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WE SIMPLY BLOCK FIRE

A Technical HSE Assessment of Water Risks and Enclosed Containment Solutions for EV Fire Suppression

A Framework for Fire Leadership and Policy Stakeholders

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Foreword

The global transition to electric vehicles (EVs) represents one of the greatest fire safety challenges of the 21st century. While EVs offer clear environmental benefits, reduced carbon emissions and lower urban pollution, they also introduce new fire dynamics defined by energy-dense batteries, toxic gas generation, and unpredictable ignition behavior.

In recent times, deflagration event has been reported, occurring following the use of improper suppression tactics on EV fires with and without under fire blankets, involving the application of excessive volumes of water that created extreme overpressure conditions. The fire blanket has been in use across more than fifty countries over the past decade, and such events were previously unheard of. What has changed is not the blanket itself, but how it is used. A new practice has emerged: the extensive application of water beneath the blanket, a method not commonly employed during a decade of deployment.

In the recent incident (2025), water had been poured continuously over and under the vehicle, creating an enclosed chamber of heat, hydrogen gas, and pressure. When oxygen was reintroduced, the result was a deflagration event.

Bridgehill was present during one such test, not as an intervener but as an observer. The lessons learned from that experience were critical and form the foundation of this manual.

This document exists for one purpose: to separate myth from mechanism, and protocol from speculation. It provides fire service leadership and authorities with an evidence-based, science-backed framework for managing EV fires, especially concerning deflagration risks and the correct use of fire blankets. It corrects a dangerous misconception: fields evidence indicates the hazard arises from misuse, not the blanket itself. Nevertheless, the incident teaches us that usage outside of the procedure may lead to deflagration. There are several incidents where the deflagration has happened with no use of blankets, only extensive use of water. In this document, we show why use of water should not be used in lithium battery fire, in the same way as we never use water on deep fryer fire, melted metal, and strong voltage.

> This document proves with science that any protocol for fire blankets not should under extensive use of water and is perfectly doing its job when oxygen is not introduced. Simply cover the car with the blanket and leave it alone until the temperature is the same as the ambient temperature.

Our aim is singular: safer operations, stronger science, and protocols that protect both responders and communities.

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Executive summary

As electric vehicles (EVs) become increasingly common, so do the unique challenges they present during fire incidents. This paper provides a structured and science-based analysis of a specific risk scenario: *the buildup of hydrogen gas and pressure beneath fire blankets during the misuse of water in EV fire suppression.*

It is important to note that in the vast majority of EV fire responses involving water, no explosive outcome occurs. In many cases, water is used safely and effectively in open or ventilated environments. However, a concerning pattern has emerged in enclosed or sealed fire zones, particularly where large volumes of water are introduced under fire blankets. In such cases, a small misstep can escalate into a dangerous deflagration event due to rapid gas accumulation and subsequent ignition when oxygen re-enters the environment.

Contrary to some misconceptions, the fire blanket itself is not the source of risk. When deployed correctly, without sealing the environment and without introducing water, it remains one of the safest, most effective, and environmentally responsible tools for EV fire containment.

Key takeaways:

- EV battery fires differ fundamentally from ICE fires, involving delayed ignition, gas buildup, reignition potential, and thermal runaway.
- Water applied under a fire blanket may lead to hydrogen accumulation and overpressure, especially in closed environments.
- Proper fire blanket use enables containment without the need for water, while reducing toxic emissions, suppressing reignition risk, and minimizing environmental runoff.
- Documented incidents of deflagration have stemmed from procedural errors, not from the blanket itself, but from:

– Sealed, accumulated hot combustible gases that suddenly become exposed to oxygen when the blanket is lifted.

– Extensive volumes of water may generate steam around hot lithium metal, producing large amounts of hydrogen that can potentially cause strong deflagration.

- Normal lithium-ion cell, lithium is stored as ions intercalated in the graphite anode, not as metal. When the cell heats above ~200 °C, this structure breaks down, and lithium is released and reduced to highly reactive metallic lithium. If water or high humidity is present, the metallic lithium reacts to form large amounts of hydrogen gas.

- This paper offers global guidance through standard protocols, peer-reviewed evidence, and case studies aimed at preventing injury, dispelling myths, and building operational confidence.

Chapter 1: The role of EV fire blankets fire safety

Unlike traditional firefighting methods that prioritize suppression, the containment approach using fire blankets focuses on hazard isolation, controlled cooling, and toxic gas management. In addition to their safety benefits, fire blankets require minimal resources to deploy, both in terms of personnel and equipment. Making them highly effective even for small or specialized response teams.

When deployed early and correctly, fire blankets act as part of a ***Controlled Cooling System****, providing several key benefits:*

- *Immediate Containment of flames and reduction of radiant heat, protecting surrounding infrastructure and reducing risks to nearby structures and civilians.*
- *Slowing of fire progression and prevention of spread.*
- *Reducing accelerating toxic gases and particulates, including CO, hydrogen and hydrogen fluoride, which are hazardous to both health and the environment.*
- *No need for water, avoiding contaminated runoff that can pollute groundwater and the surrounding environment*

Fire blankets are particularly valuable in:

- Underground parking garages
- Marine environments such as ferries and ports
- Confined transit spaces (tunnels, containers)
- High-density urban areas with limited evacuation routes

The greatest risks associated with fire blanket use stem not from the technology itself but from procedural lapses, insufficient training, and the use of substandard equipment. An influx of poorly tested products has complicated procurement, making it vital for agencies to insist on third-party certification and to implement clear standard operating procedures.

Chapter 2: The EV fire paradigm shift

EV fires often begin as silent, invisible threats. Internal damage within lithium-ion battery cells can accumulate undetected over time, potentially triggering a delayed thermal runaway hours or even days later. In other cases, it can escalate rapidly into a severe event within seconds.

Thermal runaway doesn't ignite the entire battery at once. Instead, it typically propagates from cell to cell, akin to a wildfire. Once one cell enters thermal runaway, the intense heat rapidly raises temperatures in surrounding cells, forcing them into their own runaway events. This chain reaction leads to a self-sustaining, unpredictable fire far more intense than those involving conventional fuels.

