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List of Abbreviations

AFFF	Aqueous Film Forming Foam
AFV	Alternative Fuel Vehicle
BEV	Battery Electric Vehicle
BTEXS	Benzene, Toluene, Ethyl Benzene, Xylenes, Styrene
CCTV	Closed-Circuit Television
ERG	Emergency Response Guide
EV	Electric Vehicle
FD	Fire Department
FMRC	Factory Mutual Research Corporation
FSRI	Fire Safety Research Institute
GC-HRMS	Gas-Chromatography High Resolution Mass Spectrometry
HEV	Hybrid Electric Vehicle
HRR	Heat Release Rate
IBK	Institut für Brand- und Katastrophenschutz
IC	Incident Command
ICEV	Internal Combustion Engine Vehicle
ICPMS	Inductively Coupled Plasma Mass Spectrometry
LC-MS	Liquid Chromatography-Tandem Mass Spectrometry
MCF	Myndigheten för Civilt Försvar
NIPV	Nederlands Instituut Publieke Veiligheid
NIOSH	National Institute of Occupational Safety and Health
OEM	Original Equipment Manufacturer
PAH	Polycyclic Aromatic Hydrocarbons
PFAS	Per- and Polyflouroalkyl Substances
PHEV	Plug-in Hybrid Electric Vehicle
PPE	Personal Protective Equipment
PVC	Polyvinyl Chloride
RP	Reporting Party
SB	Schmidt-Boelter Heat Flux Gauge
SCBA	Self-Contained Breathing Apparatus
SOP	Standard Operating Procedure
TIC	Thermal Imaging Camera
ULRI	UL Research Institutes
UVN	Under-vehicle Nozzle
VCE	Vapor Cloud Explosion
VOC	Volatile Organic Compounds

Executive Summary

Electric Vehicles (EVs) have been growing in popularity in recent years, in large part due to the competitive driving range permitted by energy dense Lithium-Ion Battery (LiB) technology. However, this large scale adoption of new technology also introduces new challenges for first responders. EV fires have garnered attention for unique fire hazards that anecdotally differ from those associated with conventional internal combustion engine vehicles (ICEVs), such as prolonged burning, resistance to extinguishment, reignition, toxic and flammable gas release, flame jetting, and explosion or deflagration hazards.

Despite increasing operational experience with EV incidents, a lack of systematic, full-scale experimental data has limited the development of evidence-based firefighting strategies. This study addresses these knowledge gaps through a comprehensive, multi-year experimental investigation conducted by UL Research Institutes' (ULRI) Fire Safety Research Institute (FSRI). Eighteen vehicles common to the North American market were burned at full-scale, including both ICEVs and EVs. The experiments included free burn experiments to characterize fire growth and burning behavior, as well as suppression experiments designed to assess the effectiveness of commonly available firefighting tactics and equipment under conditions representative of vehicle burning behavior at the time of fire department arrival. Key findings derived from the experiments are summarized below.

EV fires tend to match ICEV fires in characteristics such as fire growth rate, peak fire size, and fire duration. This overlap is attributed to the fact that the design and materials of vehicle passenger compartments are virtually identical regardless of powertrain type and the plastics, foams, and other ordinary combustibles constitute a major source of the fuel load in a standard vehicle fire. With all vehicles, burnout occurred in less than 90 minutes when no suppression efforts were made.

Suppressing the passenger compartment fire with water quickly mitigates thermal and chemical hazards. Vehicle construction prevents effective cooling of the cells in the battery pack, even when vent holes or damage holes are targeted directly with hose streams. Limiting water flow to exposure protection and preventing the passenger compartment from (re-)igniting while allowing the battery to burn itself out can lead to incident resolution in under 30 minutes with only 2900 L (760 gal), indicating that copious application of water to the battery pack is both ineffective and unnecessary. The addition of an encapsulating agent (F-500) did not improve fire suppression performance.

EV fire blankets can effectively control passenger cabin fires, but cannot control the battery fire and have limited effectiveness for controlling battery fire related hazards. While fire blankets can be useful in reducing thermal and smoke exposures to the surrounding environment; fire blanket use on batteries in thermal runaway resulted in reduced awareness of vehicle/battery burning state, and uncontrolled release of flammable gases after accumulating under the blanket. Uncontrolled releases of flammable gases can result in flash fires and deflagrations both under the blanket and in confined operating environments. It was also found that use of an under-vehicle nozzle introduced hazards into the use of a fire blanket without improving overall suppression performance. For these reasons, it was found that misguided use of fire blankets may increase risk to responders. Water-based suppression is recommended as the default means of vehicle fire control.

Potential for hazardous exposures to the chemicals in smoke exists regardless of vehicle powertrain type (e.g., volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs)). A significant portion of the EV fire chemical exposure is driven by the passenger compartment fire and thus matches the exposure profiles of ICEVs. Elevated concentrations of metals and particulate fluoride associated with the battery fire were measured in smoke and suppression runoff water, as well as contaminated firefighting turnout gear. The impacts on human health resulting from exposures to EV specific contaminants are not yet understood, but contaminants produced from both EV and ICEV fires are known to have negative effects on human health. As with smoke exposures from structural and training fires, firefighters should continue to wear full structural turnout gear with SCBA, to work from upwind and uphill, use the reach of the hose stream to minimize smoke exposures, to perform preliminary exposure reduction and shower as soon as possible, and to decontaminate gear following the procedures in NFPA 1850.

The following recommendations are provided to the fire service based on the findings of this study:

- Continue to prioritize life safety. Vehicle powertrain type should not distract from searching for and removing occupants.
- Execute rapid control of the passenger compartment fire using conventional hose stream tactics, which will assist with identifying whether a battery is involved in the fire.
- When a battery is found to be off-gassing or flaming, if an initial extinguishment effort is not successful, limit water flow to exposure protection and preventing passenger compartment from reigniting while allowing the battery to burn itself out.
- Recognize and communicate prolonged reignition hazards, and work with second responders in removing the vehicle from the scene. An escorted tow is recommended.
- Practice comprehensive smoke exposure management for firefighters and bystanders throughout the incident.

The findings of this research support the continued development of evidence-based operational guidance, firefighter training, and incident decision-making tools for EV fire response. As battery technologies and vehicle designs continue to evolve, further research may be necessary to confirm the validity of these suppression strategies, and to address any potentially unique new fire behaviors and hazards.

1 Introduction

Electrification is a central component of the global efforts to reduce carbon emissions, increase the resilience of our electrical infrastructure, meet growing energy needs and deliver reliable, affordable power, increase convenience in consumer electronics and numerous other benefits. Advances in lithium-ion battery (LiB) energy and power-density, combined with their economical mass production, have enabled widespread adoption of LiBs into an immense array of end-uses such as: consumer electronics, grid-scale and residential energy storage, and nearly all forms of transportation. However, as LiB products have proliferated, it has become a common occurrence to observe failures of inadequately engineered, misused, abused or otherwise failed LiB powered products that have led to noteworthy incidents.

It is well documented that li-ion cells in failure can experience thermal runaway and produce a myriad of different hazards that include: flaming, flame jetting, release of flammable, asphyxiant and toxic smoke products, delayed ignitions which can lead to flash fires, deflagrations or explosions, and finally, stranded energy which may cause persistent electric shock hazards and the potential for reignition [1].

Li-ion specific burning characteristics and their accompanying hazards are being incorporated into LiB-powered products and are significantly different than the generally well understood burning behavior and hazards inherent to the power sources that they are replacing. The unprecedented exothermicity of LiB fires, which involves successive li-ion thermal runaways, frequently overwhelms and can limit the effectiveness of manual and automatic fire suppression technologies even when extinguishing agents are applied directly to the LiB. This is especially true when the construction of a LiB powered product precludes direct application of the extinguishing agent (e.g., a battery pack enclosure, or outer battery door of a product assembly) to cells experiencing thermal runaway and the adjacent unreacted cells.

When discussing the LiB-induced shift in the landscape of fire response hazards with global fire service professionals, electric vehicle fires are frequently cited as presenting the greatest perceived LiB risk in their communities. Automotive manufacturers have responded to demand for vehicles with increased performance and extended driving range with progressively larger battery systems and evolving battery chemistries. LiB Electric vehicle (BEV, often simply just EV) use has grown rapidly across the globe. Incidents involving damaged or burning electric vehicles and the associated LiB fire behavior have become more commonplace. The fact that LiB-specific hazards are being reported to occur on a wide scale indicates that these hazards are not adequately mitigated by common EV battery pack design. As a result, firefighters are reporting that EV fires burn differently than fires involving internal combustion engine vehicles (ICEVs). Concerns have surfaced that EV fires may develop more rapidly, produce larger peak heat release rates, burn for substantially longer durations, and prove resistant to suppression using conventional firefighting strategies and tactics. Uncertainty surrounding EV fire hazards has contributed to the rapid proliferation of misconceptions, sensationalized media coverage, and the introduction of unvalidated suppression products and tactics marketed specifically for EV fires.

Despite the growing volume of EV fire incident response experiences, and although the unique behavior of LiB fires has been researched for years, limited systematic research has documented the extent to which electric vehicles present objectively different fire hazards or firefighting challenges. In response to the need for an evidence-based understanding of EV fire hazards and effective firefighting practices, UL Research Institutes' Fire Safety Research Institute, initiated this comprehensive electric vehicle fire research project in 2023. The study consisted of a three-year research effort with input from a 17-member technical panel representing stakeholders from the North American fire service, automotive original equipment manufacturers (OEMs), and subject matter experts in vehicle and fire safety.

Full-scale fire experiments were conducted in a controlled laboratory environment using 18 vehicles, including both ICEVs and EVs (3 ICEVs and 15 EVs). The experimental program included free burn experiments designed to characterize fire development and burning behavior, as well as suppression experiments specifically designed to evaluate the effectiveness of different firefighting strategies and tactics for controlling EV fires.

The findings presented in this report are intended to address critical knowledge gaps regarding EV fire hazards, improve firefighter operational decision-making, and support the development of evidence-based practices for safely and effectively managing incidents involving electric vehicles.

1.1 Scope

The focus of this research was to establish a fundamental understanding of EV fire behavior, to identify factors impacting manual fire suppression, and to develop guidance for more effective firefighting. The following research questions defined the design of the experiments.

1. Are hazards changing with a transition to EVs? If so, how?
2. What fire control strategies can firefighters use to mitigate the demonstrated hazards?

To answer these questions, this study evaluated the most common electric vehicle models, by sales volume at the time of project initiation (Q1 2023). These fell into the subcompact, compact and crossover SUV size categories and use nickel manganese cobalt (NMC) lithium-ion battery chemistry. No lithium iron phosphate (LFP) chemistry batteries were included as LFP batteries still only power a small portion of the EVs on the road. It was determined that the fires should begin within the battery to enable a focus on investigating the impact of battery involvement on fire suppression.

For the suppression experiments, fire department response was simulated by withholding firefighting efforts until the approximate time of arrival for most North American fire responses. By the time of simulated fire department arrival, both the passenger cabin and battery were involved in the fire. The fire suppression strategies that were evaluated are based on strategies and equipment commonly available in North America, though these strategies and equipment are effectively the same as those utilized internationally (i.e., fire apparatus carrying limited water and means to convey that water onto the burning vehicle). Specialized equipment that requires extensive training and significant cost to implement across the United States were not evaluated, particularly because they do not reflect the current response capacity globally, and because improvements to firefighting effectiveness with existing equipment can be adopted immediately at no cost.

Some scenarios are not covered within the scope of this study. These include fires resulting from severe crashes or requiring victim extrication efforts, and incidents in which the EV traction battery is experiencing thermal runaway without any external flaming, though it is probable that the content within this report can support and significantly improve decision-making for those scenarios as well.

Battery and EV technology is constantly evolving, with higher energy densities and new battery chemistry formulations constantly reaching the market. The findings of this report apply to the current generation of LiB powered EVs, but it is anticipated that significant advances in battery technology will continue to evolve battery burning characteristics and hazards. Incidents with sufficiently advanced technologies should be studied to evaluated whether additional research is needed to update the guidance within this document.

1.2 Objectives

The following research questions were developed to translate the project scope into objectives that can be evaluated with measurement data. These questions were developed based on feedback from the technical panel, feedback from li-ion battery symposia, fire service social media sites, and direct discussions with firefighters and other stakeholders who have experienced EV fires and/or are in a position of responsibility for addressing EV fire hazards.

- Do EV fires grow faster, bigger, or last longer than an ICEV?
- What is the chemical exposure to firefighters and the public resulting from EV fire?
- How effective is standard firefighting equipment and vehicle firefighting tactics for suppressing an EV fire? Can existing equipment be used more effectively?
- Can fire blankets or water additives increase firefighting effectiveness?
- What guidance can be developed for firefighters to improve safety and efficacy of EV firefighting?

2 Background

2.1 Peer-reviewed Vehicle Fire Research

Full-scale burning of vehicles for scientific study is not a novel prospect. This area of research has been undertaken numerous times in the past decades, for various reasons. Several works have aimed to best summarize the catalog of vehicle fire research such as Janssens et al. 2007 [2], Tohir et al. 2015 [3], Sun et al. 2020 [4], and Miechówka et al. 2025 [5]. Some of the findings of these studies will be summarized here, and some of the more pertinent primary research reviewed individually. The primary focus of this review is to understand research that compares internal combustion engine vehicle (ICEV) fire behavior with electric vehicle (EV) fire behavior.

Miechówka et al. 2025 identified 11 peer reviewed scientific papers containing vehicle fire research data, with a total of 148 individual records [5]. This fulls-scale vehicle fire research includes studies on free burning vehicle fire behavior, car park fire behavior, fire propagation within vehicle cabins, vehicle tunnel fire research, and fire and suppression in car stackers (i.e., vertical vehicle storage). Additional literature review identified 8 works of interest published outside of Miechówka's review, with one work focused on ICEV burning and 7 focused on EV burning or comparison of ICEV and EV burning. These new works supplemented an additional 21 vehicle burns for a total of 169 individual records. Of these individual records of a burning vehicle experiment, 83 measured and published heat release rate (HRR) data.

The major body of North American vehicle fire testing took place in the early 2000's with involvement from General Motors R&D, the National Institute of Standards and Technology (NIST) and Factory Mutual Research Corporation (FMRC) with reports authored by Santrock. These works were designed to fulfill three main objectives: (1) conduct crash tests to evaluate the potential for fire initiation, (2) develop and conduct fire spread tests, and (3) to develop realistic fire initiation protocols for vehicle tests [6–14]. Given that modern vehicles have been increasing in size and plastic content (by mass) since the early 2000's, there is a perceived gap in modern ICEV fire measurement data [15].

The research identified spans publishing dates from 1994 to 2025 with sample vehicle model years spanning approximately 1970 to 2020. Electric vehicle research samples with HRR data comprise about 20 % of the total available data (17 EVs, 66 ICEVs). Of all the tested vehicles, North American manufactured vehicles only comprise 25 % of the available data; with all other vehicles manufactured in Europe or Asia. Of the electric vehicles tested with HRR data available, only one was manufactured in North America and its battery was removed pre-experiment [16].

Through the review of previous vehicle fire research a clear gap was identified. North American vehicles, and particularly North American EV's lacked experimental burning data and particularly HRR data of any kind. This study aims to address this research gap by burning North American market ICEV's and EV's and making the resulting data available publicly.

2.2 Review of EV Fire Suppression Research

Significant interest in EV fire suppression has not only come from the fire service, but also the roll-on roll-off (RoRo) vehicle transportation industry, as well as operators of parking garages and tunnels. The scope, scale and diversity of stakeholders of EV fire suppression research means that a significant portion of research that has been conducted in this field is not published in peer-reviewed journals, but rather in the form of project reports. The ultimate purpose of these research efforts has been to develop guidance for the best strategy to mitigate EV fires in different situations. Generally, the goals of individual experimental campaigns were to quantify the efficacy of different fire suppression methods, focusing on the time, resources and manpower required to achieve extinguishment. Additional analyses included assessing the ability of different methods to contain fire spread, be deployed in tight spaces, as well as quantifying the hazard of smoke, particulates and water runoff during and after the use of each method.

This literature review identified 45 published full-scale EV fire experiments across 11 studies in 4 languages that included a suppression component as part of their testing matrix [17–27]. The full-scale studies varied in their extent, burning between 2 and 15 EVs, and in their purposes. The studies can be roughly divided into different categories depending on the fire suppression methods that were studied. Most full-scale fire suppression experiments were conducted by government institutions and included multiple EVs in different configurations with multiple suppression methods [17, 18, 22, 24, 25, 27, 28]. Some studies with a more limited scope focused on one suppression method, or tested several suppression methods sequentially on the same vehicle [20, 21, 23]. Several component-level studies were identified that investigated aspects of EV fire suppression without burning a full EV [28–30].

Suppression methods that were evaluated included the use of a standard nozzle and handline [18, 20, 22, 24, 29], EV fire blankets [18–20, 22–24], penetrating and direct water introduction devices (i.e. lance-type and water jet cutting devices) [19, 22, 24–26], over-head and under-carriage spray appliances, as well as water curtains [17, 18, 24]. Some tests also considered different portable extinguishers and foam systems [18, 23].

Ignition of the vehicles was achieved through several means. Several studies used hydrocarbon fuel burners in the form of pool fires or gas burners placed underneath the vehicle [18, 20]. Others mechanically pierced the battery pack to induce a fire [17, 24, 28] or induced a short circuit in the battery [19, 22, 27]. Installing a heater inside the battery pack to simulate failure of a cell was also used as an ignition method [23, 25]. Anecdotally, this is what some manufacturers do to assess if the thermal runaway of one or more cells will lead to thermal runaway propagation. The scope of research included burning individual vehicles in an unconfined environment [24], fire spread from an EV to other surrounding vehicles [18, 19, 27] and suppression of EVs in confined spaces and/or tunnels [18, 19, 22, 27]. Ancillary research, along with some of the full-scale studies mentioned above, also investigated aspects such as the composition of vent gas and fire effluents. The contamination of water runoff used to extinguish LiB fires and PPE of firefighters was also investigated [21, 22, 24, 30–32].

Research from the Swedish Civil Defence and Resilience agency (Myndigheten för Civilt Försvar, MCF), as well as the Dutch Institute for Fire Safety (Nederlands Instituut Publieke Veiligheid, NIPV) investigated the efficacy of direct water introduction into the EV battery pack via ultra-high pressure water jet systems [25, 26]. Both organizations found the use of a water cutting system or direct water injection to have a small benefit in suppressing the battery fire, after the cabin fire was extinguished with a handline. Both organizations found that the battery fire could be extinguished in about 10 minutes once the water jet system was deployed. The MCF found that direct water injection was able to interrupt thermal runaway propagation in pack-level experiments. It was noted that the use of such unique systems requires practice and training, as well as significant coordination on scene. For this reason, because cabin fires are generally controlled by handline suppression, and because the NIPV has also found that EV fires more frequently do not involve the battery at the time of suppression [33], NIPV recommended that such systems be limited to specialized units that could be requested by the incident commander if the need arises.

Complete characterization of EV fire smoke and water runoff requires many specialized measurement approaches and analyses to identify the broad range of potential contaminants and then to quantify their concentrations. To date, published research has identified several characteristic components as shown in Table 2.1. In addition, water runoff was found to be significantly more electrically conductive. A change in pH was also detected that could range from more acidic to more basic. Bourdes et al. postulate that acidic water runoff may be associated with water application during non-flaming venting due to precipitation of HF and HCl while basic water may be associated with precipitation of cathode metal hydroxides [30].

Table 2.1: Composition of smoke and water runoff associated with EV fires.

Effluent	Identified components	References
Smoke	Water (steam), Formaldehyde, Methane, CO_2, CO, Hydrogen, Hydrogen Chloride, Hydrogen Fluoride, Hydrogen Cyanide, Carbonyl Fluoride, Phosphoryl Fluoride, Phosphoric Acid, Organic carbonates	[22, 24, 31]
Water Runoff	Chloride, Sulfide, Bromide, Fluoride, Phosphate, Cyanide, PAHs, Organic carbonates, Metal ions: Mn, Li, Zn, B, Al	[21, 24, 30, 31]

By far the most comprehensive published study to date was conducted at the Institute for Fire Protection and Disaster Management (Institut für Brand- und Katastrophenschutz, IBK) in Heyrothsberge, Germany [24]. This study included 15 EVs and investigated the efficacy of handlines, direct water introduction into the battery, EV fire blankets and under-vehicle cooling devices, both during the developing, and the fully developed stages of an EV fire ignited by piercing the battery. Furthermore, the study also investigated the hazard posed by the water runoff, smoke and PPE contamination [32]. The authors found that a fully developed EV fire could be effectively extinguished with as little as 960 L (254 gal) in about 24 minutes using only a handline. The authors concluded that no benefit was found for the use of an EV fire blanket, noting the possibility of reignition and unpredictable fire behavior after application. Attacking the fire in the developing stage extended the resolution time and led to higher water volumes, as the battery casing was more likely to be intact and resist water ingress. Direct introduction of water into the battery was beneficial to handline suppression only during the developing battery fire, prior to cabin involvement.

Several limitations were identified across different reports that emphasize the need for additional research. In many experiments, there was limited instrumentation and multiple suppression methods were used sequentially, which makes it impossible to objectively quantify the efficacy of an individual method. Several studies featured few or no repeat experiments for each configuration. The fact that reports published by governmental agencies are likely to be exclusively published in their native language means that studies from non-English speaking countries are likely underrepresented in this review, as demonstrated by the IBK report. These limitations present an ongoing challenge in identifying the current state of EV fire suppression research.

Overall, the results from the available literature indicate that direct application of water via a conventional handline shows great effectiveness at combating the bulk of the fire, limited by its ability to be introduced into the battery and inhibit or stop thermal runaway. EV fire blankets are reported to be ineffective at combating the battery fire but may reduce exposure to surrounding objects from the cabin fire. Direct introduction of water into the battery appears to be somewhat effective at extinguishing the battery fire with efficient use of water, but comes with additional logistical challenges and often requires the bulk of the fire to be extinguished prior to deployment. Further research is needed to gain a better insight into chemical exposure hazards, as well as a quantitative understanding of suppression method efficacy.

2.3 Observed EV Fire Phenomena and Hazards

EV fires and associated fire phenomena have been the subject of extensive, oftentimes sensational media coverage. While EV fires pose unique challenges to firefighters and emergency responders, such coverage can lead to a distorted perception of the fire risk, fire severity and hazards associated with responding to EV fire incidents. Data from the Highway Loss Data Institute (HLDI) shows that incidents of non-crash insurance claims per vehicle per year related to fire are slightly higher for ICEV versions of the same vehicle as opposed to their electric counter-parts, even when taking the age of the vehicle into account [34].

While there is no comprehensive database of EV fires, efforts have been made to compile lists of incidents either from publicly available news sources [35], or by relying on reports from public safety officials [36]. Data compiled from news sources introduce significant limitations and biases, since media coverage will likely be skewed towards severe or exceptional incidents, underrepresenting "routine" or low-acuity incidents. The following section will not attempt to provide statistics of EV fire incidents. Instead, exemplary individual incidents are presented to provide insights into characteristic fire challenges commonly associated with EV fires. It is anticipated that greater insights into North American EV fire frequency and severity, as well as the commitment of fire service resources, will be available in the near future as the National Emergency Response Information System becomes fully functional and data becomes publicly accessible [37].

2.3.1 Resistance to Extinguishment

One of the most common reported challenges regarding EV fires is that large volumes of water are required to extinguish them. In many cases, the passenger cabin fire is extinguished quickly, but the battery fire is unresponsive to water application. Often, hose streams are applied to attempt extinguishment or at least cooling for significant amounts of time. This extinguishment challenge has motivated fire departments to experiment with alternative means of fire suppression, such as applying fire blankets, using specialized tools to inject water into the battery, or to add extinguishing agents into hose streams. A selection of incidents with suppression challenges are presented in the following subsections.

2.3.1.1 High Suppression Water Volume Incidents

The use of large volumes of water for fire suppression was one of the most reported aspects found in a review of news reports regarding EV fire suppression. Incidents involving EVs where fire departments used copious amounts of water to manage the fire have been documented. These incidents also typically entailed responders remaining on scene for extended durations of time (i.e., several hours).

For example, a Nissan Leaf connected to a level 3 charger ignited in September of 2023 in Nashville, TN. The responding fire department reportedly used upwards of 171 000 L (45 000 gal) to extinguish the fire and remained on scene for over 5 hours [38]. Another incident occurred in August of 2023 in Wareham, MA where the fire department responded to an EV fire of unspecified make and model. The initial fire attack was completed within 30 minutes, but crews remained on scene for 3 hours and used over 41 800 L (11 000 gal) of water to cool the battery [39]. These results are a reflection of the need to incorporate new information about EV construction and battery fire behavior into firefighter training and into emergency response guides provided by manufacturers.

These reports stand in contrast to fires involving ICEVs. Anecdotally, ICEV fires can commonly be suppressed in less than 2 min which translates to a suppression water volume of 380–1100 L (100–300 gal).

2.3.1.2 Incidents With Fire Blanket Deployment

Fire blanket products intended for the use in EV fire control have proliferated on the market in recent years [40–43]. Accordingly, fire departments have begun to incorporate EV fire blankets into their responses with the intention of overcoming EV suppression challenges.

One such instance occurred in January 2019 in Centennial, CO when a Jaguar I-Pace caught fire while charging in a residential garage. Upon fire department arrival, a fire attack was conducted to prevent fire spread to the structure. Then, the burning vehicle was towed out of the garage and an EV fire blanket was deployed [44].

Other incidents where EV fire blankets were deployed include an EV fire in Granite Falls, WA in 2025 [45], and a fire in Tallahassee, FL in 2024 [46].

Anecdotally, operational concerns about fire blanket deployment include accumulation of flammable gases from the battery leading to backdrafts, unanticipated deflagrations, flash fires from battery smoke that escapes the containment of the blanket, potentially increased chemical exposure in the immediate vicinity of a deployed blanket, and damage or contamination of the blanket that cannot be remediated.

The greatest concern remains inducing an ignition of accumulated battery gases that causes a backdraft or deflagration. In rare cases, some gas ignitions have released energy with enough force and abruptness to present an explosion hazard. Based on footage shared in social media, an explosion appears to have occurred during EV fire blanket usage in North Bang Khae, Bangkok, Thailand in September 2025 [36]. In a personal communication with EV Fire Safe, who maintains an EV fire incident database, the following narrative was shared:

"Firefighters were called out to an incident with a PHEV in a car repair shop that began to smoke while charging, shortly after catching fire. Firefighters deployed a fire blanket, and during extinguishing efforts a VCE [Vapor Cloud Explosion] was observed while the blanket was over the vehicle. Firefighters flooded the vehicle with water, removing a cover over the battery pack between the front seats to find it still smouldering and producing smoke."

Figure 2.1: Explosion occurred during fire blanket use on an PHEV in Bangkok, Thailand, September 2025.

A similar event occurred during a full-scale EV fire experiment conducted by the Fire Protection Research Foundation, and resulted in a near-miss incident. The near-miss incident, as well as the deflagration behavior documented in this research project, motivated the Fire Safety Research Institute and the Fire Protection Research Foundation to release a joint safety advisory about potential hazards during fire blanket use on electric vehicles [47].

2.3.2 Explosions and Deflagrations

Instances of explosions and deflagrations of Battery Electric Vehicles have been recorded.

In October 2024, vapor emanating from a Mercedes-Benz EQE deflagrated in a parking garage. The resulting fire, exacerbated by an inactive sprinkler system [48], caused 21 injuries and destroyed 70 vehicles. The incident was captured by closed-circuit television (CCTV) [49] which shows vent gases emanating from the vehicle shortly before the deflagration.

A more violent explosion occurred in Neuss, Germany in 2023. Fire departments responded to a reported explosion and arrived to find a destroyed single car garage with severe damage to adjacent structures. Initially, crews suspected gas cylinders to be the culprit. A subsequent investigation revealed that a Renault Zoe EV had gone into thermal runaway inside the garage and the subsequent ignition of vent gases likely triggered the explosion [50]. Another event in the same model of vehicle was caught on camera in Sankt Augustin, Germany in the spring of 2026. The footage shows the passenger compartment filled with white vapors. Shortly after fire department arrival, and immediately before approaching, a significant explosion occurred with subsequent fire. The explosion reportedly damaged several windows in adjacent structures [51]. A similar incident also occurred in October 2025 in Izegem, Belgium, where a PHEV of unspecified type exploded in a residential garage located in the courtyard of an apartment building. The explosion destroyed the residential structure the garage was located in, caused significant structural damage to the adjacent buildings and sparked a fire in a neighboring apartment [52, 53]. Another explosion occurred when gases venting from a hybrid Jeep Wrangler 4xe in Erie, CO, that caused the garage door to be thrown almost 9.1 m (30 ft), nearly hitting a fire officer [54]. The explosion severity and failure behavior of the garage door closely resemble that observed in a series of Fire Safety Research Institute experiments conducted 6 months prior to evaluate this particular hazard [55].

Most reported explosions appear to be associated with incidents that occur in confined spaces such as garages, and parking structures. However, there have also been incidents of explosions occurring in the absence of confining structures, such as the aforementioned explosion of the Renault Zoe in Sankt Augustin or the explosion of a Hybrid Jeep Wrangler 4xe in Ghent, Belgium which exploded after firefighters broke the vehicle's windows to access the passenger compartment during a thermal runaway event [56].

2.3.3 Reignition

The fire service lacks sufficient explanation of residual risk of reignition after the fire is out and reignition timing remains unpredictable. Reignitions have been observed weeks, months, and allegedly in Phoenix, more than a year after sitting in storage without any apparent external cause. A recent story out of a Texas salvage yard demonstrated reignition of a submerged EV after about 3 weeks [57].

Reignition of EVs after extinguishment has been observed by firefighters and scrap yard operators for significant periods of time, in some cases days to weeks after the initial incident was resolved. Data collected by EV FireSafe indicates that reignition occurred in about 13 % of incidents. The time scales and number of ignitions vary significantly, including one vehicle that reignited four separate times within 48 h. Another vehicle saw a reignition 68 d after the initial incident [58]. Reignition may also refer to delayed ignition of the vehicle following a non-flaming thermal runaway event, as was seen in June 2022 in Sacramento, when an EV reignited three weeks after a collision. No fire had occurred during the original incident.

Data trends and anecdotal observations show that the phenomenon of delayed EV reignition can occur in a wide range of ways over vast time scales. Reignition may occur as a result of heat spreading to previously unaffected cells, or due to a short circuit precipitated by debris, a conductive liquid such as suppression water or mechanical damage. Firefighters currently have no tools to accurately assess or prevent this hazard. Thermal imaging cameras can help eliminate hot spots that may cause hot surface ignition, but reignition due to stranded energy is challenging to assess. Proximity voltage detectors, commonly used by workers working with high-voltage equipment, are effective at identifying alternating current, but not direct current, which is the predominant form of electric current found in EVs. Furthermore, the battery may be energized even in the absence of a current. The only reliable method of assessing stranded energy requires directly handling the battery pack, which is outside of the scope of fire department operations.

2.3.4 Flame jetting

The occurrence of jet flames has been anecdotally described by firefighters on scene of EV incidents. This phenomenon has also been observed in the context of scientific study [23, 59]. These tended to be observed originating from openings in the battery (often engineered vent points) near the bottom of the vehicle. Such jet flames tended to be short-lived, on the order of ten seconds and project to distances of up to 2.6 m (8.5 ft). Due to the variations in the location of engineered vent points, as well as unpredictability of damage, jet flames can project in any direction and different models may exhibit different behaviors.

2.3.5 Electrical Hazards

After rigorous review, it does not appear that there are any publicly available reports of first responders harmed by electricity at EV fire incidents, so the likelihood of such a hazard appears to be low. This is supported by data from EV FireSafe, who report that they have not found any verified reports of electrical injuries to first responders caused by electric vehicles [60]. While the potential for hazardous voltages exist whenever the HV system of an EV is involved, such systems include multiple, redundant design features and safety mechanisms to reduce the risk of exposure to high voltage and ensure that the HV system is disabled or isolated in the event of a collision or fire. Additionally, EVs are equipped with cut loops that are designed to be cut by first responders to render the HV system of the vehicle inert, although the battery will retain its charge. There currently is no way for firefighters to discharge the battery in the field. However, first responders should remain aware and vigilant of the risk of electrical hazards, because safety systems are often damaged by fires and may be rendered ineffective. An example of this type of damage and potential hazard is shown in 4.6 with respect to experiment E-TM-S.

2.3.6 Chemical Exposure

While the health hazards of smoke from vehicle fires are still an active area of research, it is commonly understood that such smoke is harmful to health. Only a few incidents involving acute injuries from exposure to smoke resulting from EV batteries in thermal runaway, have been documented. EV smoke chemical exposure health hazards are a current area of research and such cases are difficult to isolate. The chemical species emitted from EVs, especially when cells are in thermal runaway without burning, have not yet been well characterized. Further, the potential health effects from EV smoke are not well understood. However, a review of incidents and literature produced two documented cases worth examining further.

In the first case, five firefighters with the Sacramento Fire Department in Sacramento, CA were exposed to LiB vent gases from a Tesla Model S when its battery went into thermal runaway during overhaul activities [61, 62]. The firefighters were not on air at the time and reported a metallic taste. Four out of the five exposed firefighters have been placed on long-term medical leave. It is still not clear whether their injuries can be attributed to battery vent gases, so this incident has generated significant interest in investigating all lithium-ion battery smoke exposure risks.

In the second case, two Danish firefighters extinguished a Tesla Roadster battery fire in a repair shop in 2019. After the fire was extinguished and breathing apparatus was removed, one of the firefighters experienced a burning sensation in the mouth, which then spread to their throat and lungs. Following the initial symptoms, headaches/migraines continued for a month and a "slimy" cough persisted for 6 months. Ultimately the firefighter recovered completely [63].

It is not clear whether the aforementioned injuries are attributable solely to exposure to EV smoke, and further research is needed to investigate EV smoke health hazards as well as whether other exposures may have been the cause of injury.

2.4 Review of EV Fire Suppression Training

Survey results from the NTSB [64] as well as the University of Alabama [65] indicate that a large portion of Fire Departments in North America have received minimal or no training related to responding to incidents involving EVs. This is exacerbated by the fact that there is no standardized curriculum for EV incident response. Nonetheless, a number of organizations have identified the need for and developed courses, guides and reference materials for firefighters ranging in scope from articles and self-paced online learning modules to full-scale classroom and live-fire instruction.

In-person, hands-on courses have been developed by several agencies including EV Fire Safe (Australia) [66], the International Fire Centre (UK) [67], the International Association of Firefighters (USA) [68], the National Volunteer Fire Council (USA) [69], Energy Security Agency (USA) [70], and GMS Fire and Rescue (Germany) [71], among others. Such courses are typically hosted at fixed facilities allowing for both classroom instruction as well as hands-on demonstrations and live-fire exercises. While such training allows for a high level of fidelity and direct feedback, it can be expensive and requires participants or instructors to travel, typically for several days. Most training programs also focus on fire suppression training using gas-fired vehicle props, or extrication scenarios which do not involve fire. In short, it is not practical or safe to burn electric vehicles for hands-on training. For these reasons, it is not feasible for many departments to send their members to in-person hands-on training. Instead, many of the above organizations also offer train-the-trainer courses, which are designed to allow participants to return and host department-level trainings for their home[1] departments.

Remote training resources exist in the form of online courses, either with a live instructor, or using self-paced modules. The National Fire Protection Association (USA) offers a 4-hour online training course for alternative fuel vehicles [72]. Another course was recently published by the Australian and New Zealand Council for Fire and Emergency Services [73]. Likewise, most of the organizations hosting in-person trainings mentioned above also offer online training resources and response guides.

Another source for training is the information in emergency response guides (ERGs) published by vehicle manufacturers, which are accessible through the vehicle manufacturer's website, or, in the United States, the NHTSA [74]. In most cases, these emergency response guides are long and technically dense documents that outline vehicle specific manufacturer recommendations for firefighter response as well as information on the location of various components of interest for emergency responders. For some vehicle models, an abbreviated rescue data sheet is available [2]. However, true training modules for first responders provided by auto manufacturers are uncommon. One such example is an online, self-paced, first responder EV course provided by GM [75].

Other EV and AFV training curricula and response guides have been deployed by several institutions and fire academies both in North America and elsewhere [76–78], such as Texas A&M [79], the West Virginia University National Alternative Fuels Training Consortium [80] and the Illinois Fire Service Institute [81], among others.

Beyond dedicated training courses, there also exists a wide variety of individual department trainings, articles and guides developed independently as well as courses developed by fire training companies [82–86]. These are often developed from information collected from publicly available sources as well as anecdotes and observations from personal or departmental experience, as well as partnerships with equipment manufacturers, such as the Spartanburg-Pruitt protocol [87], which advocates for combining the use of an EV fire blanket and under-vehicle nozzle (UVN).

The recent proliferation of training offerings of AFVs and EVs is an indication that emergency services have identified a significant lack of information in the realm of EV and AFV fire response. Continuing research efforts are required to develop and test best practices to support ongoing education efforts. Likewise, developers of EV training courses, as well as fire department training

[1] or neighboring

[2] generally all vehicle models from European manufacturers are required to have such data sheets

officers should ensure that they incorporate the latest findings from research into their training materials.

2.5 Review of EV Fire Suppression Standard Operating Procedures

Development of Standard Operating Procedures (SOPs) for incidents involving EVs is still ongoing for many fire departments around the world. The NTSB reported in 2018 that only about 10% of fire departments surveyed had written protocols or Standard Operating Procedures for electric vehicles [64]. Tactics continue to evolve as fire departments continue to make observations and incorporate fire research results into their operational practices.

In order to gain an understanding of the current practices and SOPs that are in effect, we surveyed fire departments from the US, Denmark, Japan, Netherlands, Germany, Romania and Portugal. The goal was to identify fire department positions on various EV fire suppression methods, under what circumstances they might be used, as well as the perceived pros and cons for each method. Representatives from several departments also kindly supplied copies of their EV fire SOPs to review.

Table 2.2: Overview of Survey Responses regarding EV Suppression Tactics.

Tactic	Popularity	Perceived Pros	Perceived Cons
Conventional Vehicle Fire Attack	High	Same tactic as other vehicle fires	Potential for large water volumes, hazardous water runoff, battery compartment is sealed
Let Vehicle Burn Out	High	No need for additional Resources	Potential exposures, hazardous smoke, does not extinguish fire
EV Fire Blanket	High	Available when water is not Viable option for fire containment	Cost, impossible to monitor conditions, deflagration hazard
Relocate Vehicle	Medium	Ability to move vehicle out of high-risk places	Labor-intensive, not always feasible
Manufacturer Installed Battery Access Ports	Medium	Direct application of water into battery	Not standardized, not available on all vehicles
Battery Penetration	Medium	Direct application of water into battery	Direct interaction with HV systems, not allowed in some jurisdictions
Water Cutting Tools	Medium	Direct application of water into battery	Need for special equipment and training, not allowed in some jurisdictions, significant cost
Submersion Container	Medium	Effective extinguishment	Resource intensive, requires & contaminates large volumes of water, only feasible if vehicle fits
Mobile Sprinkler	Medium	Light on manpower Effective for protecting exposures	Unlikely to extinguish fire
Water Additives (AFFF or Battery specific)	Low	Familiar tactic from ICEV fires	Not been observed to be effective
Extinguishment Bag	Low	Potentially useful for transport by 2nd responders	Cumbersome to use
Non-water Agent in Metal Container (i.e. Aerosol, CO2, Clean Agent, Sand)	Low	-	Not feasible, not effective, requires large quantity of agent

The qualitative survey responses shown in Table 2.2 indicate that using conventional vehicle fire attack methods, i.e. the application of water, had the highest popularity among the surveyed departments, followed by non-intervention, provided that a lack of exposure protection requirements made non-intervention feasible. The third most popular tactic was the application of an EV fire blanket, typically as a second line tactic for incidents where neither water suppression nor non-intervention are feasible.

Less popular were tactics that included relocating the affected vehicle away from exposures, penetrating and flooding the battery using mechanical devices or water cutting tools, the use of container immersion as well as the use of mobile sprinklers or under-vehicle nozzles (UVNs). While these tactics may hypothetically overcome impediments to suppression (e.g., the water-tight battery enclosure), they can be resource intensive. Relocating the vehicle requires significant manpower, placing the vehicle into a submersion container requires a container, heavy equipment and large volumes of water which then become contaminated[1], and battery penetration requires expensive specialized equipment and training that may be prohibited in certain jurisdictions[2]. These factors typically make these less popular tactics infeasible for most fire departments.

Finally, the least popular tactics were the use of water additives such as AFFF or additives marketed specifically for use with EVs, as well as placing the vehicle into an enclosed container and deploying clean- or aerosol-based suppression agents. Respondents reported that the use of "foams" had no benefit compared to the use of water. Likewise, the cost and logistic challenges of deploying an enclosed container with dry suppression agents were reported to be disproportionately high compared to any benefit such a system might provide. Furthermore, the explosion hazard associated with thermal runaway vapors and operational experiences both indicate that placing a damaged or suspect EV into an enclosed container, even with gaseous or aerosol extinguishing systems will be ineffective and extremely dangerous.

