operational and legal consequences of a hazard that is currently unaddressed in fire restoration standards, investigation protocols, and insurance assessment frameworks. It is a hazard with direct implications for the responsible advancement of clean energy.

2. Field Observations

Observations were conducted by CCR personnel during routine research, testing, and investigative activities. Rather than applying a single predefined observational framework, data collection was guided by the objectives of each investigation and focused on relevant environmental conditions, fire and material characteristics, testing procedures, observed outcomes, and factors that could affect interpretation of the results. Observations were documented through field notes, test records, photographs, video, laboratory documentation, and other contemporaneous records, as appropriate to the setting.

Three modes of data collection were used in this work: direct post-fire site investigation, in-facility laboratory observation, and real-world destructive testing in the Clean Core Research Inc. (CCR) mobile research unit. Together, these activities provided field-based and practice-informed observations of fire dynamics, material behaviour, suppression conditions, and operational challenges across a range of settings. Records were reviewed iteratively to identify recurring patterns, contextual factors, and observations relevant to the paper's objectives. The observational findings were used to characterize practical conditions and inform the interpretation of the broader results. Observations are not intended to provide standardized estimates of frequency, prevalence, or causal effect.

2.1 Post-Fire Site Investigation

Post-incident assessments were conducted at LIB fire sites within days to weeks of thermal runaway events. Each assessment included visual inspection and photographic documentation of all metallic surfaces in the fire-affected and HVAC-dispersal zones, pH surface testing using calibrated pH paper and digital pH meters at metallic surfaces to assess acid deposition, physical probing of conductor surfaces to assess pitting depth and distribution, air quality monitoring using photoionization detection (PID) and electrochemical sensor arrays for HF, HCl, CO, SO_2, and VOC species, soot sample collection from metallic surfaces and HVAC components using fluoride-resistant sampling containers, and HVAC register and ductwork inspection for soot distribution mapping.

2.2 CCR Laboratory Observation

Clean Core Research's laboratory operations provided a secondary observational environment. All metallic surfaces and instruments that had contact with post-fire investigation materials were monitored for the onset, progression, and failure of corrosion. Documentation included timestamped photographic records of tool and instrument condition before and after each field deployment; calibration logs for measurement instruments showing drift following exposures in the LIB fire environment; surface pH measurements on laboratory metal surfaces following processing of post-fire samples; and records of equipment replacement attributed to LIB byproduct-induced degradation.

CCR's purpose-built mobile research unit, a sealed steel shipping container configured for controlled battery-fire testing, serves as a real-world destructive-testing environment. LiB thermal-runaway events were induced under controlled conditions within the unit. Multi-gas sensor arrays captured species concentrations during and following thermal runaway. Interior metallic surfaces of the unit itself were monitored for post-event corrosion progression, providing a closed-system confirmation of the soot-to-metal corrosion pathway independent of building-specific variables.

3. Mechanism

3.1 Electrolyte Decomposition

Within LiB cells, the most common electrolyte is lithium hexafluorophosphate (LiPF6) dissolved in organic solvents (Burton et al., 2025). A simplified reaction sequence for the decomposition of hydrogen fluoride (HF) is presented below (Kawamura et al., 2006; Larsson et al., 2014; Yang et al., 2006).

$$LiPF_6 \rightarrow LiF + PF_5 \tag{1}$$

$$PF_5 + H_2O \rightarrow POF_3 + 2HF \tag{2}$$

$$LiPF_6 + H_2O \rightarrow LiF + POF_3 + 2HF \tag{3}$$

$$POF_3 + H_2O \rightarrow POF_2(OH) + HF \tag{4}$$

Decomposition begins with the formation of lithium fluoride (LiF) and phosphorus pentafluoride, PF_5, from lithium hexafluorophosphate ($LiPF_6$), Eq. (1). POF_3 and HF are formed from PF_5 in the presence of water, Eq. (2). A direct reaction can occur from LiPF6 to produce LiF, POF_3 and HF in the presence of water, Eq. (3). It is also suggested that HF and $POF_2(OH)$ can form through the reaction of POF_3 with water, Eq. (4).