Key hazards are:

- **Thermal runaway**: self-reinforcing chemical chain reactions
- **Reignition**: fires may restart after apparent suppression
- **Toxic and flammable gases**: especially hydrogen (H_2), carbon monoxide (CO), and hydrogen fluoride (HF)
- **Electrical hazards**: 400–800V systems can remain live post-crash
- **Sealed enclosures**: battery pack casings hinder suppression access

EV fires are not driven by combustible fuels, but by energy released through thermal chain reactions within the battery. The presence of heat does not always imply visible flames. Containment enables controlled cooling, gas management, and hazard isolation. Especially critical when battery pack access is restricted.

> *Traditional fire services are trained to fight open-flame fires, in most cases using water. But in electric vehicle (EV) scenarios, the instinct to suppress must shift toward a containment mindset to prevent hazard outcome.*

The most advanced fire departments have already begun to rethink their playbook. Containment-first methods, particularly non-invasive tools like high-temperature fire blankets are proving superior in:

- Suppress external fire sources (trim, upholstery ++)
- Starve the fire of oxygen
- Eliminate runoff and chemical contamination
- Allow gases to dissipate passively

This passive dissipation is not accidental; it is enabled by the blanket's natural venting characteristics. Unsealed fabric zones along the lower edges and folds allow gases to escape gradually without admitting oxygen, preventing pressure buildup while maintaining full containment. Figure 1 illustrates how these passive venting points appear in practice.

Figure No. 1: *Passive airflow; no sealed edges transform the fire from a "sealed bomb" to a controlled pressure system.*

2.1 **Hydrogen generation and deflagration risk in EV fires**

It is important to clarify that a fire involving a lithium-ion battery, by itself, does not inherently produce large volumes of hydrogen gas. While some hydrogen may form due to internal cell decomposition and limited water interaction, this alone is not sufficient to generate deflagration-level pressures.

The severity of deflagration and the quantity of toxic gases released from an electric vehicle (EV) battery undergoing thermal runaway (TR) depend on several factors. These include battery chemistry (e.g., NMC, NCA, LFP), electrolyte composition and fluorine content, the total energy content of the battery pack, cell format and pack design, the battery's state of charge (SoC) prior to the event, and the fire suppression method used.

Generally, larger high-voltage battery packs pose a greater safety risk than smaller packs, as increased energy content results in more intense reactions, higher pressures, accelerated propagation, and higher volumes of toxic gases. Long-range electric vehicles with battery capacities of 90 kWh or greater represent significantly higher risks compared to hybrid and city cars equipped with battery packs below 50 kWh.

It is not recommended to apply conventional water streams directly onto battery packs undergoing active thermal runaway, particularly when combined with sealed or non-vented fire blankets. This can exacerbate hydrogen accumulation and pressure build-up beneath the blanket, or in confined or poorly ventilated spaces such as parking garages or enclosed storage areas.
The risk escalates significantly for battery packs exceeding 90 kWh. Water mist and sprinkler systems can be used for cooling without causing large overpressure.

2.2 **Risk assessment EV categories**

The following table outlines these categories and the corresponding water-use recommendations.

Category	***Battery size***	***Risk level***	***Water use guidance***
Hybrid / City EV	Up to 50 kWh	Low to moderate	Standard suppression likely safe
Mid-Range EV	50–90 kWh	Moderate	**Use caution**; avoid full stream
Long-Range EV	90+ kWh	High	**Avoid water**

2.3 **Hydrogen release in dry scenarios**

In this context, dry scenarios refer to situations where no external liquids, such as water or other firefighting agents, are introduced to the battery system. The battery still contains its internal liquid electrolyte, but in the absence of added water. This definition of dry scenarios is used throughout this report to distinguish between incidents involving external liquid interaction and those occurring in air-only environments.

The total hydrogen (H_2) release from a long-range high-voltage battery pack, such as a 100-kWh system using typical 18650 NCA cells (like Tesla uses, approximately 3 Ah capacity), will theoretically under dry scenarios release around 9,200–14,700 liters of hydrogen (826–1,321 grams H_2 / per cell 0.10–0.16 grams). Meanwhile, the volume available under a fire blanket is typically around 4,000 liters of gas space. This means the total hydrogen release could theoretically generate about 230–370% of the volume under the blanket if all gas were released instantly. This is equal to a pressure of about 0.5–0.8 bar (Amano et al., 2023).

In reality, hydrogen gas from battery cells is not released all at once; Instead, it is emitted sequentially as the thermal event propagates through the battery pack. However, the propagation between cells can occur very quickly, sometimes within seconds to a few minutes. The flammable gases may accumulate rapidly beneath the blanket as they are released. As a result, a complete high-voltage battery pack can burn out over the course of several minutes to a few hours.

A well-engineered EV fire blanket is specifically designed to prevent pressure buildup beneath the blanket from reaching levels where hazardous deflagration could occur in dry scenarios. The blanket incorporates features that allow controlled venting of gases. This controlled ventilation ensures that hydrogen gas is gradually released and diluted with ambient air, keeping the pressure and gas concentration under the blanket at a safe level, well below the threshold for dangerous deflagration.

2.4 **Scenarios for deflagration initiation beneath a fire blanket**

Risk Pathways via Fire Triangle Completion

Two scientifically grounded scenarios which outline how deflagration can occur underneath a fire blanket during an electric vehicle (EV) battery fire are described below. Both scenarios are framed within the context of the fire triangle, which identifies three necessary components for combustion: fuel, heat, and oxygen. When the third missing component becomes available, rapid combustion (deflagration) may be initiated, posing significant safety risks.

> *Studies show that hydrogen has ignition energy as low as 0.02 mJ, requiring approximately ten times less energy to ignite compared to gasoline vapor. It is also highly flammable in air, with a wide flammability range from 4% to 75% hydrogen by volume (Ono et al., 2007; Rui et al., 2021; Minimum Energy for Ignition - an Overview | ScienceDirect Topics, n.d.).*

Case 1: *Sudden Oxygen Ingress in a Hydrogen-Rich, Heated Environment*

In this scenario, excessive water has been applied to the burning lithium-ion battery, leading to a high concentration of hydrogen gas buildup under the fire blanket. The battery continues to burn, providing sustained heat, but the oxygen level under the blanket remains very low. As a result, the fire triangle lacks only oxidizer.