Preferences for tactics varied regionally, owing to differences in EV adoption, fire department culture/sensibilities and regulatory frameworks. Europe saw earlier and more widespread adoption of EVs [88]. Consequently, fire departments in Europe had a head start on searching for new tactics and tools to manage EV fires, with varying results. Generally, European departments were faster to adopt specialized tools with the objective of managing EV battery fires with less water, while North American departments have focused on high-volume water application. Nonetheless, tactics have converged in recent years to favor a water-based conventional vehicle fire attack first and, if feasible, specialized tools or non-intervention, as departments incorporated observations from real incidents.

A review of current SOPs from various departments internationally shows that most SOPs highlight the use of water to manage an EV fire, although some discrepancies exist among them. Procedures in North America continue to highlight application of copious amounts of water, whereas guidance provided to the German fire service, for example, recommends using nozzles with a flow of 60 L/min (16 gal/min) to suppress the cabin fire and limiting water flow once the cabin fire is sup-

[1] In many jurisdictions, this contaminated water is no longer considered fire water runoff and is subject to strict disposal requirements.

[2] In addition to the perceived cons, OEMs will not endorse any tool or device that breaches or penetrates the battery.

pressed due to questionable efficacy of externally cooling the battery [89]. Some local differences also exist regarding second-line measures such as non-intervention and the use of EV fire blankets. In all cases, the first priority lies with life safety and the use of proper PPE and SCBA, followed by protection of property and the environment.

2.6 Review of EV Construction

To best understand fires in electric vehicles, the design and construction of electric vehicles, and other vehicles with large batteries, must first be understood.

For many years internal combustion engine vehicles have used batteries in conjunction with an alternator to power their low-voltage systems such as indicator lights, starter systems, fuel pumps, engine control systems, and the transformers that power the ignition system. These 12 V batteries typically use a lead-acid chemistry that is cost-effective, outputs high current, and is tolerant to abuse. The tradeoff is that these batteries are heavy and not energy dense. However, lead-acid battery provides enough power to turn over and start the combustion engine as needed, and the consumed energy is then replaced by the alternator converting the engine power back to electrical energy.

2.6.1 Types of Battery Powered Vehicles

In the modern vehicle landscape, three main vehicle types make use of larger batteries to supplement or replace combustion as a means of supplying a vehicle with power. Battery electric vehicles (BEVs or just EVs) are vehicles that operate entirely on energy stored in batteries. Hybrid electric vehicles (HEV) are vehicles that have both internal combustion and batteries and electric motors for power generation. Hybrids can balance the use of their electric and combustion engines to leverage the electric motor's better conversion efficiency for better fuel economy or for better acceleration performance of the electric motors. Similarly, plug-in hybrid electric vehicles (PHEV) are vehicles that use both combustion and electric motors but have a rechargeable and typically larger (i.e., larger than HEV) battery pack that can also be plugged into an external power source to be recharged. All of these vehicle types are capable of using modern energy recovery technologies like regenerative braking to recycle their kinetic energy back to electric energy stored in the vehicles' batteries.

2.6.2 Sizes of Batteries in Vehicles

All of these vehicles make use of the modern lithium-ion battery as the most cost-effective and energy dense option widely available. Typically, HEVs have the smallest batteries, with a typical capacity of about 1 kWh. PHEVs have the next largest batteries, usually ranging 5–25 kWh [90], although trends are showing a rapid increase in average PHEV battery size [91]. EVs have the largest capacity batteries, typically ranging 50–100 kWh, but as vehicle sizes and range demands increase, battery capacities will follow. There are now more than 30 electric vehicle models with a capacity over 100 kWh [92] with some models even broaching 200 kWh [93].

2.6.3 Types of Construction

As the sizes of batteries in vehicles have gradually increased, the methods of integrating the battery into the vehicle have also changed. Early HEVs and PHEVs adopted existing ICEV chassis and housed batteries in the cargo or trunk area of the cabin, often as a standalone enclosure or device. This design could be adapted to any vehicle without major design changes to the chassis, and could fit various battery sizes and formats of small to medium capacity. As vehicles demanded more battery capacity, designing the entire vehicle around the larger battery could better optimize vehicle performance and costs. Consequently, adaptations to the traditional body-on-frame and unibody vehicle design philosophies were made.

Body-on-frame designs continued to exist, and were adapted to the EV space by designing battery packs that could fit in between frame members, underneath passenger seats, and in spaces previously occupied by now unneeded mechanical drive components. The 'skateboard' design can be seen as an iteration of the unibody design; where the battery pack, electric motors, wheel and suspension systems are all integrated into a single structure. This 'skateboard' unit is designed to house the batteries low and to reduce the cost and complexity of manufacturing multiple different models of EVs. Within this skateboard design the battery pack itself can be structural, semi-structural, or non-structural. Structural packs are an integral part of the load distribution structure of the vehicle. Without the battery pack, the vehicle would not be able to support the loads associated with accelerating, braking, and collision energy re-distribution. In semi-structural designs, the pack shares some of these loads with the body structure, but does not do the entirety of the job itself. In non-structural designs the pack fulfills a similar role as those of body-on-frame designs, it may be bolted to a frame that has a designed space for it to fit. However, in this design the battery pack is not designed to share any of the load bearing capacity of the vehicle chassis.

Regardless of the structural contribution of the battery pack, the pack itself must be water-tight and fire-resistant. In the United States EVs must at least conform to Federal Motor Vehicle Standard 571 No. 305; which requires no electrical hazards, electrolyte leakage, and battery retention and safety in a post-crash vehicle. This safety standard also defines the electrical safety during normal operation including: required electrical isolation for a vehicle high voltage pack (500 Ω/V for AC high voltage, or 100 Ω/V for DC high voltage), protection against indirect contact, service disconnect protection, and charge inlet direct contact protection [96]. A revised version No. 305a accepted in 2024 added a water ingress protection under normal vehicle operation requirement, adding both an IPX5 washing-based spray test and a driving through standing water test [97]. Manufacturers also often choose to have their battery packs meet other standards such as: UN 38.3 (altitude, vibration, shock, thermal cycling), UN ECE R100 R.3 (electrical safety and isolation resistance, thermal propagation, controlled venting), UL 2580 (external fire exposure, thermal

(a) Non-structural integration of battery pack [94]. (b) Structural integration of battery pack [95].

Figure 2.2: (a) Non-structural battery pack; pack is self-contained in a case bolted to the chassis and below the interior floor of the vehicle. (b) Structural integration of battery pack; the case is constructed of features that also make up load bearing components of the chassis.

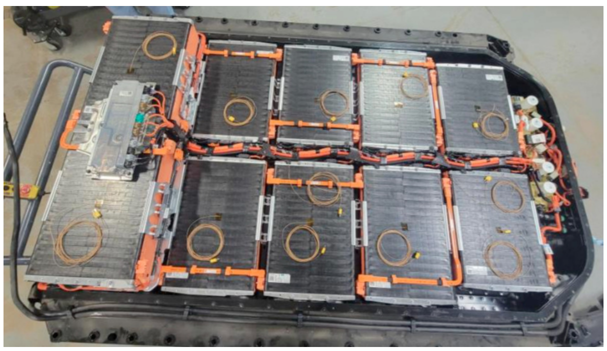
propagation). Although none of these standards are explicitly required in the United States, many vehicle manufacturers choose to conduct these tests to assess the safety of their vehicles and to affect insurance, liability, and safety risks.

Electric vehicle battery pack enclosures typically follow three distinct design formats. The oldest design is the all-steel case, seen on vehicles like the Chevrolet Bolt. This battery case is made of several stamped pieces of steel sheet, cut and bent to form each required section, and then tack welded, riveted or bolted together. These packs typically require more sealant to cover the gaps created by joining multiple pieces together to form the enclosure. The second type is the aluminum enclosure. These enclosures are typically formed from less overall pieces but otherwise follow the same design philosophy as the steel case. Pieces of aluminum are cast or otherwise shaped to form the housing geometry and then tack-welded, riveted or bolted together. The joints between plates are then sealed with closed-cell foam tapes or sprays, or with thicker caulking-type adhesives. Aluminum is often chosen because of the associated reduction in weight (which can affect driving range), corrosion resistance, beneficial thermal and mechanical properties, and manufacturing and scale considerations.

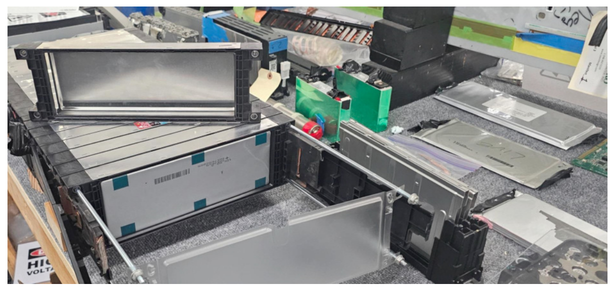
(a) Steel case battery pack after fire test. (b) Aluminum case battery pack. (c) Composite case battery pack.

Figure 2.3: Examples of the various pack enclosure construction types for vehicle batteries.

At the most fundamental level an EV battery pack is a group of energy containing cells. These cells can be small like 18650 cylindrical cells, each cell containing about 12 Wh of energy. These cells can also be quite large, some EV prismatic cells now reach over 700 Wh per cell. These cells are typically low-voltage (i.e., approximately 4 V) and are then connected together in series to raise voltage, and in parallel to raise amperage. In this way, many smaller batteries can be combined to reach a final pack with a large capacity and a high voltage. Within this grouping, batteries are typically grouped into ‘in-between’ groups, commonly known as ‘modules’. Some vehicles use fewer modules like the Tesla Model 3 with 4 modules each made of 1,104 cylindrical cells. Other vehicles contain more modules, like the Hyundai Kona SEL with 10 modules each made from approximately 30 pouch cells.

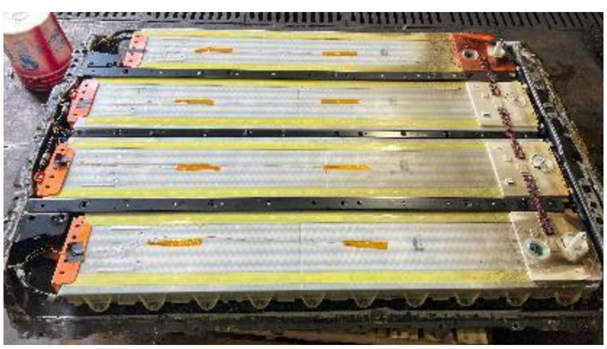


(a) Partially disassembled Ford Mustang EV battery pack. Cover has been removed modules are visible.

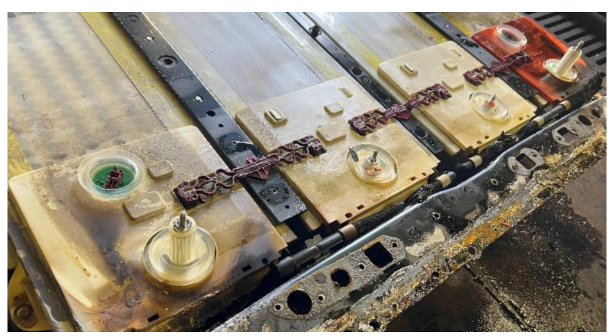


(b) Partially disassembled Chevy Bolt battery module, the pouch-style cells contain the energy in this system, and are shown on the right-hand side.

Figure 2.4: Inside of two battery packs that represent modules and pouch cell construction (a) Ford Mustang modules visible with top composite cover removed, (b) Chevy Bolt module partially disassembled, cells visible. Photos courtesy of Munro and Associates.



(a) Tesla Model 3 battery pack with cover removed showing the four modules which comprise the pack.



(b) Close up of the modules, cylindrical cells are visible through the opaque module covers.

Figure 2.5: Inside of a Tesla Model 3 extended range (a) top cover removed showing modules (b) close up with cells visible through module cover.

Regardless of construction philosophy, the end result is mostly the same. EV battery packs are water-resistant and have a designed electrical isolation, and they also must resist crash forces to a degree. EV battery packs also operate in the high-voltage range, with most packs typically designed around 300–800 V. The result is a high energy capacity high voltage battery pack that is protected from water ingress and mechanical damage. These design features, which are critical to the reliable operation of EVs, are the primary factors in the challenge of battery fire extinguishment.

3 Methods

Portions of this methods section and resulting figures and datasets were previously published in Sauer et al., *Data in Brief* (2026) and are reproduced here under the terms of the Creative Commons Attribution 4.0 International (CC BY 4.0) license. Relevant details on experimental setup, apparatus, and methods will be reproduced here for ease of readability. For additional details and a full data release, please see the full article at doi.org/10.1016/j.dib.2026.112471 [98].

3.1 Vehicles

A total of 18 experiments were performed, consisting of 9 free burn experiments (in which the vehicle was allowed to burn to completion without any intervention), 5 handline suppression experiments (in which water or water with an encapsulating agent (F-500) was employed to suppress the fire), and 4 fire blanket experiments (in which a fire blanket, in some cases in combination with water suppression, was employed to suppress the fire). The vehicles used in these experiments included 3 internal combustion engine vehicles and 15 battery electric vehicles. The vehicle make and model, vehicle identification number (VIN), energy capacity, and other details for each vehicle used in an experiment are provided in Table 3.1. The most popular electric vehicles by total United States sales volume were selected for testing, with the addition of the Hyundai Kona as the only North American vehicle that used the same chassis for its battery electric vehicle (BEV) and internal combustion engine (ICEV) chassis. Internal combustion engine vehicles had their fuel tanks filled to capacity, and electric vehicles had their batteries charged to 100 % state of charge. One vehicle model per manufacturer was burned for each experiment type. Project resources allowed for eight different vehicle models to be tested, which were chosen to provide a representative sample of vehicles that the fire service is likely to encounter in incident responses in North America, though some vehicles are sold internationally.

The experiment code is a unique identifier for each experiment that consists of 4 or 5 letters. The first letter place indicates whether the vehicle is an EV or ICEV (E, or G, to represent electric or gasoline respectively), next is a two-letter key for the make and model of the vehicle (e.g. FM for Ford Mustang), the last single or double letter place indicates the type of experiment where F indicates free burn, S indicates handline suppression and B indicates the use of a fire blanket. SA is used for suppression with an additive and BS shows a combination of fire blanket and manual handline suppression. As an example, the code E-HK-S indicates an EV (E) Hyundai Kona (HK) that was suppressed with handline suppression (S). The experiment codes for all vehicles can be found in Table 3.1.

Table 3.1: Test vehicle information.

Code	Type	Make	Model	Year	Color	Mileage	Battery /Fuel Cap. (L, kWh)	VIN
G-HK-F	ICEV	Hyundai	Kona SEL	2020	White	32,503	50 L	KM8K2CAA6LU577622
E-CB-F	EV	Chevy	Bolt EV LT	2021	Blue	17,000	65 kWh	1G1FY6S07L4121245
E-NL-F	EV	Nissan	Leaf S	2019	White	33,654	40 kWh	1N4AZ1CPXKC302461
E-HI-F	EV	Hyundai	Ioniq Limited	2019	Silver	30,019	28 kWh	KMHC05LH4KU044196
E-TM-F	EV	Tesla	Model 3 Long Range	2022	White	10,000	82 kWh	5YJ3E1EBXNF228949
E-FM-F	EV	Ford	Mustang Mach E GT	2022	Black	12,000	91 kWh	3FMTK4SE5NMA08831
E-HK-F	EV	Hyundai	Kona SEL	2020	Grey	57,000	65 kWh	KM8K23AG0LU058831
G-HK-F2	ICEV	Hyundai	Kona SEL	2020	Orange	45,035	50 L	KM8K22AA0LU567985
G-TR-F	ICEV	Toyotoa	RAV4 XLE AWD	2019	Black	71,999	55 L	JTMP1RFVXKJ006288
E-HK-S	EV	Hyundai	Kona SEL	2019	Black	47,826	65 kWh	KM8K23AG5KU032031
E-CB-S	EV	Chevy	Bolt EV LT	2021	Grey	23,000	65 kWh	1G1FY6S0XL4109431
E-TM-S	EV	Tesla	Model 3 Long Range	2021	Grey	29,000	82 kWh	5YJ3E1EBXMF983260
E-FM-S	EV	Ford	Mustang Mach E GT	2022	Blue	11,000	91 kWh	3FMTK4SX9NMA13709
E-FM-B	EV	Ford	Mustang Mach E GT	2022	Yellow	38,370	91 kWh	3FMTK4SEXNMA20344
E-TM-B	EV	Tesla	Model 3 Long Range	2022	Black	42,569	82 kWh	5YJ3E1EB6NF109389
E-FM-SA	EV	Ford	Mustang Mach E GT	2022	Black	2,281	91 kWh	3FMTK4SE4NMA077752
E-FM-BS	EV	Ford	Mustang Mach E GT	2021	Black	23,795	91 kWh	3FMTK4SE5MME02568
E-TM-BS	EV	Tesla	Model 3 Long Range	2022	Grey	44,575	82 kWh	5YJ3E1EB3NF169839

Table 3.2: Vehicle dimension specifications.

Code	Make	Model	Length (m)	Width (m)	Height (m)	Wheelbase (m)	Curb weight (kg)
G-HK-F	Hyundai	Kona SEL	4.166	1.801	1.565	2.601	1317.7
E-CB-F	Chevy	Bolt EV LT	4.145	1.765	1.610	2.601	1631.4
E-NL-F	Nissan	Leaf S	4.435	1.791	1.560	2.700	1594.5
E-HI-F	Hyundai	Ioniq Limited	4.470	1.821	1.450	2.700	1447.7
E-TM-F	Tesla	Model 3 Long Range	4.694	1.849	1.443	2.875	1825.0
E-FM-F	Ford	Mustang Mach E GT	4.732	1.881	1.613	2.985	2255.5
E-HK-F	Hyundai	Kona SEL	4.166	1.801	1.565	2.601	1688.6
G-HK-F2	Hyundai	Kona SEL	4.166	1.801	1.565	2.601	1317.7
G-TR-F	Toyotoa	RAV4 XLE AWD	4.595	1.854	1.707	2.690	1536.4
E-HK-S	Hyundai	Kona SEL	4.166	1.801	1.565	2.601	1688.6
E-CB-S	Chevy	Bolt EV LT	4.145	1.765	1.610	2.601	1631.4
E-TM-S	Tesla	Model 3 Long Range	4.694	1.849	1.443	2.875	1825.0
E-FM-S	Ford	Mustang Mach E GT	4.732	1.881	1.613	2.985	2255.5
E-FM-B	Ford	Mustang Mach E GT	4.732	1.881	1.613	2.985	2255.5
E-TM-B	Tesla	Model 3 Long Range	4.694	1.849	1.443	2.875	1825.0
E-FM-SA	Ford	Mustang Mach E GT	4.732	1.881	1.613	2.985	2255.5
E-FM-BS	Ford	Mustang Mach E GT	4.732	1.881	1.613	2.985	2255.5
E-TM-BS	Tesla	Model 3 Long Range	4.694	1.849	1.443	2.875	1825.0

Table 3.3: Battery specifications per vehicle.

Make	Model	Year	Battery Cap. (kWh)	Battery Voltage (V)	Cell Type - Format	# of cells	Cell Voltage (V)	Cell Configuration
Chevy	Bolt EV LT	2021	65	350	Pouch	288	3.65	96s3p
Nissan	Leaf S	2019	40	350	Pouch	192	3.65	96s2p
Hyundai	Ioniq Limited	2019	28	360	Pouch	192	3.75	96s2p
Tesla	Model 3 Long Range	2022	82	350	Cyl. 2170	4416	3.63	96s46p
Ford	Mustang Mach E GT	2022	91	350	Pouch	376	3.73	94s4p
Hyundai	Kona SEL	2019	65	356	Pouch	294	3.63	98s3p
Hyundai	Kona SEL	2020	65	356	Pouch	294	3.63	98s3p
Tesla	Model 3 Long Range	2021	82	350	Cyl. 2170	4416	3.63	96s46p

3.2 Laboratory Setup

All experiments were performed in an indoor laboratory space to eliminate the influence of outdoor wind conditions. The laboratory space had a footprint of 33 m by 33 m (108 ft x 108 ft). The vehicles were centered under a movable ceiling that measured 30 m by 30 m (98 ft x 98 ft) and was positioned 9.1 m (29.9 ft) above grade. An exhaust duct was located above the movable ceiling, and a flow rate of 28.3 m^3/s (1000 ft^3/s) was maintained throughout each experiment to extract fire effluent from the laboratory space. Vehicles were positioned inside a steel pan having inside dimensions of 2.44 m (8 ft) wide by 4.88 m (16 ft) long, with a lip height of 0.17 m (6.7 in). The pan was leveled on four platform scales (described below) such that the lip was 0.56 m (22 in) above grade. The inside of the pan was lined with 1.3 cm (0.5 in) thick DensDeck fiberglass mat-faced, gypsum core panels to thermally protect the pan and underlying platform scales. Figure 3.1 shows the instrumentation layout used for a majority of the free burn experiments (E-CB-F through G-TR-F); any deviations from this layout are described in the data repository.

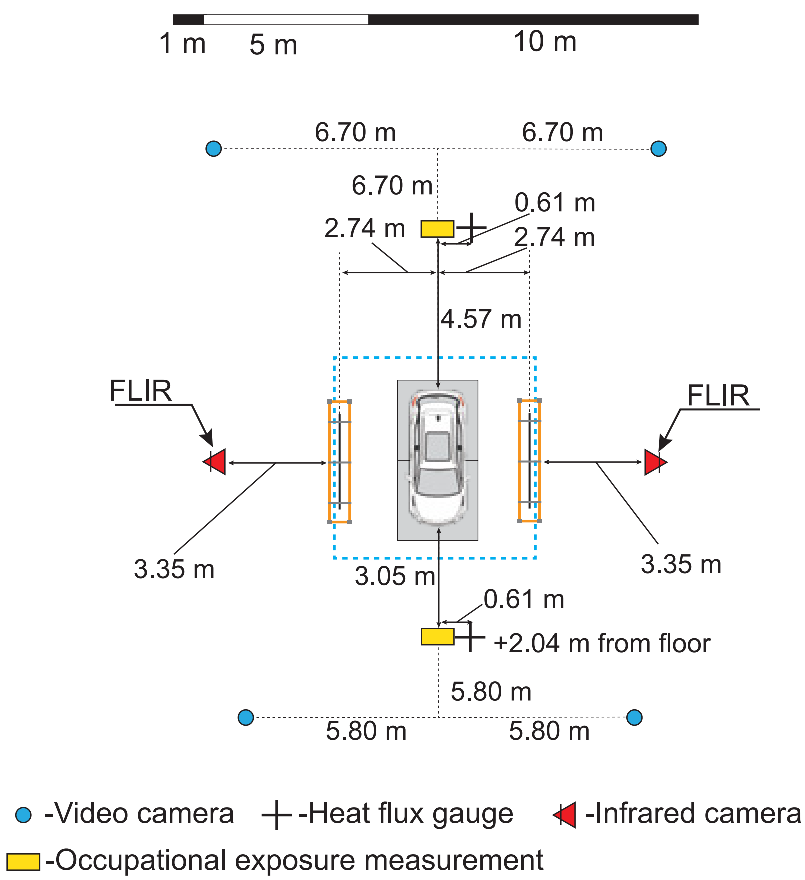


Figure 3.1: Experimental layout for vehicles during free burn experiments (to scale). Reproduced from Sauer et al. (2026), *Data in Brief*, 49, 109853, licensed under CC BY 4.0 [98].

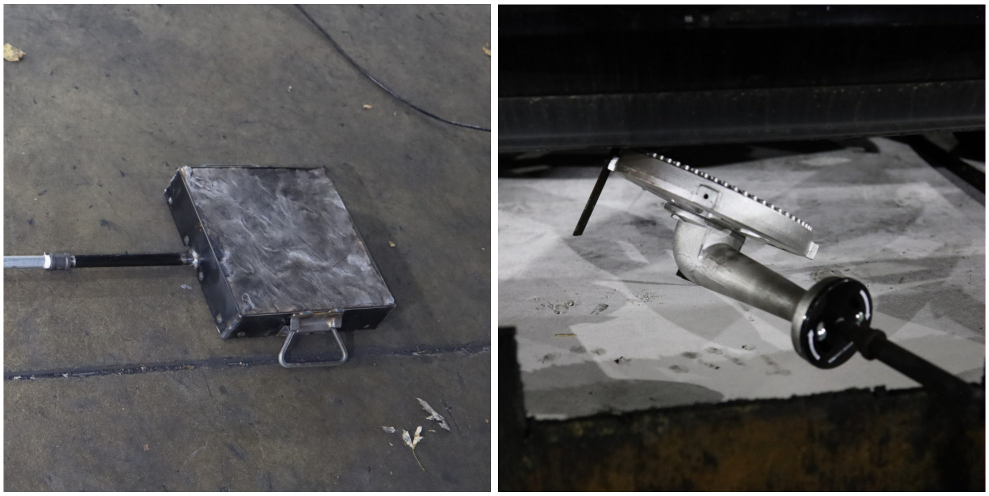
3.3 Apparatus

3.3.1 Ignition Equipment

All vehicle fires were initiated with propane burners to ensure reliable ignition of the ICEV and to ensure an initial condition of propagating thermal runaway in the EV experiments. Two different burner designs were used during the course of experimentation. The first burner design used was a diffusion style propane burner. The burner had dimensions 30.48 cm (12 in) wide by 30.48 cm (12 in) long by 7.62 cm (3 in) tall. A steel mesh supported by internal structure created a space into which a supply pipe introduced propane fuel. Fiberglass mat insulation was placed on top of the steel mesh to provide flow-resistance. In this way the pressure of the fuel gas supply pushes the propane uniformly through the steel mesh and fiberglass insulation. Above the burner the fuel mixes with ambient air and is ignited, where it burns by diffusion.

The second burner was a premixed burner. This burner was constructed from a commercially available turkey burner advertised as "200K BTU Propane Burner". The burner is designed to operate with only propane gas, supplied at up to 1.38 bar (20 psi). The flow of the propane gas through a small orifice draws in ambient air through the venturi effect and small openings. The area of these openings were controlled by an adjustable faceplate. Upon testing the original configuration was insufficient to produce short flames to prevent ignition of ordinary combustibles near the battery packs. The burners were modified by supplying an adjustable propane-air mixture, rather than just pure propane. This modification allowed a controlled increase in the volume of air present in the premix, resulting in shorter flames.

All burners were supplied propane by an Alicat Massflow controller. Burners were operated until car traction batteries were in thermal runaway or vehicle cabins were significantly involved. All tests started at a propane flow rate of 21 SLPM (0.74 ft^3/min). Some tests required slight decreases to prevent ignition of adjacent combustibles or slight increases to ensure battery thermal runaway propagation. The specific burners used and their positions underneath the vehicle are denoted in Table 3.5.



(a) Diffusion burner before a test. (b) Premixed burner before a test.

Figure 3.2: The two types of burners used in testing, unlit and shown before tests.

(a) Diffusion burner. (b) Premixed burner.

Figure 3.3: The two types of burners used in testing, difference in flame type visualized with burners operating. Adapted from Sauer et al. (2026), *Data in Brief*, 49, 109853, licensed under CC BY 4.0 [98].

3.3.2 Firefighting Equipment

Water was applied with the standard firefighting combination nozzle shown in Figure 3a with 3.8 cm (1.5 in) inlet, designed to flow 567.8 L/min (150 gpm) at 3.45 bar (50 psi) nozzle pressure (ChiefXD, Elkhart Brass, Elkhart, IN). When used, the encapsulating agent (F-500, Hazard Control Technologies, Fayetteville, GA) was introduced with an eductor (Eductor UE-125-NF, Task Force Tips, Valparaiso, IN) at a concentration of 3 %/vol, but the procedure was otherwise the same as suppression with water. Prior to the experiment with F-500, water and agent flow rates were verified with calibrated mass flow rate and mass loss rate equipment. The water flow rate was measured using a magnetic flow meter (ModMAG M2000), upstream to a gated wye to measure the flow for both handlines (or the UVN, when used). An effort was made to limit the time that both lines were flowing concurrently.

The fire blanket experiments used a 7.5 m (24.6 ft) by 10 m (33 ft) graphite blanket with a polymer coating (Car Pro X, Bridgehill, Norway). In addition, an under-vehicle nozzle (UVN) (Transformer Nozzle System, Task Force Tips, Valparaiso, IN) was used beneath the vehicle battery pack for some experiments. The nozzle was operated at the manufacturer specified 6.9 bar (100 psi) to supply a claimed flow of 567.8 L/min (150 gpm).

Firefighters were equipped with a full set of structural firefighting turnout gear and used self-contained breathing apparatus throughout all experiments.

3.3.3 Data Acquisition

Thermocouple, heat flux gauge, pressure transducer, and water flow meter data were recorded at 2 Hz (exp G-HK-F through E-HK-F) and 1 Hz (exp G-HK-F2 through E-TM-BS) using a National Instruments data acquisition system (PXIe-1088 chassis, PXIe-8861 controller, PXIe-4353 temperature modules, and PXIe-4302 voltage modules), and saved in CSV format. Mass data from the platform scale indicators were recorded at 0.5 Hz using Collect+ version 1.2.1.1 (Mettler Toledo) and saved in CSV format. Infrared thermogram sequences were recorded at 30 Hz using ViperVision 4.38.24 (Viper Imaging), and saved in compressed sequence (CSQ) format. The burner mass flow controller output was recorded at 1 Hz using FlowVision version 2.0 software (from Alicat), and saved in CSV format. Data acquisition devices were started simultaneously to ensure that all measurements were time-synced.

3.3.4 Vehicle Mass Loss

For the free burn experiments, the combined mass of the vehicle and pan were measured over time using four platform scales (one per corner of the pan). This approach to measuring the total vehicle mass is consistent with that adopted by researchers in previous experimental studies on vehicle fires [99]. Each scale (Mettler-Toledo model PFD779 US11 with a IND570 indicator) had a capacity of 1500 kg, resolution of 100 g, and repeatability of 90 g. The mass of the vehicle was not measured for suppression or fire blanket experiments due to the short burning durations in those experiments. Mass data was collected from each of the weighing platforms at a rate of 0.5 Hz (2-second interval).

3.3.5 Heat Flux

Heat flux to the immediate surroundings of the vehicle were measured using water-cooled Schmidt-Boelter heat flux gauges. Ten Medtherm 64-series Schmidt-Boelter water cooled heat flux gauges were placed in the free burn experiments. Four on each side, one front and one rear. The side gauges were placed 1.30 m (51 in.) above grade; their positions are noted in Figure 3.4. For the suppression experiments only the four gauges on the passenger side of the vehicle were used.

The central two gauges on each side (D2, D3, P2, and P3) were combination total heat flux and windowed radiometer sensors. The radiometer sensors had sapphire windows with a viewing angle of 150°. The outer two gauges on each side (D1, D4, P1, and P4) were windowed radiometer sensors, having sapphire windows with a viewing angle of 150°.

In addition, total heat flux gauges were positioned 3.0 m from the front bumper and 4.5 m from the rear bumper of the vehicle and were offset from the vehicle's longitudinal plane by 0.6 m toward the driver's side of the vehicle to accommodate the air sampling stands. Each sensor was positioned 2.0 m above grade. The positions of these gauges are shown in Figure 3.4.

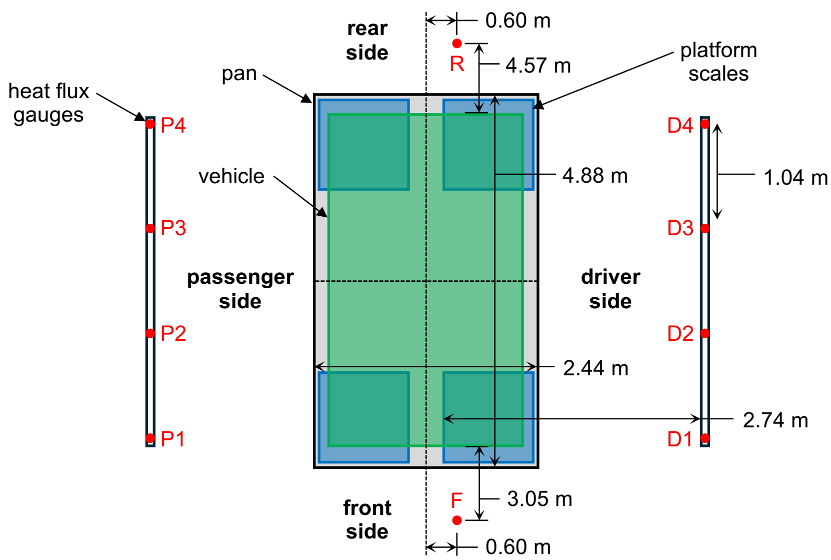


Figure 3.4: Locations of Schmidt-Boelter heat flux gauges used in this study relative to the containment pan and platform scales. Reproduced from Sauer et al. (2026), *Data in Brief*, 49, 109853, licensed under CC BY 4.0 [98].

Plate sensor arrays were also used to capture 2D spatial heat flux data. More information and full data from these plate sensors can be found in Sauer et al. 2026 and Dehghani et al. 2025 [98, 100].

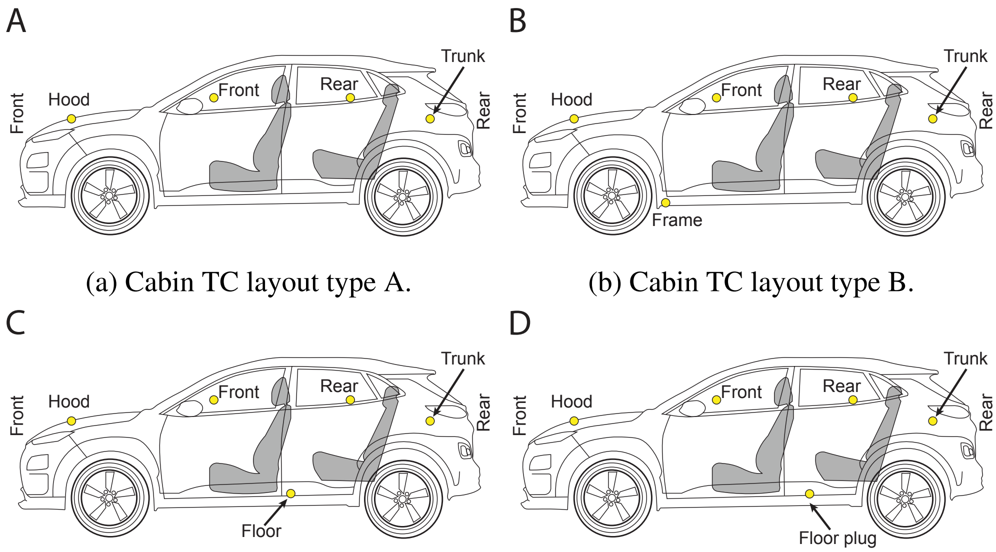
3.3.6 Temperature

Temperatures were obtained throughout the experiments at various locations including: inside of the vehicle cabin, under the vehicle hood, under the vehicle body, in the plume of the fire, and at the rear heat flux gauge locations. All thermocouples used were type-K, typically 30 Ga or 24 Ga fiberglass insulated.

All electric vehicles had thermocouples placed in or on their battery packs. In early experiments these thermocouples were surface mounted on the exterior of the battery pack enclosure or placed into the cooling plates of battery packs when available. In the later experiments, the battery packs were opened and thermocouples placed inside the pack on battery modules themselves. Additional details about thermocouple mounting procedure are provided in Sauer et al. 2026 [98]. Table 3.4 denotes the cabin and battery TC layout used for each experiment and vehicle, corresponding Figure 3.5 and Figure 3.6 detail the specific locations of these TCs.

Table 3.4: Car thermocouple layout figure key Asterisks denote TC placed inside the battery enclosure. Reproduced from Sauer et al. (2026), *Data in Brief*, 49, 109853, licensed under CC BY 4.0 [98].

Code	Make	Model	Cabin TC layout	Battery TC layout
G-HK-F	Hyundai	Kona SEL	B	N/A
E-CB-F	Chevy	Bolt EV LT	A	A
E-NL-F	Nissan	Leaf S	A	B
E-HI-F	Hyundai	Ioniq Limited	C	E
E-TM-F	Tesla	Model 3 Long Range	C	D
E-FM-F	Ford	Mustang Mach E GT	C	A
E-HK-F	Hyundai	Kona SEL	C	C
G-HK-F2	Hyundai	Kona SEL	A	N/A
G-TR-F	Toyota	RAV4	A	N/A
E-HK-S	Hyundai	Kona SEL	A	A
E-CB-S	Chevy	Bolt EV LT	A	A
E-TM-S	Tesla	Model 3	A	D
E-FM-S	Ford	Mustang Mach E	A	F
E-FM-B	Ford	Mustang Mach E	A	G*
E-TM-B	Tesla	Model 3	A	H*
E-FM-SA	Ford	Mustang Mach E	A	G*
E-FM-BS	Ford	Mustang Mach E	A	G*
E-TM-BS	Tesla	Model 3	A	H*



(a) Cabin TC layout type A.

(b) Cabin TC layout type B.

(c) Cabin TC layout type C.

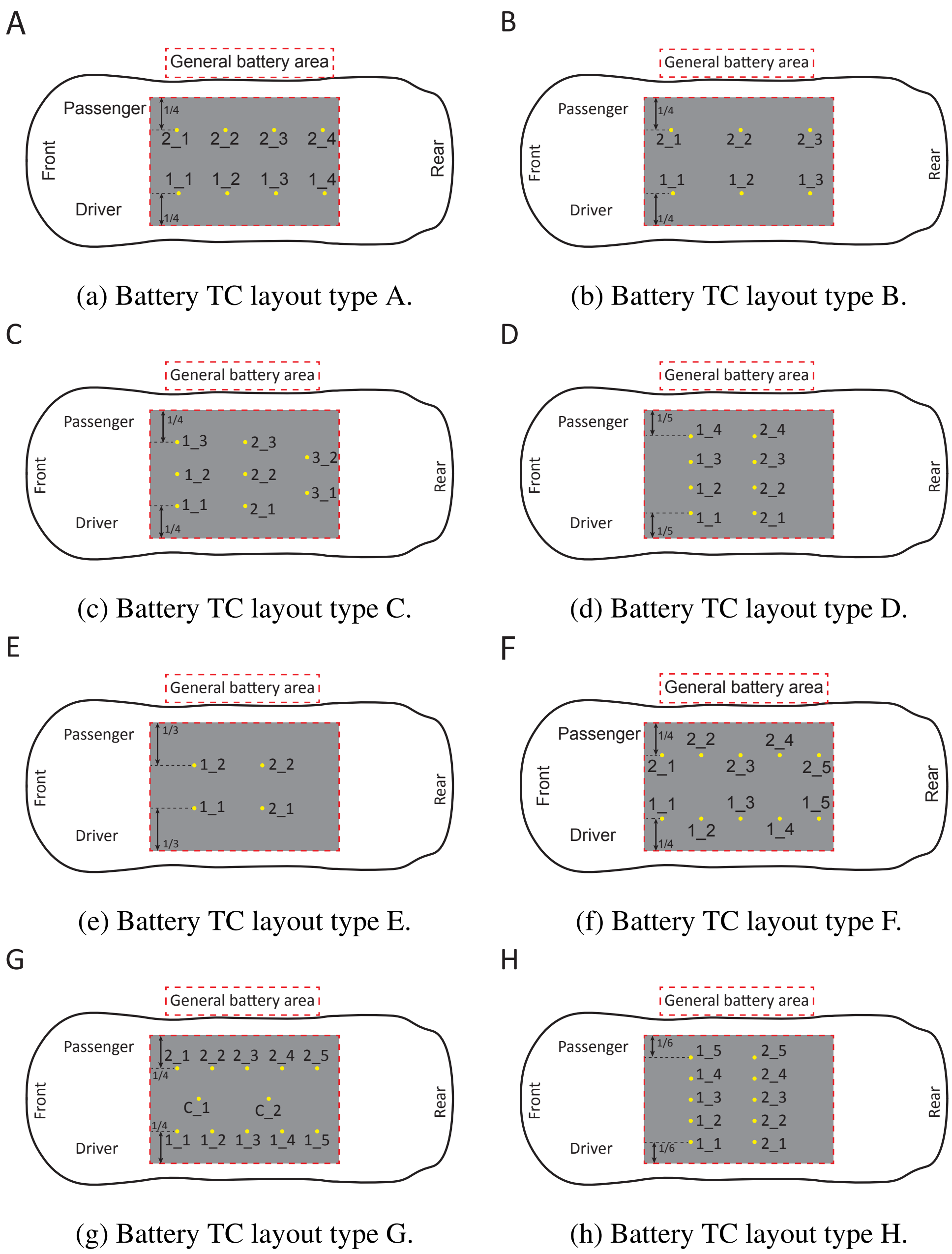
(d) Cabin TC layout type D.

Figure 3.5: Profile views of cabin thermocouple locations and layout types referenced in Table 3.4. Adapted from Sauer et al. (2026), *Data in Brief*, 49, 109853, licensed under CC BY 4.0 [98].

3.3.7 Video

During all experiments, video data was captured from multiple sources. Fixed perspective cameras on tripods surrounding the vehicle were used throughout all experiments. The most consistent setup of these cameras is expressed in Figure 3.1. Three different video recording systems were used for these experiments: Magic Technology UVST MAGIC-U16-4M, LOREX and Milestone digital video recorder (DVR) systems. The MAGIC-U recorded 1920 px by 1080 px video at 30 fps in h264 codec, the LOREX system recorded 3840 px by 2160 px at 15 fps in hevc codec, and the Milestone system recorded 2304 px by 1728 px at 30 fps in h264 codec.