The production of HF in these processes provides a reasonable explanation for the post-fire observations, where HF forms hydrofluoric acid upon dissolution in the condensed surface-moisture film. In the presence of moisture, hydrofluoric acid and fluoride-containing species can destabilize protective oxide films on aluminum and stainless steel and alter oxide or corrosion-product layers on copper and carbon steel (Dai et al., 2021). The magnitude and form of this attack depend on alloy composition, liquid-film chemistry, pH, humidity, temperature, and exposure duration, all of which vary with post-fire environments.

3.2 Cathode Material Decomposition

Modern cathode materials can release metal-containing particles and oxide-rich residues during thermal runaway. When these deposits settle on structural metals, they may contribute to localized corrosion by retaining moisture, altering local surface chemistry, or creating under-deposit conditions. In some cases, conductive or semiconductive deposits in direct electrical contact with an exposed substrate may support micro-galvanic corrosion, accelerating localized metal dissolution where a conductive electrolyte film is present (Li et al., 2024; Song et al., 2018; Wang et al., 2022).

Lithium Nickel Manganese Cobalt Oxide (NMC - $LiNiMnCoO_2$) is widely used in high-energy EV applications and can produce NiO, MnO_2, Co_3O_4. These conductive or semiconductive oxide deposits may promote localized under-deposit or micro-galvanic corrosion of steel or aluminum when electrically connected to the substrate in the presence of a conductive electrolyte film.

Lithium Nickel Cobalt Aluminum Oxide (NCA - $LiNiCoAlO_2$) can produce NiO, CoO and Al_2O_3, oxide-rich deposits that may contribute to localized deposit-related corrosion by retaining moisture or interfering with protective surface films; hard particulates, particularly Al_2O_3, may also abrade coatings or passive films under mechanical disturbance.

Lithium Iron Phosphate (LFP - LiFePO4) can produce iron oxide-rich deposits (Fe_2O_3 and Fe_3O_4) that may retain moisture and promote localized under-deposit corrosion. Fe_3O_4, which is comparatively conductive, may also support micro-galvanic acceleration where it is electrically coupled to an exposed metal substrate in the presence of a conductive electrolyte film.

Lithium Cobalt Oxide (LCO - $LiCoO_2$) can form cobalt oxide-rich deposits that contribute to localized deposit-related corrosion by retaining moisture or altering local electrochemical conditions.

3.3 Additional Halogen and Sulphur Species

Electrode binder materials, primarily polyvinylidene fluoride (PVDF), contribute additional fluorine-bearing combustion products (Lombardo et al., 2023). When PVC insulation is co-combusted, HCl is generated, forming hydrochloric acid in the presence of moisture (Huggett and Levin, 1987). Sulphur dioxide (SO_2) has been reported as a minor toxic emission produced during lithium-ion battery thermal runaway (Bugryniec et al., 2024). In cells containing sulphur-bearing electrolyte additives or other sulphur-containing components, these materials may serve as precursors to the formation of sulphur oxides. Upon dissolution in moisture-bearing surface films, SO_2 could form sulphurous acid (H_2SO_3); alternatively, it could form sulfuric acid, which would require oxidation to SO_3, followed by hydration. The post-fire environment is not a single-agent corrosion problem. It is a mixture of mineral acids operating simultaneously across all metallic surfaces within the dispersal zone.

4. Case Studies

4.1 Newfoundland Investigation Case Study

In November 2024, one week after a 20V DeWalt lithium-ion battery fire at a residential structure in Newfoundland, Canada, R.N. conducted a structured post-fire assessment, with the primary findings previously presented (Narine, 2025). The fire was initially extinguished by the homeowner using household ABC fire extinguishers; the local fire service then completed extinguishing it with their hose lines.