Should the fire blanket be lifted, either intentionally or accidentally, oxygen may rush in, instantly completing the fire triangle. This sudden influx can ignite the hydrogen-rich environment, causing a powerful deflagration. This risk is particularly acute if someone lifts the blanket from above, exposing themselves to the full force of the explosion. Such incidents have been documented in field reports from the United States, where operators were thrown backward due to such ignition events.

***Case 2**: Delayed Ignition in an Oxygen and Fuel-Rich, Low-Temperature Environment*

In this case, excessive water has again led to hydrogen gas accumulation under the blanket. However, due to cooling or extinguishing of visible flames, there is insufficient immediate heat. The environment now contains both fuel (hydrogen) and oxygen but lacks ignition sources.

The situation is deceptive because the blanket appears to suppress the fire, while internally the gas mixture becomes increasingly volatile. Any delayed spark, potentially from internal cell short-circuits, arcing from damaged connectors, or spontaneous re-ignition of hot battery components can trigger deflagration. This makes the event extremely unpredictable, as ignition can occur spontaneously at any moment, without external interference.

Scenarios cases conclusion

> *The real danger arises when large quantities of external water are applied directly onto an already burning or thermally unstable battery pack,* as *commonly occurs via fire hoses or other high-volume suppression devices. This sudden interaction can trigger electrochemical reactions that exponentially increase hydrogen gas release, posing a significant explosion risk if combined with heat and oxygen*

Both scenarios demonstrate the latent danger of hydrogen accumulation under a fire blanket, particularly when water is used excessively on battery fires. The fire blanket may delay or suppress visible flames, but if any of the missing components of the fire triangle are introduced or reappear, the conditions can shift rapidly toward deflagration. Risk mitigation should prioritize minimizing water usage, ensure continuous monitoring, and maintaining the integrity of the sealed blanket environment to avoid unintentional oxygen ingress.

2.5 **Chemical and physical basis for hydrogen generation**

A fully charged 18650 lithium-ion cell contains a graphite anode intercalated with lithium (approximate composition LiC_6). Under normal conditions, this lithium remains bound as Li^+ between the graphite layers and does not exist as free metallic lithium.

At sufficiently high temperatures, however, intercalated lithium can be released from the graphite structure and converted into metallic lithium. Studies using in-situ XRD (X-ray diffraction) show that the LiC_6 phase begins to degrade already around 80 °C, despite older data suggesting stability up to 250–330 °C (Maher et al., 2021; Liu et al., 2021) As the anode is heated, the graphite undergoes phase transitions from $LiC_6 \rightarrow LiC_{12} \rightarrow LiC_{18} \rightarrow$ graphite, during which lithium "leaks out" of the lattice.

This release is accelerated by two conditions: (1) a high state of charge (i.e., LiC_6 is present), and (2) elevated temperature. The SEI layer (solid electrolyte interphase), which stabilizes lithium, begins decomposing around 60 °C, enabling lithium to de-intercalate and form metallic lithium clusters on the anode surface. This process is often accompanied by gas evolution, including H_2, CO_2, and other species that further destabilize the cell.

When large volumes of *cold water* enter a *hot*, damaged battery pack in a closed or poorly ventilated space, a chain of reactions occurs:

1. **Reaction with metallic and intercalated lithium**
   Once metallic lithium is present inside the cell, it reacts violently with water:

   $$2Li + 2H_2O \rightarrow 2LiOH + H_2\uparrow$$

   This highly exothermic reaction releases approximately 222 kJ per mole of lithium. For 2–3 g of lithium (typical cell content), this equates to 150–250 kJ of thermal energy, sufficient to cause local boiling, steam bursts, or ignition of surrounding materials.

   In addition, 1 g of lithium produces ~1.6 L of hydrogen gas under ambient conditions. Thus, 2–3 g of lithium can release 3–5 L of H_2, posing a major overpressure hazard in confined battery modules, even without ignition.

2. **Hydrolysis of the electrolyte salt ($LiPF_6$)**
   Most lithium-ion batteries use $LiPF_6$ as their electrolyte salt. Upon water exposure, it breaks down in a two-step reaction: producing both inert LiF and corrosive HF:

   $$LiPF_6 + H_2O \rightarrow LiF + PF_5 + HF$$

   $$PF_5 + 2\,H_2O \rightarrow POF_3 + 2HF$$

3. **Explosive deflagration upon ignition**
   Once oxygen and an ignition source (e.g., a spark) are reintroduced, the mixture of H_2 and O_2 creates the exact conditions for a sudden, explosive combustion (deflagration) (Ono et al., 2007).

2.6 **Measured gas behavior under water exposure**

2.6.1 **Understanding the Explosion Spectrum**

An explosion is a sudden and violent release of energy that generates a pressure wave. There are two primary categories of chemical explosions:

1. Deflagration: a subsonic flame propagation process (below the speed of sound)
2. Detonation: a supersonic reaction front accompanied by a shock wave

Deflagrations occur across a wide range of intensities. They can vary from harmless pressure puffs to highly energetic combustion events capable of causing serious injury and structural damage. The key factors influencing this behavior include:

- The amount of unburnt gas that accumulates,
- The degree of confinement of the space, and
- How rapidly oxygen is reintroduced into the mixture.

A deflagration occurring beneath a fire blanket is not necessarily hazardous on its own. However, under certain conditions such as prolonged gas accumulation, tight enclosure, or sudden exposure to air. It can escalate into a dangerous situation.