During suppression experiments, FLIR A70 IR cameras were positioned orthogonal to the driver's side, and off of the corners of the front and rear driver's side bumpers. The IR cameras had uncooled microbolometer sensors with a spectral range of 7.5–14 µm, resolution of 640 px wide by 480 px tall, and angular field of view of 51°, and recorded at 30 fps. Firefighters conducting suppression operations captured video data from GoPro Hero 12 cameras mounted to their helmets. These cameras captured 3840 px by 2160 px at 24 fps. Infrared video during suppression experiments was also captured by a handheld FLIR K65 (320 px by 240 px) thermal imaging camera (TIC).



(a) Battery TC layout type A. (b) Battery TC layout type B.
(c) Battery TC layout type C. (d) Battery TC layout type D.
(e) Battery TC layout type E. (f) Battery TC layout type F.
(g) Battery TC layout type G. (h) Battery TC layout type H.

Figure 3.6: Top down plan views of EV battery thermocouple locations and layout types referenced in Table 3.4. Reproduced from Sauer et al. (2026), *Data in Brief*, 49, 109853, licensed under CC BY 4.0 [98].

3.3.8 Chemical Contaminants

Chemical contaminants produced by the burning vehicles were characterized in the laboratory air, in suppression runoff water, and as deposited onto control surfaces and onto personal protective equipment (PPE) samples.

Air Contamination

Air contamination was characterized through active and passive sampling systems. Active samplers consisted of battery powered sampling pumps (GilAir-Plus, Sensidyne) were placed within an insulated steel enclosure at a height of 1.3 m (4.3 ft), 3 m (10 ft) in front, and 4.5 m (15 ft) behind the vehicle (as measured from the front and rear bumper, respectively), such that the sampling inlet faced the vehicle. Other sampling pumps were located near the ceiling above the vehicle at a height of 8.7 m (28.5 ft) with the sampling inlet facing the ceiling. Additionally, stainless steel Institute of Occupational Medicine (IOM) samplers (SKC 225-76A, Eighty Four) connected to SKC XR5000 pumps, operated at 2 L/min (0.5 gal/min), were deployed at each sampling area to measure inhalable particulate up to 100 µm in aerodynamic diameter.

Passive sampling was facilitated by means of silicone wristbands. After pre-cleaning, they were sealed until deployment immediately prior to ignition. The passive samplers were deployed on the test stands, co-located with the active samplers and secured at a height of 1.4 m (4.6 ft) with steel wire in a manner that prevented contact of the sampler with the stand. Following each experiment, the samplers were removed, sealed and refrigerated before being sent to Duke University along with field blanks (samplers that captured the ambient laboratory environment, without being exposed to an experiment) for further analysis.

Details on air sampling methodology, analysis and results can be found in [101].

Surface Contamination

In the free burn experiments, surface contamination samples were collected by means of surface wipes and aluminum pans. Three sets of identical aluminum pans were placed near the vehicle, one in front at a distance of 3 m (9.8 ft) from the front bumper, and two in the rear at a distance of 1.5 m (5 ft) and 4.5 m (15 ft) from the rear bumper respectively. Once the experiment was complete, the pans were collected and four 100 cm^2 (15.5 in^2) zones were marked out as sampling areas. PAHs were sampled using two consecutive benzalkonium chloride wipes which were then stored in opaque black Falcon tubes for later analysis. Smear tabs (SKC Cat. No 225-24), moistened with deionized water were used to wipe another sampling area to measure particulate fluoride. A third sampling area was sampled using Ghost wipes (SKC Cat. No. 225-2414) which were analyzed for elements such as metals. The fourth area was wiped with a polyvinyl chloride (PVC) filter to measure hexavalent chromium. Upon collection, the wipe samples were stored in a refrigerated environment until further analysis. Leftover unsampled areas were sprayed with deionized water and tested for pH using litmus paper. Each day, a background sample was collected in identical fashion to provide a baseline for comparison.

Publication of surface contamination is underway at the time of this writing. When published, the analyses will be available at the https://fsri.org/research/fire-safety-batteries-and-electric-vehicles.

Personal Protective Equipment Contamination

Contamination of personal protective equipment was characterized via swatches of firefighting PPE samples. The samples consisted of an outer shell (PBI®Gemini™XT, 7.5 oz Black (PBI/Tencate, USA)), a moisture barrier (MB, CROSSTECH®black Type 2F) PTFE/NOMEX®pajama check laminated membrane (Gore, USA) and a thermal liner (TL, Lenzing Camouflage Green 2.3 oz, KEVLAR®/NOMEX®non-woven spun lace (Tencate, USA)). This three-layer sample simulates firefighting turnout gear that is commonly found in North America. Each ground floor test stand was outfitted with four smaller PPE swatches with an area of 240 cm^2 (38.8 in^2) and one larger swatch of 930 cm^2 (144.2 in^2) placed at the test stand in the plume. These swatches were co-located with the air contamination sampling stands described above. After exposure, each the swatches was separately stored in sealed containers and refrigerated. Samples were then sent on ice to North Carolina State University for further analysis. Details on PPE sampling methodology, analysis and results can be found in [102].

Suppression Water Runoff Contamination

For each of the experiments involving water suppression, water was sampled via a 50 mm (2 in) drain pipe leading from the front driver's side of the pan which terminated to the laboratory cistern approximately 10 m (33 ft) away. Three 950 mL (32.1 floz) amber glass jars were filled at three separate time points: 1) The first water to arrive, 2) after suppression water had been flowing for approximately 5 min, 3) once the vehicle fire had been deemed under control. Promptly after filling, each jar was removed from the laboratory and transferred to an appropriate shipping/storage container. In between experiments, the pan and sampling line were flushed with water from the handline and allowed to dry before setting up the next vehicle.

Publication of suppression water runoff contamination is underway at the time of publication of this report. When published, the analyses will be available at the following webpage: https://fsri.org/research/fire-safety-batteries-and-electric-vehicles.

3.4 Procedure

Experiments were initiated by simultaneously starting all data acquisition systems (detailed in Section 3.3.3). After collecting at least two minutes of background data, ignition of the burner was initiated. The occurrence of ignition and all other observations of note were recorded for each experiment. Battery temperatures were monitored in the initial heating phase of the experiments. If temperatures stabilized and fire was not observed to spread to involve either the cabin or battery pack, the burner output was increased by 5 kW. This procedure was repeated until the occurrence of thermal runaway or fire spread to the cabin, whichever occurred first, at which time gas flow to the burner was terminated. High voltage battery coolant was left intact for experiment E-CB-F, but it was discovered coolant in bottom-cooled HV batteries significantly hindered the initiation of thermal runaway propagation in the battery packs. All further bottom-cooled HV battery coolant was removed in all subsequent experiments. Coolant was left intact for the experiments with the Tesla Model 3 vehicles because the cooling channels run in-between cells and so burner operation was not hindered. In general, the objective of leaving the coolant intact was to recreate the conditions of the burning battery as faithfully as possible.

Upon the conclusion of each experiment, data acquisition was stopped, and data files were backed up to external media. Post-experiment photographs of the vehicle were obtained to document its condition and the fire involvement.

Vehicle make and model, experimental code as well as the important test conditions that changed between tests (HV coolant status, burner type, burner position, and weighing platforms) are included in Table 3.5

Table 3.5: Test vehicle information.

Code	Drive	Exp type	Make	Model	HV coolant	Burner type	Burner position	Platforms	Test Date
G-HK-F	ICEV	Freeburn	Hyundai	Kona SEL	N/A-ICEV	Diffusion	Front Center	under pan	11/29/23
E-CB-F	EV	Freeburn	Chevy	Bolt EV LT	intact	Diffusion	Batt. Center	under pan	1/31/24
E-NL-F	EV	Freeburn	Nissan	Leaf S	N/A-aircooled	Diffusion	Batt. Center	under pan	2/5/24
E-HI-F	EV	Freeburn	Hyundai	Ioniq Limited	N/A-aircooled	Diffusion	Batt. Center	under pan	2/7/24
E-TM-F	EV	Freeburn	Tesla	Model 3 Long Range	intact	Diffusion	Batt. Center	under pan	2/8/24
E-FM-F	EV	Freeburn	Ford	Mustang Mach E GT	drained	Diffusion	Batt. Center	under pan	2/12/24
E-HK-F	EV	Freeburn	Hyundai	Kona SEL	drained	Diffusion	Front Center	under pan	2/14/24
G-HK-F2	ICEV	Freeburn	Hyundai	Kona SEL	N/A-ICEV	Diffusion	Front Center	under pan	11/6/24
G-TR-F	ICEV	Freeburn	Toyota	RAV4 XLE AWD	N/A-ICEV	Premixed	Batt. Center	under pan	11/7/24
E-HK-S	EV	Suppression	Hyundai	Kona SEL	drained	Premixed	Batt. Center	none	11/11/24
E-CB-S	EV	Suppression	Chevy	Bolt EV LT	drained	Premixed	Batt. Center	none	11/13/24
E-TM-S	EV	Suppression	Tesla	Model 3 Long Range	intact	Premixed	Batt. Center	none	11/18/24
E-FM-S	EV	Suppression	Ford	Mustang Mach E GT	drained	Premixed	Batt. Center	none	11/20/24
E-FM-B	EV	Blanket	Ford	Mustang Mach E GT	drained	Premixed	Batt. Center	none	4/30/25
E-TM-B	EV	Blanket	Tesla	Model 3 Long Range	intact	Premixed	Batt. Center	none	5/1/25
E-FM-SA	EV	Suppression[a]	Ford	Mustang Mach E GT	drained	Premixed	Batt. Center	none	5/5/25
E-FM-BS	EV	Blanket[b]	Ford	Mustang Mach E GT	drained	Premixed	Batt. Center	none	5/6/25
E-TM-BS	EV	Blanket[b]	Tesla	Model 3 Long Range	intact	Premixed	Batt. Center	none	5/7/25

[a] Suppression experiment with water additive. [b] Blanket suppression experiment with water suppression.

3.4.1 Free Burn Experiments

For the free burn experiments, the fire was allowed to spread to involve the entire vehicle. With one exception, no attempt at suppression or other intervention was made, and the experiments were continued until fire extinction. In one instance (E-TM-F) the effluent overcame the building's exhaust capacity, and the test was terminated by water suppression.

3.4.2 Water Suppression Experiments

In water suppression experiments, the fire was allowed to grow following cabin ignition or thermal runaway, as determined by researcher judgment using a combination of sounds and visible indications, for a period of 6 minutes to replicate the standard response time goal objective for North American emergency services [103]. After 6 minutes, staff entered the laboratory, prepared fire suppression equipment, and began fire suppression operations. Fire suppression operations entailed spraying water into the burning vehicle cabin and on the burning vehicle exterior until visible flaming was extinguished. Due to battery involvement, persistent flames typically continued emanating from the bottom of the vehicles after the cabin and standard combustibles had been suppressed. Suppression operations continued for 10 minutes until a change in firefighting tactics was simulated; water flow was stopped, and the vehicle was tilted at approximately a 45° angle using powered equipment to provide more direct hose stream access to the battery pack. From this point, suppression operations continued until all visible flaming ceased. Four of the suppression experiments utilized solely water; in experiment E-FM-SA, F-500 was added to the water.

3.4.3 EV Blanket Experiments

For the two fire blanket experiments without suppression, fire blankets were deployed after a simulated 6-minute emergency response arrival time. The fire blankets were deployed using procedures recommended by the manufacturers; the blanket was positioned in front of the vehicle, unrolled/unfolded to a ready position, and firefighters pulled opposite corners on the same end of the blanket over the burning vehicle, from the front to the rear in one continuous motion. Once the vehicle was fully covered, the blanket was tucked under the base of the vehicle using brooms, smoothing the excess material and minimizing wrinkles as much as possible. As firefighters repositioned safely away from the vehicle, a cable and pulley were quickly attached to allow lifting one corner of the blanket remotely. This enabled lifting a small area of the blanket to investigate the sensitivity of vehicle and accumulated flammable gas reignition when introducing ambient air to simulate inspecting fire conditions or insertion of under-vehicle nozzles. The blanket was lifted several times from minutes to tens of minutes after its deployment.

For the two fire blanket experiments with water suppression, the vehicle fires were initially suppressed with the firefighting nozzle following the timing and procedure used in the water suppression experiments. Once the vehicle cabin fire was suppressed, the fire blanket was deployed using the same procedure as the fire blanket experiments. The blanket was initially lifted to simulate positioning of an EV-specific upward-spraying nozzle beneath the vehicle battery pack. Shortly thereafter, water flow was initiated through this nozzle and continued for several minutes. Nozzle flow was started and stopped, and the blanket was partially lifted multiple times to investigate impact on battery cooling and smoke flammability, respectively.

After the fire blankets established initial control over flaming, all blankets were partially lifted from one corner at various intervals. This action was included to emulate inspection of the conditions underneath the fire blanket by firefighters, or to simulate insertion of an under-vehicle fire suppression appliance. This action was incorporated into the experiments to investigate hazards associated with manipulating the blanket, such as the introduction of oxygen resulting in a flash fire or deflagration. This procedure was carried out with the understanding that it diverges from some fire blanket manufacturer recommendations. The timing of blanket lifting actions was informed by plausible times when a firefighter may seek to either inspect under the blanket to check for extinguishment of flames, or aforementioned suppression appliance deployment. In some cases, the blanket was lifted at times when it was subjectively judged that ignition of the smoke would be probable for the explicit purpose of investigating the severity of smoke ignition.

3.5 Analyses

3.5.1 Heat Release Rate

The mass loss system was used to obtain an effective mass-loss based HRR for these experiments. The four platform measurements were summed to produce a single mass value at each time step. Each experiment was then normalized to its background and ignition times using global times recorded manually during each experiment. The mass loss rate in kg per second was then calculated discretely and considering a time step of 2 s. Initial filtering of this mass loss rate was done by replacing mass loss rate points greater than 0.5 kg/s with a rolling average of the neighboring 30 mass loss rate points. The entire mass loss rate dataset was then smoothed with a 15-point centering rolling average. The discrete heat release rate (HRR) was then calculated by multiplying the mass loss rate by the assumed heat of combustion (25 MJ/kg). A statistical review of numerous large-scale burns of both ICEVs and BEVs recommends a mean value of 25 MJ/kg with a conservative 20 % uncertainty for this purpose [5, 104]. This value was adopted in the present analysis.

An alternative calculation was then conducted for the comparative mass loss rate and HRR. A cubic spline with a smoothing factor of 100 was then fit to the total mass data; the derivative of this spline was then taken to find a spline-derived mass loss rate. This spline-derived mass loss rate was then multiplied by the assumed heat of combustion to obtain a spline-fit HRR. Integration of the HRR curves over the duration of the experiment was used to determine total heat release rate (THR) values. An example mass loss rate curve showing the total mass measurement, and heat release rate calculated from the mass loss rate is shown in Figure 3.7. Remaining total mass and heat release rate figures can be found in Appendix A.

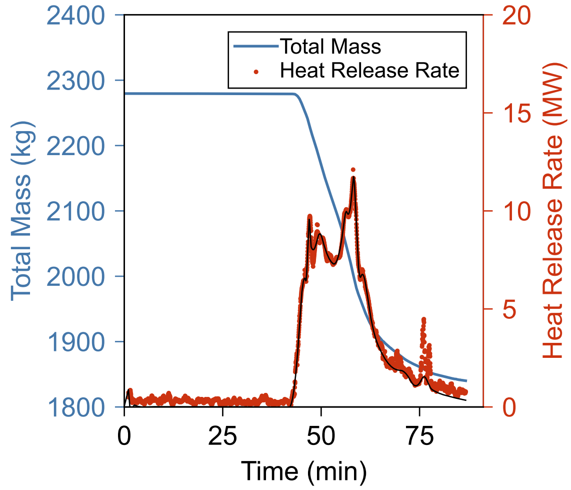


Figure 3.7: Example HRR curve, total mass loss is measured experimentally, mass loss rate is calculated then used to find the heat release rate.

Computer recording of the mass data for experiment G-HK-F2 failed, and for experiment G-TR-F mass recording failed partially during the latter portions of the experiment. Video recordings of the digital readouts of the indicators were obtained for the G-HK-F2 experiment, and these readouts were manually digitized at 4-second increments until the indicator screens became too obscured with smoke to read. Attempts were made to digitize the lost G-TR-F data, but the platform scales experienced failure during portions of the experiments when the digital readouts were impossible to read. Mass data for these experiments during periods of measurement failure has been omitted.

3.5.1.1 Parameterization of Heat Release Rate Curves

An effort to parameterize the experimental heat release rate (HRR) curves was undertaken to compare growth and decay rates across vehicles and to provide simplified versions of the curves for design use. Similar work has been completed by others in research, such as Hodges 2024 and Tohir 2025 [3, 104]. A simplified approach using an $\alpha \cdot t^2$ fit was used for this analysis. First, the experimental data time was zeroed to the ignition of the first components of the car; this offset time is provided in the parameterization table in Section 4.1 Table 4.1. The times t_1 and t_2 were then selected manually, but generally with t_1 to follow the first peak after the sustained growth period and t_2 the last peak before the sustained decay period. The value of $\dot{Q}$ was then calculated as the average between t_1 and t_2, Eqn. 3.2. With the starting and ending time of the growth period now defined, and the shape of the growth period defined as Eqn. 3.1 the value for α_g is then determined. The equation for the decay period is provided in Eqn. 3.3, where the remaining unknown is t_3. The value of t_3 was determined by matching the value of total energy released from the parameterized curve to the total value measured experimentally. Where the total for the growth period Q_g, the total for the steady period Q_s, and the total for the decay period Q_d are summed to calculate the total for the modeled value $Q_{tot,m}$ the final equation for which is shown in Eqn. 3.5.

For $0 < t < t_1$:

$$\dot{Q}(t) = \alpha_g \cdot t^2, \tag{3.1}$$

For $t_1 < t < t_2$:

$$\dot{Q}(t) = \dot{Q}_{avg} = \frac{\sum_{i=t_1}^{t_2} \dot{Q}(t)}{n}, \tag{3.2}$$

For $t_2 < t < t_3$:

$$\dot{Q}(t) = \alpha_d \cdot (t - t_3)^2. \tag{3.3}$$

The total energy release for the growth, steady, and decay regions are the areas under each curve and between each interval, respectively.

$$Q_g = \int_0^{t_1} \alpha_g t^2 dt \quad \text{and} \quad Q_s = \dot{Q}_{avg} \cdot (t_2 - t_1) \quad \text{and} \quad Q_d = \int_{t_2}^{t_3} \alpha_d (t - t_3)^2 dt, \tag{3.4}$$

The summation of these parts gives the total energy released as calculated by the area under the entire parameterized curve:

$$Q_{tot,m} = \frac{\alpha_g t_1^3}{3} + \dot{Q}_{avg} \cdot (t_2 - t_1) + \frac{1}{3} \alpha_d (t_3 - t_2)^3. \tag{3.5}$$

Replacing the modeled $Q_{tot,m}$ with the experimental total heat release, the only unknown in Eqn. 3.5 is the time to the end of the decay period (t_3), which can be solved for. In this way, we have represented both the growth and decay periods according to their maximums. The sustained release of energy is also described in the average $\dot{Q}_{avg}$ between t_1 and t_2. Finally, the total energy released is identical between the parameterized and experimental curves by shifting t_3. An example of this fitting method is shown in Figure 3.8, extended fit figures for all available experiments are provided in Appendix A.

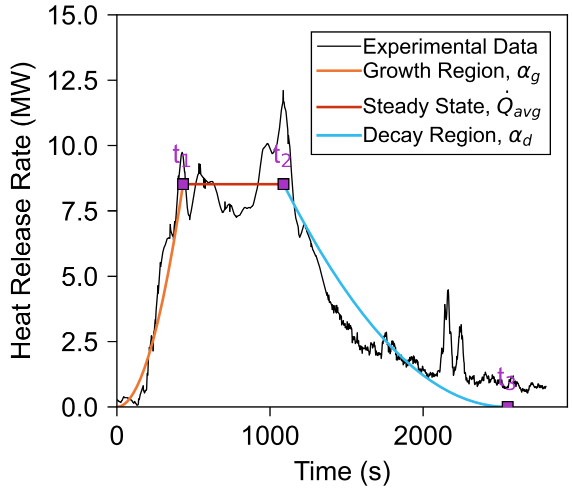


Figure 3.8: Example experimental heat release rate data and parameterized curve fits for E-FM-F experiment.

3.5.2 Schmidt-Boelter Heat Flux

A Schmidt-Boelter (SB) heat flux gauge generates a thermoelectric response (E_g) that is proportional to the net heat flux to the sensing element ($\dot{q}''_g$), which consists of a copper constantan thermopile coated with a high-absorptivity spectrally flat paint [105]. The proportionality constant (C_g) is termed the responsivity; gauge heat flux is calculated by the following expression:

$$\dot{q}''_g = \frac{1}{C_g} E_g. \tag{3.6}$$

The gauges used in this study were calibrated by the manufacturer. Three types of SB gauges were used: total heat flux gauges, windowed radiometers, and combination gauges (which include both a total heat flux and windowed radiometer sensor).

From an energy balance at the surface of a heat flux gauge, and assuming that the gauge temperature is maintained constant at T_g (the temperature of the cooling water), the gauge heat flux can be related to the incident radiative heat flux by the following expression:

$$\dot{q}''_g = \alpha \dot{q}''_i - \varepsilon \sigma T_g^4 - h_c \left(T_g - T_\infty \right), \tag{3.7}$$

where $\dot{q}''_i$ is the incident radiative heat flux ($\mathrm{W/m^2}$), α and ε are the absorptivity and emissivity of the painted surface (taken to be equal under the diffuse-grey assumption), σ is the Stefan-Boltzmann constant (5.67×10^{-8} $\mathrm{W/(m^2\,K^4)}$), h_c is the convective heat transfer coefficient ($\mathrm{W/(m^2\,K)}$), and T_∞ is the freestream temperature (K).

For total heat flux sensors, the manufacturer calibrated the gauge relative to a known source irradiance, and calculated the responsivity ($C_{g,t}$) based on the gauge response ($E_{g,t}$). Thus, the incident radiative heat flux can be calculated from a total heat flux gauge measurement by Equation 3.8.

$$\dot{q}''_{i,t} = \frac{1}{\alpha C_{g,t}} E_{g,t} + \sigma T_g^4 + \frac{h_c}{\alpha}\left(T_g - T_\infty\right). \tag{3.8}$$

For windowed radiometer sensors, the manufacturer calibrated the gauge with the window in place relative to a known source irradiance, and calculated the responsivity ($C_{g,r}$) based on the gauge response ($E_{g,r}$). This window reduces the radiation absorbed by the sensing element, and in practice, negates the influence of convective heat transfer on the gauge output. Thus, the incident radiative heat flux can be calculated from a windowed radiometer measurement by Equation 3.9.

$$\dot{q}''_{i,r} = \frac{1}{\alpha C_{g,r}} E_{g,r} + \sigma T_g^4. \tag{3.9}$$

Incident radiative heat flux to the eight SB gauges positioned on the plate sensor arrays was calculated from the gauge measurements using Eqn. 3.9. For the front and back total heat flux gauges, the gauge heat flux was the quantity of interest, and was calculated using Eqn. 3.6.

The manufacturer of the SB gauges (Medtherm) reports a measurement uncertainty of ±3 %; however, it is well known that the measurement uncertainty of the total heat flux sensors is greater for mixed-mode convective and radiative exposures, and that the spectral selectivity of the sapphire window relative to the source radiation also contributes to the measurement uncertainty [106]. The measurement uncertainty associated with any particular gauge in this study is expected to depend on the convective fraction and source emission, and this dependence could change over time with the evolving fire conditions. For the purposes of this study, a practical upper bound on measurement uncertainty is needed to contextualize the results. Previously, Pitts et al. [107] reported a total expanded uncertainty for SB gauge measurements of ±8 % based on an international study on total heat flux gauge calibrations in fire applications. In the present work, this value was adopted for the relative uncertainty in all SB gauge measurements.

3.5.3 Chemical Contaminant Characterization

Air Contamination

Area air sampling media analyzed for VOCs, aldehydes, acid gases, and metals. VOCs targeted in this study included benzene, toluene, ethyl benzene, xylenes, and styrene (BTEXS) and 1,3 butadiene. Specific aldehydes included acetaldehyde, acrolein, and formaldehyde. Acid gases included sulfur dioxide (SO2), hydrogen cyanide (HCN), hydrogen chloride (HCl), and hydrogen fluoride (HF). Particulate fluoride was also analyzed as there is significant concern in the fire service about fluoride compounds, specifically related to EV fires. Metal analysis was targeted for chromium, cobalt, copper, lead, lithium, manganese, aluminum, nickel, antimony, arsenic, and cadmium. Combustion gases were also analyzed for polycyclic aromatic hydrocarbons (PAHs).

Quartz fiber filters from the steel Institute of Occupational Medicine samplers were analyzed for inhalable particulate up to 100 µm in aerodynamic diameter each compound using NIOSH Method

0500. Passive silicone wristband samplers were analyzed for a suite of 37 different PFASs using the method published by Keith [108] . Specific focus was placed on the 16 PAHs designated as High Priority Pollutants by the US Environmental Protection Agency (EPA) [109] by using solvents to extract the contaminants and quantifying them via gas-chromatography-high resolution mass spectrometry (GC-HRMS), as well as liquid chromatography-tandem mass spectrometry (LC-MS). A detailed explanation of the analytic methods used and the process of analyzing the wristband samplers and the quartz fiber filters is available in [101].

Surface Contamination

Analysis of the surface wipe sample was conducted according to NIOSH Method 5506 for the PAH samples and OSHA Method ID-110 for the particulate fluoride samples. The samples for metals were analyzed in accordance with NIOSH Method 7303 while the samples for hexavalent chromium were analyzed according to OSHA Method W4001. The pH test strips were visually compared to the manufacturer's color chart and photographed. Further details on the analysis of the surface wipes will be provided in an upcoming publication. When published, the analyses will be available at the following webpage: https://fsri.org/research/fire-safety-batteries-and-electric-vehicles.

Personal Protective Equipment Contamination

After exposure, PPE samples were transported to an external laboratory, where sections of each swatch underwent acid digestion and the resulting mixture analyzed via Inductively Coupled Plasma Mass Spectrometer (ICPMS). Other samples were extracted using pressurized solvent extraction and then analyzed by gas chromatography-orbitrap-tandem mass spectrometry to analyze the samples for PAH concentration. Concentrations were compared to field blanks as well as unexposed samples subjected to internal standards to provide control samples. A detailed description of the analytical process for the PPE samples is provided in Probert's full publication [102].

Suppression Runoff Contamination

Water sample analysis was conducted for anions, metals, PAHs and VOCs. These were conducted for each water sample using the analytical method EPA 300.0 for Anions, SW846 6010B + LI for Metals SW846 8270C SIM for PAHs and SW846 8260B for VOCs. Further details will be provided in an upcoming publication. When published, the analyses will be available at the following webpage: https://fsri.org/research/fire-safety-batteries-and-electric-vehicles.

4 Results

4.1 Fire Size, Growth Rate and Duration

Results from the heat release rate (HRR) parameterization analysis are recorded in Table 4.1. Of particular interest for comparison between EVs and ICEVs are burn duration, maximum HRR, growth rate (α_g), and total energy released, all of which are plotted in Figure 4.1. In Figure 4.1, each colored dot represents a single vehicle, with the corresponding key above the plot detailing which vehicles are which color. In this way, it is easier to determine which specific vehicles denote the minimum and maximum sample values for each measure, normally denoted by just the bar ends on the box plots. The width of the boxes corresponds to the number of samples that constitute that box. There were 6 total EVs and 3 total ICEVs included in making this plot. When allowed to free burn to completion, the electric vehicles did not take significantly longer to burn than the ICEVs. Some discrete vehicles took longer than others, but the mean value (denoted by the $\times$ mark) is lower for EVs than ICEVs. The average maximum heat release rate is higher for EVs than for ICEVs and may be attributed to several factors. First and foremost, a study by Miechówka et al. [5] noted that ignition location can significantly affect fire propagation within a single vehicle and, consequently, the timescale over which its energy is released. A faster fire growth rate would then be assumed to correlate with a higher peak HRR, as the fire consumes the vehicle materials and grows quickly. In these experiments, all EVs were failed by heating the battery (except for E-HK-F) and all ICEVs were failed by placing the burner under the engine compartment. This could have induced slightly faster growth in EVs and slightly slower growth in ICEVs. However, the growth-rate plot indicates that behavior is more complex than the influence of ignition location alone. In fact, the Hyundai Kona EV (E-HK-F), started by placing the burner under the front hood compartment, has a growth rate that almost exactly matches the average and is almost identical to that of its ICEV counterparts; yet two EVs (E-HI-F and E-FM-F) had slower growth rates than any of the ICEVs. The average total heat release is higher for EVs than for ICEVs, as EVs are generally heavier than equivalent ICEVs. A strong correlation between initial vehicle mass and total heat release (i.e. total mass loss) has been observed in other works [5, 98, 104].

Table 4.1: Outputs from parameterization analysis on heat release rate data.

Code	$\overline{HRR}$ (MW)	α_g (kW/s^2)	α_d (kW/s^2)	Offset (s)	t_1 (s)	t_2 (s)	t_3 (s)
G-HK-F	3.74	5.71E-02	2.19E-03	100	256	1648	2955
E-CB-F	9.8	3.24E-02	1.29E-02	2400	550	950	1820
E-NL-F	11.23	6.37E-02	1.71E-02	40	420	650	1461
E-HI-F	7.47	7.47E-03	5.04E-03	950	1000	1320	2537
E-TM-F	4.28	1.17E-02	9.84E-04	1200	606	-	-
E-FM-F	8.52	4.57E-02	3.98E-03	1200	432	1088	2552
E-HK-F	2.81	3.29E-02	8.80E-04	70	292	2522	4308
G-HK-F2	2.99	4.10E-02	7.47E-04	0	270	-	-
G-TR-F	5.06	2.04E-02	4.90E-02	0	498	-	-

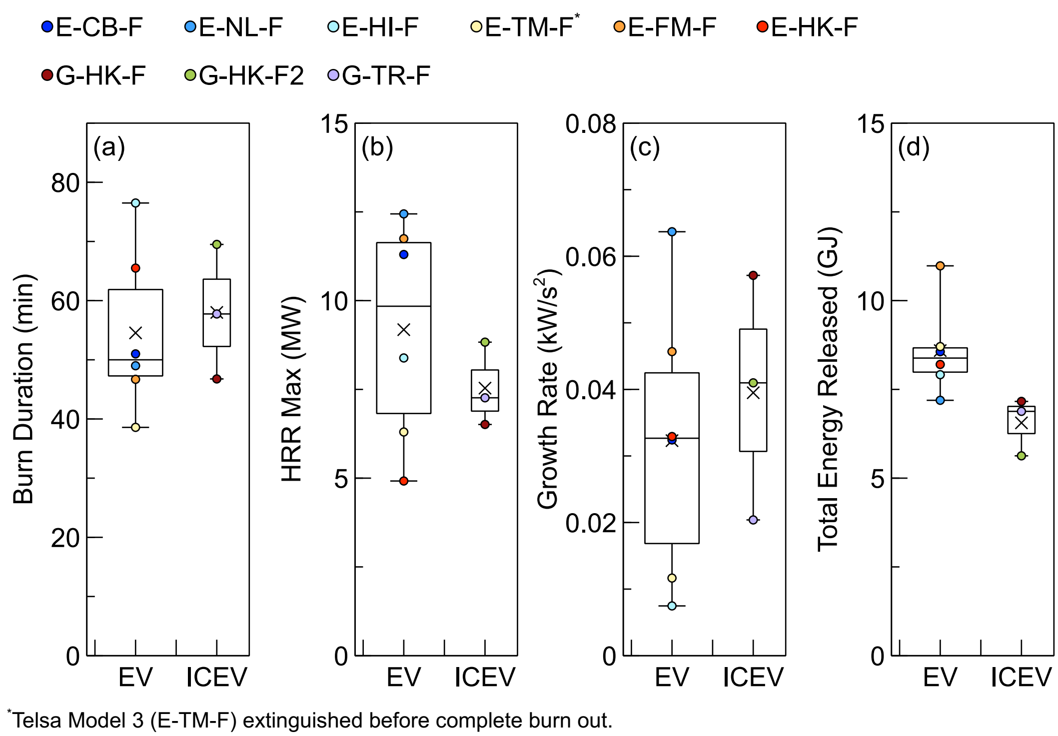


Figure 4.1: Heat release rate characteristics determined during mass analysis: (a) total burn duration, (b) maximum HRR, (c) growth rate, (d) total energy release. Box widths scaled to sample size.

4.1.1 Thermal Exposure Distance

Critical thermal exposure is a function of the distance of the target from the burning object (the source), the source fire's heat release rate (HRR) as well as the target's critical heat flux, above which thermal injury, or rapid heating and subsequent ignition in the target will occur. For objects at a distance and not subjected to the plume or in contact with the source, the primary method of heat transfer is radiation, which in turn depends on the surface areas of the source and target, and the distance between them.

In order to provide guidance on typical exposure distances for EV fires, a model was developed using the two-dimensional radiative heat flux measurements from the free burn experiments. The model assumes a cylindrical flame geometry for a fire at its peak HRR and was calibrated to match the radiative heat flux values measured during the free burn experiments. The injury threshold heat flux of $2.5\ \mathrm{kW/m^2}$ and the critical ignition heat flux of $12.5\ \mathrm{kW/m^2}$ were chosen to reflect the safety thresholds of unprotected individuals and common ignition risk for combustible materials, respectively.

The use of simplifying assumptions presented above permits the model to be dependent solely on the source fire's peak heat release rate. This value can be estimated from the weight of the vehicle, which is roughly proportional to the fire HRR. Data on the prevalence of electric vehicles in the US shows that in 98 % of incidents, the peak heat release rate of an EV fire will fall below 16 MW [15]. Dividing the critical heat flux of $12.5\ \mathrm{kW/m^2}$ by a safety factor of 2 accounts for uncertainties and limitations of the model. Using this value of $6.25\ \mathrm{kW/m^2}$, the critical separation distance below which thermal exposure is likely to be hazardous to neighboring combustible objects, was found to be 5 m (16 ft). Thermal exposure great enough to present risk may still occur at greater distances, especially if the flames are impacted by wind or deflected by a ceiling. Nonetheless, this distance serves as a reasonably conservative value for a quarantine or minimum separation distance.

The interested reader is referred to [110] and [15] for a detailed discussion of the thermal exposure model and probabilistic design fire scenarios.

4.2 Suppression Experiments

The effectiveness of different EV fire suppression methods is quantitatively evaluated in the following sections using time to extinguishment, resource expenditure (such as required water volume and flow rate to extinguish the fire), and qualitatively evaluated with video observations, first hand firefighting experience, and post-experimental damage assessments of the vehicles and their batteries. Discussion follows for the suppression experiments using water with and without an additive extinguishing agent, with an EV fire blanket, and with a combination of water suppression using an under-vehicle nozzle (UVN) and EV fire blanket.

4.2.1 Hose Stream

Five experiments were conducted to evaluate the effectiveness of conventional vehicle fire suppression tactics against electric vehicle fires (see Table 4.2). All experiments used water except for

E-FM-SA, which used a water additive (F-500) mixed into the suppression water at nominally 3 % by volume (v/v). The chart in Figure 4.2 provides an overview of the experimental timeline for each water suppression experiment. The experimental timeline is divided into the following segments; pre-suppression: the time from burner ignition to beginning of suppression efforts; cabin fire suppression: the time from beginning of fire suppression until no more flames were observed in the passenger compartment, and battery fire suppression: the time from end of cabin fire suppression until the last flame was extinguished. Intermittent cooling time encompasses any water application after no more flaming was observed until the last water was flowed. The width of the bar denotes the volume of water that was applied in total for each experiment. This value is also provided as an annotation at the right end of the bar.

Full suppression experimental procedure is detailed in Section 3.4.2. Fire suppression efforts were started after a simulated 6 min fire department response time following the first observed involvement of the battery in the fire. Although the target scenario was fire department arrival to a vehicle fire with both passenger cabin and traction battery involvement, two experiments (E-HK-S and E-TM-S) produced different conditions at the time of suppression. In experiment E-HK-S, only the vehicle cabin was burning, and suppression began before the battery entered thermal runaway. During this experiment, unusually thick smoke, loud popping/hissing sounds and battery temperatures high enough for onset of thermal runaway appeared to indicate thermal runaway had begun and, acting upon these cues, the simulated fire department response countdown clock was started, at the end of which fire suppression activities commenced. However, review suggests that the smoke and sounds likely resulted from rupture of the air conditioning system. Upon completion of the experiment, analysis of the battery determined that no cells had entered thermal runaway.

In experiment E-TM-S, only the battery was involved when suppression efforts began. Thermal runaway began in the battery after exposure to the gas burner, but the fire had not yet involved the vehicle cabin materials at the time of simulated fire department arrival.

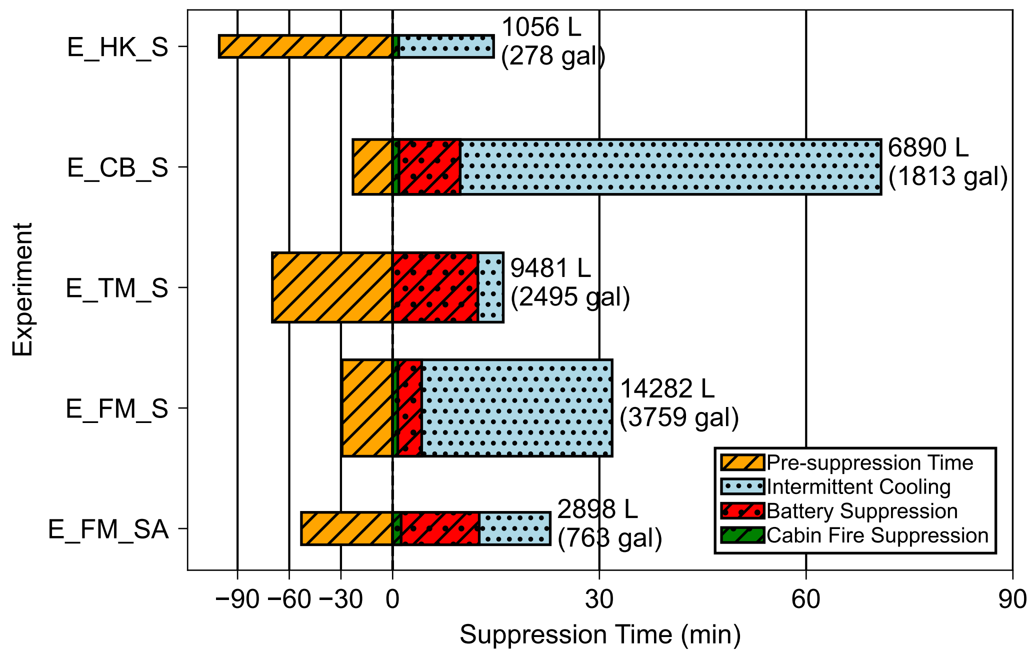


Figure 4.2: Timeline of handline suppression. Diagonal hatching indicates active flaming, dotted hatching denotes water application; width of the bar is scaled to the water volume.

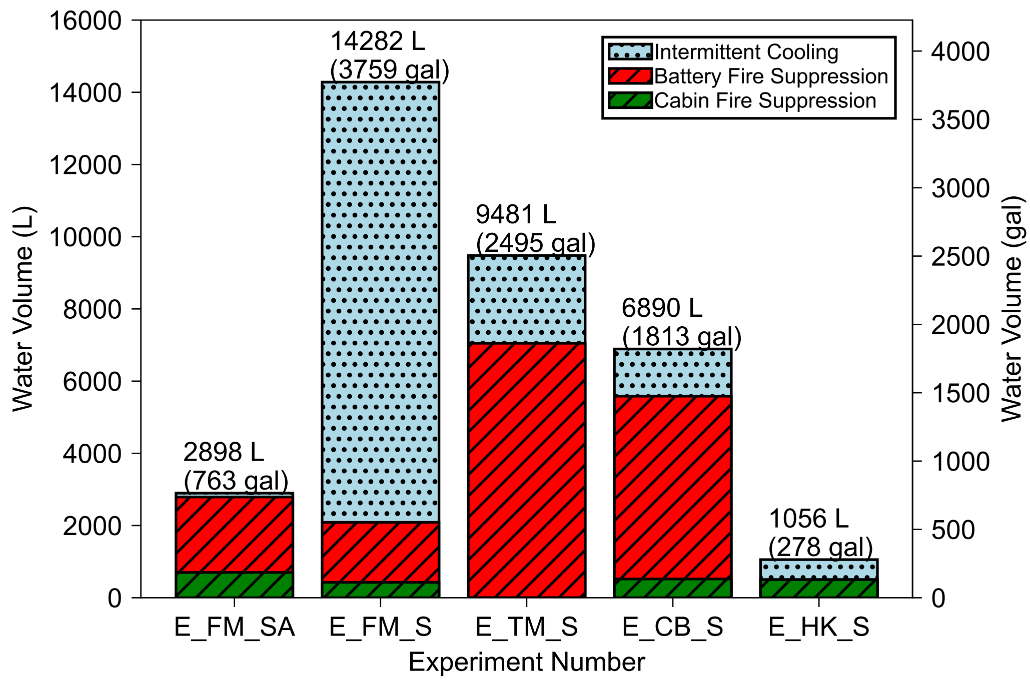


Figure 4.3: Breakdown of water volume, hatching denotes observed flaming.