The home electrical system demonstrated significant corrosion. (1) The copper busbars in the residential electrical panel showed discrete pitting corrosion on soot-exposed faces, measurable with calibrated probes and consistent with halide-induced passive layer breakdown; however, the circuit breaker-protected faces of the same busbars showed no pitting. The spatial boundary between corroded and intact surfaces corresponded precisely to the soot exposure boundary. (2) Electrical terminal connections on affected circuits showed elevated contact resistance consistent with corrosive film formation at conductor interfaces, which was determined by a local electrician and communicated to R.N. during the investigation. (3) The galvanized steel panel enclosure surfaces showed white corrosion product consistent with zinc oxide formation under fluoride exposure.

In addition to the electrical system, we observed severe corrosion on many tools in the home's workshop, which was evident one week after the fire but not visible in photos taken the day after, as shown in Figure 1. Tools were stored previously in the house and had not developed corrosion, as shown in the before photos in Figure 1.

Soot samples recovered from the HVAC ductwork at locations remote from the fire origin were chemically consistent with LiB combustion byproducts, including positive fluoride tests**.** Corresponding corrosion product deposition was visible at HVAC registers and on metallic duct components.

The property insurer declined to authorize HVAC and attic contamination testing and maintained that the damage was limited to directly burned materials. The insurer's assessment team suggested that the electrical panel could be wiped down. Newfoundland's chief electrical inspector reviewed the case study's findings and confirmed that this suggestion was inadequate. The panel was not wiped, and the electrical system remained in a structure where active chemical degradation was ongoing at the time of claim closure.

4.2 Clean Core Research Laboratory: Operational Evidence

The operations of CCR aligned with the initial findings identified during the Newfoundland Investigation. Within the facility, the following corrosion issues were identified. (1) Metal laboratory surfaces in areas processing LiB fire investigation samples showed active corrosion product formation despite regular cleaning. Surface degradation reached a point requiring intervention within months of first exposure. See Figure 2 for corrosion of the galvanized steel floor panel from the testing lab. (2) Carbon steel hand tools used at post-fire sites developed rust within days of single exposures, independent of storage conditions, and continued to degrade even after visible surface contamination was removed see Figure 3. (3) Stainless steel instruments showed pitting and surface discolouration at contact points with contaminated materials, requiring replacement after repeated exposure without adequate decontamination. (4) Calibrated electronic instruments showed contact degradation and drift after repeated post-fire site exposure without LiB-specific decontamination protocols. (5) Sampling containers with metallic fittings recovered from the post-fire site exhibited localized pitting concentrated at gasket contact lines, white crystalline metal-fluoride deposits, and loss of surface passivation (a frosted or etched appearance), signs consistent with fluoride-ion attack rather than uniform atmospheric corrosion, creating contamination integrity concerns for collected samples. These observations were also identified through significant financial impacts, as repairs and replacements were far more common than expected.

Figure 1: Corrosion of homeowners' tools. (A) DeWalt Circular Saw, one day after the fire event, no corrosion is evident. (B) DeWalt Circular Saw, one week after the fire event, new corrosion is evident. (C) DeWalt Brad Nailer, one day after the fire event, no corrosion is evident. (D) DeWalt Brad Nailer, one week after the fire event, new corrosion is evident.