To better differentiate the severity of deflagrations, they are commonly categorized into the following levels:

Phenomenon	***Flame Speed***	***Overpressure***	***Typical Effect***
Slow combustion	< 1 m/s	< 0.05 bar (kPa range)	No blast; minor heat release
Low-energy deflagration	1-50 m/s	0.05-0.2 bar (0.7-3 psi)	Audible “pop” or puff; may cause alarm but low risk
Moderate deflagration	50–200 m/s	0.2–0.5 bar (3–7 psi)	Noticeable blast wave; may break glass or disorient
Severe deflagration	200–400 m/s	0.5–2 bar (7–30 psi)	Serious blast risk; can cause injuries or structural damage
DDT Transition	500–1500 m/s	2 – 10 bar (30 – 145 psi)	Severe blast risk, structural hazard
Detonation	>1500 m/s (supersonic)	10 bar – 40 bar (145 – 580 psi)	Shock wave, catastrophic destruction

2.6.2 **Hydrogen production and explosion risk**

Exposure to water can significantly increase hydrogen gas release from lithium-ion batteries, with observed increases ranging from approximately 25 to 200 times compared to dry scenarios. The degree of increase depends on factors such as water salinity, cell chemistry, and temperature. (Li & Zhang, 2024).

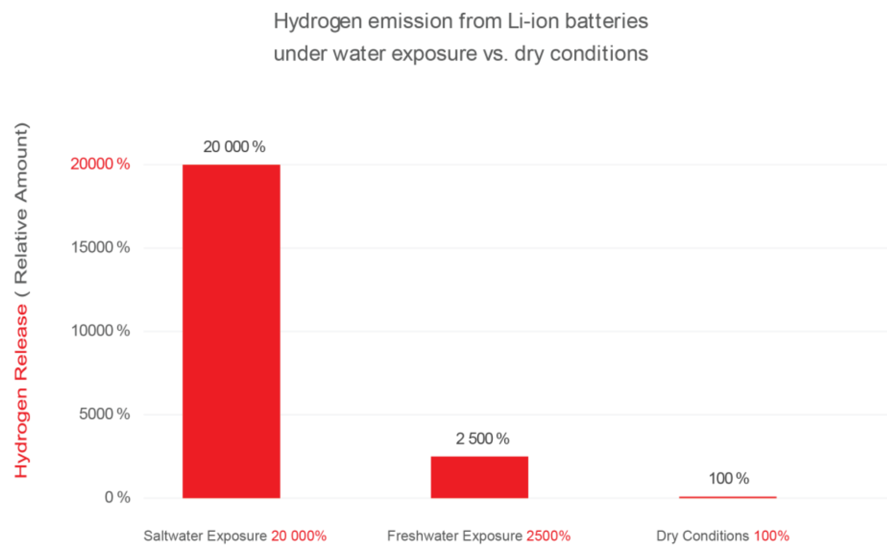

Figure No. 2: Hydrogen emission from lithium-ion batteries under water exposure, expressed as a percentage relative to dry conditions. Saltwater exposure leads to the highest hydrogen release (~20,000%), while freshwater exposure shows a significant but lower increase (~2,500%).

According to Li and Zhang (2024), exposure to water significantly increases hydrogen gas release from lithium-ion cells:

- Saltwater (≈200× increase):
  Hydrogen release was nearly 200 times higher when cells were immersed in saltwater compared to dry conditions.

- Freshwater (≈25× increase):
  In freshwater, the hydrogen evolution rate was approximately 25 times greater than under dry conditions (p. 7).

2.6.3 **Steam overpressure and expansion**

Vapor buildup inside the battery casing can create dangerous internal pressure. During thermal events, water-based components or moisture may flash to steam, expanding up to 1,700 times their original volume. However, in lithium-ion battery abuse scenarios like overcharging, the internal pressure is primarily driven by gases such as CO_2, CO, CH_4, and H_2 with measured peak internal pressures reaching approximately 7.45 bar per cell (Sun et al., 2025).

Understanding how different pressure levels affect the human body is essential for evaluating potential risks. The following table outlines typical pressure levels and their associated physiological effects:

Pressure (over ambient) and its effect on human body:

Bar	Psi	Body effect
0.1 bar	1.5 psi	You may feel mild pressure in ears or chest
0.3 bar	4.5 psi	Uncomfortable, especially in confined space
0.5 bar	7 Psi	Pain, risk of eardrum damage
1-2 bar	**15-30 psi**	**Serious internal injury if rapid (blast)**

- **Delayed thermal runaway**
  Water may temporarily suppress visible signs of overheating, masking internal heat buildup and delaying thermal runaway leading to sudden, uncontrolled combustion.
- **Toxic electrolyte reactions**
  Interaction with water can trigger reactions in the electrolyte, producing hydrogen fluoride (HF) gas, which is both toxic and highly corrosive.

2.7 Lithium-metal and water historical lessons and upcoming fire risks

Some of the earliest electric vehicle batteries used pure metallic lithium as the anode material. While lithium-metal offers extremely high energy density, it also introduces significant safety risks. Most notably its violent reactivity with water. This hazardous behavior was one of the main reasons why lithium-metal batteries were quickly replaced by lithium-ion systems, in which lithium exists in ionized form, intercalated in graphite or other host materials.

Battery technology is now circling back toward lithium-metal anodes, particularly in solid-state batteries, which use solid electrolytes to prevent dendrite formation and improve safety. These systems aim to combine the energy density of lithium-metal with the thermal stability of lithium-ion. However, fire suppression protocols must evolve accordingly: if metallic lithium becomes exposed during a fire or mechanical failure, even small amounts of water may trigger hydrogen release, posing renewed explosion risks.

The historical lessons of lithium-metal reactivity are essential to understanding the emerging challenges of future battery chemistries, especially in the context of firefighting operations that involve containment, cooling, and water interactions.

Chapter 3: The critical role of reducing hydrogen fluoride (HF)

3.1 **Hydrogen fluoride(HF) gas formation**

Hydrogen fluoride (HF) is one of the most dangerous gases produced during lithium-ion battery fires. Even in small quantities, HF poses an immediate threat to firefighter safety, public health, and the surrounding environment. For this reason, understanding how HF is generated, how water accelerates its formation, and how to prevent dangerous exposure is essential for anyone involved in EV fire response..