Table 4.2: Water volume and time to last flaming for the handline suppression tests. The asterisk denotes no battery involvement.

Experiment	Phase	Water Volume [L (gal)]	Last Flaming After Suppression
E-HK-S*	Developing	1056 (278)	0 min 53 s
E-CB-S	Full	6890 (1813)	9 min 49 s
E-TM-S	Developing	9481 (2495)	12 min 22 s
E-FM-S	Full	14 282 (3759)	3 min 22 s
E-FM-SA	Full	2898 (763)	12 min 34 s

The results from the handline suppression experiments show that the required time and water volume to achieve fire suppression varied between experiments. Battery involvement had the greatest impact on time and water volume. Experiment E-HK-S did not show signs of battery involvement and was extinguished with under 1100 L (290 gal) of water in under 1 min. This condition mimics fire suppression of a conventional gasoline vehicle. In the cases where the battery was involved, suppression of the passenger compartment fire was typically concluded within 2 min, while the battery fire suppression efforts could take 10 or more minutes longer before the last flames were observed. In experiment E-FM-S, total flaming was controlled within 4 min. However, the battery continued off-gassing due to ongoing thermal runaway propagation in the battery. Cooling operations continued for a longer duration as this off-gassing persisted as efforts were focused on stopping the continued thermal runaways via cooling. This led to a high consumed water volume and low suppression time. Overall, the suppression efforts were not effective in stopping thermal runaway propagation inside this battery pack. The only exception was E-TM-S where large portions of the bottom battery cover melted, allowing for direct access of the hose stream to the battery cells, resulting in a portion of the cells remaining intact.

The required suppression time and water volumes were observed to depend on whether the battery was involved, rather than the phase in which fire attack began. During experiment E-TM-S, it was observed that the fire in the battery continued to grow during the initial suppression efforts. In the course of the experiment, parts of the passenger compartment began to burn due to the continued flaming from underneath the vehicle but were quickly extinguished. Likewise, the passenger compartment was quickly extinguished in all experiments where the vehicle was fully involved at the time suppression was initiated, which made the battery fire easier to discern and allowed the firefighters to shift their focus toward the battery fire.

(a) 01:04:29
Fire before suppression.

(b) 01:10:40
Suppression starts.

(c) 01:14:10
Fire grows despite suppression.

(d) 01:16:31
Peak fire intensity.

(e) 01:20:09
Vehicle is tilted.

(f) 01:28:29
Extinguishment.

Figure 4.4: Timeline of experiment E-TM-S, time is in hours minutes and seconds since ignition.

Effect of Water Additive

One experiment (E-FM-SA) used an encapsulating agent (F-500) marketed as a water additive for the suppression of LiB and EV fires. The E-FM-SA experiment was conducted on a fully involved Ford Mustang EV with confirmed involvement of the battery.

Firefighting personnel were instructed to use no more than half of the total agent supply for fire suppression of the vehicle passenger compartment, and the remaining half for cooling the battery once the vehicle tilt operation was complete. For this reason, initial suppression efforts were reduced after 10 minutes. Once the vehicle was tilted, continued application of water and agent to the battery was indistinguishable from the impact of the same hose stream application with just water without any additives (E-FM-S). Taking into account previous experiments where prolonged water application had been observed to be ineffective, firefighters decided to withhold continued cooling and transitioned to more disciplined water application focused on preventing the fire from spreading back into the passenger compartment. It would be misleading to conclude the lower volume of suppression water 2898 L (793 gal) vs 14 282 L (3759 gal)] used with this additive is attributable to the addition of the extinguishing agent. The reduction in water usage resulted from adjustments to firefighting procedures and increase in fire suppression experience as more experiments were conducted.

Ultimately, inspection of the battery following the experiment (see Section 4.3.3) showed that all cells were destroyed by thermal runaway, which indicates that the water and F-500 did not stop thermal runaway propagation. Overall, water with 3 % F-500 was not observed to be more effective than water on its own.

(a) 00:51:04
Fire before suppression.

(b) 00:55:33
Suppression start.

(c) 00:56:48
Cabin fire controlled.

(d) 01:11:15
Vehicle is tilted while fire is controlled.

(e) 01:12:47
Battery Reignition.

(f) 01:26:39
Extinguishment (battery burnout).

Figure 4.5: Timeline of experiment E-FM-SA, time is in hours minutes and seconds since ignition.

Impact of Firefighting Personnel Experience

Although fire suppression operations were conducted by experienced firefighting personnel, initial suppression experiments were naturally less efficient than subsequent experiments, resulting in a longer suppression timeline and a higher water volume. At first, much of the applied water was observed bouncing off of the vehicle chassis, especially when targeting the battery, without significantly contributing to suppression. In the course of the experiments, the firefighters were also able to refine their fire attack based on their observations, leading to improved nozzle technique (e.g., less use of straight stream on the chassis) and more deliberate application of the hose stream. This resulted in the later experiments using less water. This experience underlines that training is an important aspect in improving the efficiency of firefighting operations.

4.2.2 EV Fire Blanket

Two experiments were conducted on two different electric vehicles to test the efficacy of using an EV fire blanket. Two additional blanket experiments were conducted combining the use of a blanket with additional water suppression. The latter experiments are discussed in further detail in a subsequent section. An overview of all experiments including a fire blanket and their results are listed in Table 4.3.

Table 4.3: Deployment time and suppression water volume for EV fire blanket suppression tests. Asterisks denotes no battery involvement.

Experiment	Deployment Time	Water Volume [L (gal)]	Initial Flaming Controlled
E-FM-B	3 h 33 min	none	No
E-TM-B*	1 h 6 min	none	Yes
E-FM-BS	>2 h 10 min	3873 (1019)	Yes
E-TM-BS	2 h 21 min	4095 (1078)	No

In experiments using only the fire blanket, flaming was controlled shortly after the vehicle was fully covered by the blanket, and the blanket bottom edge was pushed towards the vehicle. A small amount of smoke was observed permeating through the blanket in all experiments. The smoke generated beneath the blanket was observed to be flammable in all cases, but most notably when it was ignited by flames emanating from beneath the blanket during deployment in E-TM-B, and by deflagration and reignition events in experiments E-FM-B and E-TM-BS. No ignition of the permeating smoke was seen in experiment E-FM-BS, likely because no fire behavior occurred which would have ignited it. When ignited, small flames propagated through the permeating gases in short-lived bands moving along the surface of the blanket. These phenomena subsided within 30 s of onset, or were extinguished by lightly dousing the blanket surface with water.

Large volumes of thick grey/white smoke emanated from beneath the blanket in all experiments except for E-TM-B. This experiment also did not see the battery becoming involved in the fire, as confirmed by subsequent inspection. Some smoke/effluent vapors were heavier than air and flowed along the floor (Figure 4.7b). Most of the vapors were buoyant, but since there was no flaming and plume temperatures were lower than the temperature of a typical fire plume, the movement appeared slower than normal smoke. This indicates that while vehicle and battery vent gas flaming was controlled, the thermal runaway propagation inside the battery was not stopped. Ongoing thermal runaway in the cells continued to produce significant volumes of gas. This observation is supported by the battery temperature data from these experiments, which showed that temperatures exceeded those required for the onset of thermal runaway and rapid temperature increases (see Figure 4.6). The battery temperature behavior measured in the EV blanket experiments was consistent with propagation of thermal runaway among cells inside the battery.

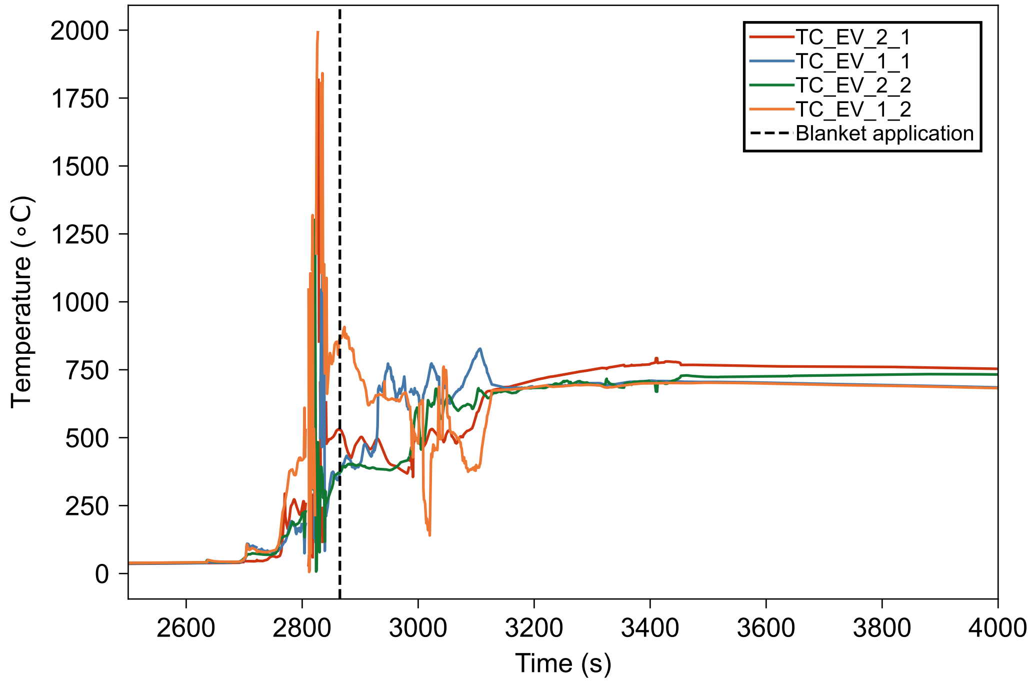


Figure 4.6: Evolution of the battery pack surface temperatures after fire blanket deployment.

Once the fire blankets were in their final deployed position and initial flaming subsided, no significant changes in fire behavior occurred until one corner of the fire blanket was intentionally lifted. In most experiments, there was no immediate reaction to the first exchange of smoke and ambient air. However, in experiment E-FM-B, the second lift was followed by a significant deflagration and sustained flaming. The deflagration propagated from the rear of the vehicle to the front, with visual cues of the blanket billowing and lifting likely following the propagating flame front underneath. Flames were observed escaping from all areas of the blanket that had been displaced or lifted by the deflagration pressure. Application of a hose stream was required to re-extinguish these flaming areas. Figure 4.7 shows the timeline of this experiment.

No abnormal fire behavior was observed in experiment E-TM-B. This experiment also did not show the characteristic heavy grey/white vapor at any point during the blanket deployment. The blanket was lifted several times, but no deflagration occurred. An inspection after the experiment showed that the battery was not involved in the fire, explaining the absence of smoke and severe fire behavior.

The observed deflagration was not preceded by any notable indications, and the only action that preceded it was the lifting of the blanket. It is theorized that flammable products of incomplete combustion and exhaust from battery thermal runaway had collected and reached concentrations above the upper flammability limit underneath the blanket. Lifting the blanket introduced oxygen which proceeded to mix with the trapped gases and lowered the concentration below the upper flammability limit and into the flammable range. The flammable mixture was then ignited by a hot surface or other ignition source in the vehicle. A more detailed discussion of the reignition and deflagration hazard is provided in Section 4.2.4.

In all experiments, after blanket application and a waiting period of several hours the blanket was removed and the resulting debris analyzed. Both E-FM-B and E-TM-B had suffered extensive damage to the chassis, leaving the interior almost completely burnt out. The experiments varied in the level of observed battery damage. Post-test inspection showed that the battery in E-FM-B had completely burnt out while there was no evidence of any battery involvement for E-TM-B. More details on the post-test inspection are presented in Section 4.3.3.

(a) 0:47:20
Before blanket deployment.

(b) 0:51:50
Characteristics of battery smoke.

(c) 1:26:32
Battery smoke subsides.

(d) 1:27:22
Second lift of blanket.

(e) 1:27:39
Deflagration.

(f) 4:21:24
After fire blanket removal.

Figure 4.7: Timeline of experiment E-FM-B, time is in hours minutes and seconds since ignition.

4.2.3 EV Fire Blanket Combined with Under Vehicle Nozzle Suppression

Two experiments were conducted to compare fire blankets to a combination of fire blankets and under-vehicle nozzle (UVN) suppression using similar makes and models of vehicles as in the blanket-only tests. The cabin fire was briefly suppressed with a handline for fewer than 10 s prior to blanket deployment. Blanket application and subsequent fire behavior resembled the blanket only experiments without additional suppression. Characteristic thick white/grey smoke emanating from the blanket edges was observed in both experiments.

Following the application, the blanket was lifted at a corner to simulate the insertion of the UVN, which in the experiments was prepositioned. The UVN water flow was then activated remotely by a gate valve. No abnormal behavior was observed for experiment E-FM-BS, both for the lifting of the blanket, as well as the activation of the UVN.

However, in experiment E-TM-BS, the smoke and vapors under the blanket ignited immediately upon lifting the blanket corner and flames reached a height of approximately 6 m (20 ft). Hose stream suppression was employed to extinguish flaming, but the force of the hose stream initially disturbed the blanket and entrained more air. In an effort to further reduce flaming, the UVN was activated, upon which a large fireball escaped from the driver's side of the vehicle, lifting the blanket in the process. It is hypothesized that this was the result of steam expansion, generated from the nozzle spraying water onto the hot battery surfaces. Further suppression via hose stream was required, and the flames remained large and unpredictable. Final extinguishment appeared to depend on re-establishing uniform contact between the blanket and the floor and control was eventually re-established. In the following 8 minutes, the smoke appearance became light and wispy. The fire blanket was remotely lifted two more times to investigate ignition potential. There were no immediate changes in smoke/fire behavior following the second blanket lift. A deflagration occurred ten seconds following the 3rd blanket lift. Two more delayed reignitions with decreasing intensity occurred in the following 20 minutes, each following the previous one by about 9 min. In both cases, there were neither any actions taken to induce the deflagrations, nor were there any indications of their imminent occurrence. A timeline of experiment E-TM-BS is shown in Figure 4.8.

(a) 00:03:57
After burner ignition.

(b) 0:56:29
Fire before suppression.

(c) 0:56:42
Initial cabin fire knockdown.

(d) 0:58:52
TR vent gases following blanket deployment.

(e) 0:59:14
First lift and reignition.

(f) 1:01:45
Blowout following UVN activation.

(g) 1:07:53
Third lift.

(h) 1:17:44
Deflagration, not preceded by a lift.

(i) 3:21:05
Termination of experiment.

Figure 4.8: Timeline of experiment E-TM-BS. Time is in hours minutes and seconds since ignition.

4.2.4 Deflagration Hazards

Backdrafts and deflagrations were seen in the experiments involving EV fire blankets. For the purposes of summarizing the observed behavior, a backdraft is "a deflagration resulting from the sudden introduction of air into a confined space containing oxygen-deficient products of incomplete combustion." A deflagration is "the propagation of a combustion zone at a velocity that is less than the speed of sound in the unreacted medium." Both definitions are provided in NFPA 1700 Guide for Structural Firefighting, and NFPA explosion safety standards [111–113].

Both of these types of event could be induced by lifting the blanket (e.g., to inspect burning conditions or to insert a suppression appliance). A backdraft occurred in experiment E-TM-BS seconds after the first time the blanket was lifted. Deflagrations also occurred well after any manipulation of the blankets.

Deflagrations occurred under two scenarios during the experiments with fire blankets. In the first scenario, oxygen was introduced by remotely lifting the blanket. This brought the mixture of gases in the space under the blanket into the flammable range in the presence of some ignition source. A deflagration occurred seconds after the blanket had been returned to its original position. It is assumed that the delay was due to fresh air mixing with the smoke until an flammable mixture formed near an ignition source. This was observed in experiments E-FM-B the second time the fire blanket was lifted and in E-TM-BS the third time the blanket was lifted. The sequence of events in E-FM-B was the same as the events that led to the near-miss deflagration incident experience in the Fire Protection Research Foundation EV experiments [114]. The deflagrations were similar in severity, and capable of producing significant injury to nearby personnel. It is worth noting that the ignition propensity is stochastic, the deflagration did not occur in E-FM-B the first time the blanket was lifted, nor did a backdraft occur.

In the second scenario, unprovoked deflagrations occurred. It is hypothesized that after creating a mixture within or above the flammability limit, ambient makeup air diffused into the volume under the EV blanket as the mixture of battery smoke and pyrolysates diffused out, since the blanket material is not gas tight. The presence of persistent ignition sources either due to active thermal runaways, hot surfaces, or electrical shorting provided a competent ignition source for the flammable mixture. This phenomenon occurred twice in experiment E-TM-BS, 9 and 17 minutes after the last time the blanket was lifted. While no experiments were conducted in which an EV fire blanket was deployed and left in place without manipulation until the completion a simulated EV fire incident, this demonstrated that unforeseeable deflagrations may be possible even without fire blanket manipulation.

It is unclear how energetic or hazardous a potential deflagration during fire blanket use can be. With the exception of experiment E-FM-B, deflagrations observed under the blanket in these experiments were relatively mild in severity. Since the factors that control the severity of these deflagrations are not well defined for this scenario, deflagration risk should be recognized and treated with caution.

A third type of event occurred in experiment E-TM-BS which does not fit well with the descriptions of backdraft or deflagration. In this case, a fireball was vented out from underneath the blanket when water was applied to the bottom of the battery with the UVN. It is probable that the water was rapidly vaporized into steam. This expanding volume of steam, fuel, and air rapidly grew in size to larger than could be contained by the blanket. The water vapor appears not to have rendered the mixture inert, as it vented from the loose sides of the blanket and rapidly ignited.

An overview of the time and preceding events of deflagrations is given in Table 4.4.

Table 4.4: Deflagration and reignition events during EV fire suppression using fire blankets.

Experiment	Event	Time Since Deployment	Events Preceeding
E-FM-B	Deflagration	39 min 54 s	2nd blanket lift
E-TM-BS	Backdraft	2 min 17 s	1st blanket lift
E-TM-BS	Fireball	4 min 47 s	Start of underside cooling
E-FM-BS	Deflagration	11 min 24 s	3rd blanket lift & start of underside cooling
E-FM-BS	Deflagration	20 min 47 s	None
E-FM-BS	Deflagration	28 min 24 s	None

Overall, there were no discernible warning signs that directly preceded the deflagrations. Temperature visualization from a TIC as well as smoke volume and velocity remained unchanged. Conditions shortly before deflagration for selected cases are shown in Figure 4.9. In all deflagration cases, heavy white/grey vapor indicating battery involvement had been observed at some point prior to the deflagration. The vapor was similar in appearance and movement to water vapor clouds produced when dry ice is placed into a bowl of water. However, the deflagrations occurred after the venting of heavy white vapor had terminated. This type of vapor was never observed in experiment E-TM-B, for which there were no backdrafts or deflagrations, and also no battery involvement in the fire. This shows that battery involvement is the driving factor in the deflagration hazard.

(a) Experiment E-FM-B 58 s before deflagration.

(b) Experiment E-FM-B deflagration.

(c) Experiment E-TM-BS 15 s before lift and reignition.

(d) Experiment E-TM-BS Reignition during lift.

(e) Experiment E-TM-BS 2 s before delayed reignition.

(f) Experiment E-TM-BS delayed reignition.

Figure 4.9: Conditions immediately preceding deflagrations for Experiments E-FM-B and E-TM-BS.

The battery capacity required to raise the concentration of vent gases above the lower or upper flammable limit (LFL/UFL, respectively) in a given volume (such as the passenger compartment of a vehicle, the space under a fire blanket) can be linearly approximated. Assuming well-mixed conditions and using data on battery gas production and flammability limits from [55, 115], the required battery capacity can be calculated as follows:

$$E_{bat} = C_{crit} \left(\frac{V_{free}}{V'_{prod}} \right). \tag{4.1}$$

Where E_{bat} is the capacity of the battery in kWh, V_{free} is the free volume in m^3, C_{crit} is the critical concentration (i.e. LFL or UFL) and V'_{prod} is volume of gas produced per kWh of battery capacity in $m^3/(kWh)$.

Table 4.5: Gas flammability properties of NMC and LFP batteries.

Battery Chemistry	V'_{prod} [m^3/kWh]	LFL [%]	UFL [%]	Reference
NMC	0.55	10.8	50.3	[55, 115]
LFP	0.23	5	51	[55, 116]

Using the gas properties shown in Table 4.5, an estimation for flammable volume size and required battery capacity for batteries using NMC and LFP chemistry can be created and is shown in Figure 4.10. In Figure 4.10 dashed lines represent LFP chemistry gas production and solid lines represent NMC gas production, orange represents UFL estimations and blue LFL estimations. As free volume (x-axis) increases the size of battery needed to cross the LFL and UFL also increases linearly. There are estimations for fire blanket volume, single car garage volume, two-car garage volume, and three-car garage volume denoted by labels and vertical black lines.

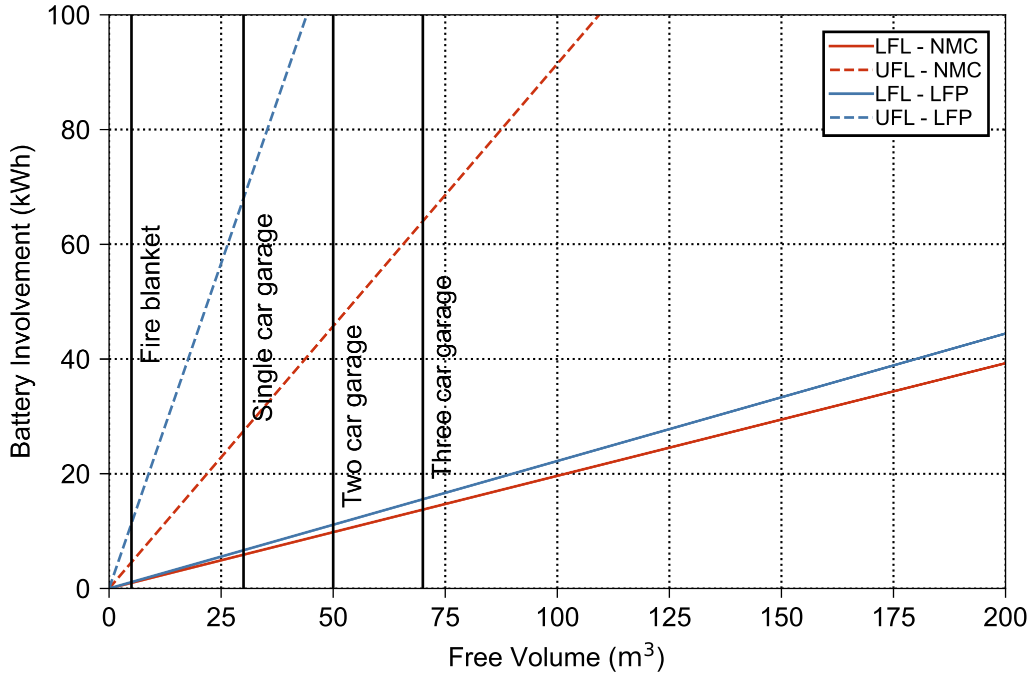
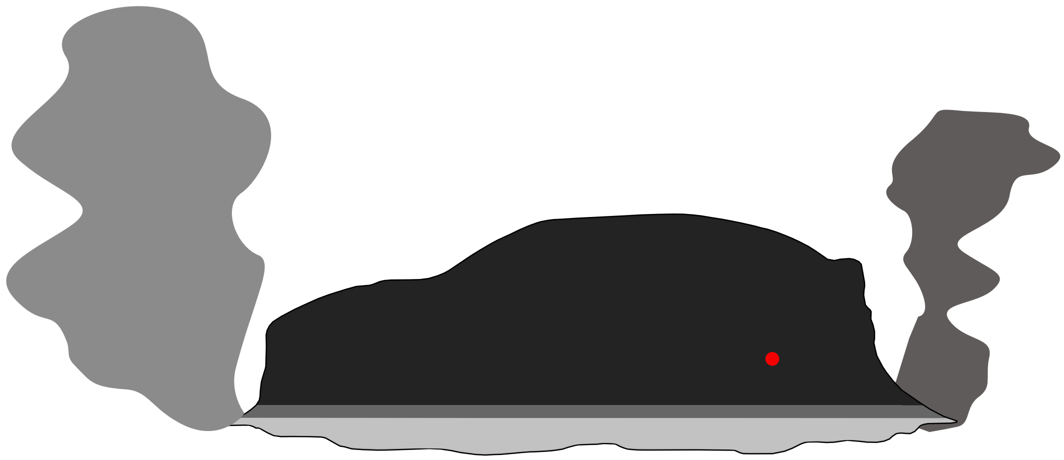
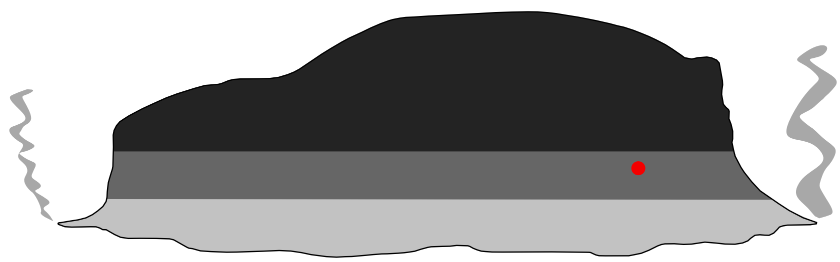


Figure 4.10: Size of the battery required to produce an explosive atmosphere plotted against the free volume.

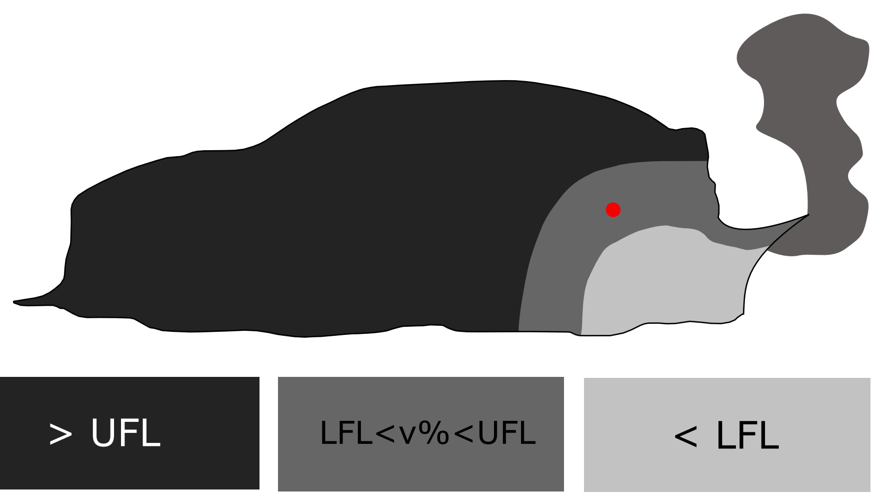
The correlation in Figure 4.10 shows that only a fraction of the capacity of an EV traction battery needs to react to release a volume of gas exceeding the flammable limit under a fire blanket. It also shows that a common EV traction battery is likely capable of forming an explosive atmosphere in a residential garage under certain circumstances. As an example the Ford Mustang Mach E tested in these experiments utilized a 91 kWh traction battery, in the free volume present under a fire blanket only 0.981 kWh or 1.1 % of this battery would need to produce gas to create an environment above the LFL, and only 4.575 kWh or 5.03 % to create an environment above the UFL. This also demonstrates that deflagrations may be possible when applying fire blankets to PHEVs and potentially even HEVs.



(a) Gas around the ignition source above the flammable range.



(b) Ignition source located in the flammable region, despite apparent improvement in smoke condition.



(c) Deflagration risk due to blanket manipulation.

Figure 4.11: Conceptual depiction of the deflagration hazard associated with fire blankets illustrating how the smoke condition appears to improve while a deflagration risk continues to be present. A representative ignition source, such as a hot surface, is denoted by the red dot.

Buoyancy effects and the spatial distribution of the flammable gas also play a significant role in the risk of deflagrations (See Figure 4.11). Thermal runaway effluent gases are a mix of several gases, including methane, hydrogen, carbon monoxide, carbon dioxide and hydrocarbons. When an EV fire blanket is deployed, the cabin fire quickly consumes all remaining oxygen in the now confined volume, while the battery continues off-gassing. Unburnt pyrolysates as well as battery gases collect under the blanket, giving the blanket an inflated appearance. At some point the free space is filled and heavy grey/ white vapors emanate from beneath the blanket. As battery thermal runaway continues, the production of new gases can outpace venting and maintain the environment under the blanket above the UFL (Figure 4.11a). When thermal runaways end, the smoke condition appears to improve. Without the production of more smoke, the leaking of smoke from around the blanket edges slows or even stops (Figure 4.11b). The introduction of air, whether through a gap between the floor and blanket or manual manipulation, can form a region where the concentrations of oxygen and flammable smoke fall into the flammable range. If this region overlaps with an ignition source, such as a hot surface of the vehicle, a deflagration occurs (Figure 4.11c). The reignition, flash fire and deflagration hazard is a multifaceted problem that has the potential to occur on many different scales if the flammable smoke venting from beneath the blanket accumulates in open or enclosed operating environments (e.g., a residential or commercial parking garage). It was seen in these experiments occurring in the volume created by the fire blanket and vehicle chassis, although there is a risk anywhere that flammable battery gas can accumulate, mix with ambient air containing oxygen, and reach an ignition source.

4.2.5 Effect of External Battery Cooling

Thermocouples were installed on the tops of battery modules inside the traction battery enclosure in the last five experiments. These thermocouples gave insight into the behavior of the battery modules during the fire and during suppression and cooling efforts. In previous suppression experiments, thermocouples were placed between the bottom plate and the casing, as discussed in Section 3.3.6. Unfortunately, these installation locations did not provide measurements that clearly indicate whether the modules had experienced thermal runaway or been hot enough to have been destroyed by the fire.

Of particular interest are experiments E-FM-B, E-FM-BS and E-FM-SA. E-FM-B and E-FM-BS can be used for a direct comparison, as both experiments had battery involvement;

Figures 4.13 & 4.12 show the temperature in two battery modules in the same vehicle after the fire blanket was applied. In experiment E-FM-B (Figure 4.12), the module temperatures are increasing at the time of fire blanket application. This is consistent with battery thermal runaway, which was occurring simultaneously with fire blanket application. Once thermal runaway propagation ends roughly 5 minutes later, the temperatures of the modules were greater than 700 °C. This is indicative of the large thermal mass of the battery, as well as the insulating properties of the battery case, vehicle chassis and EV fire blanket, all reducing the rate of heat loss. Assuming the battery was fully consumed, with no remaining cells to react and generate heat, Newton's Law (i.e., model) of Cooling suggests that it would take more than 6 hours for the battery to return to ambient temperature at the rates of cooling observed. More detail on cooling compared to E-FM-SA follows below.

The module temperatures in E-FM-BS (Figure 4.13) remained near ambient during fire blanket application, though thermal runaway was confirmed elsewhere within the battery when flames were visually observed emanating from the battery. Temperature measurements are believed to be specious, during underside cooling with the UVN because the changes in temperature are more rapid than appears reasonable for such a large thermal mass. Some temperatures increased, while some decreased. However, temperature measurements appear physically reasonable after the water flow was stopped, at which point the modules were hotter than before the water flow was first initiated. After 7000 s, the module temperatures were effectively the same as the end of the thermal runaway activity in experiment E-FM-B. Thus, flowing approximately 3800 L (1000 gal) of water with the UVN did not have a meaningful impact on thermal runaway propagation or measurable reduction in the battery temperatures.

Inspection of the battery packs after the experiments showed that in both cases the cells in all modules had completely reacted. Furthermore, no penetrations were observed in the bottom plate for E-FM-BS through which water could have entered the battery and cooled the cells. Instead, the bottom plate itself was cooled, possibly preventing such openings from forming altogether. Although no deflagrations were observed in E-FM-BS, the occurrence of a deflagration in E-TM-BS when operating the UVN shows that UVN use does not mitigate the hazards of a deflagration beneath a fire blanket and could instead cause the deflagration. It should be mentioned that a deflagration occurred for E-FM-B which was not the case in E-FM-BS. However, several deflagrations were observed with E-TM-BS, indicating that the use of underside cooling does not prevent the accumulation and ignition of flammable gas.

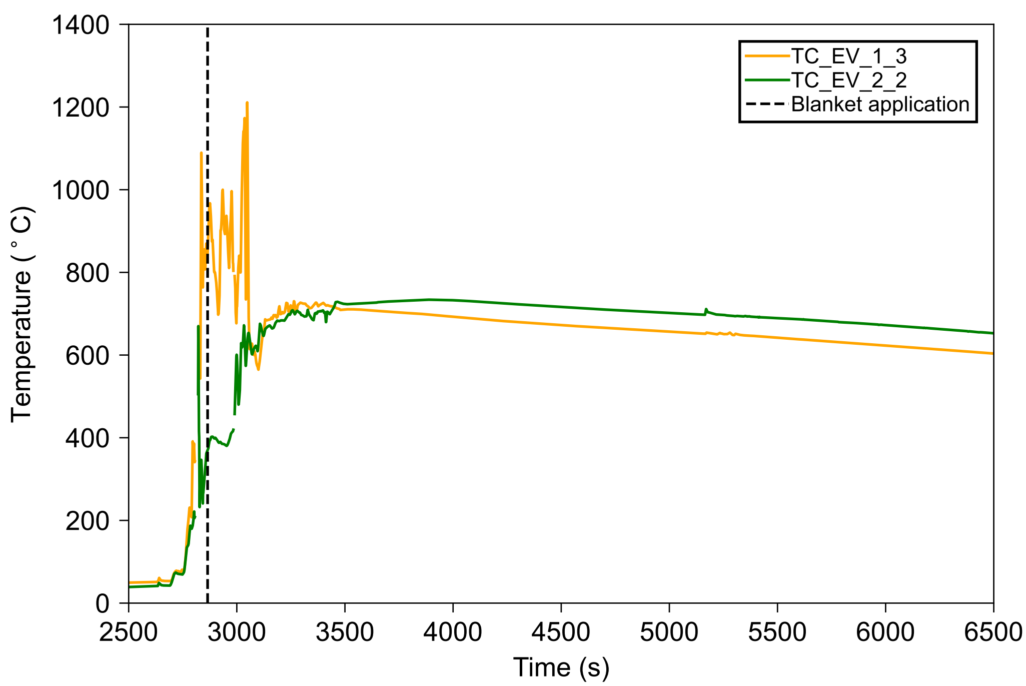


Figure 4.12: Battery temperature evolution after fire blanket deployment in E-FM-B.

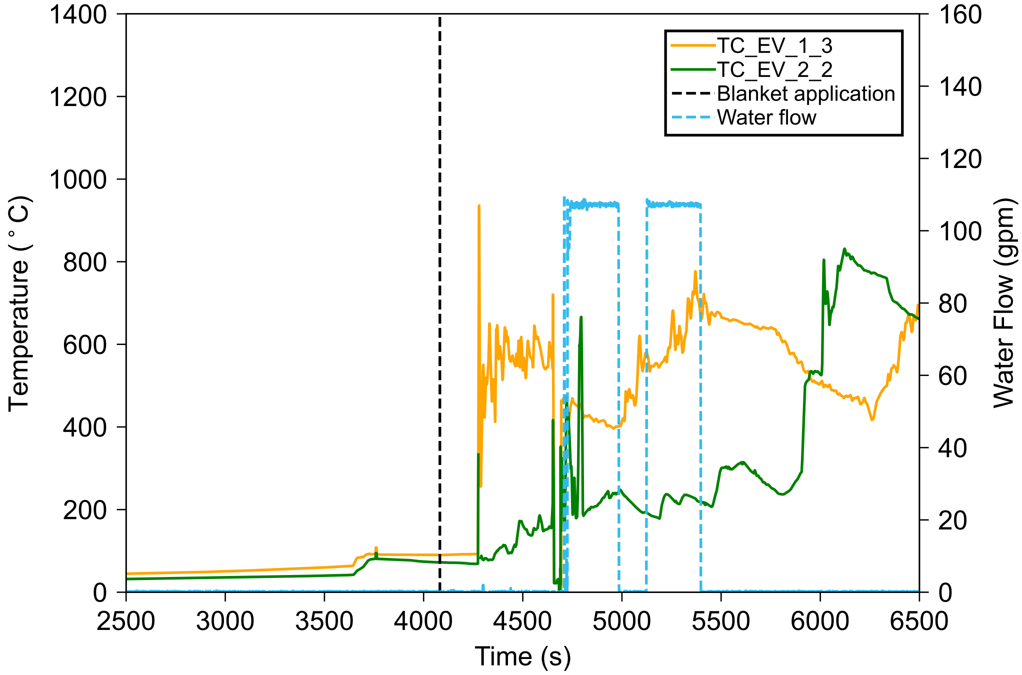
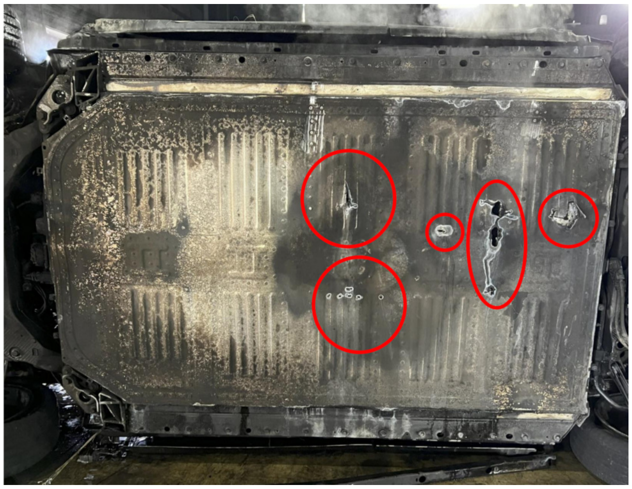


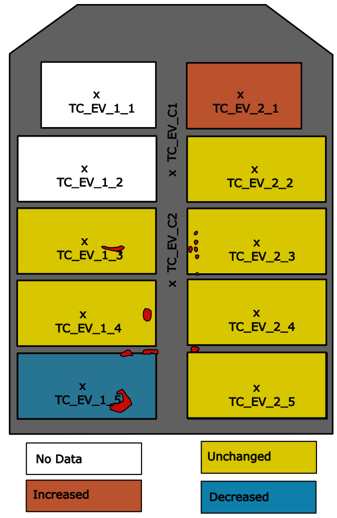
Figure 4.13: Battery temperature Evolution after fire blanket deployment with underside cooling in E-FM-BS.

E-FM-SA was the only hose-stream suppression experiment that had thermocouples in direct contact with battery modules. As discussed in Section 4.2.1, the additive had no quantifiable effect on the suppression efficacy as compared to water. Instead, this experiment can be used to gain an understanding of the effectiveness of applying water to openings in the battery casing in a targeted manner.

During the E-FM-SA experiment, penetrations were burned into the bottom plate of the battery (see Figure 4.14a). Once the vehicle was tilted, firefighters attempted to introduce water into the battery pack by targeting the largest opening with a hose stream. This did not appear to be effective and suppression efforts were soon terminated to conserve suppression agent. An image of the penetrations is shown in Figure 4.14a, and an overlay of these penetrations and the quantified effect of cooling efforts (increase, decrease, no change) is shown in Figure 4.14b. While water entering the battery through the penetrations was able to cool the module it contacted, it was not able to contribute to faster battery cooling in the other modules. In theory, the direct introduction of water is more effective at cooling the battery than cooling it externally, but in practice the additional compartmentalization within the battery appears to limit the effectiveness of this tactic.



(a) Penetrations in the bottom plate of the battery, highlighted in red.



(b) Temperature trend of the battery modules in E-FM-SA, overlaid approximate penetration locations in the bottom plate (bright red). Blue: cooling during and after suppression; yellow: no appreciable change in temperature; red: increase in temperature; white: no data available.

Figure 4.14: Effectiveness of targeted water application at the battery pack in experiment E-FM-SA.

The effectiveness of targeted water application compared to absence of active suppression battery cooling can be characterized by comparing the cooling rates between E-FM-SA and E-FM-B. The rate of temperature change was observed to be slow for both experiments. By applying a logarithmic regression to both time-temperature curves in a regime of uniform temperature decrease (i.e. after termination of suppression) the rate of cooling can be estimated via the derivative of the logarithmic regression (see Eqns. 4.6 and 4.7). The general form of the logarithmic fit being

$$T(t) = A - B\ln(t), \qquad t > 3500 \text{ s}, \tag{4.2}$$

for E-FM-B,

$$T_{FM-B}(t) = 1021.7 - 35.5\ln(t), \tag{4.3}$$

and for E-FM-SA,

$$T_{FM-SA}(t) = 2885.2 - 278.0\ln(t). \tag{4.4}$$

Differentiating Eqn. 4.2 gives

$$\dot{T}(t) = \frac{-B}{t}, \tag{4.5}$$

which gives a cooling rate of

$$\dot{T}_{FM-B}(t) = \frac{-35.5}{t}, \tag{4.6}$$

$$\dot{T}_{FM-SA}(t) = \frac{-278.0}{t}. \tag{4.7}$$

The cooling rate estimation indicates that the cooling rate inside the battery was an order of magnitude higher for E-FM-SA than for E-FM-B, but cooling from post-experimental temperatures to ambient temperature took multiple hours in both cases. Introduction of water is likely responsible, although the penetrations themselves may also have contributed to faster cooling. Conversely, the blanket in E-FM-B likely reduced convective cooling, leading to a slower battery cooling rate. Nonetheless, the calculated cooling rates were still observed to be very low in both cases averaging about 0.4 K/min (0.7 deg F/min) for E-FM-B and 4.4 K/min (7.9 deg F/min) for E-TM-BS.