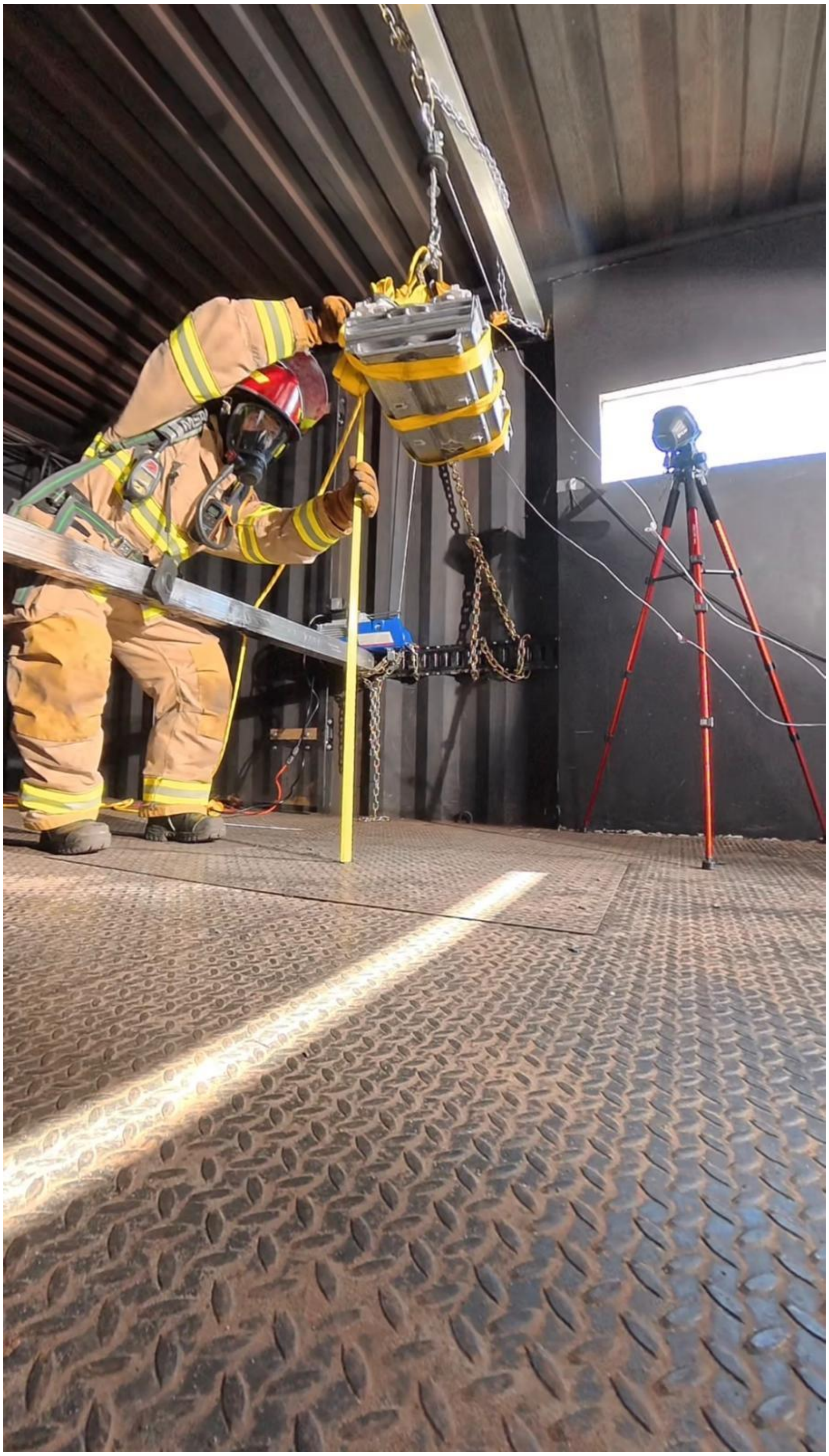

Figure 1: Galvanized steel plate showing corrosion from CCR's destructive testing facility.