The interaction between water and electrolyte salts (such as $LiPF_6$) accelerates the release of hydrogen fluoride (HF), resulting in a much higher emission rate compared to dry lithium-ion battery fire; Even if the total amount of HF generated remains similar. This phenomenon is well-documented by both laboratory experiments and real incidents (Larsson et al., 2017; Han & Jung, 2022).

As demonstrated in the figures below, introducing water to $LiPF_6$ causes a sharp increase in HF^+ intensity detected by mass spectrometry, confirming that water can dramatically accelerate the formation of toxic HF gas during battery decomposition.

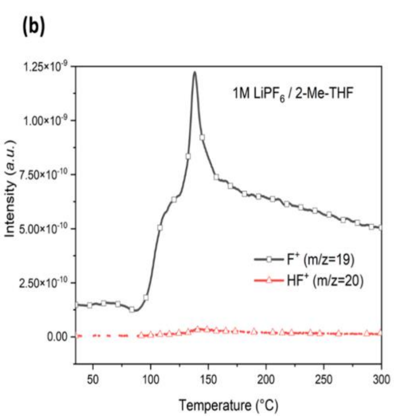

Figure No.3: Dry conditions (without water): Only a minor HF release is observed as the temperature rises.

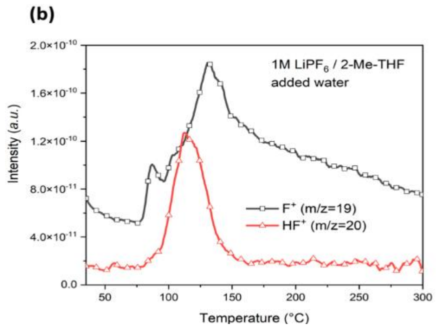

Figure No.4: With water present: HF formation surges rapidly at much lower temperature, greatly increasing the risk of acute toxic exposure for anyone nearby.

Source: (Han & Jung, 2022, pp. 13–14)

3.2 **HF toxicity risk evaluation**

According to NIOSH (National Institute for Occupational Safety and Health), exposure to ≥30 ppm HF (hydrogen fluoride) is acutely life-threatening, even after a short duration of exposure (Hydrogen Fluoride - IDLH | NIOSH | CDC, 2020).

High level of hydrogen fluoride scenarios

Based on the battery chemistry discussed earlier in this document, A typical 100 kWh Tesla battery pack contains approximately 8,256 type 18650 cells. In a worst-case fire scenario, each cell can release up to 200 mg of hydrogen fluoride (HF), totaling around 1.65 kg of HF. The IDLH (Immediately Dangerous to Life or Health) threshold for HF is 30 ppm, which corresponds to just 2.46 g (0.00246 kg) in a 100 m³ enclosed spaces, such as a garage (6.00 m × 6.94 m × 2.40 m). This means a single battery pack has the potential to exceed toxic exposure levels more than 671 times over.

(Larsson et al., 2017, pp. 6–7).

Even small amounts of water interacting with damaged cells in confined areas can accelerate HF concentrations. Dry containment and gas monitoring are essential to responder safety.

Role of Temperature:

Temperature also plays a critical role in the release of hydrogen fluoride (HF) during lithium-ion battery fires. At temperatures below 120 °C (248 °F), HF emissions remain very low. However, as the battery heats up, the lithium salt in the electrolyte, lithium hexafluorophosphate ($LiPF_6$) can decompose even at relatively moderate temperatures (above 60 °C/140 °F), especially in the presence of moisture or water. This reaction rapidly generates HF and other toxic byproducts, with the rate of HF formation increasing dramatically if water is used by firefighting.

In addition, the thermal decomposition of polyvinylidene fluoride (PVDF), a common binder in battery electrodes, begins to generate HF at approximately 600 °F (315 °C), and the evolution becomes rapid at around 700 °F (370 °C).

Studies have shown that the complete release of fluorine from PVDF occurs at temperatures above 500 °C (932 °F), and by 900 °C (1652 °F) nearly all of the fluorine content has been released into the gas phase. Notably, the total amount of HF released does not vary significantly between 750 to0 900 °C, indicating that most HF is produced during the early, high-temperature phases of battery decomposition (PVDF Safety Data Sheet, MTI Corporation, 2009; Danz et al., 2019; Larsson et al., 2018).

During a thermal runaway event in a high-voltage battery pack, the cells heat up progressively. This means that HF gases may be released gradually over an extended period, especially if the fire is not contained.

Allowing a vehicle to burn down completely can result in significant contamination of the surrounding environment. On the other hand, if water is applied to extinguish the fire, HF emissions may accelerate and peak even more rapidly due to the interaction between water and lithium salts ($LiPF_6$). Potentially increasing the health risks for firefighters and first responders exposed to these toxic gases (Li & Zhang, 2024; Han & Jung, 2022).

Chapter 4: Suppression of thermal runaway propagation in lithium-Ion batteries under oxygen-limited conditions

This chapter addresses the influence of oxygen-deprived environments on the behavior of lithium-ion batteries during thermal runaway events. It summarizes how the absence of external oxygen and surrounding combustible materials limits cell-to-cell propagation, reduces heat feedback, and inhibits the complete combustion of evolved gases.

4.1 **Thermal runaway and oxygen availability**

In ambient conditions, thermal runaway in lithium-ion cells is often exacerbated by the presence of oxygen and additional heat from surrounding materials. However, experiments conducted in inert or oxygen-deprived atmospheres show markedly lower severity of propagation. The spread of thermal runaway is severely inhibited in an inert atmosphere due to the suppression of combustion reactions (Golubkov et al., 2014)

4.2 **Suppression of surrounding combustion**

Combustion of plastics and other vehicle components can significantly increase the overall temperature during an electric vehicle fire, facilitating propagation. In oxygen-limited conditions such as those achieved by deploying a fire blanket. The absence of such secondary heat sources reduces the chance of thermal runaway spreading to adjacent cells. Without ambient oxygen, combustion of electrolytes and surrounding polymers is prevented, significantly lowering the heat feed to adjacent cells (Wang et al., 2019).