Overall the results show that external water application, whether applying a hose stream to the bottom of a titled vehicle or by use of the UVN directly on the battery, had little effect on the battery temperatures and incident resolution time. Longer duration flows also increase runoff, which may be another exposure concern to manage. The combination of fire blanket and underside cooling eliminated the water reduction benefit of a fire blanket without providing improvements in safety or faster incident resolution. During the experiments, it was observed that the use of a UVN produced large volumes of the most contaminated water, which was sampled and is being analyzed for future publication. Access to the analysis will be provided at https://fsri.org/research/fire-safety-batteries-and-electric-vehicles when it is published.

EV traction batteries are densely packed, and also contained in enclosures designed to be waterproof, impact resistant, as well as thermally and electrically insulating. The reader is referred to Section 2.6.3 for a detailed discussion of battery construction. In some cases for batteries with specific enclosure materials it is possible for holes to appear due to heat or mechanical damage, and this may allow for direct cooling of the cells inside. A targeted application of the hose stream into the battery via these openings resulted in a measurable, but limited increase in battery cooling rate, including after suppression efforts were terminated. Cooling rates were highest in the module directly above the penetration, however the density and internal confinements of the battery pack prevented the water from reaching and effectively cooling other modules. As energy density and battery pack capacity are increased, these limitations such as increasing encapsulation may become more common.

4.3 Post-Test Observations

4.3.1 Reignition

Reignition refers to cases where the flaming has subsided and the fire is believed to be extinguished, and is distinct from reignitions seen during fire blanket deployments as discussed above. Instances of reignition occurred across two experiments, E-TM-S and E-FM-B. Four reignitions occurred during active battery suppression efforts in experiment E-TM-S when water was being applied to the tilted vehicle, and through a large hole melted through the bottom of the pack. The flaming stopped, but then restarted after seconds to minutes of apparent inactivity. Several additional reignitions occurred after the experiment was terminated and the vehicle had been removed from the test stand, hours after initial ignition.

Another observed instance of reignition occurred after terminating the E-FM-B experiment. The EV fire blanket had been applied for a period of approximately 4 h, and then removed. An ignition of partially burned cabin contents occurred approximately 30 min after the blanket was removed, and after data collection had been terminated. However, video evidence and battery temperatures (approximately 350 °C) corroborate a hypothesis that thermal energy retained within the hot battery induced a hot surface ignition of the combustible cabin contents once fresh air was available after removing the fire blanket.

4.3.2 EV Fire Blanket Condition After Single Use

Each fire blanket suppression experiment utilized a fresh fire blanket and each blanket was inspected after use for damage patterns. A sample of blanket material was taken for further damage analysis and for characterization of contaminants. All blankets that were used showed indications of damage, including discoloration and chemical deposits, see Figure 4.15. The damage and deposits were greatest on the side that had been facing the vehicle during deployment, although discoloration was also evident on the side facing away from the vehicle. The presence of sooty and oily deposits on the blanket indicates a high level of contamination; this is discussed further in Section 4.4.3. In several cases, small tears were visible in the blanket as well. In the case of E-TM-BS the damage to the blanket was especially severe. Discoloration was visible on the blanket exterior and several tears were found. This damage could potentially compromise blanket integrity during a subsequent operation, but this was not attempted in these experiments. In general, discoloration and potential weakening of the blanket appeared in areas where sustained flaming occurred. An efficient blanket deployment with quick control of flaming may result in little to no damage to a fire blanket, whereas sustained flaming may compromise the integrity of a fire blanket for further use.

(a) Discoloration visible on the applied blanket, E-TM-BS.

(b) Discoloration visible. Note the square hole is a blanket sample that was removed for laboratory analysis.

Figure 4.15: EV fire blanket damage in experiment E-TM-BS.

Samples were taken from the fire blanket for further analysis of deposits and contamination. Results will be made available in a future publication.

4.3.3 Damage Assessment

Following the experiments, vehicle damage was assessed and documented. This included visually inspecting the vehicle chassis, passenger compartment interior, as well as the battery. The battery was inspected for external signs of damage and then removed from the vehicle and disassembled to inspect the extent of damage inside the battery, as well as the electrical hazard posed by the damaged battery as identified by the presence of a voltage and whether a responder could plausibly come into contact with such a voltage.[1]

4.3.3.1 Handline Suppression

Damage was consistently severe when the battery pack was involved. Thermal runaway propagated throughout the battery pack in all but two experiments. In most cases, penetrations of the bottom cover plate of the battery pack were found. In experiment E-TM-S, the bottom cover had melted completely, dropping a large number of cells into the pan below the vehicle (Figure 4.16h). Partial battery damage occurred in experiments E-FM-S and E-HK-S. In experiment E-FM-S, two battery modules retained a voltage of 28.5 VDC, although inspection showed that the cells in those modules had been destroyed. Furthermore, some evidence of arc damage was

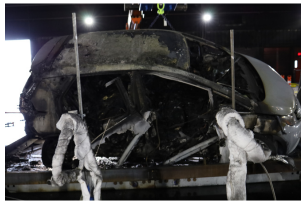
[1] The insulation resistance is another metric used to assess the integrity of the HV system poses a hazard. However due to the requirements of specialized tools and training, such measurements could not be performed as part of this damage assessment.

discovered in several experiments. In E-HK-S, all modules were intact, although the plastic cover and expanded polystyrene components inside showed evidence of heat damage and melting. The damaged module retained its nominal voltage of 81.8 VDC, signs of thermal damage can be seen in Figure 4.17a. The battery pack measured 328 VDC across the service disconnect terminals, consistent with 100 % SoC and expected of an intact battery. However, abnormal voltages of 273 VDC and 93.5 VDC were measured between two service disconnect terminals and the battery casing, respectively. This indicates a loss of high voltage isolation between the high voltage components of the battery and the battery case. While this represents an electrical hazard, the circuit must still be completed by coming into contact with one of the terminals in the service disconnect which is a near physical impossibility. While the risk may be low, the loss of isolation is still noteworthy and indicative of the unpredictability of electrical hazards when energy systems have been damaged by fire. Damage for each suppression experiment can be seen in Figure 4.16. A summary of the damage patterns for the water suppression experiments is provided in Table 4.6.

Table 4.6: Damage patterns for the EV suppression experiments.

Experiment	Chassis Damage	Battery Damage	Electrical Hazard
E-HK-S	Severe front end damage Interior destroyed	Thermal distortion inside pack Module plastic melted	328 VDC across terminals Loss of HV isolation 273 VDC from terminal to battery casing
E-CB-S	Heavy damage Passenger doors completely melted Interior completely destroyed	Top plate molten with exposed glass fiber All modules completely burnt through Evidence of short circuit events	None
E-TM-S	Minor damage to exterior Very little interior damage	Bottom cover largely melted Cells scattered on floor ca 40 % of cells unburnt and charged	28.5 VDC across exposed current collector and chassis prior to disassembly
E-FM-S	Complete interior and exterior damage	Penetrations in bottom plate All modules destroyed	None
E-FM-SA	Complete interior and exterior damage	Penetrations in the bottom plate All modules underwent thermal Runaway	None

(a) External damage for E-HK-S.



(b) The damage of the passenger's side for E-CB-S.

(c) External Damage for E-TM-S.

(d) External Damage for E-FM-S.

(e) External Damage for E-FM-SA.

(f) Battery Damage for E-HK-S.

(g) Battery Damage for E-CB-S.

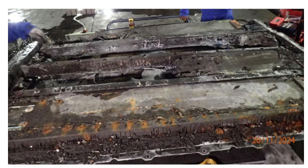
(h) Battery Damage for E-TM-S.

(i) Battery Damage for E-FM-S.

(j) Battery Damage for E-FM-SA.

(k) Open battery for E-HK-S.

(l) Open battery for E-CB-S.



(m) Open battery for E-TM-S.

(n) Open battery for E-FM-S.

(o) Open battery for E-FM-SA.

Figure 4.16: Damage patterns for water-based suppression experiments.

A potential electrical hazard was also identified in experiment E-TM-S. In this case the bottom battery cover had burnt through, exposing the individual cells and the current collectors, as seen in Figure 4.17b. Significant quantities of the cells had not fallen out onto the floor and were retained within the pack. Before removing and disassembling the battery, a voltage measurement was taken between an exposed current collector and the chassis of the vehicle and was found to be 22.5 VDC. While this voltage is not considered dangerous within commonly accepted electrical workplace safety standards like NFPA 70E [117], other module fragments had measured voltages of 45.8 VDC and 66.6 VDC. For this reason, hazardous voltages between exposed battery components and the vehicle frame are not inconceivable. This represents a different type of hazard from the one found in E-HK-S, as the vehicle body is much easier to contact simultaneously if attempting to handle exposed battery components. Furthermore, threshold DC voltages that present hazards often refer to dry contact and typical body resistance, whereas a firefighting environment may be wet, the water may be of increased conductivity due to contaminants or firefighting agents, and contact pressures may be high if a firefighter is physically pressing against a vehicle battery pack as part of a task. Alternatively, a low resistance metal tool may be used on or leaned against a damaged battery which would complete the circuit.

(a) Battery module with thermal damage from E-HK-S.

(b) The current collector in E-TM-S was readily exposed posing a potential electrical hazard.

Figure 4.17: Electrical hazards resulting from battery damage.

Comparison between the experiment using water (E-FM-S) and F-500 (E-FM-SA) did not indicate any reduction of damage, or interruption of thermal runaway in the experiment where agent was used. Damage to the chassis appears equally severe. Similarly, the batteries were completely destroyed in both experiments, indicating that neither water nor water with the agent had the ability to stop battery thermal runaway propagation within the battery. This strengthens the conclusion that the reduction in water for the suppression with agent tests resulted from improved firefighting experience, and not from the impact of the agent.

4.3.3.2 Fire Blanket Suppression

A summary of the damage patterns is given in Table 4.7.

Table 4.7: Damage patterns for the EV fire blanket experiments.

Experiment	Chassis Damage	Battery Damage	Electrical Hazard
E-FM-B	Rear bumper/trunk damage Interior destroyed	All modules destroyed Top cover destroyed Bottom plate penetrated	None
E-TM-B	Catastrophic interior/exterior damage Right rear suspension disconnected	All cells largely intact Moderate damage to rear of pack No indication of TR	398 VDC on battery Terminal (100 % SoC)
E-FM-BS	Composite exterior materials melted Interior damaged	All modules destroyed Moderate top cover damage Bottom plate intact	None
E-TM-BS	Heavy exterior damage Interior mostly intact	All cells destroyed Bottom plate burnt through Cells scattered on the ground	None

The damage to the chassis of the vehicles was generally extensive and consistent with the damage seen in ICEV experiments. The exterior chassis showed scorch marks and burn damage with the most extensive damage generally affecting components made from composite materials. The same is true for the interior of the vehicles. Except for E-TM-BS, all combustible materials were severely damaged or completely burned away.

(a) External damage for E-FM-B.

(b) External damage for E-TM-B.

(c) External damage for E-FM-BS.

(d) External damage for E-TM-BS.

(e) Internal damage for E-FM-B.

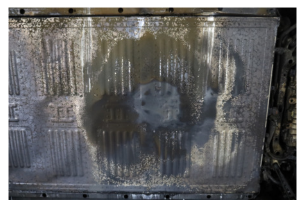
(f) Internal damage for E-TM-B.

(g) Internal damage for E-FM-BS.

(h) Internal damage for E-TM-BS.

(i) Battery damage for E-FM-B.

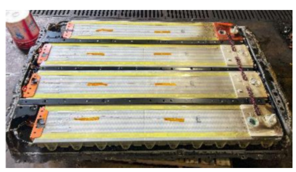
(j) Battery damage for E-TM-B.



(k) Battery damage for E-FM-BS.

(l) Battery damage for E-TM-BS.

(m) Open battery for E-FM-B.



(n) Open battery for E-TM-B.

(o) Open battery for E-FM-BS.

(p) Open battery for E-TM-BS.

Figure 4.19: Damage patterns for the EV fire blanket experiments.

In the blanket experiments the batteries were completely burned out in all cases except for E-TM-B, where the battery was damaged, but never became involved in the fire. Significant battery pack damage such as penetrations in the bottom plate were observed in E-FM-B, E-FM-BS and E-TM-BS. E-TM-BS had the highest level of battery damage, the bottom plate had almost completely melted away, dropping the cells into the catchment pan below. No voltages were present in any experiments except for E-TM-B. In this experiment a voltage of 398 VDC, consistent with 100 % SoC, was measured across the service disconnect terminals. While these are inaccessible in the scope of FD operations, the presence of a voltage indicates that other elements of the vehicle may be charged, if HV isolation systems fail.

4.4 Chemical Exposure

Understanding the hazards posed by chemical exposure to firefighters and bystanders during a vehicle fire incident is important for incident commanders and firefighters to assist them in making decisions on how to better protect the public and themselves. This section provides an overview of the preliminary findings and a qualitative characterization of the chemical exposure hazards between air contamination, turnout gear contamination, suppression runoff, and surface contamination. Research efforts are still underway and more comprehensive analyses will be submitted for peer-reviewed publication in the near future. All peer-reviewed journal articles submitted for publication as part of this research will be made available as they are published on the following webpage at https://fsri.org/research/fire-safety-batteries-and-electric-vehicles.

Acute and chronic health effects of chemical exposure associated with vehicle fires generally and EV fires specifically are very complex and the subject of ongoing research. While this investigation cannot provide a comprehensive analysis of the health effects of EV fire chemical exposure, a number of known carcinogens as well as other known or suspected harmful compounds were identified. Further research will be required for a more complete understanding or chronic and acute health effects.

4.4.1 Air Contamination

Air contamination from the battery thermal runaway and the vehicle fire was measured in the fire plume, as well as at head height in front of and behind the vehicle during free burn and suppression experiments. Firefighters were equipped with active and passive air sampling to characterize the chemical exposures from operating near the vehicles. Chemical species of interest were volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), per- and polyflouroalkyl substances (PFAS), acid gases, metals, and particulates. Measurements were taken both for ICEV and EV fires.

Results showed that the chemical concentrations of VOCs and PAHs were largely similar for ICEVs and EVs. Similar concentrations of acid gases (including hydrogen fluoride) were also measured between vehicle powertrain types. PFAS were detected for both the EVs and ICEVs, and can plausibly be explained by partial combustion of the air conditioning system refrigerant and interior finishings. Concentrations of inhalable particulate up to 100 µm were also similar between the two different powertrains. However, EVs were found to produce higher concentrations of particulate fluoride which can potentially deposit on turnout gear or form hydrofluoric acid if introduced to sweaty skin or mucus membranes. EVs also produced nickel, manganese, cobalt and lithium metal particulates, likely originating from battery materials.

Concentrations represent the average across the duration of the test, as methodological limitations prohibited measurements of peak concentrations or time-based concentrations. Overall, the analysis shows that many of the targeted compounds were found in similar concentrations between

EVs and ICEVs but two key differences exist: EV fire effluent showed higher concentrations of heavy metals and of particulate fluoride. It is not yet clear whether these differences present unique risks for acute or chronic health effects, and further research is needed to make these determinations. However, the results for both ICEV and EV air contamination measurements underscore the need to conduct vehicle firefighting operations with full structural firefighting PPE and self-contained breathing apparatus, adopt firefighting practices which reduce smoke exposure, and perform preliminary exposure reduction per NFPA 1850 after the fire is extinguished and overhaul is completed.

Water and fire blanket suppression measurably impacted the air contaminants. The suppression experiments for both water and the use of a fire blanket showed significantly lower measured amounts of LiB-related metals as compared to the free burn experiments of the same vehicle. Similar trends were observed for particulate fluoride. However, a rise in plume concentrations of PAHs and VOCs was observed, especially when the use of a fire blanket was combined with a UVN.

A more detailed discussion of airborne chemical hazards is presented in [101]. Further analysis of air contamination, including time-based concentrations of combustion gases and the impact on firefighting on the air contamination, is the subject of ongoing efforts. Any additional findings will be published at https://fsri.org/research/fire-safety-batteries-and-electric-vehicles.

4.4.2 Water Contamination

In the EV experiments using water suppression, samples of suppression water were collected with the procedure described in Chapter 3.3.8. No direct comparisons are possible with ICEV runoff water because no ICEV extinguishment experiments were conducted. EV runoff water was analyzed for anions, metals, PAHs, and VOCs. In one water suppression experiment, E-HK-S, the battery did not experience thermal runaway or become involved in the fire, which allows for inferences to be drawn about the contribution of the battery to water contamination.

Figure 4.20: Visibly contaminated water runoff from experiment E-TM-BS.

In the course of the experiments, the suppression water runoff appeared visually contaminated (see Figure 4.20) with particulates, debris and sediment. Further analysis showed relatively high levels of fluoride and hydrogen cyanide for experiments with battery involvement, while the experiment without battery involvement showed the highest concentration of sulfate ions.

Results for metal contamination mirrored the air contamination results with elevated concentrations of cobalt, lithium and nickel detected in the water runoff. Concentrations of these metals were low in experiment E-HK-S, which instead had highest median concentrations of zinc, barium and lead. Several other metals were tested for (Sb, Cu, Mo), but were either not detected or found in low concentrations.

Concentrations of PAHs varied between experiments, with naphthalene typically present in the median highest concentrations. The experiment that featured complete burnout of the battery and failure of the battery enclosure (E-TM-BS), also resulted in the highest median concentrations across all PAH species detected. This may be attributable to the amount of battery thermally decomposed and the loss of containment. Similar failure of the enclosure was also observed in E-TM-S, however, approximately 40% the battery remained intact, and a lower concentration of PAHs were measured.

The measurements of VOCs in runoff water found elevated concentrations of benzene, toluene and styrene for suppression experiments and even higher levels for experiments combining the use of an EV fire blanket with under-vehicle nozzle suppression. The lowest concentrations were again measured in the experiment with no battery involvement.

Overall, the runoff water was contaminated with elevated concentrations of anions, metals, PAHs, and VOCs, which present a potential chemical exposure as well as an environmental hazard. However, concentrations were lowest in the experiment with no battery involvement. For this reason, a quick fire attack that prevents the battery from becoming involved may reduce chemical exposure and environmental hazard by limiting the release of these hazardous compounds.

While elevated concentrations were measured for various potentially harmful compounds, preliminary results suggest that early suppression of the fire with water can have a significant public safety impact. Just as with existing considerations for controlling ICEV fire suppression runoff water, reasonable efforts should be made to prevent contaminated water runoff from entering sensitive areas, such as drinking water supplies or streams. A more thorough discussion on the results of the water runoff analysis is currently in peer-review and will be made available once published at https://fsri.org/research/fire-safety-batteries-and-electric-vehicles.

4.4.3 Surface Contamination

Surface contamination during EV and ICEV free burns was assessed using aluminum collection pans, as well as surface wipes which were analyzed for the presence of metals and PAHs at different distances from the vehicle. The samples were collected immediately after the conclusion of the experiment and placed into sealed bags to be analyzed.

Preliminary results show high concentrations of the NCM battery metals nickel, manganese and cobalt, as well as lithium, of which concentrations for nickel were the highest. These metals were not detected in the samples for ICEVs. Nonetheless, several metals were detected in similar quantities between ICEVs and EVs such as barium, calcium, zinc, iron, copper and magnesium. Concentrations of lead were elevated in the samples from the ICEV experiments.

Surface wipes detected PAHs in both EV and ICEV experiments, but showed higher concentrations, especially of naphthalene and phenanthrene in the ICEV experiments. PAHs in EV experiments showed lower concentrations of PAHs in total, although a larger number of different PAH species were measured. In contrast, concentrations of particulate fluoride were higher for surface wipe samples from EVs compared to ICEVs. Surface samples generally tended to have pH values shifted into the basic region, regardless of powertrain type.

The differences in surface contamination indicate that residue from EV fires has a different hazard profile than that of ICEV fires. While PAHs tend to disperse over time, metal ions may persist and could become re-aerosolized during cleanup operations. Fluoride particulate may react with water from suppression or sweat to form hydrogen fluoride.

A more comprehensive analysis of the surface contamination is currently in the peer-review process and will be made available once published at https://fsri.org/research/fire-safety-batteries-and-electric-vehicles.

4.4.4 Contamination of Personal Protective Equipment

An important aspect of chemical exposure in EV fires is the chemical contamination of turnout gear. Of particular interest is how well the PPE resists chemical penetration and thus protects the wearer from exposure.

Preliminary results mirrored those outlined in the chemical exposure sections above. EV fires were characterized by higher concentrations of metals that were associated with the battery, in particular nickel, manganese and cobalt, of which nickel was the most prominent. Concentrations of PAHs were similar between EV and ICEV fires. Swatches that were deployed at plume level showed higher concentrations of metals and PAHs than those deployed at ground level. The highest concentrations were found on the swatches attached to the firefighters who actively engaged in fire suppression, indicating that fire suppression may result in significant contamination of PPE.

In terms of chemical penetration resistance, between 80 % and 90 % of metal contamination was confined to the outer shell layer of the PPE samples. This demonstrates that for metals, the outer shell layer provides a limited degree of protection. For PAHs, however, this is not the case. Low molecular weight PAHs were found to have penetrated into the moisture barrier and the thermal liner. While higher molecular weight PAHs tended to remain on the outer shell, the potential for PAHs to penetrate into and through the PPE layers shows that there is concern for secondary exposures of firefighters due to contaminated PPE and exists both for EVs as well as ICEVs. The analysis of PPE contamination by metals and PAHs can be found in a recent publication by Probert [102].

Contamination of PPE is the subject of ongoing research efforts with a focus on understanding the effectiveness of PPE decontamination procedures. The present results indicate that PPE that was exposed to vehicle fire smoke presents a secondary contamination hazard, regardless of powertrain type, and should promptly be decontaminated. Turnout gear provides limited chemical protection, highlighting the importance of good hygiene practices, especially showering soon after returning to quarters and laundering the clothes that were worn under the turnout gear.

4.4.5 Impact of Firefighting Control Strategy on Chemical Contaminant Release

Preliminary results indicate that in nearly all experiments, initiating suppression efforts of any kind reduced air contamination compared to the free burn experiments. The use of water suppression with a handline resulted in a dramatic decrease in anions (including HF and particulate fluoride), metals and PAHs measured in the plume at a height of 1.5 m (5 ft). VOC concentrations were generally reduced, but increased in one experiment. Similarly, the use of an EV fire blanket and the combination of the fire blanket and UVN resulted in dramatically lower concentrations of anions, metals and PAHs being detected. However, a significant increase of VOCs was measured compared to the free burn in all experiments. This increase was dramatically higher for the combination of blanket and UVN.

Generally, firefighting operations and the resulting exposure to EV fire effluents were associated with higher levels of chemical contamination of the PPE, especially battery metals in the outer shell layer of the PPE, along with limited penetration of PAHs through the turnout gear. Smaller, more volatile VOC molecules were detected on the silicone wristband samples worn by the firefighters under their turnout gear at levels similar to those detected on the wristband samplers outside of the gear, indicating that lightweight VOCs such as benzene, were able to penetrate through the PPE.

Concentrations of all compounds in the runoff water were found to be higher in the runoff from the blanket + UVN combination than the handline suppression, with some variation between different vehicle types. Measurements from the experiment where F-500 was used showed higher concentrations of fluoride ions (both HF and particulate) in the plume. Concentrations for metals and PAHs were reduced compared to the free burn experiments, but not as much as the experiments using just water alone. Lower concentrations of VOCs were detected than for water alone. Runoff water concentrations generally fell between those of the blanket + UVN experiments and those just using water.

Across all compounds, the greatest reduction in measured plume and water runoff concentrations occurred when suppression was initiated early enough to prevent battery involvement in the fire.

4.5 Summary of Results

The results from the EV free burn and suppression experiments show that the primary exposure characteristics including fire growth rate, peak heat release rate, fire duration, thermal exposure, and chemical contaminant release are similar to fires in ICEVs, especially if the battery is not involved in the fire. This is attributed to the fact that the materials and construction of the passenger compartment of these vehicles are the same between EVs and ICEVs powertrains. Therefore differences between ICEVs and EVs are attributed to when fire involves the large traction battery packs. Compared to ICEVs, EV fires with battery involvement showed higher levels of metals and hydrogen- and particulate fluoride, elements commonly found in the battery. Finally, in contrast with an EV battery, it is implausible for an ICEV fuel tank to be the source of ignition for a vehicle fire without other clear external causes (like a vehicular collision).

The nine suppression tests give insights into the effectiveness of each suppression method and additional challenges that accompany them. Characterizing suppression effectiveness was achieved through visual observations, battery temperature measurements from within the battery and post-test damage assessments.

Battery damage documented across all suppression experiments demonstrated that while the bulk of a vehicle fire can be controlled with typical firefighting equipment and water or fire blankets, the fires fueled by batteries involved in propagating thermal runaways were unresponsive to suppression efforts in effectively all cases. The only exception occurred in experiment E-TM-S where the bottom of the battery pack had completely burned away allowing direct access to the interior of the battery over a large area, resulting in a number of cells remaining intact. A similar failure of the bottom cover was observed in experiment E-TM-BS. In this case, however, a UVN was unable to interrupt thermal runaway propagation. In general, vehicles with batteries involved in the fire could be managed by using the hose stream to redirect the flaming vent gases and/or preventing (re-)ignition of the passenger compartment. While this was carried out, the cells in the battery pack continued in thermal runaway until all cells had reacted.

Water was found to be the most effective suppression agent for controlling an EV fire. In particular, early suppression of the cabin fire eliminated the bulk of the fire exposure hazard within seconds of suppression initiation. The use of copious volumes of water was found to be unnecessary as it could not interrupt thermal runaway in the battery. A review of vehicle construction and temperature data from the battery modules indicate that water was not meaningfully cooling the cells inside the battery pack. Introducing water into the battery through natural openings had a marginal effect on reducing battery temperatures and cooled only the area immediately around the opening, but was only able to interrupt thermal runaway if a large portion of the battery enclosure had burned open, which in turn was associated with easy access to potentially high voltages. The use of F-500 did not observably or measurably alter the effectiveness of fire suppression as compared with water alone. These findings mirror those from other EV fire suppression research studies [18, 24, 31].

As our firefighters became more familiar with EV fire behavior and improved their nozzle technique, less and less water was used. They found that the most effective method for managing the fire was to begin with extinguishing the passenger compartment. The passenger compartment represents the most significant source of fuel for the fire, which in turn drives the majority of the thermal and chemical hazard. Additionally, it is difficult to assess battery involvement in an apparently fully-involved vehicle, but battery involvement becomes easy to identify after the passenger compartment fire had been extinguished. While water-based suppression reduced airborne contamination at the expense of producing contaminated runoff water, the overall chemical exposure was reduced by water suppression as the source of the contaminants was extinguished. Chemical contaminant release, and concerns about battery specific contaminants, were further reduced when the vehicle was extinguished before the battery became involved in the fire.

Fire blankets were effective for quickly controlling passenger compartment flaming, but were not effective at controlling thermal runaways and the ensuing hazards from a non-flaming release of flammable gases and contaminants in battery smoke. This can change the risk profile of a vehicle fire incident to be similar to that of a gas leak from a finite source. Subsequently, fire blankets create the potential to contribute to unanticipated and thus potentially dangerous fire behavior. The experiments demonstrated that the vehicle underneath the blanket continued posing a backdraft and deflagration risk for no less than an hour after deployment. Four deflagrations were observed between experiments E-FM-B (one deflagration) and E-TM-BS (three deflagrations). In addition, a large backdraft during experiment E-TM-BS showed additional instances of fire behavior that may be unanticipated and therefore risk causing injuries. No universal indications of impending backdrafts or deflagrations could be identified, but it is clear that manipulating a deployed blanket within this 1 h approximate window significantly increased the risk of both hazards (e.g., to assess fire conditions or insert a suppression appliance like an under-vehicle nozzle). Additional research is needed to narrow down the window in which a backdraft or deflagration is possible. Combining EV fire blankets with the use of underside cooling did not prove effective. The benefit of water reduction/elimination was negated without any commensurate improvement in incident resolution time or safety for responders, as experiment E-TM-BS demonstrated. As such, EV fire blankets may be appropriate under limited conditions, and trade off for a risk profile as-yet unfamiliar and complex to the fire service. A summary of events can be seen in Table 4.4.

EV and ICEV fires alike represent a significant chemical exposure hazard and require first responders to implement exposure management strategies accordingly. Guidance pertaining to exposure management and reduction is provided in more detail in the following chapter.

5 Discussion

Observations from the experiments and analysis of the measurement data were used to develop electric vehicle (EV) fire incident response considerations. These are categorized into strategic and tactical considerations. Strategic considerations guide the decisions by providing the benefits and drawbacks of different EV fire suppression strategies while tactical considerations provide insight for executing those strategies.

5.1 Operational Priorities

The operational priorities for an EV fire incident are the same as any other passenger vehicle fire. First and foremost is life safety of vehicle occupants by facilitating the immediate rescue of victims and accounting for responder safety by donning full structural firefighting PPE and SCBA. EV-specific considerations should not delay any necessary life safety measures, such as suppression to support extrication or victim removal.

The next priority is the identification of exposures and the vehicle propulsion type and involvement of the battery. Electric vehicles may be difficult to identify in a fire, especially if the vehicle model is available with different configurations of powertrains (e.g., gas-only, hybrid, plug-in hybrid or fully EV) or if the fire is obscuring any identifying features (e.g., badging, charging doors, or a lack of tailpipes or radiator). For these reasons, it may not be possible to identify whether a vehicle includes LiBs in its construction until an expedient initial suppression effort is made. This situation is discussed in greater detail in sections that follow. Once vehicle type is confirmed, this can inform specific hazards and concerns and allow for an appropriate mitigation strategy to be selected.

Fire suppression and exposure protection efforts should run in parallel and be continuously reevaluated for their effectiveness and account for changing conditions. In particular, bystanders should be protected from smoke exposure, either by evacuating exposed areas, or by ordering occupants of neighboring buildings to close doors and windows. The most effective exposure management strategy is to extinguish the fire, but if that is not possible, the fire size/intensity should be reduced as much as possible.

5.2 EV Fire Control Strategy

The experiments conducted during this research provide data to assess three EV fire control strategies debated at a high level across the fire service, globally. The fire control strategies are suppression with water using a handline, deployment of an EV fire blanket, or non-intervention (i.e., a "let-it-burn" approach).

Factors that inform fire control strategy include the location of the burning vehicle, the exposure hazards posed to surrounding people and property, the resources available, and whether a traction battery is involved in the vehicle fire. In the majority of cases, a water-based conventional fire attack will be the most effective strategy to control the burning EV. There are limited circumstances where deployment of an EV fire blanket, or letting the vehicle burn itself out may be favorable alternatives.

In addition to the guidance below, an EV Fire Tactical Decision Aid was developed to visualize and communicate more clearly how incident factors can be used to inform decision-making for fire control strategy. The full Decision Aid can be found in Appendix B. A step-by-step explanation of the Decision Aid is provided in Appendix C. The Decision Aid will also be permanently hosted, with any updates, at https://training.fsri.org/resources/462/electric-vehicle-fire-tactical-decision-aid-passenger-vehicle

5.2.1 Water-Based Fire Attack

A water-based fire attack using a handline is recommended as the first choice suppression strategy for an EV fire. This strategy is effective at quickly controlling the main body of the fire, as evidenced in the suppression experiments, and explained in the vehicle construction analysis. Extinguishing the passenger compartment produces an immediate reduction in associated thermal and chemical exposure hazards, does not require additional or specialized equipment, uses techniques that firefighters are familiar with, and relates to vehicle firefighting experience firefighters already have. This strategy involves extinguishing the cabin fire to reduce the fire intensity and then confining the flames to the battery fire until flaming stops. In the experiments, this occurred within 5–20 min, though fires that move slower through the battery pack may be possible if the battery is at a lower state of charge. All vehicle fires were managed with less than 7500 L (2000 gal) water total, which can be reduced to as low as 3000 L (800 gal) with disciplined water application. The cabin fire requires less than 750 L (200 gal). In some instances, early suppression of the vehicle can prevent the battery from becoming involved, reducing the complexity of the incident considerably. Data gathered by the Dutch fire service indicates that the majority of EV fires did not involve the battery, and can thus be controlled by just extinguishing the passenger compartment [33]. The electrical hazard posed by the high voltage system of the vehicle to the firefighters operating the handline is considered to be low but was not assessed in this study.

The negative consequences of a water-based fire attack lie primarily in the risk of chemical exposure. Firefighters operating in smoke, debris and water runoff will experience higher levels of exposure than firefighters who use wind and the reach of the hose stream as much as is practicable. The water runoff will be contaminated regardless of powertrain type and should be prevented from entering sensitive areas. Using water will reduce the overall production of contaminants by eliminating the bulk of the fire. Existing practices for control of firefighting runoff water to sensitive areas should be continued. In the unlikely event water is not an available resource, non-intervention or fire blankets may be considered.

5.2.1.1 Tactical Guidance

When attacking an EV fire with water, firefighters should approach the vehicle from a 45° angle, to reduce exposure to projectiles such as bursting tires and struts, as is the case with ICE vehicles. Jet flames can emanate from anywhere underneath the vehicle. In cases where the battery is observed to be off-gassing without any flaming, a jet flame or flash fire may develop suddenly and without warning. For this reason, appropriate PPE and respiratory precautions should be used even if no flames or off-gassing are visible.

Efficient suppression of the vehicle is less a result of water volume, but rather effective water application. Large volumes of water that are applied ineffectively will provide little tactical benefit and result in large amounts of contaminated runoff.

It is recommended that suppression efforts begin with protecting exposures and controlling the bulk of the fire in the passenger compartment. The passenger compartment fire represents a significant portion of the fire's total heat release rate and can easily be extinguished with water. Once the compartment fire is suppressed, suppression should pivot to confining the fire to the battery. Water flow should be limited to exposure protection and preventing the passenger compartment from (re-)igniting while allowing the battery to burn itself out. Copious use of water is discouraged. Use of copious amounts of water demonstrated little impact on cooling the battery, even with improved access by tilting the vehicle on its side. Vehicle construction analysis shows that the water applied to the battery enclosure will not reach the interior of the battery, making it ineffective for stopping thermal runaway propagation.

Instead, water should be intermittently applied to cool the passenger compartment and prevent its reignition. If necessary, a fog stream can be used to redirect flaming gases away from exposures. Use of a fog stream may extinguish the flaming gases, but the production of flammable gases will continue as thermal runaway continues in the battery pack. If available, water can be directed into the battery via openings resulting from the fire or designed vents in the pack. This may increase cooling inside the battery, but is not likely to interrupt thermal runaway. Penetrating the battery or creating new openings are not recommended, particularly if flaming has never occurred. Doing so could risk causing thermal runaways, which may defeat the purpose of the effort, and may also introduce risks to the firefighters working to penetrate the battery.

While water suppression will produce contaminated runoff, suppression will limit the further production of contaminants and thus reduce airborne chemical exposure overall. Fire suppression should be followed by an observation period as reignitions are possible when the battery does not completely burn out. Generally, reignition risk is understood to reduce over time, but must be assumed to be present until the vehicle is physically relocated to a salvage area, as is explained in greater detail in 5.3.4. It is recommended that firefighters escort the damaged vehicle as it is transported to a salvage area in the event of a reignition. At the salvage area, the vehicle should be stored in a location accessible to the fire department with a quarantine distance of at least 5 m (16 ft) from any combustibles.

5.2.2 EV Fire blanket

Although an EV fire blanket will not stop the battery fire, the use of a fire blanket may be helpful to limit the fire and protect exposures if there is no water available, or if the use of water would pose an unacceptable runoff water contamination risk, such as near public water supplies or sensitive environmental areas. However, incident commanders must understand how the deployment of an EV fire blanket changes the risk profile of an incident.

A fire blanket with suitable construction[1] was demonstrated to be effective for establishing initial control of flaming when the deployment process was efficient and fast. However, it was demonstrated that fire blankets cannot control propagation of thermal runaway inside the battery pack. Fire blanket deployment visibly reduced the output and reach of the fire plume, but the blankets did not contain the smoke and vent gases produced by ongoing thermal runaway. Following a blanket deployment, there are two environments in which a deflagration hazard may emerge. The first environment develops beneath the blanket, where flammable gases accumulate in the presence of ignition sources. The second environment is the operational area around the vehicle. Smoke emanating from beneath and through the blanket may accumulate if operating in an enclosed or partially enclosed space.

The first environment exists under the fire blanket and develops conditions in which only the introduction of air is necessary to produce a reignition that may result in a flash-fire, fireball, or fast-moving deflagration. Air may be introduced quickly if the blanket is lifted for any reason before these gases have dissipated, and air is also introduced as the gases diffuse through the blanket and into the atmosphere. It is currently unclear how severe a deflagration needs to be to risk injuries, but the deflagration that occurred in E-FM-B was severe enough to potentially cause severe harm to firefighters close enough to the release of energy. Deflagrations occurred both after manually lifting the blanket and after externally visible, flammable gases had dissipated long after the blanket was initially applied.

The second hazardous environment forms in the vicinity of the vehicle, where firefighters may be operating. This area may be at risk for flash fires or deflagrations if the smoke accumulates in concentrations above the lower flammability limit. This environment also increases chemical exposure hazard, as operating firefighters may be exposed to unburned smoke and vapors emanating from the battery. If this environment develops in an enclosed space, such as in an underground parking structure, the flammable gases resulting from battery thermal runaway and/or unburnt pyrolysates may form an explosive atmosphere. For this reason, it is inadvisable to use an EV fire blanket indoors or in confined spaces.

[1] Fire blankets must withstand the thermal insult of a fire without falling apart, and be resistant to tearing during use. DIN SPEC 91489 [118] was not yet published when these experiments were carried out. The blanket model that was used in that experimental campaign is now advertised as conforming to the requirements of this standard.

5.2.2.1 Tactical Guidance

If an EV fire blanket is to be deployed, the firefighters should be familiar with the deployment procedure of their specific blanket and deploy it according to manufacturer instructions. At least two firefighters should deploy the blanket, with four being ideal, to ensure that the blanket is quickly applied and made to have uniform and intimate contact with the ground, smoothing any wrinkles that could allow airflow under the blanket. The use of taglines may help firefighters keep a greater distance to the vehicle during deployment or removal, while brooms can be used to seal the blanket with the ground. Once a fire blanket has been deployed, firefighters should maintain a safe distance and not manipulate the blanket in any way, as doing so can potentially introduce oxygen under the blanket and lead to reignition or deflagration. This includes lifting and repositioning the blanket. Should it become necessary to manipulate the blanket, the blanket should be removed completely. A charged hoseline should be on standby throughout the duration of fire blanket deployment. A gentle fog stream can be used to extinguish flaming outside of the blanket. However, care should be taken, as applying a hose stream to the blanket may result in displacement, loss of seal and reignition of escaping gases.

Personnel should seek to exercise high situational awareness and remain clear of the covered vehicle and refrain from leaning any tools against the vehicle that could become projectiles in the event of a deflagration. While deflagrations can occur without warning, the following signs were observed in experiments that featured deflagrations. Absence of these signs does not exclude the possibility of a deflagration.

- Blanket deployment time of less than one hour
- Current or prior evidence of battery involvement (e.g., thick, white or grey smoke seeping from under the blanket)
- Current or prior manipulation of the EV fire blanket
- Prior occurrence of reignition/deflagration
- Bloated appearance of the fire blanket

All personnel operating in the vicinity of the vehicle must wear structural firefighting PPE and use an SCBA. Even while on air, contact with smoke and battery exhaust gases should be minimized or eliminated, where possible. Appropriate decontamination procedures as described in Section 5.3.3 should occur after every fire.

Using an EV fire blanket, the incident can be resolved with little to no water usage. However, this incident resolution time becomes more difficult to determine and will likely lie above two hours. The blanket will be heavily contaminated after use and should be disposed of properly.

5.2.3 Non-Intervention

A non-intervention strategy is tactically the simplest, as the vehicle will stop burning once all the fuel has been consumed. Likewise, the thermal runaway in the battery will subside once all the cells have reacted. Consequently, the risk of reignition due to stranded energy will be reduced[1].

Non-intervention may be a viable strategy if there are no immediate exposures and if a water-based attack is not possible. Letting the vehicle burn out may also be favorable if using water presents an unacceptable chemical exposure hazard, such as runoff which may threaten public water supplies. However, letting the vehicle burn out may result in increased smoke exposure, conflict with department procedures, or risk damaging the public perception of the fire department. Conditions should be continuously reevaluated to determine if non-intervention remains the best course of action.