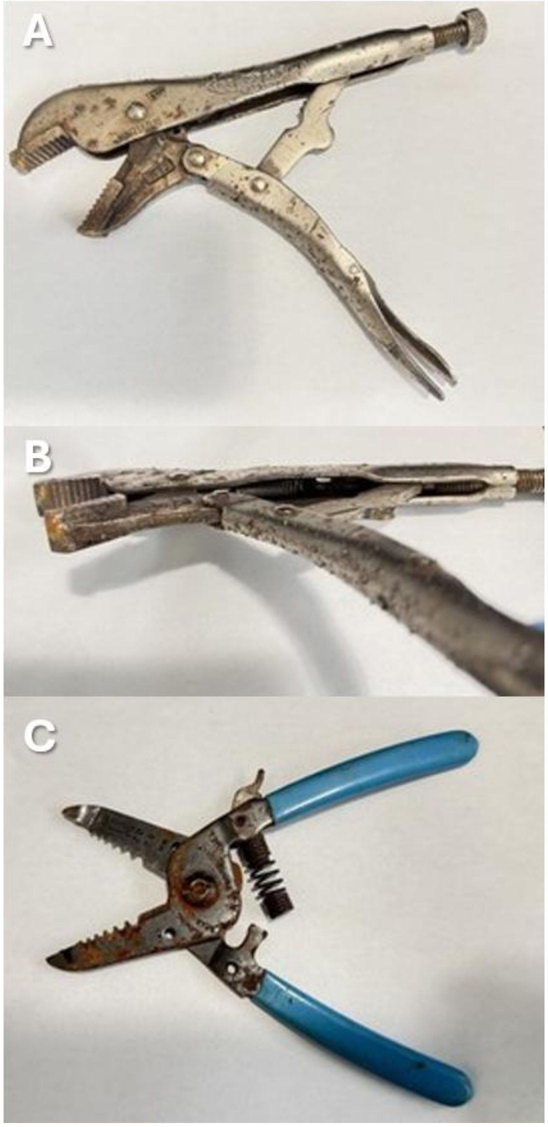

Figure 3: (A) Irwin Vise-Grip locking pliers, full body view. Scattered corrosion initiation sites are distributed uniformly across all exposed metal surfaces. The discrete, isolated oxidation pitting pattern, rather than continuous surface rust, is a diagnostic signature of halide-induced localized passive film breakdown. The pliers were in serviceable pre-exposure condition before entering LiB post-fire environments. (B) Same Vise-Grip, close-up detail of the jaw and body mechanism. The dense distribution of discrete pitting sites across the metal body is visible. Corrosion concentrated at machined surfaces and fastener contact points, consistent with galvanic acceleration of dissimilar metal interfaces. (C) Wire strippers with polymer-coated handles. Heavy rust formation on the pivot bolt, cutting blades, and return spring. Corrosion was confined to uncoated metal components; the polymer grip surfaces remained unaffected.

4.2.1 Decontamination and Surface Protection Protocols

To address the corrosion issues within the laboratory and field environments. We have implemented the following procedures that have demonstrated significant reductions in degradation. (1) We treat all tools and instruments entering LiB post-fire environments as chemically compromised from first contact. Tools are not returned to service until chemical decontamination is complete. (2) We apply alkaline decontamination solution (sodium bicarbonate at a minimum 5% concentration or equivalent rated alkaline cleaner) to all metallic surfaces following LiB fire environment exposure. These are then rinsed with deionized water. Lastly, we verify pH neutrality at the surface before storage. (3) We have adopted the use of fluoride-resistant sample containers (HDPE or glass with PTFE-lined closures) for all sample collection and evidence storage from LiB fire scenes. (4) We recalibrate all measurement instruments against traceable standards after any LiB post-fire environment exposure before using results analytically or evidentially. (5) We document pre- and post-exposure tool condition with timestamped photography to establish equipment replacement records. (6) We have applied protective coatings rated for fluoride and chloride exposure to metal laboratory surfaces that have repeated contact with LiB fire investigation materials.

5. Discussion and Implications

LiB thermal runaway produces reactive acids, halogen compounds, and catalytically active metal oxides that continue to interact with metal surfaces after the fire is extinguished. Our observations extend the evidence base of the existing work that identifies these compounds in controlled environments (Bugryniec et al., 2024; Hynynen et al., 2023; Shibu Nair et al., 2026; Sturk et al., 2019; Wang et al., 2023; Willstrand et al., 2025). We have identified that the likely consequences of their presence extend beyond the initial fire period. This chemical persistence is not a variation of a known hazard but should be considered a new hazard. Additionally, our findings will need to be investigated in controlled experiments and replicated in multiple environments, as similar corrosive effects were not identified in a previously controlled laboratory study of electric vehicle LiB fires, where corrosion mass loss was assessed on a rack of corrosion monitoring plates and significant mass loss was not observed (Held et al., 2022).