4.3 **Unburnt gases and inhibited oxidation**

During thermal runaway, gases such as hydrogen, methane, carbon monoxide, and ethane are released. In the absence of oxygen, these gases remain largely unburnt, resulting in reduced thermal output. However, they may accumulate and pose a secondary risk if re-exposed to oxygen and an ignition source. (Golubkov et al., 2014).

4.4 **Limited endogenous oxygen**

While lithium-ion cells may generate limited oxygen internally (e.g., via cathode decomposition), the quantity is insufficient to sustain ongoing combustion or significant thermal feedback. The sealed conditions created by a fire blanket therefore further reduce available oxidizers for continued propagation.

The text explains that when lithium-ion batteries undergo thermal runaway in low-oxygen or oxygen-free environments, such as under a fire blanket, both heat generation and the risk of fire spreading from one cell to another are significantly reduced. Without oxygen, neither the gases released by the battery nor surrounding materials like plastics can burn, making the situation more controllable. This highlights the effectiveness of fire blankets in containing electric vehicle fires.

Chapter 5: Environmental footprint of EV fire incidents

Electric vehicle fires create an environmental footprint that differs fundamentally from conventional vehicle fires. When a lithium-ion battery enters thermal runaway, it releases a complex mixture of toxic gases, acidic aerosols, dissolved metals, and particulate matter. These substances spread simultaneously through smoke, steam, surface deposition, soil penetration, and contaminated runoff. The result is a diffuse and unpredictable contamination pattern that is difficult to control and significantly more demanding to remediate.

5.1 **Airborne and steam-driven contamination**

In the initial stages of an EV fire, airborne emissions rapidly become the dominant transport mechanism. Hydrogen fluoride, soot, volatile organic compounds, and nanoscale metal particles rise with the smoke column and disperse outward with convection and wind. HF binds readily to moisture, and when the plume contains steam or microdroplets, the gas becomes more mobile and capable of traveling much farther before settling. This process intensifies when water is introduced during suppression. As water contacts hot battery surfaces or burning cells, it flashes to steam, lifting HF, electrolyte aerosols, and metals higher and carrying them farther than smoke alone. Studies show that HF concentrations can increase during water application, not because of more HF forms, but because existing HF is redistributed more effectively through steam-driven lofting. Without a physical barrier, these airborne contaminants spread widely across buildings, pavements, vehicles, vegetation, and indoor structures (Bisschop et al., 2019).

5.2 **Surface deposition and soil penetration**

Surface deposition adds another layer of environmental impact. As airborne pollutants cool and settle, HF forms acidic films on asphalt, façades, windows, and painted structures, while metal nanoparticles embed into porous materials and soil. These deposits are corrosive, persistent, and require chemical neutralization and high-pressure cleaning to remove. In outdoor environments, even relatively small EV fires can affect tens of meters around the vehicle, while in enclosed settings such as parking garages or tunnels, contamination can infiltrate ventilation ducts, drainage channels, and structural components. Soil contamination is particularly problematic because fluoride-rich acids and metal ions migrate into surface layers, where they bind to mineral and organic compounds, making removal labor-intensive and costly (Horn et al. 2022; Held et al. 2022).

5.3 **Runoff as a major pollution pathway**

The most severe environmental consequences arise when water is used for suppression. As water flows across the fire scene, it dissolves metals, fluorides, electrolyte decomposition products, ash, and carbon particles. This creates a chemically concentrated runoff containing nickel, cobalt, manganese, aluminum, lithium salts, acids, and soot residues. The runoff migrates into storm drains, soil, permeable ground, and in the worst cases groundwater. Water interacting with damaged cells also accelerates internal corrosion, releasing additional metals and electrolyte compounds that further increase the chemical load. This combination of dissolved pollutants and suspended particles makes runoff one of the most challenging contamination pathways to manage, especially in urban areas with interconnected drainage systems (Quant et al., 2023).

5.4 **Environmental remediation requirements**

Environmental cleanup after an EV fire is extensive and begins immediately upon extinguishment. Crews must collect and analyze residues, remove contaminated soil, neutralize acidic films, and wash façades, pavements, and nearby assets. Suppression water is often treated as hazardous waste and must be pumped, contained, and disposed of under controlled conditions. Drainage systems, sumps, HVAC ducts, and ventilation channels may require flushing or replacement because fine battery aerosols can infiltrate and accumulate inside enclosed systems. Soil and sediment tend to show elevated concentrations of metals such as nickel, cobalt, manganese, and aluminum, necessitating excavation or chemical stabilization. In more severe cases, cleanup operations can extend for weeks or months (Kuti et al., 2025)

5.5 **Long-term environmental and health consequences**

If remediation is incomplete, long-term ecological effects can arise. Metals and fluorinated compounds may accumulate in soil, vegetation, and wildlife, disrupting nutrient cycles and weakening immune and reproductive systems. According to the Centers for Disease Control and Prevention (CDC) residual HF on surfaces or contamination of groundwater can cause respiratory irritation, skin exposure risks, endocrine disruption, or chronic neurological impacts depending on concentration and exposure duration. These long-term effects underscore the importance of proper containment and cleanup after EV fire events (Gan et al., 2022).

5.6 **Documented incidents and cleanup burden**

Real-world incidents illustrate both the scale and complexity of environmental contamination. The APS McMicken ESS explosion in Arizona contaminated the building interior, HVAC systems, surrounding soil, and structural materials with fluorides and metal residues. Mitigation required demolition, full decontamination, and soil replacement, with costs estimated between 15 and 25 million dollars (DNV GL, 2020).

Even smaller EV-fire incidents in Europe and North America require removal of acidic films, flushing of storm drains, and excavation of contaminated soil. Cleanup commonly exceeds tens of thousands of dollars and can reach hundreds of thousands when runoff penetrates drainage infrastructure or soil layers (Heffernan, 2024; U.S. EPA, 2022).