The incident resolution time for letting the vehicle burn out will likely be less than that for deploying an EV fire blanket. In the experiments, vehicles burned out in approximately 40 to 80 minutes. In most cases, a total incident resolution is expected in about 90 minutes. Burnout will likely result in the greatest airborne chemical contaminant release as production of harmful species will continue even after the flaming fire subsides.

5.3 Operational Considerations for EV Fire Response

There are additional factors that may play a role on the scene of an EV incident that first responders might need to address.

5.3.1 Electrical Hazards

The high voltage systems of electric vehicles are designed with redundant safeguards in place to prevent hazardous voltages from forming where responders can come into contact with them. Nonetheless, the performance of these systems after a fire cannot be guaranteed. Previous research, such as Hessels 2024 [26], has shown that the electrical hazard to firefighters during EV fire suppression efforts is low, although it may be higher for personnel directly in contact with the vehicle, such as during overhaul or inspection, where there is a possibility of coming into direct contact with damaged elements carrying a hazardous voltage.

In these experiments, the electrical hazard was related to the degree of involvement of the battery and electrical system in the fire. Risk was higher when thermal damage was present, with damage to electrical insulation and the loss of high voltage isolation while battery modules remained intact. One experiment demonstrated that a battery can be opened by a fire and have physically accessible

[1] Although it cannot be eliminated.

components with a voltage potential present in the course of standard firefighting operations. The risk is lowest when the battery was completely destroyed. However, even when the battery was completely destroyed, assessment of the electrical risk required specialized tools and training outside of the scope of first- and second responders. Responders should use caution whenever direct contact with the vehicle is made.

5.3.2 Thermal Runaway Without Flaming

Incidents involving an electric vehicle off-gassing in the absence of flames should be treated as an imminent battery fire with the potential to escalate to flash fire or explosion hazard if the vehicle is in a confined area where unburned gases can accumulate. This can occur in a space like a residential or commercial parking garage. It is recommended that full structural firefighting PPE with self-contained breathing apparatus be worn, a charged hoseline should be prepared and kept available, and the vehicle should be supervised while the battery is left to react. Firefighters should keep an adequate distance, as sudden ignition of the vent gases is possible. 4- or 5-gas measurements may provide qualitative information on the atmosphere around the vehicle, however, due to the potential for cross-sensitivities between CO and H_2 some readings for CO and lower explosive limit may not be trustworthy. In all cases, areas impacted by vent gases should be evacuated. Presently, it is not possible to provide ventilation guidance because there have been few incidents and no experiments on which to base recommendations. However, the U.S. Department of Homeland Security has recently awarded a grant for research to develop guidance on this concern.

5.3.3 Chemical Exposure

Both EV and ICEV fires can result in chemical exposures with potential health risks. Vehicle fires without battery involvement (such as EVs with cabin-only fires or ICEV fires) can produce similar concentrations of organic compounds (PAHs and VOCs) and inhalable particulates. However, EV fires with battery involvement can produce smoke with significant concentrations of particulate fluoride and metals, specifically those found in the battery (nickel, manganese, and cobalt). Due to the presence of these compounds with known negative health impacts, vehicle fire smoke presents significant acute and chronic exposure hazards. For this reason, civilians should be evacuated from areas impacted by smoke and occupants of impacted buildings should be advised to shelter in place, or evacuated, regardless of the type of vehicle on fire. Any fire personnel operating on scene should be wearing full structural fire PPE. Responders who may be exposed to the fire effluents should utilize self-contained breathing apparatus. Furthermore, firefighters should take precautions to avoid operating in the smoke and limit contact with debris and runoff water whenever practically possible. Potentially harmful compounds from the smoke and debris may deposit onto, and possibly penetrate into, the turnout gear. Nitrile gloves should be worn when handling turnout gear, tools, and equipment that has been contaminated with solid particulate, as such contamination may subject responders to secondary exposures until it has been properly cleaned. Staging and approaching the fire from upwind, attacking the fire from a distance by utilizing the range of the hose stream, and minimizing time near the vehicle can potentially reduce chemical exposure.

Following vehicle fires, regardless of propulsion type, all firefighters that operated near the fire should utilize contamination control strategies such as on-scene preliminary exposure reduction per NFPA 1850, skin cleaning, and gear bagging prior to rehab[1]. Contaminated gear should be transported in a separate compartment to reduce contamination of the crew compartment when returning to quarters. Turnout gear should be properly cleaned according to NFPA 1850 / 2026 edition before being returned to service and responders should shower, change, and launder their clothes as soon as practically possible after returning from the incident.

5.3.4 EV Battery Reignition Risk

The risk of reignition is present until the battery is manually discharged or destroyed after any incident involving a LiB. After the fire appears extinguished, damaged cells may still contain stored electrochemical energy. These cells may enter thermal runaway without intentional external stimulus. These delayed thermal runaway events can be categorized as 'reignition.' This should be treated as the default for all incidents involving a battery, including a complete burnout through non-intervention, but risk is particularly high where the state of the battery is unknown. Once the battery has been damaged, agitation such as jostling the car during handling and transport can increase the risk of reignition, as elements of the battery construction or individual cells can move and create shorts leading to new thermal runaway events.

Based on these EV experiments, other battery research, and incidents in which reignition has occurred months after the initial incident, the risk of reignition is highest immediately after the flaming fire is out, and this risk drops as the hot and damaged battery cools off. However, the risk should never be considered to drop to zero (see Figure 5.1) unless the battery can be visually confirmed to be completely burned out. The high thermal mass of the battery means that the process of cooling to ambient may take many hours and temperatures high enough to induce thermal runaway in remaining cells may persist even if the outside of the pack has cooled. Furthermore, stranded electrical energy still presents a hazard, even once the thermal energy from the initial fire has dissipated. Short-circuiting damaged battery pack components or within a damaged cell may induce thermal runaway suddenly. Once these shorted cells dissipate their stored energy the reignition risk is then likely greatest during handling, where damaged/loose parts can cause new external/internal short circuits. Once the initial thermal energy has dissipated, the remaining hazard due to the remaining charged and intact cells, slowly declines over time based on the self-discharge rate of the damaged battery. The self discharge rate for a battery in normal operating condition is typically cited to be 1–5 % per month [119].

[1] Contamination control approaches and rehab should happen in different locations on scene.

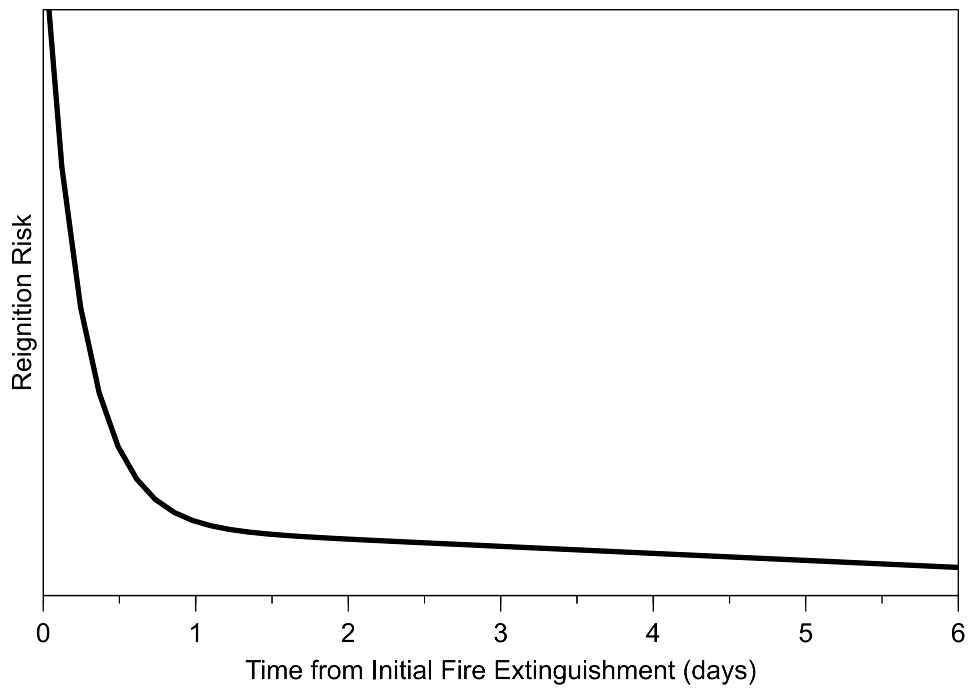


Figure 5.1: Qualitative suggestion of EV battery reignition risk after initial fire extinguishment.

5.3.5 Incident Termination

All fire damaged EVs should be treated as reignition risks regardless of the means of fire control used during the incident. Therefore, it is recommended that all vehicles be escorted from the scene by a suppression unit to a safe storage location (e.g., 5 m (16 ft) from anything combustible in a salvage yard).

Experiments demonstrated that the most likely drivers of reignition risk were high vehicle temperatures and physical movement. A reignition was observed in E-FM-B when the blanket was removed because the vehicle was still hot enough for a hot surface reignition. Reignitions were observed in experiment E-TM-S both while the battery was at a high temperature after suppression, and during the process of physical relocation. It is likely not practical to wait for an EV to cool to ambient temperature, and waiting longer provides diminishing returns in reducing reignition risk. Therefore, vehicles should be removed at the discretion of the incident commander based on when the vehicle is at a low enough temperature to be safely handled by firefighting staff and without risking thermal damage to the tow vehicle. Inspection guidelines are provided in the Decision Aid to support assessing significant risks of battery reignition.

The inspection should include ensuring that no factors of continued battery involvement, or imminent risk of reignition are present. The vehicle should be assessed for smoking, sounds, and temperature conditions. Smoking or steaming likely indicates continued heat generating activity, or cells that may have safety vents opened and are releasing unburned electrolyte vapors. Sounds may include clicking, hissing, or popping which can indicate the activation of cell safety features, the release of cell contents under pressure in a buildup to a cell thermal runaway, or it may indicate hot metal surfaces expanding or contracting. Finally, since cells can be induced into thermal runaway by heating, hot spots or overall above ambient temperatures can indicate the risk of reignition as heat spreads through now heat-impacted cells. Once these factors have stopped presenting themselves, the reignition risk can be considered as low as it can be assessed on-scene without specialized tools.

Once the observation period has been completed, the vehicle can be transferred to second responders. Due to the increase in reignition risk inherent to moving the vehicle, personnel operating around the vehicle should remain on air when operating around the vehicle, even if no hazards appear present. Fire departments should strongly consider escorting the tow truck to the tow lot with a suppression unit to allow for rapid recognition of a reignited vehicle in transport and suppression, if necessary. A quarantine distance of at least 5 m (16 ft) should be used at the tow lot to prevent fire spread in the case of delayed reignition.

6 Conclusions

The previous chapters have presented the results of a multi-year study on the electric vehicle fire dynamics and the effectiveness of water suppression, EV fire blanket, and non-intervention control strategies for Electric Vehicle (EV) fires. Nine free burn experiments were conducted (3 ICEVs and 6 EVs) to examine the vehicle fire dynamics where the vehicles were allowed to burn completely without intervention. Nine additional EVs were ignited, and different fire control strategies (handline, handline with water additive, fire blanket, fire blanket with under-vehicle nozzle) were used to evaluate fire control strategy effectiveness, as well as important operational considerations. In total 18 vehicles were burned under realistic, but controlled laboratory conditions with appropriate instrumentation to answer the research questions presented in Section 1.2 and draw the following conclusions:

6.1 EV Fires Burn Similarly to ICEVs

The data resulting from the free burn experiments demonstrated that fire dynamics and associated chemical hazard in both EVs and ICEVs are primarily driven by the fire in the passenger compartment materials, and thus were similar between powertrain types. The time to burnout, peak heat release rate, and total energy release were similar between EVs and ICEVs. EV fires did show a greater variability in fire growth rate, exhibiting both faster and slower growth rates than their combustion engine counterparts. Through analysis of vehicle construction and video review, this appears to be due to the length of time between the first recognition of thermal runaway and the amount of time it took for flames to emerge from the battery and then involve the vehicle chassis in the fire, usually from the outside-in. Though anecdotally there have been concerns about major differences in EV fire behavior, no evidence was found that EVs burn hotter, or last longer than their conventional counterparts. EVs demonstrated resistance to fire growth for a significant period of time followed by rapid fire growth once the battery became involved.

6.2 EVs Produce Additional Chemical Contaminants but Firefighting Exposure Control Guidance Remains Unchanged

Many compounds, especially PAHs and VOCs, were found in similar quantities or concentrations between EV and ICEV fires, especially those associated with combustion of the materials found in the passenger compartment. However, EV fires showed elevated levels of nickel, manganese and cobalt, metals that are associated with NMC battery chemistry. HF was found in limited quantities for both powertrain types, although particulate fluoride levels were elevated in the EV fire experiments.

Results from the chemical exposure characterization indicate that prompt suppression of the vehicle fire will reduce the overall chemical exposure to firefighters and the public. While production of contaminated water runoff will be unavoidable, it will likely be preferable to ongoing smoke exposure. Examination of PPE samples shows that firefighting turnout gear provides important but limited protection against chemical exposure, both for EVs and fires involving ICEVs. Regardless of powertrain type, the full structural PPE ensemble, including SCBA should be worn by everyone operating near the vehicle. If possible, firefighters should attempt to limit contact with smoke and debris by making use of the reach of the hose stream, and by approaching from the upwind direction. Firefighters returning to staging or rehab should undergo preliminary exposure reduction while still breathing from SCBA and all exposed turnout gear should be bagged on scene, transported to quarters separately from staff, and cleaned according to manufacturer instructions. Firefighters should shower and launder any clothes worn under the turnout gear promptly upon returning to quarters.

Preliminary results from surface contamination measurements indicate that residue from EV fires has a different chemical contaminant profile than that of ICEV fires. Both powertrain types produced PAHs, but EVs produced unique metal ion contaminants. High concentrations of the NCM battery metals nickel, manganese and cobalt, as well as lithium, were detected, with nickel present at the highest concentrations.. These metals were not detected in the samples for ICEVs. While PAHs tend to disperse over time, metal ions may persist and become re-aerosolized during cleanup operations. Fluoride particulate may react with water from suppression or sweat to form hydrogen fluoride. First and second responders working around or handling post-fire EV debris should wear respiratory protection equipment, nitrile gloves and protective clothing to prevent dermal contact with contaminated surfaces, and shower and launder any clothes worn as soon as possible after work concludes.

6.3 Standard Firefighting Equipment is Effective for EV Fires

Data indicates that the majority of EV fires do not involve the battery initially [33]. Accordingly, if a fire attack is mounted before battery involvement occurs, the incident resolution will be accelerated.

Results from the suppression experiments indicate that the cabin fire is readily suppressed with water and can be extinguished in under a minute with less than 760 L (200 gal) of water. Continuous water flow to suppress the burning battery proved ineffective and wasteful. Limiting water flow to exposure protection and preventing the passenger compartment from (re-)igniting while allowing the battery to burn itself out led to incident resolution in under 30 min with only 2900 L (760 gal), indicating that copious application of water to the battery pack is ineffective and unnecessary. The use of F-500 did not have an observable impact on the effectiveness of handline suppression over water.

6.4 Fire Blankets Are Effective for Cabin Fire Control but Can Complicate Risks When Deployed Over an Involved Battery

EV fire blankets were able to quickly control the flaming cabin fire if they were applied and brought into intimate contact with the ground efficiently; however, propagation of thermal runaway in the battery and the associated production of flammable gases continued. One of the blanket experiments exhibited a deflagration following the lift and release of the blanket, due to the introduction of oxygen into an atmosphere that was above the flammable limit. Utilizing the fire blanket and an under-vehicle nozzle (UVN) did not appear to improve the efficacy of the blanket and resulted in the use of significant amounts of water, negating the main benefit of the fire blanket strategy. In one of the blanket & UVN experiments, emission of a large deflagration and flame was caused by the activation of the UVN. Notably, potentially dangerous fire behavior could persist for significant periods of time after blanket deployment, even if the external conditions have appeared to improve.

The results of the EV fire blanket experiments show that while fire blankets can be useful in certain situations, they change the hazard profile of the incident in meaningful ways that should be considered prior to their adoption and deployment. In particular, once deployed, the blanket should not be disturbed for at least one hour after the last observed smoke or fire emanating from under the blanket. It is inadvisable to deploy a fire blanket on an EV burning indoors or in a confined environment due to the danger of flammable gases accumulating and forming an explosion hazard.

6.5 Guidance for Controlling EV Fires

Immediately Suppress EV Fire With Water While Protecting Exposures

Suppression with a handline with water (no additives) is recommended as the first choice of suppression strategy, similar to a conventional vehicle fire attack. The use of tools designed to introduce water directly into the battery pack was not examined in this work. However, firefighters should not open or pierce the battery pack outer case. See Section 5.2 for further details.

Fight the Vehicle Fire First, the Battery Fire Second

The fire in the passenger compartment represents a significant portion of the thermal and chemical exposure hazard and will readily respond to water. Rapid suppression of the cabin fire reduces the thermal and chemical exposure hazard to surrounding objects, civilians and first responders, especially if battery involvement is prevented.

The battery fire is best controlled by supervising the battery fire until thermal runaway stops. Water should be applied intermittently to prevent reignition of the rest of the vehicle and redirect flames from exposures if necessary. Applying copious amounts of water to the battery enclosure is wasteful and will not stop thermal runaway. Likewise, introducing water into an uninvolved battery may increase (re-)ignition risk. See Section 5.2.1.1 for details.

Use Caution if Deploying Fire Blankets

Fire blankets, while not recommended as the first choice in suppression strategy, may be effective under limited operational scenarios. They will not stop thermal runaway or the resulting production of flammable gases, and they limit firefighters' ability to monitor the vehicle. Firefighters should not manipulate the blanket once it is deployed and remain cognizant of the latent reignition and deflagration hazard. It is inadvisable to use fire blankets in areas where flammable gases may accumulate and form an explosive atmosphere, such as indoors. Fire blankets should remain undisturbed for at least one hour after the last visible fire or smoke emanating from under the blanket. See Section 5.2.2 for a detailed discussion of the use of fire blankets.

Limit Chemical Exposure

Regardless of powertrain type, all firefighters operating near vehicle fires should wear full structural PPE and make use of an SCBA if they may be exposed to smoke, including non-flaming emissions from a battery. Contact with smoke, debris and runoff water should be minimized wherever practically possible. Bystanders should be evacuated from areas that are impacted by smoke or shelter in place. Additionally, initiating firefighting interventions will likely reduce airborne chemical exposure to the public.

Exposure to thermal runaway smoke can occur in the absence of fire and may continue throughout an active fire, even after flaming has been extinguished. Due to the smoke appearance, it may be confused with steam. Firefighters should continue to use their SCBA when overhauling or inspecting the vehicle to protect themselves in the event of sudden reignition, even if the vehicle appears inert.

On-scene preliminary exposure reduction should occur before unclipping the SCBA regulator by brushing or rinsing. Exposed turnout gear should be removed and bagged on scene and transported separately from the crew compartment, and cleaned according to manufacturer instructions. Firefighters should shower and launder their clothes upon returning to quarters. See Section 5.3.3 for a more detailed discussion.

After the Fire

Following extinguishment, the vehicle should be observed for reignition risk to identify any ongoing hazards. Release of the vehicle should occur after inspection has identified the relative reignition risk. Even if the battery appears to have burnt out, it cannot be excluded that moving the vehicle may cause a short circuit and subsequent reignition of remaining intact cells. For this reason, firefighters should remain vigilant and continue to use an SCBA during overhaul and inspection. Fire departments should consider escorting the tow truck to the tow lot to ensure rapid identification and suppression should reignition occur. A quarantine distance of at least 5 m (16 ft) to any other combustible object should be left at the salvage yard.

EV Fire Tactical Decision Aid

The recommendations outlined above have been incorporated into an EV Fire Tactical Decision Aid that outlines the recommendations in the framework of the overall incident response. The complete Decision Aid is attached to this report in Appendix B. An explanation of the Decision Aid is given in Appendix C. The Decision Aid will also be permanently hosted, with any updates, at https://training.fsri.org/resources/462/electric-vehicle-fire-tactical-decision-aid-passenger-vehicle.

6.6 Recommendations for Vehicle Manufacturers

Overcoming the challenges associated with EV fire suppression will likely require continued advances in battery and vehicle safety engineering alongside improvements in firefighting tools and tactics. From a fire service perspective, one of the primary challenges observed throughout this research was the difficulty of controlling propagation by delivering water to the cells undergoing thermal runaway within the battery pack. While battery safety, crashworthiness, manufacturability, cost, and performance all impose important design constraints beyond the scope of this work, these findings suggest that designs which facilitate better firefighter access to the battery during rare but severe fire events may warrant further consideration. One example is the Renault Zoe, which incorporates a firefighter access port beneath the rear seat that allows water to be introduced into the battery enclosure once the cover has burned away [120]. There are significant cautions about implementing such a design, including providing a pathway for battery effluent to enter the passenger compartment and thus creating an explosion hazard. This method demonstrates one possible approach to incorporating firefighting considerations into vehicle design. Likewise, greater standardization of responder-facing features, such as high-voltage disconnects, vent locations, and safety markings, could simplify emergency operations across manufacturers.

The thermal runaway initiation methods used in this study were intentionally severe to produce representative, well-developed battery fires. Nevertheless, little evidence was observed that battery pack construction substantially limited cell-to-cell thermal runaway propagation once propagation had begun. Continued advances in battery cells, chemistries, and pack designs that improve resistance to thermal runaway propagation, while balancing the many competing objectives of vehicle design, could reduce the resources required for fire suppression and improve responder safety. Ongoing collaboration and open communication between vehicle manufacturers, battery developers, researchers, and the fire service will likely be important in achieving these goals.

References

[1] Know the hazards from Lithium-Ion Batteries, 2025. URL https://fsri.org/research-update/online-training-available-science-fire-and-explosion-hazards-lithium-ion-batteries.

[2] M. Janssens. Development of a Database of Full-Scale Calorimeter Tests of Motor Vehicles. Technical report, SAE International, April 2007. URL https://saemobilus.sae.org/papers/development-a-database-full-scale-calorimeter-tests-motor-vehicles-2007-01-1233.

[3] Mohd Zahirasri Mohd Tohir. *Multiple Vehicle Design Fire Scenarios in Car Parking Buildings*. PhD thesis, University of Canterbury, Christchurch, New Zealand, 2015.

[4] Peiyi Sun, Roeland Bisschop, Huichang Niu, and Xinyan Huang. A Review of Battery Fires in Electric Vehicles. *Fire Technology*, 56(4):1361–1410, July 2020. ISSN 0015-2684, 1572-8099. doi:10.1007/s10694-019-00944-3.

[5] Bartosz Miechówka and Wojciech Węgrzyński. Systematic Literature Review on Passenger Car Fire Experiments for Car Park Safety Design. *Fire Technology*, February 2025. ISSN 0015-2684, 1572-8099. doi:10.1007/s10694-025-01701-5.

[6] J Santrock. Demonstration of enhanced fire safety technology-fire retardant materials-part 1, Full scale vehicle fire tests of a control vehicle and a test vehicle containing an HVAC module made from polymers containing flame retardant chemicals. *NHTSA Document*, 1998-3588:190, 2002.

[7] J Santrock. Evaluation of Motor Vehicle Fire Initiation and Propagation Part 3: Propagation of an Engine Compartment Fire in a 1996 Van Passenger. *NHTSA Document*, NHTSA-1998-3588-119, 2001.

[8] J Santrock. Evaluation of Motor Vehicle Fire Initiation and Propagation Part 4: Propagation of an Underbody Gasoline Pool Fire in a 1996 Passenger Van. *NHTSA Document*, NHTSA-1998-3588-188, 2002.

[9] J Santrock. Evaluation of motor vehicle fire initiation and propagation. Part 6. Propagation of an underbody gasoline pool fire in a 1997 rear wheel drive passenger car. *NHTSA Document*, NHTSA-1998-3588-158, 2002.

[10] J Santrock. Evaluation of motor vehicle fire initiation and propagation, part 7: Propagation of an engine compartment fire in a 1997 rear wheel drive passenger car. *NHTSA Document*, NHTSA-1998-3588-178, 2002.

[11] J Santrock. Evaluation of Motor Vehicle Fire Initiation and Propagation Part 9: Propagation of a Rear-Underbody Gasoline Pool Fire in a 1998 Sport Utility Vehicle. *NHTSA Document*, NHTSA-1998-3588-188, 2002.

[12] J Santrock. Evaluation of Motor Vehicle Fire Initiation and Propagation Part 10: Propagation of a Mid-Underbody Gasoline Pool Fire in a 1998 Sport Utility Vehicle. *NHTSA Document*, NHTSA-1998-3588-189, 2002.

[13] J Santrock. Evaluation of Motor Vehicle Fire Initiation and Propagation Part 12: Propagation of an Underbody Gasoline Pool Fire in a 1998 Front-Wheel Drive Passenger Vehicle. *NHTSA Document*, NHTSA-1998-3588-201, 2003.

[14] J Santrock. Evaluation of Motor Vehicle Fire Initiation and Propagation Part 13: Propagation of an Engine Compartment Fire in a 1998 Front-Wheel Drive Passenger Vehicle. *NHTSA Document*, NHTSA-1998-3588-203, 2003.

[15] Nathaniel G. Sauer, Jonathan L. Hodges, and Matthew J. DiDomizio. Probabilistic design fire scenarios for performance-based design involving passenger vehicles. *Fire Safety Journal*, 162:104721, July 2026. ISSN 03797112. doi:10.1016/j.firesaf.2026.104721.

[16] Giovanni Di Cristina, Matthew Bundy, and Anthony Hamins. Vehicle Fires in a WUI-Type Scenario. In *8th International Conference on Fires in Vehicles*, 2025.

[17] Magnus Arvidson and Örjan Westlund. Water Spray Fire Suppression Tests Comparing Gasoline-Fuelled and Battery Electric Vehicles. *Fire Technology*, 59(6):3391–3414, November 2023. ISSN 0015-2684, 1572-8099. doi:10.1007/s10694-023-01473-w.

[18] Jaime Bleye and Covadonga Suarez. Development and testing of APV firefighting routines, equipment, and tactics. Technical Report D06.8, RISE Research Institutes of Sweden, Sweden, June 2023. URL https://lashfire.eu/media/2023/10/LASH-FIRE_D06.8_-Development-and-testing-of-APV-firefighting-routines-equipment-and-tactics.pdf.

[19] Elena Funk, Konrad Wilkens Flecknoe-Brown, Thushadh Wijesekere, Bjarne P. Husted, and Blanca Andres. Fire extinguishment tests of electric vehicles in an open sided enclosure. *Fire Safety Journal*, 141:103920, December 2023. ISSN 03797112. doi:10.1016/j.firesaf.2023.103920.

[20] Ana Olona and Luis Castejon. Full-Scale Experimental Analysis of the Behavior of Electric Vehicle Fires and the Effectiveness of Extinguishing Methods. *Fire*, 8(8):301, July 2025. ISSN 2571-6255. doi:10.3390/fire8080301.

[21] Maria Quant, Ola Willstrand, Tove Mallin, and Jonna Hynynen. Ecotoxicity Evaluation of Fire-Extinguishing Water from Large-Scale Battery and Battery Electric Vehicle Fire Tests. *Environmental Science & Technology*, 57(12):4821–4830, March 2023. ISSN 0013-936X, 1520-5851. doi:10.1021/acs.est.2c08581.

[22] Peter Sturm, Patrik Fößleitner, Daniel Fruhwirt, Robert Galler, Robert Wenighofer, Simon Franz Heindl, Stefan Krausbar, and Oliver Heger. Fire tests with lithium-ion battery electric vehicles in road tunnels. *Fire Safety Journal*, 134:103695, December 2022. ISSN 03797112. doi:10.1016/j.firesaf.2022.103695.

[23] Chenxi Zhao, Wenhao Hu, Di Meng, Wenzhong Mi, Xuehui Wang, and Jian Wang. Full-scale experimental study of the characteristics of electric vehicle fires process and response measures. *Case Studies in Thermal Engineering*, 53:103889, January 2024. ISSN 2214157X. doi:10.1016/j.csite.2023.103889.

[24] Michael Neske, Julia Kaufmann, Daniel Butscher, and Christoph Vogel. Evaluierung von Technischen Verfahren zur Löschmitteleinbringing in Hochvoltspeicher: Untersuchungen zum einsatztaktischen Mehrwert gegenüber anderen Löschtechniken und -taktiken bei Vollbränden und Entstehungsbränden. Technical Report 210/216, Institut für Brand- und Katastrophenschutz Heyrothsberge, 2025. URL https://ibk-heyrothsberge.sachsen-anhalt.de/fileadmin/Bibliothek/Politik_und_Verwaltung/MI/IDF/IBK/Dokumente/Forschung/Fo_Publikationen/imk_ber/IMK_210_216.pdf.

[25] Myndigheten for Samhallsskydd och Beredskap. Demonstration av släckmetod för litiumjonbatterier: Metodtillämpning på olika aggregationsnivåer – modul, sub-batteri, elbilspack och fordonsnivå. Technical Report MSB2184, Myndigheten for Samhallsskydd och Beredskap (MSB), 2023. URL https://ctif.org/sites/default/files/2023-03/Putting%20out%20battery%20fires%20with%20water.pdf.

[26] T Hessels and H Brans. Fire experiment to examine the use of ultra high pressure extinguishing systems for fires in batteries of electric vehicles. Technical report, Netherlands Academy for Crisis Management and Fire Service, Nederlands Instituut Publieke Veiligheid (NIPV), Arnhem, the Netherlands, November 2024. URL https://nipv.nl/wp-content/uploads/2024/11/20241126-NIPV-Fire-experiment-to-examine-use-of-UHD-extinguishing-systems-for-fires-in-batteries-electric-vehicles.pdf.

[27] Alexander Kleinman, Nicklas Koch, Konrad Brown, Elena Funk, Thushadh Wijesekere, Bjarne P. Husted, Blanca A. Valiente, Sean Meehan, and Carsten Møller. The ELBAS Project - Electric Vhicle Fires at Sea: New Technologies and Methods for Suppression, Containment and Extinguishing of Battery Car Fires Onboard Ships. Technical Report DBI-ELBAS-FIXFU21008, Danish Institute of Fire and Security Technology, Hvidovre, Denmark, December 2022. URL https://brandogsikring.dk/files/Pdf/FogU/ELBAS/DBI%20ELBAS%20Report%20-%20Executive%20Summary%20-%20Final%20(rev.%201).pdf.

[28] T Hessels and T Geertsema. Onderzoek dompelcontainers. Technical report, Nederlands Instituut Publieke Veiligheid, Arnhem, February 2023. URL https://nipv.nl/wp-content/uploads/2023/03/20230206-NIPV-Onderzoek-dompelcontainers.pdf.

[29] Lotta Vylund, Pierrick Myndikowski, and Krister Palmkvist. Methods and equipment for fire fighting with alternative fuel vehicles in ro-ro spaces. Technical Report 2019:90, RISE Research Institutes of Sweden, 2019. URL https://www.diva-portal.org/smash/get/diva2:1703440/FULLTEXT01.pdf.

[30] Arnaud Bordes, Arnaud Papin, Guy Marlair, Théo Claude, Ahmad El-Masri, Thierry Durussel, Jean-Pierre Bertrand, Benjamin Truchot, and Amandine Lecocq. Assessment of Run-Off Waters Resulting from Lithium-Ion Battery Fire-Fighting Operations. *Batteries*, 10(4):118, March 2024. ISSN 2313-0105. doi:10.3390/batteries10040118.

[31] NW van Veen, EM van Putten, F Bakker, ME Boshuis-Hilverdink, and PAM Heezen. Meetresultaten bij branden met elektrische voertuigen en gebruik van ultrahogedruk snijen blussystemen. Onderzoek van rook, depositie en bluswater. Technical report, National Institute for Public Health and the Environment, 2025. URL https://www.rivm.nl/bibliotheek/rapporten/2025-0072.pdf.

[32] Julia Kaufman, Sandra Wegner, Christian Heiser, and Martine Schadach. Belastung der Persönlichen Schutzausrüstung und des Löschwassers durch Schwermetalle bei der Brandbekämpfung von Hochvoltspeichern, August 2025. URL https://ibk-heyrothsberge.sachsen-anhalt.de/fileadmin/Bibliothek/Politik_und_Verwaltung/MI/IDF/IBK/Dokumente/Forschung/Fo_Publikationen/imk_ber/20250804_Bericht_PSA_Metalle_final.pdf.

[33] Netherlands Institute for Public Safety. Annual report 2024: Incidents with alternative fuel vehicles. Technical report, Netherlands Institute for Public Safety (NIPV), April 2025. URL https://nipv.nl/wp-content/uploads/2025/05/20250415-NIPV-Factsheet-Annual-report-2024-Incidents-with-alternative-fuel-vehicles.pdf.pdf. Factsheet.

[34] Highway Loss Data Institute. Electric vehicle noncrash fires: an exploration of the data. HLDI Bulletin 11, Highway Loss Data Institute, April 2021. URL https://www.courthousenews.com/wp-content/uploads/2022/04/highway-loss-data-report-EV-noncrash-fire.pdf.

[35] Tesla Fire: Digital record of Tesla fire incidents, 2024. URL https://www.tesla-fire.com/.

[36] Home | EV FireSafe, 2021. URL https://www.evfiresafe.com/.

[37] NERIS - The National Emergency Response Information System, 2023. URL https://neris.fsri.org/.

[38] Caleb Wethington and Marissa Sulek. Firefighters battle electric car fire for hours at Nissan HQ, used 45K gallons of water, September 2023. URL https://web.archive.org/web/20240114050444/https://www.wsmv.com/2023/09/06/firefighters-battle-electric-car-fire-hours-nissan-hq-used-45k-gallons-water/.

[39] Heather Morrison. Mass. firefighters use over 11,000 gallons of water to fight EV fire, August 2023. URL https://www.firerescue1.com/lithium-ion-battery-fires/articles/mass-firefighters-use-over-11000-gallons-of-water-to-fight-ev-fire-qT389N0a2nkfNane/.

[40] EV Fire Blanket & Car Fire Blankets, 2025. URL https://bridgehill.com/fire-blankets/.

[41] Li-Fire | Fire Blankets, Covers, & Bags, 2026. URL https://li-fire.com/.

[42] EV Fire Blankets for Lithium Battery Fires, 2026. URL https://www.avdfire.com/fire-blankets/.

[43] Brimstone Fire Protection, 2025. URL https://brimstonefireprotection.com/.

[44] Elena Luchian. Jaguar EV Catches Fire in a Garage, Firefighters Use Ground-Breaking Blanket To Put It Out, January 2024. URL https://www.autoevolution.com/news/jaguar-ev-catches-fire-in-a-garage-firefighters-use-ground-breaking-blanket-to-put-it-out-227772.html.

[45] Steven Symes. Fire Department Celebrates Using An EV Fire Blanket, March 2025. URL https://autos.yahoo.com/fire-department-celebrates-using-ev-160000112.html.

[46] Lewin Day. These Firefighters Have A Great Solution To Electric Car Fires: A Giant Blanket, August 2024. URL https://www.theautopian.com/these-firefighters-have-a-great-solution-to-electric-car-fires-a-giant-blanket/.

[47] Learn more about Potential Hazard Involving EV Fire Blankets, 2025. URL https://fsri.org/news/potential-hazard-involving-ev-fire-blankets.

[48] Cho Yong-Jun. Damage after EV explosion caused by deactivated sprinkler system, fire authorities say, August 2024. URL https://www.koreajoongangdaily.com/business/damage-after-ev-explosion-caused-by-deactivated-sprinkler-system-fire-authorities-say/11299030.

[49] Sarah Chea. 21 injured after Mercedes EV explodes in parking lot, August 2024. URL https://koreajoongangdaily.joins.com/news/2024-08-01/business/industry/Sixteen-injured-after-MercedesBenz-explodes-in-parking-lot/2103770.

[50] Tobias Stahl. Neuss: Garage mit E-Auto explodiert: Feuerwehr zeigt Fotos und schafft Fakten, September 2023. URL https://www.focus.de/auto/elektroauto/news/neuss-garage-mit-e-auto-explodiert-feuerwehr-zeigt-fotos-und-schafft-fakten_id_203425476.html.

[51] Christoph Hensgen. Batterieblock explodiert: Gross einsatz wegen brennendem E-Auto in Sankt Augustin, February 2026. URL https://www1.wdr.de/nrw/rheinland/elektroauto-brennt-sankt-augustin-100.html.

[52] VRT NWS. Wrak van ontplofte hybride auto van onder puin gehaald in Izegem | VRT NWS: Nieuws, October 2025. URL https://www.vrt.be/vrtnws/nl/2025/10/16/wrak-van-ontplofte-hybride-auto-van-onder-puin-gehaald-in-izegem/.

[53] Lottie Verrier. Hybrid car explodes in Belgium: Experts warn dual engines more dangerous, October 2025. URL https://euroweeklynews.com/2025/10/13/hybrid-car-explodes-in-belgium-experts-warn-dual-engines-more-dangerous/.

[54] Mitchell Byars. Photos: Hybrid Jeep explosion sends garage door flying, April 2023. URL https://www.firerescue1.com/vehicle-fire/articles/photos-hybrid-jeep-explosion-sends-garage-door-flying-BxvNTeJi35MHZdau/.

[55] Nathaniel G. Sauer, Benjamin Gaudet, and Adam Barowy. Experimental investigation of explosion hazard from lithium-ion battery thermal runaway effluent gas. *Fuel*, 378: 132818, December 2024. ISSN 00162361. doi:10.1016/j.fuel.2024.132818.

[56] Jeep wrangler hybrid explosion close call, November 2023. URL https://www.firefighterclosecalls.com/jeep-wrangler-hybrid-explosion-close-call/.

[57] Jamie Burch. Check this out! Submerged electric vehicle causes water to boil for 13 hours, 2025. URL https://abc7amarillo.com/news/local/check-this-out-submerged-electric-vehicle-causes-water-to-boil-for-13-hours-amarillo-fire-department-ignite.

[58] Ev fire reignition, 2021. URL https://www.evfiresafe.com/ev-fire-reignition.

[59] Yan Cui, Jianghong Liu, Beihua Cong, Xin Han, and Sumiao Yin. Characterization and assessment of fire evolution process of electric vehicles placed in parallel. *Process Safety and Environmental Protection*, 166:524–534, 2023. ISSN 0957-5820. doi:10.1016/j.psep.2022.08.055. URL https://www.sciencedirect.com/science/article/pii/S0957582022007455.

[60] EV FireSafe - Electrocution Risk, 2021. URL https://www.evfiresafe.com/04-6-risks-of-electrocution.

[61] Susan Nicol. Exposure to Tesla Battery Fumes Sidelines Sacramento, CA, Firefighters, February 2026. URL https://www.firehouse.com/safety-health/cancer-prevention/video/55355214/no-san-antonio-firefighters-have-died-from-cancer-since-2023.

[62] Sacramento Fire Department. Green sheet: Electric vehicle mva and ensuing fire—causing respiratory injuries to responding firefighters, April 2025.

[63] Jesper Wedel Jensen. Charging stations for electrical vehicles in sub terrain car parks: A study on the extent of emission of hydrogen fluoride gasses from fires in lithium-ion batteries. Technical report, Technical University of Denmark (DTU), 2021.

[64] International Association of Fire Chiefs and National Volunteer Fire Council. Survey Responses on Hybrid Eelectric and Electric Vehicles. Technical report, National Transportation Safety Board, June 2018. URL https://data.ntsb.gov/Docket/?NTSBNumber=HWY19SP002.

[65] Jun Liu, Ningzhe Xu, Yangming Shi, Timothy Barnett, and Steven Jones. Are first responders prepared for electric vehicle fires? a national survey. *Accident Analysis & Prevention*, 179:106903, 2023. ISSN 00014575. doi:10.1016/j.aap.2022.106903. URL https://linkinghub.elsevier.com/retrieve/pii/S0001457522003384.

[66] EV fire training, 2021. URL https://www.evfiresafe.com/05-ev-fire-training.

[67] Electric vehicle course, 2025. URL https://iftcentre.com/ev/.

[68] IAFF Energy Hazard Guide - IAFF, 2025. URL https://www.iaff.org/news/now-available-iaff-energy-hazard-guide/.

[69] In-person - EV/AFV incident management: Safety and response techniques, 2026. URL https://www.nvfc.org/event/in-person-ev-afv-incident-management-safety-and-response-techniques-19/.

[70] Fire service training, 2026. URL https://energysecurityagency.com/fire-service-training/.

[71] GMS training – training for alternative vehicles, 2026. URL https://gms.training/.

[72] Register for alternative fuel vehicles (AFV) online training, 2026. URL https://www.nfpa.org/product/nfpas-alternative-fuel-vehicles-training-program-ol/evt004.

[73] Electric vehicle response, 2026. URL https://www.afac.com.au/resources/ev-training.

[74] Emergency response guides | NHTSA, 2026. URL https://www.nhtsa.gov/emergency-response-guides.

[75] First responders, 2025. URL https://www.gmstc.com/index.php/first-responders.

[76] Rolf Erbe. Brandbekämpfung bei Elektrofahrzeugen und Lithium-Batterien Erkenntnisse aus Feuerwehreinsätzen, 2018. URL https://www.lfs.sachsen.de/download/Brandbekaempfung_bei_Elektrofahrzeugen.pdf.