Our findings of dispersed impacts align with other contamination processes observed during non-LiB fire events. Firefighting water can mobilize and transport contaminants generated during combustion, including soot, dissolved combustion products, particulate matter, metals, and residues from damaged building materials and consumer products (Jefferson Fowles et al., 2000; McNamee et al., 2020; Peeters et al., 2021). In structures, the water will move through the fire scene and redistribute contaminants into concealed building cavities, flooring systems, HVAC components, drainage pathways, and other areas beyond the immediate zone of fire damage. In the environment, water can enter aquatic ecosystems, transporting chemicals from combustion and firefighting additives (Graetz et al., 2020).

Atmospheric transport is well established in fire events, where contaminants cause elevated air pollution concentrations and deposit into soils, water and other components of the ecosystem (Deary and Griffiths, 2024).

We observed a limitation in the existing insurance claims assessment framework in the Newfoundland case. The challenge posed by LiB fire events was not a failure of assessor competency, but that the damage category does not exist. Conventional fire damage assessment distinguishes between direct loss from flame and heat, and consequential loss from smoke and soot. Those two categories were developed around a fire chemistry where the damage, however extensive, is largely complete when the fire is suppressed. An adjuster working within that framework, examining a building after a LiB fire, would find burn damage in the fire zone and soot staining in adjacent areas. However, the ongoing metal corrosion may not become apparent for days after the event, and it does not fall under any standard damage category. The result is that claims for this type of damage have been denied, not out of bad faith, but because the adjuster evaluating the claim had no framework to recognize it as part of the covered loss event. The corrosion that began during thermal runaway and is progressing in the building's walls, HVAC ducts, and electrical infrastructure does not register as fire damage in the existing system. Our initial findings presented here underscore the need for a framework to identify, document, and assess this category of damage.

Property owners and restoration contractors should address corrosion concerns by chemically testing metallic surfaces throughout the contaminated building volume, rather than only inspecting visually burned or smoke-stained materials following a LiB fire. We should require HVAC system assessment and decontamination as a standard scope element. Specify that electrical infrastructure assessments include a physical examination for pitting on conductor surfaces, not only a visual inspection for smoke staining. Request that building water infrastructure in the HVAC-served volume be inspected for corrosion at accessible metallic fittings and connections. Retain technical specialists with documented competency in LIB fire chemistry before accepting a restoration scope as complete.

6. Conclusion

Lithium-ion batteries are one of the defining technologies of the clean energy transition. They are also a technology that, when they fail, produces a chemical residue with unique hazardous properties. Understanding residue behaviours, impacted materials, the timeframe for impact, and the pathways through which impacts occur is foundational work for every sector that will intersect with LIB fire events as battery deployment accelerates.

We have presented a post-fire metallic degradation hazard observed over years of real-world investigation and occurrences in CCR's own laboratory operations. The precursor fire emissions are well established within the literature, and the plausible chemical pathways exist. We believe the gap that needs further addressing is the integration of this risk into existing frameworks, which will allow a clearer understanding of its scope and the development of appropriate fire response protocols, restoration standards, investigation procedures, insurance assessment practices, and water quality monitoring.

Metal is a universal material. It is in the pipes that carry water, the wires that carry electricity, the tools carried by the people who respond to emergencies, and the equipment used to investigate them. A fire chemistry that persistently and invisibly attacks metal and enters water systems through suppression runoff, without triggering any monitoring response, has implications that extend well beyond the building's property line where the battery failed. Recognizing that scale is the starting point for an adequate response.

The clean energy transition will produce a safer future. Ensuring it also produces a well-informed one, where the hazard profile of the technologies enabling it is fully understood and appropriately managed, is necessary and immediate.

Conflict of Interest Statement: R.N. operates Clean Core Research, a non-profit organization that conducts large-scale destructive testing and public safety research on clean energy products, including matters relevant to the subject of this study. This affiliation is disclosed in the interest of transparency.

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