5.7 **HSE and environmental benefits of fire blanket encapsulation**

Fire blankets can be deployed within one minute without requiring immediate or mandatory use of hoses or pumps. Once applied, the blanket encapsulates the vehicle and suppresses the upward movement of hot gases and combustion aerosols. By limiting airflow and containing the plume at the source, it reduces the emission and spread of respirable particles that would otherwise disperse through tunnels, parking structures, industrial halls, or urban streets. After deployment, firefighters can withdraw to maintain a safe distance from the battery while the incident stabilizes. Because the blanket allows the fire to cool without generating large volumes of steam, it prevents the steam-lofting effect in which HF, electrolyte aerosols, and metallic nanoparticles attach to water vapor and travel far beyond the fire scene. This significantly lowers immediate inhalation exposure for firefighters and bystanders and reduces the contamination footprint that later requires environmental remediation. Fire blankets also have relatively low cost, minimal service requirements, and long operational lifespan. Their durability and reusability make them well suited for long-term storage by municipalities, airports, tunnels, and fleet operators seeking scalable and environmentally responsible emergency response solutions.

5.8 **Conclusion**

The environmental footprint of an EV fire is shaped by simultaneous dispersion through air, steam, surfaces, soil, and contaminated water. These pathways can transport hazardous compounds far beyond the immediate fire scene, resulting in complex and often costly remediation efforts if not effectively controlled. Early isolation and physical containment remain the most effective means of reducing contamination, protecting public health, and ensuring that the environmental footprint of an EV fire remains as small and manageable as possible.

Chapter 6: Misconceptions and clarification

Recently, several media outlets and training agencies have circulated claims that fire blankets are dangerous, suggesting they cause explosions or pressure events during EV fires. These narratives often stem from misinterpreted incidents, incomplete testing setups, or improper use of equipment.

This chapter breaks down the most common misconceptions, traces their origins, and replaces speculation with validated science and documented field experience.

6.1 Misconception 1: **“Fire blankets cause explosions”**

Truth: The blanket itself is not the source of danger. In extremely rare cases, limited propagation may occur, but only under highly specific conditions. Explosions typically result from misuse, such as introducing water or oxygen beneath under a sealed blanket; this traps hydrogen and steam, increasing ignition risk.

- Fuel (e.g., H_2) + Oxygen (air) + Ignition (heat) = Deflagration
- The blanket removes oxygen. Water can increase ignition risk.

6.2 Misconception 2: **“Blankets trap hazardous gases”**

Truth: This is intentional and safe. The blanket design allows some hydrogen to escape slowly at the base, while still containing larger combustion particles and external flames.

6.3 Misconception 3: **“Blankets obstruct scene monitoring”**

Truth: Fire blankets protect the scene and do not hinder monitoring when standard tools are used.

- Gas sensors and thermal cameras enable remote observation
- The protocol requires no lifting until safe conditions are confirmed.

6.4 Misconception 4: **“Blankets don't stop battery fire propagation”**

Truth: Fire blankets are highly effective in limiting battery fire propagation by removing oxygen from the environment. EV batteries are constructed in modules separated by fire barriers. In full vehicle fires, extreme heat from burning materials throughout the vehicle can heat the entire battery pack and cause widespread propagation. However, when fire blankets are applied early, the lack of oxygen prevents combustion of plastics and organic material around the cells, reducing heat and isolating the fire to the initial battery cells.

Chapter 7: Fire blanket protocol for global agencies

This chapter presents a global standard protocol for safe deployment, monitoring, and removal of high-temperature fire blankets in EV fire scenarios. The procedures herein are designed to prevent gas-related deflagration, eliminate human error, and reduce environmental impacts.

7.1 **Bridgehill's Fire blanket safety protocol:**

BRIDGEHILL
WE SIMPLY BLOCK FIRE

FIRE BLANKET SAFETY PROTOCOL
FOR TRAINED PERSONNEL AND FIREFIGHTERS

FOLLOW THE STEPS BELOW CAREFULLY

01
IDENTIFY

A. Determine the vehicle's power source (EV, hybrid, combustion)

B. Recognize:
- *Fire location (engine compartment, undercarriage, battery area)*
- *Risk of thermal runaway or battery fire*

C. If available, consult the vehicle's Emergency Response Guide

02
ASSESS

A. Wind direction; approach with the wind behind you, if possible
B. Surrounding risks: buildings, people, other vehicles
C. Available application space
D. Is it safe? (e.g., fuel spills, slope, toxic clouds)

03
PREPARE FOR DEPLOYMENT

A. Minimum of 2 trained personnel with PPE and SCBA
B. Assign a safety officer
C. Keep the fire blanket pre-rolled and positioned upwind
D. Pre-check:
- *Fire suppression lines ready (if needed)*
- *Vehicle wheels chocked on the least affected side to prevent rolling*
- *Establish a safety distance of at least 15–20 m (50–65 ft)*

04
DEPLOYMENT STEPS

A. Two operators each hold a handle, lift the fire blanket, and hold it firmly (do not drag)

B. In heavy torching conditions (e.g., battery fires), apply water to knock down flames before deploying the fire blanket

C. Move quickly and steadily toward the vehicle until it is fully covered and the fire blanket is centered

D. Reevaluate deployment if conditions become unsafe

E. Seal the blanket edges firmly around the vehicle in an "L" shape

USE CAUTION!

DO NOT LIFT THE FIRE BLANKET AFTER DEPLOYMENT.
The fire blanket immediately reduces temperature and helps slow thermal runaway. Never introduce tools, objects, water, or any liquids under the fire blanket after deployment, as this may break the seal, introduce oxygen, and create an unsafe environment or risk deflagration.
All assessment of the situation shall be conducted only by trained firefighting personnel.