[77] Frank Hüsch. Einsatzhinweise für alternativ angetriebene Fahrzeuge und alternative Energieträger, 2018. URL https://www.lfs-bw.de/fileadmin/LFS-BW/themen/einsatzlehre/th/dokumente/Einsatzhinweise_Alternative_Antriebe.pdf.

[78] Operational guide 2025: Emergency response for electric vehicles | CTIF - international association of fire services for safer citizens through skilled firefighters, 2025. URL https://ctif.org/node/3112.

[79] Electric vehicle (EV) safety for the first responder | TEEX.ORG, 2026. URL https://teex.org/class/cef102/.

[80] First responder safety training | naftc, 2026. URL https://naftc.wvu.edu/afv-safety-training-home/.

[81] Alternative fuel vehicle course description, 2026. URL https://www.fsi.illinois.edu/content/courses/programs/description.cfm?course_id=1348.

[82] Energy emergencies: Electric vehicles - fire engineering training, May 2025. URL https://fireengineeringtraining.com/courses/energy-emergencies-electric-vehicles/.

[83] Patrick Durham. Electric vehicle response: Fire attack and extrication basics, June 2024. URL https://www.firerescue1.com/electric-fire/articles/electric-vehicle-response-fire-attack-and-extrication-basics-PwPBmx8uuMuMOR2G/. Section: Electric Vehicles & Fire Apparatus.

[84] Electric vehicle firefighter and first responder safety training, automotive technician electric vehicle and alternative fuel vehicle training at AFV educate, 2025. URL https://www.afveducate.org/.

[85] Vehicle response training, 2026. URL https://vehicleresponsetraining.com/ev-fire-training.

[86] EV battery fire vehicle removal | firefighter training, October 2023. URL https://www.firespotlight.com/ev-battery-fire-vehicle-removal-firefighter-training/.

[87] Toxic Suppression. Electric vehicle fire solutions - introducing the spartanburg-pruitt protocol for ev fires, 2024. URL https://www.toxicsuppression.com/_files/ugd/bec483_3a9f2e9c52a04820b3217e464f6ba0f2.pdf.

[88] Hannah Ritchie. Tracking global data on electric vehicles. *Our World in Data*, February 2024. URL https://ourworldindata.org/electric-car-sales.

[89] Hinweise für die Brandbekämpfung von Lithium-Ionen-Akkus bei Fahrzeugbränden, November 2023. URL https://publikationen.dguv.de/widgets/pdf/download/article/3907.

[90] Mika Takahashi. Plug-in Hybrids Experience a Boom, but the Future Is All Electric, December 2024. URL https://www.idtechex.com/en/research-article/plug-in-hybrids-experience-a-boom-but-the-future-is-all-electric/32297.

[91] Adamas Inside. The average battery size of plug-in-hybrids is soaring, October 2023. URL https://www.adamasintel.com/ev-increase-battery-capacity-average-kwh-phev-up-27-percent/.

[92] Marklines. Automotive Sales Data, 2026. URL https://www.marklines.com/en/vehicle_sales/index.

[93] Austin Lott. 2022 GMC Hummer EV Weight, Range and Battery Size, February 2022. URL https://www.edmunds.com/car-news/2022-gmc-hummer-ev-range-battery-pack-and-weight-revealed.html.

[94] Norsk Elbilforening. 2013 nissan leaf cutaway (2). Wikimedia Commons, 2013. URL https://commons.wikimedia.org/wiki/File:2013_Nissan_Leaf_cutaway_(2).jpg. Licensed under Creative Commons Attribution 2.0 Generic (CC BY 2.0).

[95] DutchTreat. Lucid air chassis – center and rear. Wikimedia Commons, 2023. URL https://commons.wikimedia.org/wiki/File:Lucid_Air_Chassis_-_center_and_rear.jpg. Licensed under Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0).

[96] National Highway Traffic Safety Administration. Federal motor vehicle safety standard 571.305 Standard No. 305; electric-powered vehicles: Electrolyte spillage and electrical shock protection. 49 CFR § 571.305, 2024.

[97] National Highway Traffic Safety Administration. Federal Motor Vehicle Safety Standards; FMVSS No. 305a Electric-Powered Vehicles: Electric Powertrain Integrity Global Technical Regulation No. 20, Incorporation by Reference. 49 CFR § 571.305a, December 2024.

[98] Nathaniel G. Sauer, Matthew J. DiDomizio, Richard M. Kesler, Shruti Ghanekar, Parham Dehghani, Gavin P. Horn, and Adam Barowy. Measurement data from full-scale fire experiments of battery electric vehicles and internal combustion engine vehicles. *Data in Brief*, 65:112471, April 2026. ISSN 2352-3409. doi:10.1016/j.dib.2026.112471.

[99] Sungwook Kang, Minjae Kwon, Joung Yoon Choi, and Sengkwan Choi. Full-scale fire testing of battery electric vehicles. *Applied Energy*, 332:120497, February 2023. ISSN 03062619. doi:10.1016/j.apenergy.2022.120497.

[100] Parham Dehghani, Matthew J. DiDomizio, Nathaniel G. Sauer, and Adam Barowy. Heat exposure from electric vehicle fires: Experimental results and analysis. *Fire Safety Journal*, 158:104535, December 2025. ISSN 0379-7112. doi:10.1016/j.firesaf.2025.104535.

[101] Richard M. Kesler, Nathaniel G. Sauer, Adam Barowy, Chandler Probert, Danielle L. Neumann, Alexander C. Mayer, Micah Niemeier-Walsh, Kenneth W. Fent, Heather M. Stapleton, and Gavin P. Horn. Evaluation of combustion products in air from electric and internal combustion engine vehicles during full-scale fire experiments. *Fire Safety Journal*, 158: 104558, December 2025. ISSN 03797112. doi:10.1016/j.firesaf.2025.104558.

[102] Chandler A. Probert, Richard M. Kesler, Adam Barowy, R. Bryan Ormond, and Gavin P. Horn. Polycyclic aromatic hydrocarbon and metal contamination of firefighter turnout gear after full-scale electric vehicle fire exposure. *Fire Safety Journal*, page 104865, 2026. ISSN 03797112. doi:10.1016/j.firesaf.2026.104865. URL https://linkinghub.elsevier.com/retrieve/pii/S037971122600233X.

[103] Stephen Kerber. Analysis of changing residential fire dynamics and its implications on firefighter operational timeframes. *Fire technology*, 48(4):865–891, 2012.

[104] Jonathan L. Hodges, Urvin Salvi, and Anil Kapahi. Design fire scenarios for hazard assessment of modern battery electric and internal combustion engine passenger vehicles. *Fire Safety Journal*, 146:104145, June 2024. ISSN 0379-7112. doi:10.1016/j.firesaf.2024.104145. URL https://www.sciencedirect.com/science/article/pii/S0379711224000584.

[105] C T Kidd and C G Nelson. How the Schmidt–Boelter gauge really works. In *Proceedings of the 41st International Instrumentation Symposium*, volume 24, pages 347–368, Aurora, CO, 1995. Instrument Society of America.

[106] Jonathan L. Hodges, Jason E. Floyd, and Matthew J. DiDomizio. Separation of heat transfer modes in fire: Review and analysis. *Fire Safety Journal*, 153:104353, 2025. doi:10.1016/j.firesaf.2025.104353.

[107] William M Pitts, Annageri V Murthy, John L de Ris, Jean-Rémy Filtz, Kjell Nygård, Debbie Smith, and Ingrid Wetterlund. Round robin study of total heat flux gauge calibration at fire laboratories. *Fire Safety Journal*, 41(1):459–475, 2006. doi:10.1016/j.firesaf.2006.04.004.

[108] Lawrence H. Keith. The Source of U.S. EPA's Sixteen PAH Priority Pollutants. *Polycyclic Aromatic Compounds*, 35(2-4):147–160, March 2015. ISSN 1040-6638. doi:10.1080/10406638.2014.892886.

[109] Susie Proctor, Jane A. Hoppin, Sharon Zhang, Heather M. Stapleton, Detlef R.U. Knappe, and Nadine Kotlarz. Per- and Polyfluoroalkyl Ether Acid (PFEA) Concentrations in Indoor Dust are Higher in Homes Closer to a Fluorochemical Manufacturing Facility. *Environmental Science & Technology*, 59(14):7200–7210, April 2025. ISSN 0013-936X. doi:10.1021/acs.est.4c07043.

[110] Matthew J. DiDomizio and Adam Barowy. Thermal hazards from electric vehicle fires: Experimental data and predictive model. *Fire Technology*, 62(3):66, 2026. doi:10.1007/s10694-026-01895-2.

[111] NFPA 1700 Guide for Structural Firefighting, December 2025.

[112] NFPA 68 Standard on Explosion Protection by Deflagration Venting, December 2022.

[113] NFPA 69 Standard on Explosion Prevention Systems, December 2023.

[114] Roman Jesse. Testing tools and tactics for electric vehicle fire incident response. *NFPA Journal*, August 2025. URL https://www.nfpa.org/news-blogs-and-articles/nfpa-journal/2025/08/06/testing-tools-and-tactics-for-ev-fire-incident-response.

[115] Adam Barowy, Alexandra Schraiber, and Robert Zalosh. Explosion protection for prompt and delayed deflagrations in containerized lithium-ion battery energy storage systems. *Journal of Loss Prevention in the Process Industries*, 80:104893, December 2022. ISSN 09504230. doi:10.1016/j.jlp.2022.104893.

[116] Xinwei Yang, Hewu Wang, Minghai Li, Yalun Li, Cheng Li, Yajun Zhang, Siqi Chen, Hengjie Shen, Feng Qian, Xuning Feng, and Minggao Ouyang. Experimental Study on Thermal Runaway Behavior of Lithium-Ion Battery and Analysis of Combustible Limit of Gas Production. *Batteries*, 8(11):250, November 2022. ISSN 2313-0105. doi:10.3390/batteries8110250.

[117] NFPA 70E Standard for Electrical Safety in the Workplace, May 2026.

[118] Jürgen Peitz, van Lier Marco, Mohamed Ajaoun, Tim Pelzl, Jens Erbstößer, René Penno, Michael Gebhardt, Christoph Vogel, Dana Meißner, Stefan Jung, Andreas Meißner, Friedhelm Schwender, Tim Schulte-Frankenfeld, Jörn-Bo Hein, and Jacobs Stefan. Din spec 91489 requirements for fire limitation blankets for use with electric vehicles, November 2024.

[119] John Warner. Lithium-Ion and Other Cell Chemistries. In *The Handbook of Lithium-Ion Battery Pack Design*, pages 65–89. Elsevier, 2015. ISBN 978-0-12-801456-1. doi:10.1016/B978-0-12-801456-1.00007-5.

[120] Fireman Access, an exclusive innovation by Renault Group, is now available with a free licence, February 2018.

Appendix A

Heat Release Rate

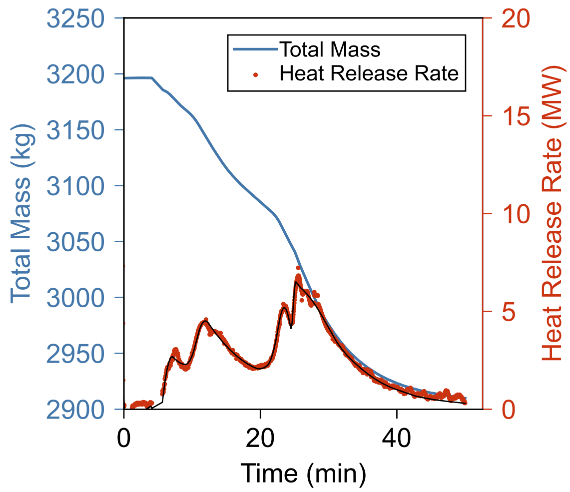
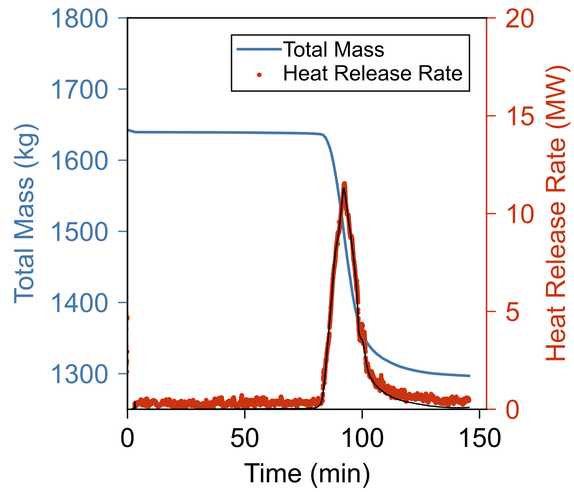


Figure A.1: G-HK-F mass and HRR data.



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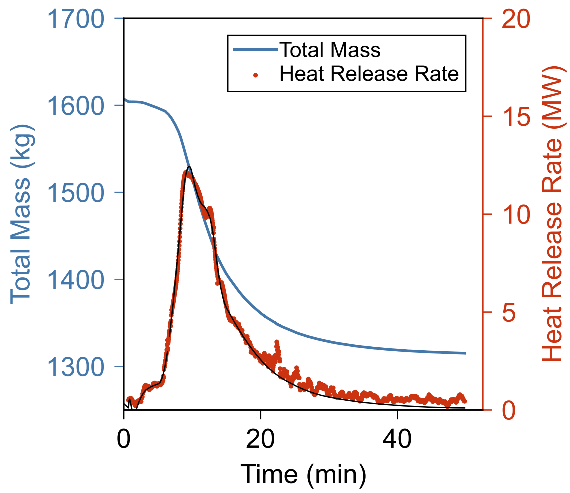

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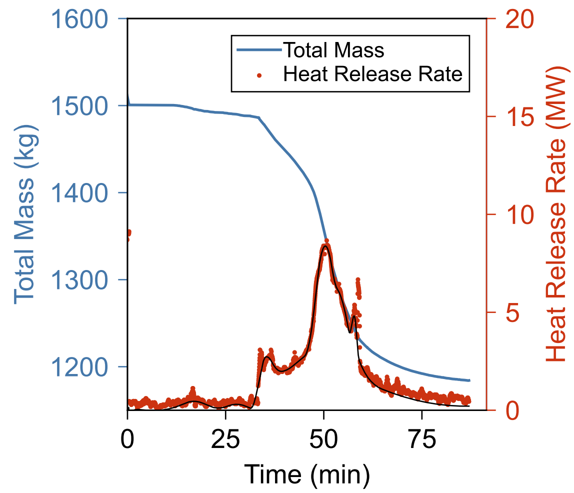

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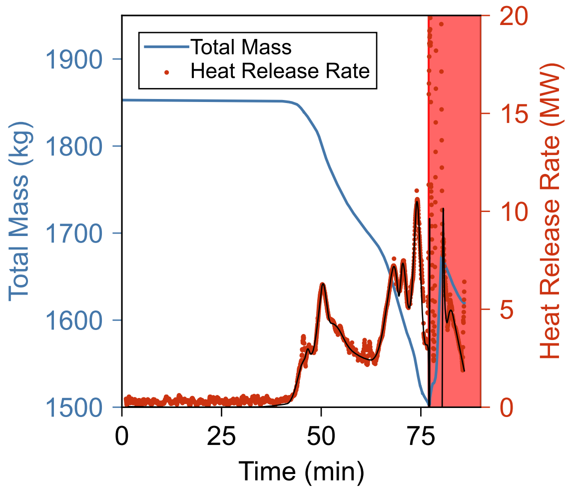

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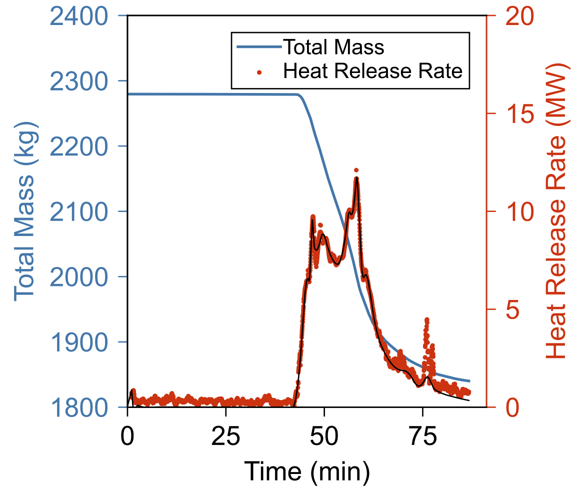

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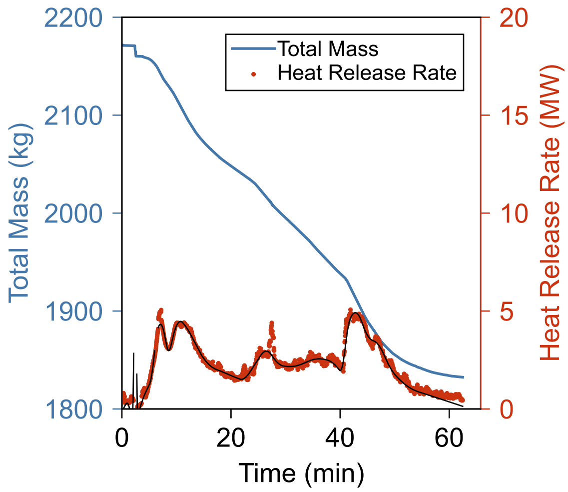

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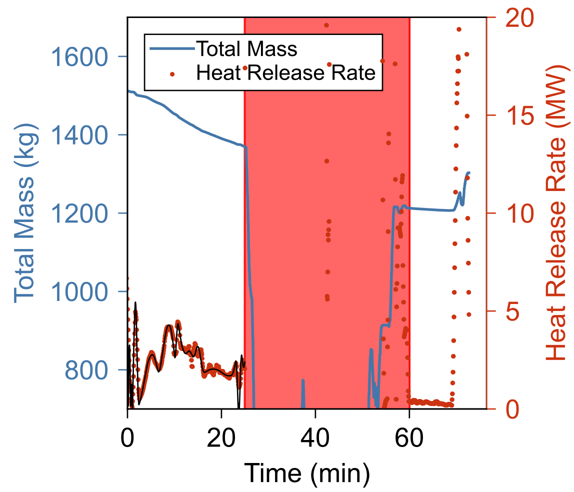


Figure A.8: G-HK-F2 mass and HRR data.

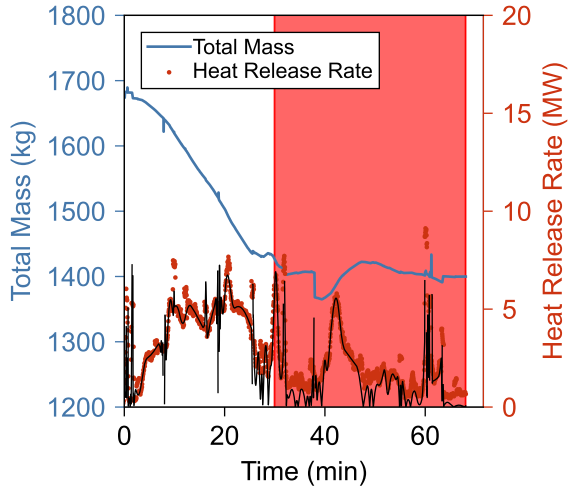


Figure A.9: G-TR-F mass and HRR data.

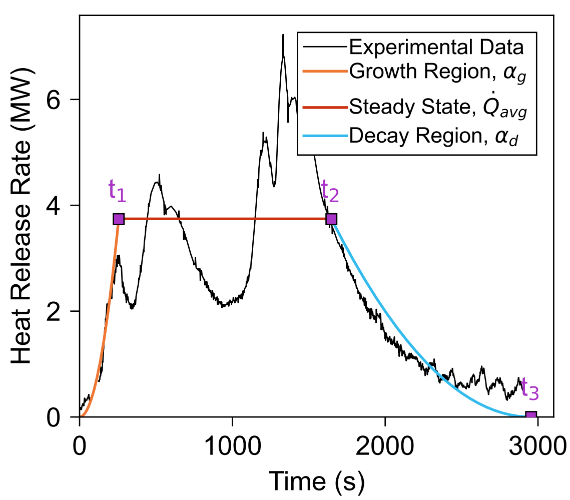


Figure A.10: G-HK-F HRR fitting visualization.

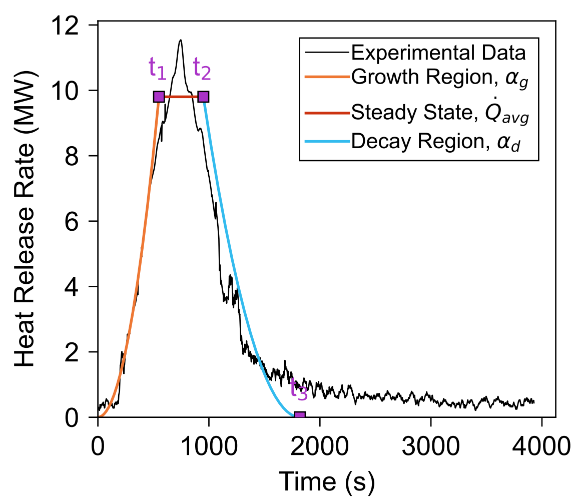


Figure A.11: E-CB-F HRR fitting visualization.

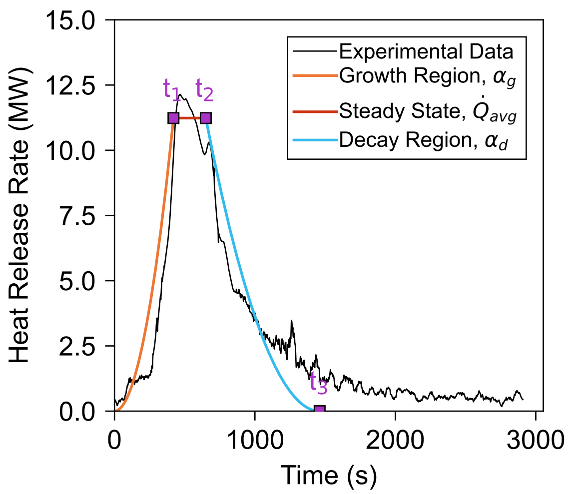


Figure A.12: E-NL-F HRR fitting visualization.

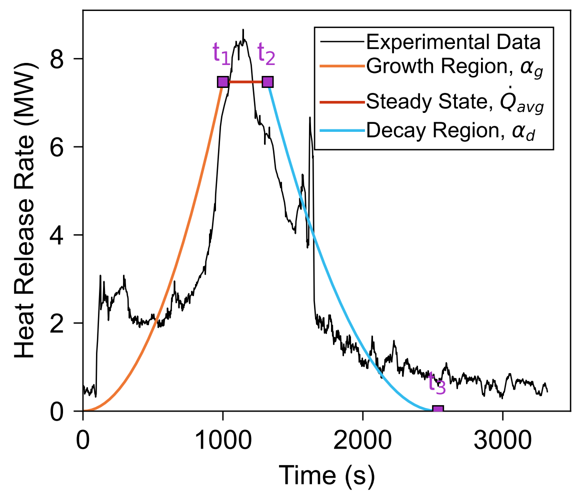


Figure A.13: E-HI-F HRR fitting visualization.

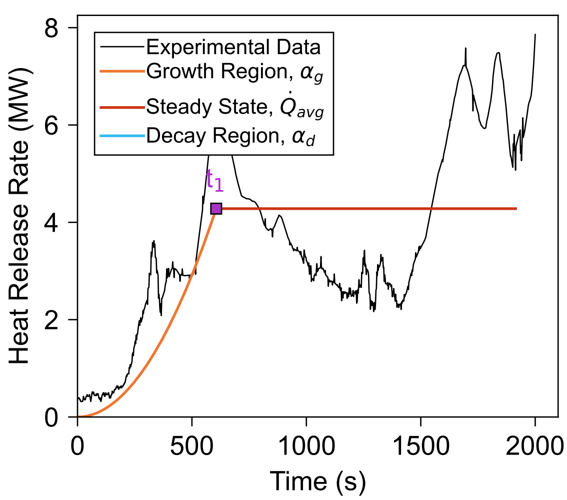


Figure A.14: E-TM-F HRR fitting visualization.

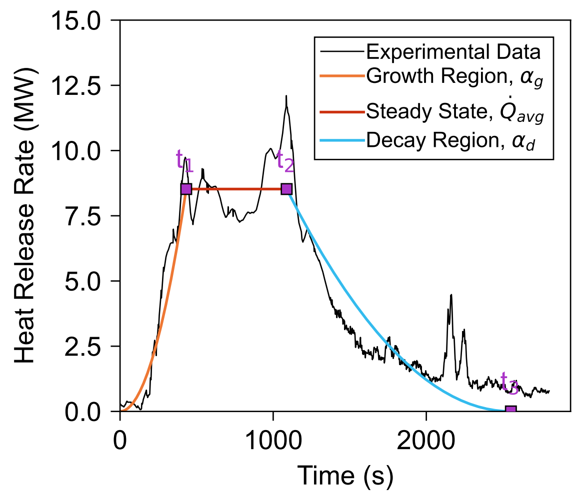


Figure A.15: E-FM-F HRR fitting visualization.

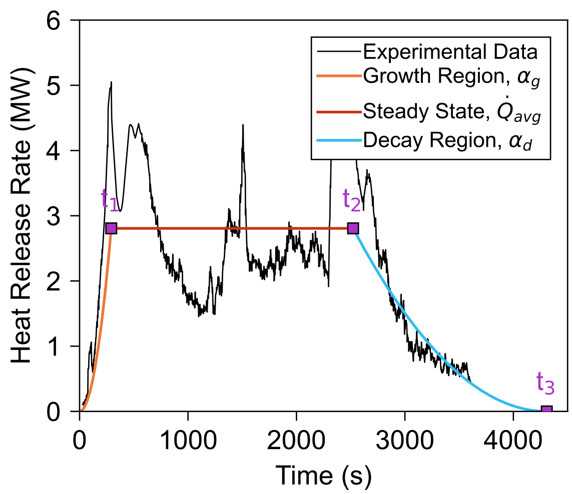


Figure A.16: E-HK-F HRR fitting visualization.

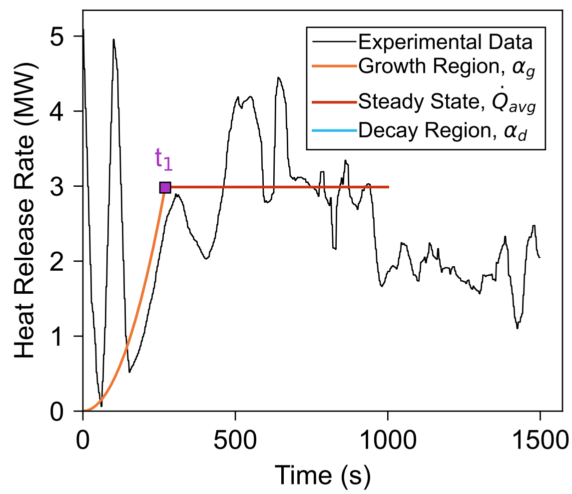


Figure A.17: G-HK-F2 HRR fitting visualization.

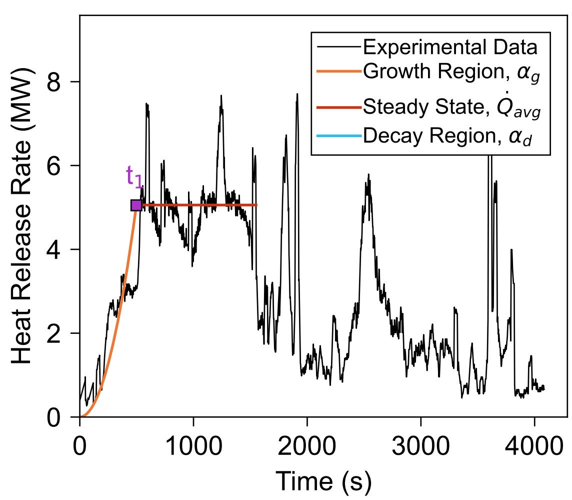


Figure A.18: G-TR-F HRR fitting visualization.

Appendix B

EV Fire Tactical Decision Aid

The EV Fire Tactical Decision Aid was developed using the conclusions drawn from results of the EV fire suppression experiments with the intention to provide concise, practical guidance to members of the fire service. The main intention was to show how EV-specific considerations fall into the overall framework of a vehicle fire incident from arrival on scene to incident termination. The overall steps of initial incident response, exposure assessment, size up, fire control, and incident termination will be familiar to every company officer. The main addition in the case of an EV fire is the split of fire control into vehicle fire control and battery fire control which is in line with the fire suppression considerations outlined in Chapter 5. Furthermore, the EV Fire Tactical Decision Aid provides guidance for determining incident management strategies by providing context for decision-making throughout the incident.

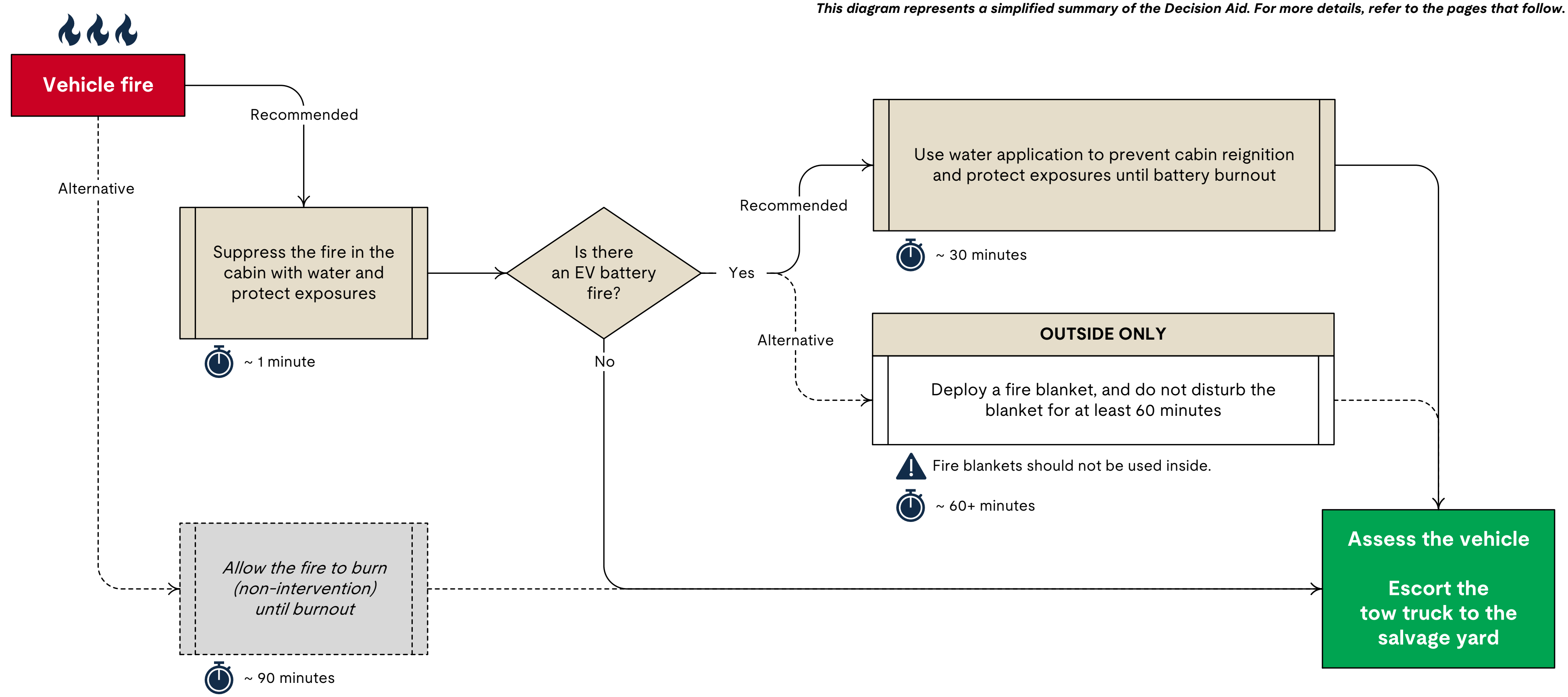
The full Decision Aid is provided below and a detailed walkthrough of each step can be found in Appendix C. The Decision Aid will also be permanently hosted, with any updates, at https://training.fsri.org/resources/462/electric-vehicle-fire-tactical-decision-aid-passenger-vehicle.

EV Fire Tactical Decision Aid: Passenger Vehicle

Research Institutes | Fire Safety

Perform the Initial Incident Response	Assess Exposures	Size-Up the Vehicle	Control the Vehicle Fire	Control the Battery Fire	Terminate the Incident
Start of Incident			*Incident Progress*		*End of Incident*
Perform the initial scene safety size-up, smoke exposure mitigation, and life safety tactical response.	*Assess exposures and determine the exposure protection strategy.*	*Assess the vehicle and identify it as an EV or non-EV.*	*Begin fire suppression, protect exposures, and suppress the vehicle cabin fire.*	*Assess and contain the battery fire while protecting exposures. Assess the risk of ignition.*	*Perform the inspection, hand off, and post-incident exposure reduction.*

This diagram represents a simplified summary of the Decision Aid. For more details, refer to the pages that follow.



Key

- Starting Event
- Ending Event
- Recommended Step or Decision
- *Out of Scope (See Notes)*
- Alternative Step or Decision
- Recommended Path (solid line)
- Alternative Path (dashed line)
- **Connector:** Go to the referenced letter to follow the path.
- **More Info:** Go to the referenced page note for detailed guidance on how to address EV fire considerations.

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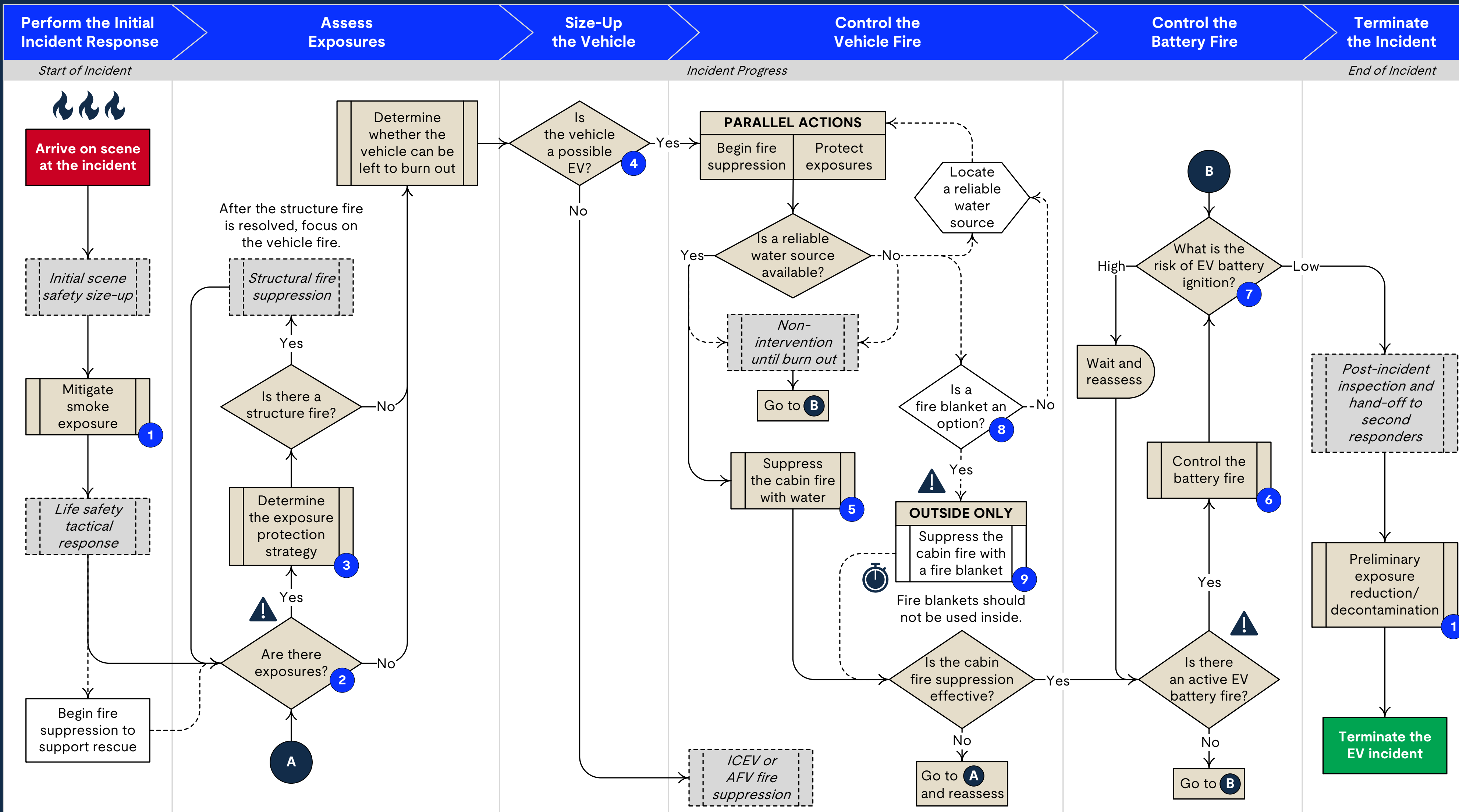
EV Fire Tactical Decision Aid: Passenger Vehicle



Key

- Starting Event
- Ending Event
- Recommended Step or Decision
- *Out of Scope (See Notes)*
- Alternative Step or Decision
- Recommended Path
- Alternative Path
- **Connector:** Go to the referenced letter to follow the path.
- **More Info:** Go to the referenced page note for detailed guidance on how to address EV fire considerations.

Notes

- This Decision Aid covers tactical considerations for common fire incident scenarios involving passenger electric vehicles (EVs) with lithium-ion (Li-ion) battery systems, including plug-in EVs, battery EVs, and hybrid EVs. Unexpected fire events may occur in the field. Responders should always apply the best situational judgment, according to tactical SOPs, training, and experience.
- The following vehicle types are not represented in this Decision Aid: compressed natural gas (CNG) vehicles, hydrogen fuel cell EVs, buses, and non-passenger vehicles (tractor trailers).
- Out of scope steps should be addressed by applying traditional tactical fire incident response SOPs, training, and experience.
- For more information about lithium-ion battery system hazards, explore the Fire Safety Academy's free online course, *TheScience ofFireand Explosion Hazards fromLithium-Ion Batteries*.

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EV Fire Tactical Decision Aid: Passenger Vehicle

Mitigate smoke exposure

Mitigate smoke exposure 1

Use the following guidelines along with fire response best practices to take action and respond to this step.

Minimizing Exposure

- Chemical exposure depends on dose and time.
- Wear full structural firefighting PPE.
- Use a self-contained breathing apparatus (SCBA).
- Position the apparatus uphill and upwind.
- Minimize contact with smoke, debris, and runoff as much as practicable.
- Use the range of the hose stream to attack the fire from a distance.
- Remain on air when operating around the vehicle, even if flaming stops.

Preliminary Exposure Reduction

- Dry-brush or rinse before unclipping the SCBA regulator.
- Remove PPE before entering firefighter rehab.
- Bag PPE and transport it separately from the crew when returning to quarters.
- Clean PPE according to the manufacturer's instructions.
- Launder personal clothing and shower as soon as possible after the incident.
- Use nitrile gloves and an N95 respirator when handling exposed tools and gear.

After taking smoke exposure precautions, return to the ***Decision Aid*** *to continue.*

Key

Starting Event | Ending Event | Recommended Step or Decision | *Out of Scope (See Notes)* | Alternative Step or Decision

Recommended Path

Alternative Path

Connector: Go to the referenced letter to follow the path.

More Info: Go to the referenced page note for detailed guidance on how to address EV fire considerations.

Notes

- Proper smoke exposure precautions should occur at every fire, regardless of the vehicle drivetrain type. Remain vigilant throughout the incident.
- The possibility of a sudden reignition means a potential exposure risk still exists even if the fire appears to be extinguished. Firefighters should remain on air when operating around the vehicle.

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EV Fire Tactical Decision Aid: Passenger Vehicle

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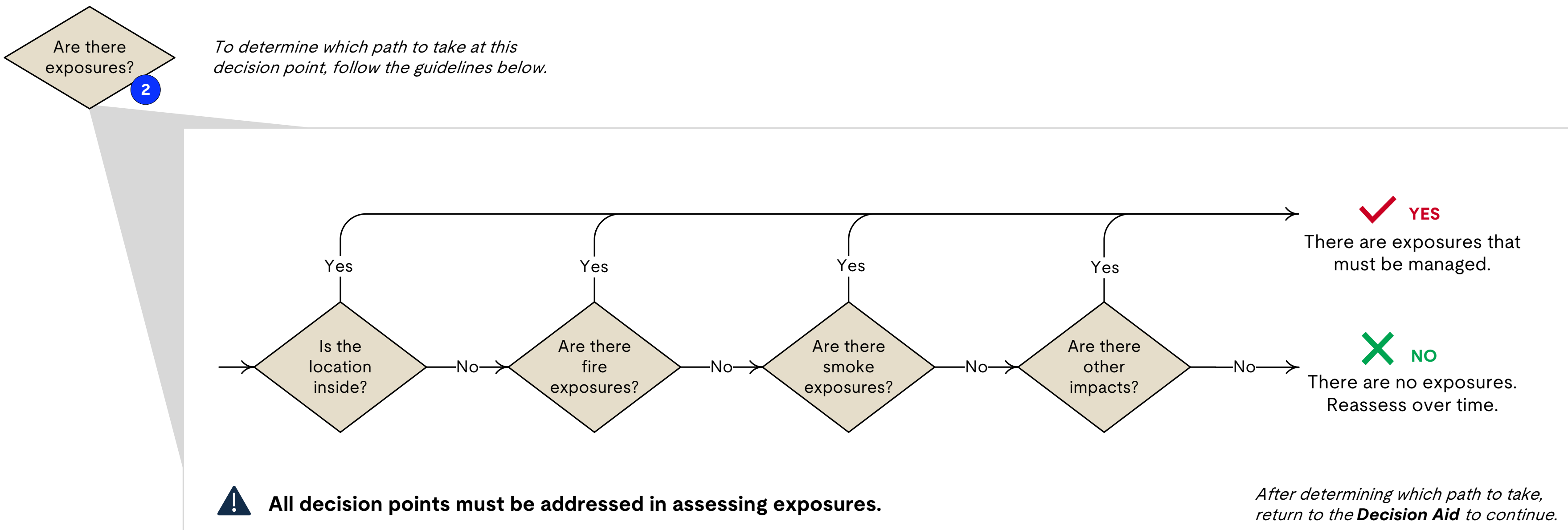
Are there exposures?