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IF AVAILABLE, USE THE FOLLOWING EQUIPMENT: Fire blanket • 10 m (33 ft) rope • Thermal imaging camera

05 BLANKET REMOVAL RECOMMENDATIONS

A. Before removing the fire blanket, ensure that:
- *Surface temperature is aligned with the outdoor temperature*
- *No visible smoke is escaping from the folds of the fire blanket*

B. Rain or temperature changes can affect thermal cameras readings, stay alert and adapt as needed

C. Attach a rope to one handle and position the rest of the crew at a distance of 15–20 m (50–65 ft)

D. Always operate gas detectors in accordance with local safety guidelines, but never lift the fire blanket

E. Ensure suppression lines are ready during vehicle removal

F. Slowly remove the fire blanket in a continuous motion

06 POST-REMOVAL MONITORING

Reassess:

If the vehicle reignites, repeat from Step 04

Plan for:
- A designated quarantine area
- A vehicle recovery/ removal team
- Decontamination of personnel and exposed equipment

07 EVACUATION SIGNAL & CONSIDERATIONS

A. Evacuate areas affected by smoke or hazardous gases if:
- *Hazardous gases persist*
- *Smoke spreads beyond the safe zone*

B. Ensure all team members are trained in toxic and flammable gas risks

C. Establish a clear evacuation signal before any escalation occurs

D. Only trained personnel should operate in areas with toxic or flammable gases

E. Agree on a clear evacuation signal that instructs all personnel to leave the area immediately

08 TRANSPORTATION OF THE VEHICLE

A. Place the vehicle on the tow truck and redeploy the fire blanket over it

B. Always secure the fire blanket using straps or ropes to prevent movement during transport

C. The fire blanket must remain in place during transportation and storage to minimize the risk of re-ignition and contain toxic residues

NOTES & SAFETY REMINDERS

WARNING! RISKS OF VAPOR AND DEFLAGRATION
- Flammable gases may accumulate beneath the blanket.
- Introducing oxygen may ignite vapors → Deflagration risk.
- **NEVER** deploy or remove a blanket without full PPE, active temperature and gas monitoring.

7.2 **Special conditions and adjustments**

7.2.1 **Confined or enclosed areas**

- In parking structures or narrow spaces, deploy the blanket and wait for significant cooling.
- Use a tow strap or cable attached to the car to pull the vehicle out while the car is covered.

7.2.2 **Transport with recover vehicle**

Keep the blanket on while towing.

- All recovery vehicles should carry a fire blanket.
- Use cargo straps around the wheels and down to the ground to keep the blanket secure and follow the recovery procedures.
- This minimizes oxygen access that increases the transport and therefore reduces reignition risk.
- Some blankets are reusable and come in sealed, odor-proof bags.

Chapter 8: Future risks; New battery chemistries

Preparedness for EV fires must evolve in step with battery technology. Battery technology is evolving rapidly. New battery types are constantly introducing novel chemical compositions and reaction mechanisms, bringing with them more complex and potentially hazardous scenarios. This places high demands for fire suppression products: they must be robust, reliable, and non-reactive with the wide range of battery chemistries currently on the market.

Every battery fire is unique. That is why we ask ourselves these questions in the development of modern fire blankets:

- **Is more metallic lithium forming than previously expected?**
  At high states of charge (SOC) and in large battery packs, the likelihood of metallic lithium formation increases during failure. Metallic lithium reacts violently with water, releasing significant heat and hydrogen gas.

- **How do emerging battery technologies affect the risk landscape?**
  While today’s protocols primarily focus on lithium-ion, emerging chemistries such as solid-state batteries, lithium-metal anodes, and sodium-ion are already in development. These technologies bring new challenges for fire suppression and reinforce the need for universal, non-reactive tools like fire blankets. Solid-state batteries, which use metallic lithium as an anode, may make thermal runaway events even more unpredictable and more difficult to contain.

- **What are the safety implications of increasing battery sizes?**
  Many modern electric vehicles have battery packs exceeding 100 kWh. This dramatically increases both gas generation and heat output during a runaway event, potentially requiring massive ventilation to safely manage hydrogen and other hazardous substances.

> *When battery fire chemistry is unpredictable, why introduce water that could intensify the hazard, when a fire blanket provides passive control without added risk?*

8.1 **Key emerging battery types**

- **Solid-State Batteries:** High energy density, solid electrolyte, but unpredictable thermal behavior
- **Lithium-Metal:** High capacity, but extremely reactive with water; risk of explosion and internal short circuits
- **Sodium-Ion:** More affordable and accessible, but immature technology with unknown gas reactions

8.2 **Technology vs. suppression method (Compatibility)**

Battery Chemistry	Water Use	Blanket Use
Lithium-Ion	Risk	Ideal
Lithium-Metal	Hazardous	Only recommended
Solid-State	Limited research	Safest so far
Sodium-Ion	Not fully evaluated	Least risk

8.3 **Future regulatory needs**

- Ensure standardized and accessible labeling of EV battery types such as on plates or QR data to support first responder access.
- Establish scenario-based training for solid-state and metal-based batteries
- Create joint expert groups to assess new battery technologies and risks

8.4 **Strategic conclusion**

As batteries evolve, suppression protocols must be technology-agnostic. Fire blankets are already future-ready.

Chapter 9: Hands-On drills and scenario training

Theoretical knowledge alone saves no lives. Effective response during EV fires requires practical experience, training discipline, and inter-agency coordination. This chapter outlines how realistic exercises build confidence, faster decision-making, and correct protocol use under stress.

9.1 **Primary objectives of EV drills:**

- Train for rapid and correct deployment of fire blankets
- Learn to identify signs of thermal runaway and gas buildup
- Practice operations in tight, enclosed environments (garages, tunnels, boats)
- Integrate fire, police, EMS, and towing services into joint response

9.2 **National Training Consistency: A Prerequisite for Safety**

Emergency response agencies must receive standardized training in the combined and appropriate use of fire blankets and water during electric vehicle fires. It is essential that all firefighting personnel, regardless of region, are equipped with the same foundational knowledge and decision-making framework when responding to EV fires. This includes:

- Understanding the interaction between thermal runaway, hydrogen gas accumulation, and oxygen reintroduction
- Knowing when and how water can be used safely, and when it must be avoided
- Practicing deployment and monitoring protocols that avoid procedural lapses
- Recognizing the risks associated with sealed environments and delayed ignition

Inconsistent training leads to inconsistent outcomes and in the case of battery fires, inconsistency can be fatal. National fire academies and municipal leadership should therefore prioritize synchronized instruction that aligns with field-tested fire blanket protocols.

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