Inside Exposure Conditions

Indoor confinement may cause additional hazards, including:

- Explosion or deflagration hazard.
- Increased chemical exposure hazard.

Fire Exposure Conditions

Possible fire exposures include:

- Structural burning near the vehicle fire.
- Combustible or structural material above the vehicle.
- Less than 16 ft (5 m) of separation between the vehicle and combustible materials.
- Risk of unacceptable damage to the road surface underneath the vehicle.

Smoke Exposure Conditions

Smoke exposure may result in acute and chronic illness. Move or shelter living things from the smoke to avoid:

- Exposure to people.
- Exposure to animals.
- Environmental impact, including local regulations on air emissions.

Other Impact Conditions

Possible impacts may include:

- Unacceptable traffic conditions.
- Environmental impacts such as water runoff and debris.
- Potential social or public perception concerns.
- Conflicts with the department's response protocols, philosophy, or best practices.

Key

Starting Event | Ending Event | Recommended Step or Decision | *Out of Scope (See Notes)* | Alternative Step or Decision

Recommended Path

Alternative Path

Connector: Go to the referenced letter to follow the path.

More Info: Go to the referenced page note for detailed guidance on how to address EV fire considerations.

Notes

- Exposures should be continuously reevaluated throughout the course of the incident.

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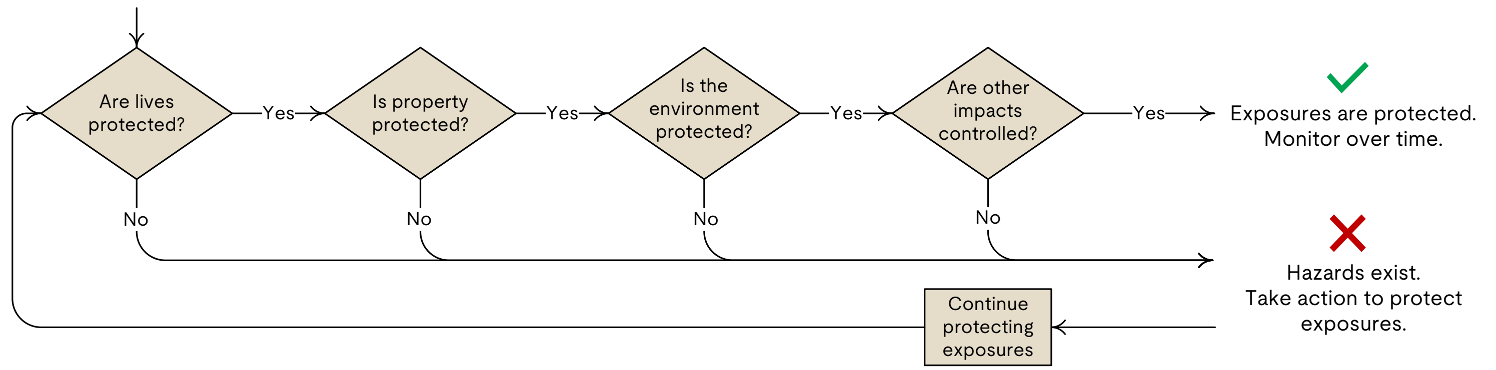
Determine the exposure protection strategy

Determine the exposure protection strategy (3)

Use the following guidelines along with fire response best practices to take action and respond to this step.



All decision points must be addressed in protecting exposures.

After protecting exposures, return to the ***Decision Aid*** *to continue.*

Protect Lives

Consider:

- Early suppression to search the cabin.
- Isolating and denying entry to the scene.
- Evacuating the affected area(s).
- Shelter-in-place orders where evacuation is not feasible or practical.

Protect Property

Consider:

- Suppressing the cabin to reduce thermal exposure.
- Cooling adjacent combustible objects.
- Moving exposed objects and vehicles.

Protect the Environment

Consider:

- Suppressing the cabin to reduce airborne chemical exposure.
- Retaining debris and suppression runoff where practicable.
- Informing the local water department if water runoff enters drain systems.
- Non-intervention in protected water supply areas.

Key

Starting Event | Ending Event | Recommended Step or Decision | *Out of Scope (See Notes)* | Alternative Step or Decision

Recommended Path

Alternative Path

Connector: Go to the referenced letter to follow the path.

More Info: Go to the referenced page note for detailed guidance on how to address EV fire considerations.

Notes

- Early suppression of the cabin fire will reduce chemical and thermal exposure hazards, especially if battery involvement can be prevented.

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EV Fire Tactical Decision Aid: Passenger Vehicle

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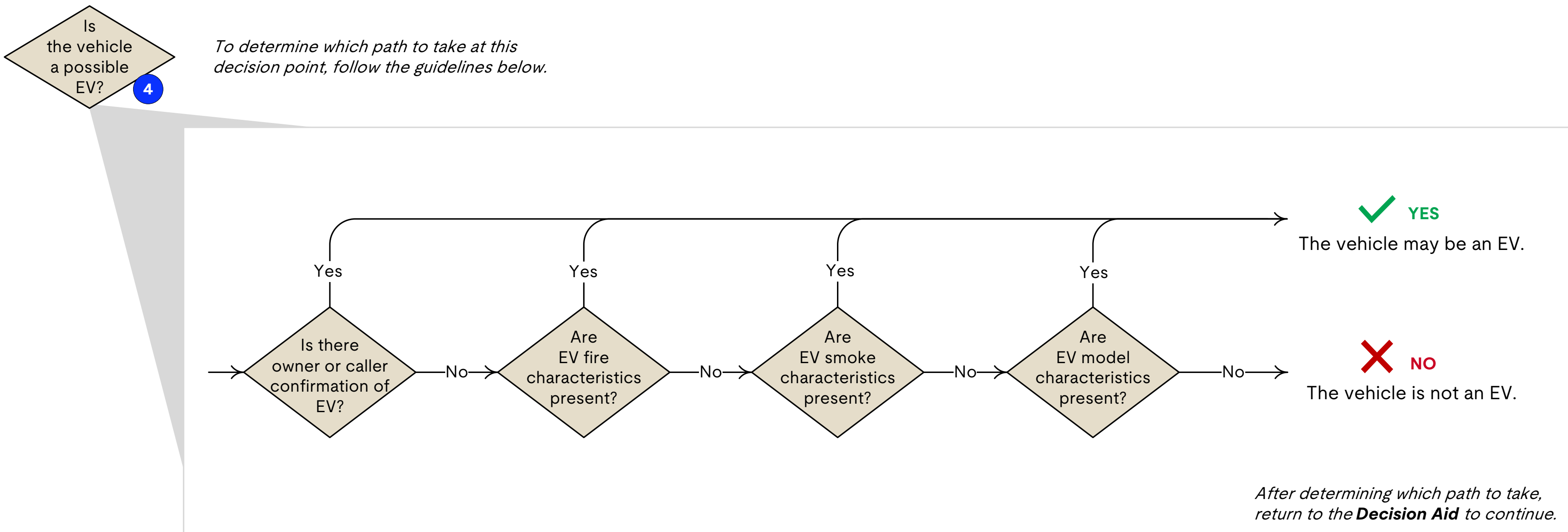
Is the vehicle a possible EV?



EV Fire Characteristics

EV fires demonstrate unique patterns that can be observed when performing the vehicle size-up. Possible indicators include:

- Jetting flames.
- Flames projecting out from underneath the vehicle.
- Flames projecting out from the fender wells of the vehicle.

EV Smoke Characteristics

EV fires produce smoke patterns that can be observed when performing the vehicle size-up. Possible indicators include:

- Opaque, thick, white, or grey smoke.
- Smoke that is heavier than air.
- Unique, solvent-like odor.

EV Model Characteristics

Some EVs can be identified by unique characteristics, while others may be indistinguishable from internal combustion engine vehicles (ICEVs). Possible indicators include:

- Badges, emblems, or unique body styling (i.e., Cybertruck).
- Tailpipes.
- Charging ports.
- Radiator.

Key

Starting Event | Ending Event | Recommended Step or Decision | *Out of Scope (See Notes)* | Alternative Step or Decision

Recommended Path

Alternative Path

Connector: Go to the referenced letter to follow the path.

More Info: Go to the referenced page note for detailed guidance on how to address EV fire considerations.

Notes

- EV-specific concerns should not delay life-saving measures.
- An EV fire may appear similar to a fire in an ICEV. If in doubt, begin by suppressing the cabin and reassessing based on the fire behavior.

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EV Fire Tactical Decision Aid: Passenger Vehicle

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Suppress the cabin fire with water

Suppress the cabin fire with water (5)

Use the following guidelines along with fire response best practices to take action and respond to this step.

Apply Water to Suppress the Burning Cabin

- Controlling the cabin fire will significantly reduce the chemical and thermal exposure.
- Approach the vehicle from a 45-degree angle, along the corners of the vehicle.
- Use the range of the hose stream to reduce exposure to smoke and jet flames.

Critical Considerations

While indoors:

- The release of unburnt vapors may lead to flash fire or deflagration.
- Flammable vapors in a confined environment may pose an explosion hazard.
- Consider and monitor thermal exposure to structural members.
- Smoke confinement increases exposure risk.
- Thermal runaway exhaust vapors may gather in low-lying areas.

Both indoors and outdoors:

- Continuous application of water to the battery enclosure will waste large volumes of water.
- Significant water runoff may result in environmental impacts.
- Struts, airbags, and tires may fail violently and become projectiles.
- Firefighters involved in suppression are subject to chemical exposure and should perform exposure reduction and decontamination.

After the fire in the cabin has been suppressed, return to the ***Decision Aid*** *to continue.*

Key

Starting Event | Ending Event | Recommended Step or Decision | *Out of Scope (See Notes)* | Alternative Step or Decision

Recommended Path

Alternative Path

Connector: Go to the referenced letter to follow the path.

More Info: Go to the referenced page note for detailed guidance on how to address EV fire considerations.

Notes

- Data indicates that a large portion of EV fires do not start in the battery.
- Early suppression of the cabin may prevent involvement of the battery and improve incident resolution.

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EV Fire Tactical Decision Aid: Passenger Vehicle

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Control the battery fire

Control the battery fire (6)

Use the following guidelines along with fire response best practices to take action and respond to this step.

Tactical Guidance

- Use water to protect exposures and prevent the cabin from igniting while allowing the battery to burn itself out.
- The sustained application of water to the battery enclosure will likely not stop thermal runaway.
- Flames and exhaust gases can be redirected from exposures with a fog stream, if necessary.
- Targeting openings in the battery may be helpful, but moving or lifting the vehicle introduces undue risk.

⚠ **Do not manually breach the battery or fuel tank.**

Critical Considerations

While indoors:

- The release of unburnt vapors may lead to flash fire or deflagration.
- Flammable vapors in a confined environment may pose an explosion hazard.
- Consider and monitor thermal exposure to structural members.
- Smoke confinement increases exposure risk.
- Thermal runaway exhaust vapors may gather in low-lying areas.

Both indoors and outdoors:

- Continuous application of water to the battery enclosure will waste large volumes of water.
- Significant water runoff may result in environmental impacts.
- Struts, airbags, and tires may fail violently and become projectiles.
- Firefighters involved in suppression are subject to chemical exposure and should perform exposure reduction and decontamination.

After containing the battery fire, return to the ***Decision Aid*** *to continue.*

Key

Starting Event | Ending Event | Recommended Step or Decision | *Out of Scope (See Notes)* | Alternative Step or Decision

Recommended Path

Alternative Path

Connector: Go to the referenced letter to follow the path.

More Info: Go to the referenced page note for detailed guidance on how to address EV fire considerations.

Notes

- The use of water cutting or water injection devices was not evaluated in this research study.
- Water cutting or water injection systems should only be used by trained personnel in accordance with manufacturer instructions and jurisdictional protocols.

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EV Fire Tactical Decision Aid: Passenger Vehicle

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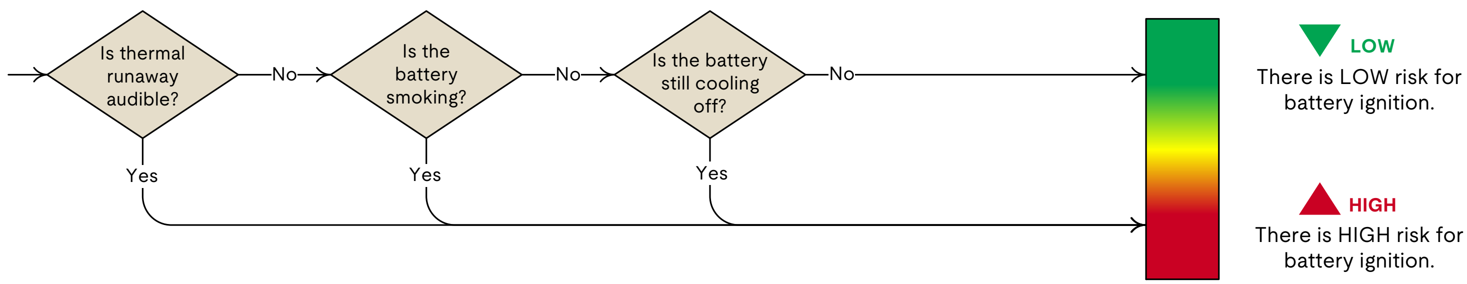
What is the risk of EV battery ignition?

What is the risk of EV battery ignition? 7

To determine which path to take at this decision point, follow the guidelines below.



Do not breach the battery.

If the vehicle is moved, shaking and vibration may cause short circuiting and/or battery ignition due to stranded energy.

After determining which path to take, return to the ***Decision Aid*** *to continue.*

Reignition Risk

- Reignition risk is highest right after the incident and drops over time.
- Reignition risk increases when the vehicle is moved.
- Stranded energy may cause reignition if intact cells are short-circuited (i.e., by debris or water).
- Stranded energy is impossible to assess without specialized tools.

Signs of Elevated Reignition Risk

Signs that a battery fire may be emerging include:

- Smoke exiting the battery enclosure.
- Elevated and increasing temperatures.
- Abnormal sounds, such as whistling, clicking, or popping.

Other Evaluation Considerations

Factors to consider when waiting, observing, and reassessing the risk of battery ignition include:

- Consider escorting the tow truck with a suppression unit.
- Sudden reignition may expose firefighters if PPE (including SCBA) is not used.
- The battery may take a long time to cool.
- The vehicle can be removed once it is cool enough to handle safely.

Key

Starting Event | Ending Event | Recommended Step or Decision | *Out of Scope (See Notes)* | Alternative Step or Decision

Recommended Path

Alternative Path

Connector: Go to the referenced letter to follow the path.

More Info: Go to the referenced page note for detailed guidance on how to address EV fire considerations.

Notes

- The scaling on a thermal imaging camera (TIC) can be misleading for temperature assessment.
- Smoke from thermal runaway may be confused with steam resulting from suppression.

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EV Fire Tactical Decision Aid: Passenger Vehicle

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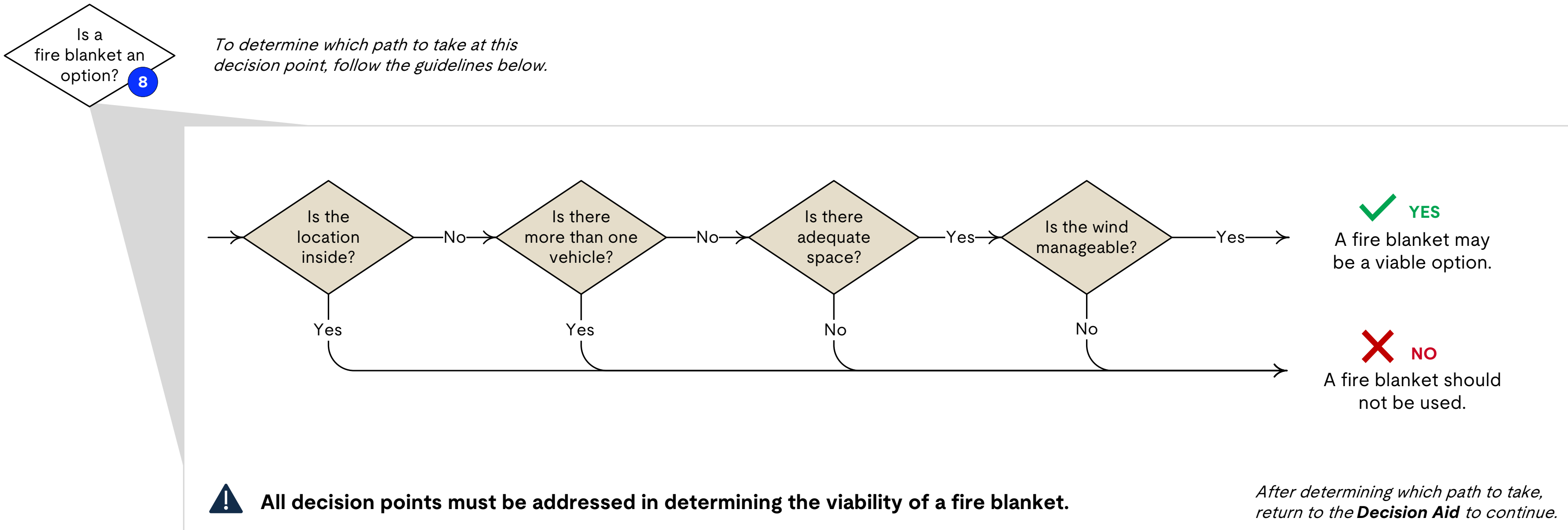
Is a fire blanket an option?

To determine which path to take at this decision point, follow the guidelines below.



All decision points must be addressed in determining the viability of a fire blanket.

After determining which path to take, return to the ***Decision Aid*** *to continue.*

Fire Blanket Limitations

Fire blanket limitations lead to inconsistent results due to:

- No standards for quality in blanket construction and material.
- Variations in blanket characteristics and performance.
- Fire impingement and improper handling, which may result in rips, tears, and burn-through holes in the fabric.

Critical Considerations

Viability of using a fire blanket must consider the potential exposure risk and incident-specific factors, including:

- A fire blanket should not be used inside.
- A fire blanket is not feasible for use in a multi-vehicle fire. A single fire blanket is not intended to cover multiple vehicles.

Environmental Conditions

Environmental factors can influence the viability of using a fire blanket, including:

- Free space is required to cover the vehicle and maintain a safe distance.
- Wind interference during deployment can prevent successful positioning.
- Wind disruption after deployment can lead to ineffective fire suppression.

Key

Starting Event | Ending Event | Recommended Step or Decision | *Out of Scope (See Notes)* | Alternative Step or Decision

Recommended Path

Alternative Path

Connector: Go to the referenced letter to follow the path.

More Info: Go to the referenced page note for detailed guidance on how to address EV fire considerations.

Notes

- Successful deployment requires intimate contact between the blanket and the ground.
- Do not lean tools against the vehicle after blanket deployment.
- Deployment of an EV fire blanket should be practiced according to the manufacturer's instructions.

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EV Fire Tactical Decision Aid: Passenger Vehicle

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Suppress the cabin fire with a fire blanket

OUTSIDE ONLY
Suppress the cabin fire with a fire blanket
9

Use the following guidelines along with fire response best practices to take action and respond to this step.

Deploy the Blanket, Reposition Operators to Safety

When using a fire blanket, follow fire safety best practices to wear full structural PPE (including SCBA), adequately cover the vehicle, minimize disturbance, and maintain a safe distance while monitoring conditions at the scene.

- Do not disturb the blanket after deployment.
- Watch for bloating, which is a sign that gas is accumulating under the blanket.
- Watch for signs of blanket failure, including rips, tears, melting, and burn-through holes. Adjust tactics to control flaming, as necessary.
- Look for signs of flaming or thermal runaway, and restart the 60-minute monitoring window after the last observable signs.
- If the blanket is ineffective, remove it completely and do not redeploy it.
- Continue efforts to bring a charged hoseline into service as quickly as possible.

⚠ **Keep at least one hoseline charged and ready to use in the event of escalation.**

Critical Considerations

Potential hazards:

- Deflagration beneath the blanket can cause smoke and other flammable gases to accumulate and lead to dangerous pressure waves, projectiles, and thermal injuries.
- Accumulated smoke can lead to flash fire or explosion, if the smoke ignites.
- Hot surfaces of the vehicle represent an ignition source.

Key tactical concerns:

- A fire blanket will not stop thermal runaway propagation and interferes with continuous size-up of the battery temperature.
- A blanket cannot contain pressure. If the battery generates more smoke or flammable gas than can fit under the blanket, it will be released from under the blanket.
- Blankets may be heavily contaminated with metals, hydrocarbons, and other materials that require controlled disposal after the incident.

After the fire in the cabin has been suppressed, return to the ***Decision Aid*** *to continue.*

Key

Starting Event | Ending Event | Recommended Step or Decision | *Out of Scope (See Notes)* | Alternative Step or Decision

Recommended Path

Alternative Path

Connector: Go to the referenced letter to follow the path.

More Info: Go to the referenced page note for detailed guidance on how to address EV fire considerations.

Notes

- No additional notes to support this process step.

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Appendix C

EV Fire Tactical Decision Aid Walkthrough

The purpose of this Decision Aid is to provide evidence-based recommendations to fire departments and training officers developing or updating EV incident operating procedures and training. Additionally, the Decision Aid can be used as an educational reference for pre-incident training and as a reference for incident commanders on the scene of an EV fire.

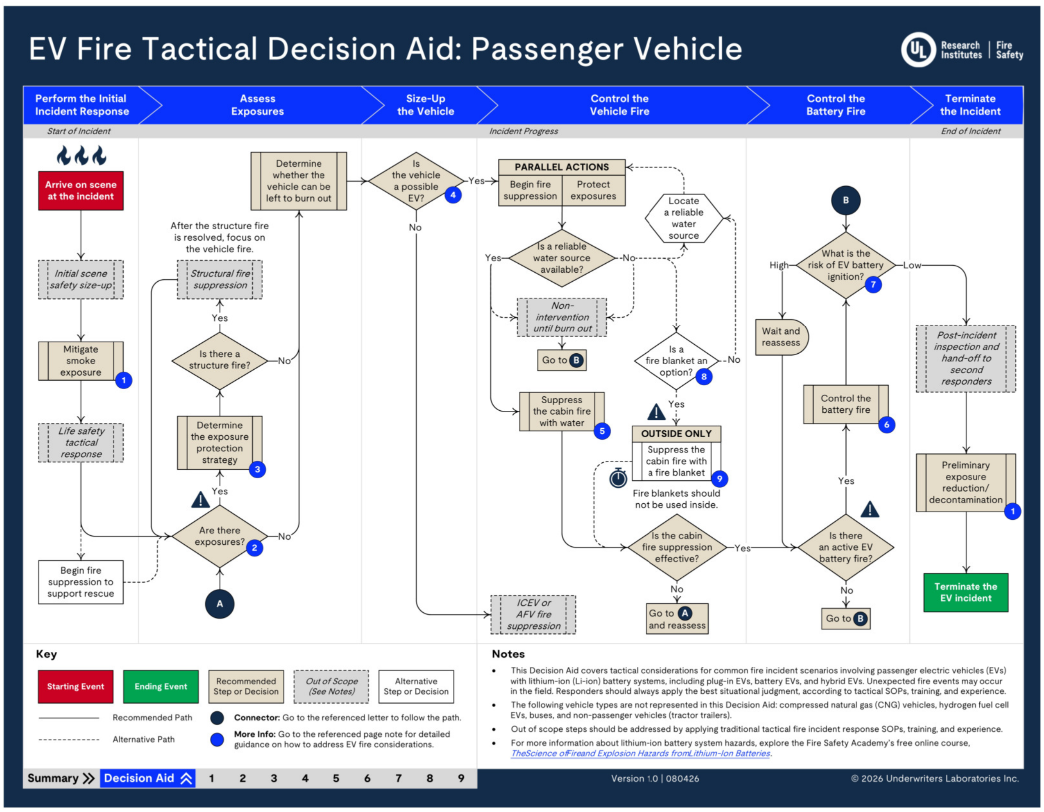

Figure C.1: Tactical Decision Aid.

The Decision Aid separates an electric vehicle fire incident response into six individual sections, most of which also apply to conventional vehicle fire incidents: the initial incident response, exposure assessment, vehicle size-up/identification, vehicle fire management, battery fire management and incident termination. The flow is arranged to be chronological, although it is understood that many decision-making processes and actions can occur concurrently in real incidents, such as determining the need for life-saving measures and initial fire suppression. Additionally, simplifications were made to ensure readability of the Decision Aid. The Decision Aid aims to show how EV-specific firefighting measures fit into the overall vehicle fire response framework rather than proposing prescribed steps in a fixed operating procedure that must be rigidly adhered to.

Symbology and layout of the Decision Aid were designed to be easy to understand and minimize confusion. Rectangular boxes indicate an action or process, while diamonds indicate a decision which will impact further operations. "Arrive on scene at the incident" is highlighted in red to indicate that this is the start of the timeline covered by this Decision Aid, and "Terminate the EV incident" is highlighted in green to indicate the incident is considered complete. Throughout the Decision Aid, there are boxes colored in khaki, which fall along the recommended course of action. The recommended course of action is explained in the walkthrough and is based on an assessment of experiment data, consideration of typical incident response resources (e.g., staffing, equipment, water supply, etc.), and feedback from the project technical panel. Boxes in grey are provided to acknowledge actions that are always or often part of a vehicle fire incident response but fall outside the scope of this vehicle fire research, and for which well-established guidance exists elsewhere. Finally, boxes in white, connected by dashed lines present "alternate" steps which may be necessary during the incident response or may be pursued at the discretion of the incident commander.

Several boxes are annotated with numbers. These indicate a reference to additional explanations, focused on elements where either EV-specific guidance diverges from conventional vehicle fire attack, or where data from this research can assist with evidence-based decision-making. The number of additional icons was kept as low as practicable, and placed where special considerations are emphasized. Care was taken to ensure that the Decision Aid is well-organized and easy to follow. However, a step-by-step walkthrough is provided in the following sections.

C.1 Initial Incident Response

The initial incident response encompasses all aspects from the start of the incident, to arrival on scene. This includes the initial incident notification by the reporting party (RP), the dispatching of resources, response to the scene, scene size-up and initial life safety measures. This stage of the incident will likely be similar for all passenger vehicle fires, regardless of powertrain type. Nonetheless, this stage can already serve to provide responders with critical information even before arrival of the first due unit. Depending on local dispatch procedures, dispatchers may be able to ask targeted questions and identify the likely propulsion type of the vehicle from the RP, as well as observed fire behavior. Based on information from the RP, the dispatcher can dispatch appropriate resources and relay information to the incoming units. Furthermore, the dispatcher can begin mitigating hazards by informing the RP to evacuate themselves and others from the area and advising against attempts at extinguishment. Even in the best of circumstances, it is possible for dispatch information to be faulty and incomplete. It will be the first due company officer’s job to verify the dispatch information and act accordingly. Upon arrival on scene, the priority in this stage will lie in obtaining an initial picture of the incident, ensuring crew safety and identifying the need for any life-safety interventions, such as extrication or rapid suppression to affect an extrication.

The box "Chemical Exposure Precautions" was chosen to prompt company officers to begin considering chemical exposure to firefighters and bystanders from the start of the incident. While there are chemical species that are unique to EVs (i.e., battery specific metal particulates, and fluoride particulates, see Section 4.4), hazardous exposures to volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs) and inhalable particulates are similar to those produced by ICEVs [101]. For this reason, any vehicle fire should be approached uphill and upwind when possible. Any crews operating in the vicinity of the vehicle must wear structural fire PPE and use a self-contained breathing apparatus (SCBA) without exception. Even outdoors, vehicle fire smoke is present in concentrations that can produce harmful acute and chronic effects. Apparatus scene positioning and no-entry zones for bystanders should be selected depending on local wind conditions to minimize smoke exposure to operating units and the public.

Once crew safety is addressed, the need for immediate lifesaving measures should be identified and necessary measures taken without delay in accordance with local protocols and SOGs/SOPs. Priority should lie with searching and clearing the passenger compartment, suppressing fire as necessary. Examples of lifesaving measures include, but are not limited to suppressing the fire with apparatus tank-water or a portable fire extinguisher to support rapid extrication of entrapped occupant(s), even if no reliable water supply is available.

C.2 Assess and Identify Exposure Management Strategy

Considerations for selecting an exposure protection strategy depend heavily on the conditions on scene and will inform the further actions that are taken on scene. Before any action can be taken, however, the first step is to gather information and determine a strategy. Identification of exposures follows the format outlined in Figure C.2, and includes four primary considerations: whether the scene is indoors, whether there are exposures to fire, whether there are exposures to smoke and whether there are any other impacts. Accurately identifying the exposures permits employing an appropriate strategy to manage the exposures as well as the fire itself.

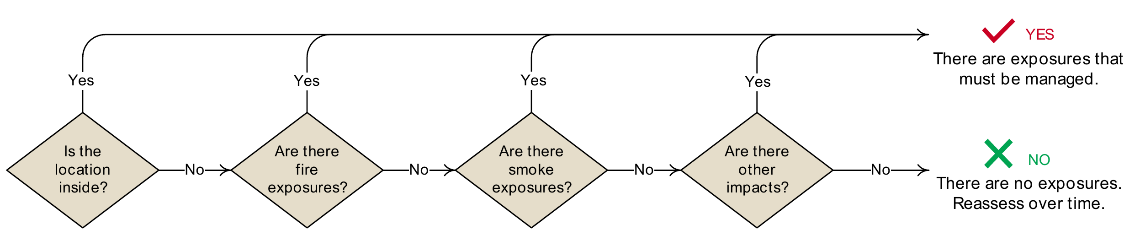

Figure C.2: Exposure identification flow from the EV Fire Tactical Decision Aid.

A scene that is in a confined area, such as a residential or commercial parking garage, can represent an explosion or deflagration hazard, due to the potential for flammable gas accumulation, especially if a fire blanket were to be used. For this reason a different suppression strategy should be selected. In addition to the deflagration hazard, fires in such confined areas also present an increased level of chemical exposure. Fire exposure both to neighboring vehicles and nearby or surrounding structures present another concern. Of particular interest is any potential for fire spread to combustible structural members nearby as well as potential fire impingement on structural elements above the vehicle. Any combustible objects closer than 5 m (16 ft) should be considered an exposure subject to an ignition hazard. The potential for any unacceptable damage to the surface under the vehicle should be considered. Exposure to smoke and vapor from an actively burning or off-gassing EV represents an acute and chronic health hazard. Smoke mobility means that the incident commander must not only consider exposures directly surrounding the burning vehicle, but also areas, occupancies and environmentally sensitive exposures (e.g. drinking water supplies or streams) that may be impacted by smoke downwind from the scene. Finally, there may be additional exposures specific to the scene which may require mitigation. Such considerations include road closure, protecting sensitive areas from water runoff, or scene-specific hazards to first responders such as vehicle traffic. If the answer to any of the questions in Figure C.2 is yes, further consideration is required to select an appropriate exposure protection strategy.

EV fires involved in structure fires, such as fires occurring in a residential garage, should first be viewed as a structure fire. Strategy should be adjusted to prioritize the structure fire and additional units should be requested accordingly. Once the structure fire has been suppressed, suppression efforts should return to the vehicle with an emphasis on preventing reignition of the structure.

Other considerations informing exposure management include the available resources and manpower. These factors must be weighed when selecting an appropriate strategy for managing the vehicle fire. Managing the exposure may mean focusing on extinguishment of the vehicle to quickly eliminate the chemical and thermal hazard. However, in cases where direct extinguishment is deemed unfeasible, other strategies, such as cooling or removing adjacent exposures, issuing evacuation or shelter-in-place orders.

Once the exposures have been assessed, the IC may consider whether letting the vehicle burn out is a viable, or necessary strategy. In most cases, suppression of the vehicle will likely be the preferable option. In any case, the impact on exposures should be considered before letting the vehicle burn out. Assessing exposures should be a continuous process to ensure that the exposure management strategy remains effective and appropriate, even if conditions change.

C.3 Vehicle Size-up and Identification

Identifying a burning electric vehicle may not always be possible based on vehicle model characteristics or fire behavior or smoke appearance alone. Badges or emblems may be destroyed by the fire and the fire itself will likely be indistinguishable from an ICEV before water application occurs. In fact, identifying the vehicle as an EV might only occur after water has been applied and a battery fire can be recognized. The EV Fire Tactical Decision Aid provides additional guidance in the explanatory pages as is shown in Figure C.3.

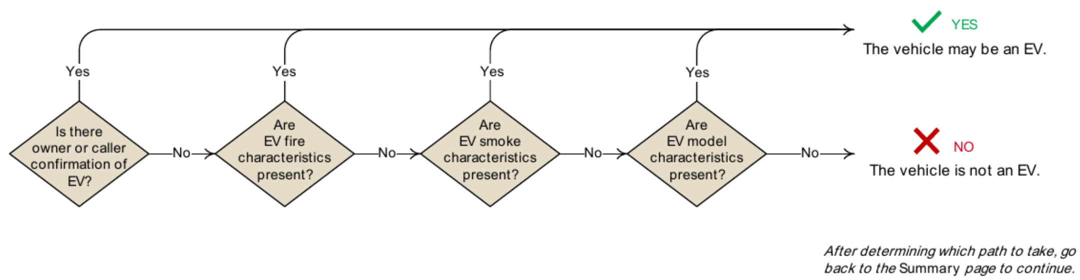

Figure C.3: EV identification guide.

Some battery or hybrid electric vehicles can be recognized by unique body styling (e.g., the Tesla Cybertruck), the presence or absence of tailpipes and charging ports, badges and emblems that indicate the propulsion method. However, these features should not be considered reliable indicators of a vehicle powertrain. Some vehicle platforms (e.g., the Hyundai Kona, the Kia Niro) have multiple powertrain configurations (e.g., ICEV, HEV, PHEV and BEV) the specific model/powertrain may only be identifiable by their badges if present. Even the presence of an exhaust pipe does not necessarily exclude the presence of a traction battery system in the case of a hybrid electric vehicle.

Vehicle powertrain identification based on physical features can be impeded by fire involvement. For example, a fire involving only the passenger compartment of an EV is indistinguishable from an ICEV passenger compartment fire. Flames from a passenger compartment and combustible bodywork (rocker panels, door trim, etc) may physically obscure unique vehicle characteristics, or damage them beyond recognition. However, there are unique fire characteristics that can occur when the traction battery is involved. Jet flames, while they did not always occur in these EV fire experiments, may emanate from the bottom of the vehicle or wheel wells where the traction battery is typically located. Some electric vehicle traction batteries include vent ports that have been positioned to direct flames away from passengers egressing the vehicles, so they are positioned in or near the wheel wells. If there are no vent ports, jets may appear from holes created by battery pack damage or burn-through. Flames also tend to emanate consistently from the bottom of the vehicle, which is visually distinct from ICEV fires, which tend to have little combustible material beneath the vehicle or have a gasoline spill fire, which is easily identifiable. The flames that emanate from under the vehicle are also persistent; they may shift to one side or another due to wind or hose stream application, but they generally appear to be consistent as if the vehicle was placed over the top of a flammable gas leak. Responders should keep in mind other propulsion systems, such as CNG vehicles, may exhibit similar fire behavior such as jet flames, but require alternative strategies and tactics beyond the scope of this Decision Aid.

Fires in the traction battery are often accompanied by hissing and popping sounds from cell thermal runaways. These sounds can be difficult to interpret, but consistent hissing and popping is a likely indication of thermal runaway propagation through cells in the traction battery. The difficulty can be in distinguishing them from the hissing and popping that can be associated with the rupture of the air conditioning system, struts, tires, or other pressure-containing components. Safety features such as airbag inflators and seatbelt pretensioners can also issue similar sounds, but are generally much louder.

In certain situations, smoke behavior can be a reliable indication of battery involvement when there is no flaming yet involving the vehicle. Smoke released during thermal runaways often appears thick, with a white or grey color. Multiple densities of smoke are typically released at once, buoyant smoke rising and beginning to form a layer similar to flaming fires, but simultaneously, a lesser quantity of smoke may be heavier than air and spread with a liquid-like appearance along the floor. The smoke generally has an aromatic, solvent-like odor.

Generally, identification of vehicle propulsion type should follow an index of suspicion. Bystander information and a combination of vehicle styling and fire behavior can serve as indicators for propulsion types, but firefighters should remain aware of other propulsion types as well. If no clear identification can be made, it is best to begin suppression efforts and subsequently reassess.

C.4 Managing the Vehicle Fire

Managing the vehicle fire encompasses suppression, or containment of the vehicle fire while implementing the exposure protection strategy developed above. This column of the Decision Aid presents several alternative paths that can be chosen depending on what fire management strategy is most appropriate for the given incident. Furthermore, the decision to separate cabin fire management and battery fire management represents a tactical suggestion developed from firefighter experience during EV suppression tests.

In the majority of cases, the first unit on scene will likely have water suppression capabilities that are adequate for an initial fire attack (i.e., an engine with a tank capacity of $\geq$ 1900 L (500 Gal)). For this reason, it is recommended that responders do not delay water application, even if a different fire management strategy such as EV fire blanket deployment or vehicle burnout is being considered. Depending on the exposure assessment and the availability of a sustainable water supply, the IC may determine to apportion water to fire suppression or exposure protection.

Water application on the vehicle cabin is recommended due to the likelihood of improved outcomes, and the simplicity of the approach, especially when considering conventional vehicle firefighting tactics. It was found in the experiments that a significant portion of the fire load that the cabin fire represents was extinguished within seconds to minutes and required low volumes of water. This reduction in fire size may in itself protect exposures and reduce chemical exposure.

If no reliable water supply can be established, it may be necessary to ration water and take other exposure protection measures until more resources arrive on scene or even for the duration of the incident. Alternatively, other fire management strategies can be considered, based on the judgment of the incident commander. This may take the form of letting the vehicle burn out under supervision while protecting exposures or deploying a fire blanket. The incident commander should take into account that doing so will change the risk profile of the incident, as is further discussed in the next paragraph. In the majority of cases, it will likely be faster, easier, and safer to use water to control the cabin fire and then manage the battery fire.

Should the deployment of an EV fire blanket be considered, the IC should ensure that the following conditions are met: The vehicle must be located outdoors, as fire blanket use in a confined space may lead to flammable gases accumulating and forming an explosive atmosphere. Next, there needs to be sufficient space around the vehicle to ensure a quick deployment and that the blanket can make good contact with the ground on all sides. Using tools such as brooms to tuck the blanket and ensuring good ground contact can help personnel maintain a distance from fire effluents. Deploying the fire blanket in high wind conditions should be avoided. Considerations for EV fire blanket deployment are shown in Figure C.4.

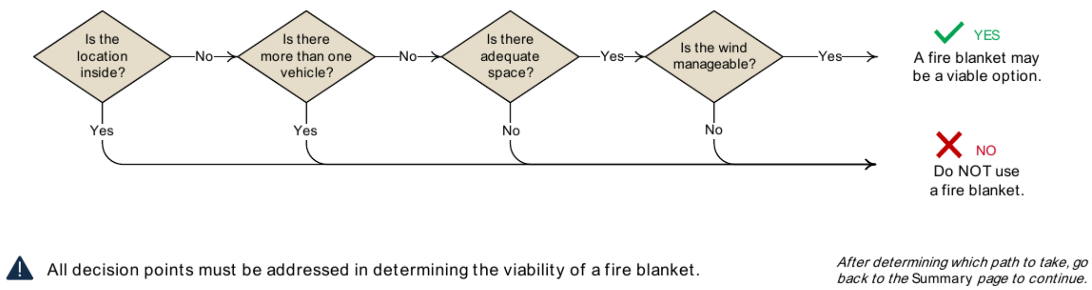

Figure C.4: Critical considerations for EV fire blanket deployment.

Once the fire blanket has been deployed, it should remain undisturbed for a minimum of 1 h, and any manipulation of the blanket should be avoided to reduce the risk of deflagration or reignition, which may persist for a significant time. Should manipulation of the blanket be necessary, it is recommended to quickly and completely remove the blanket to prevent pressure buildup should reignition occur. In all cases, a charged and manned hoseline should stand by for the duration of the blanket deployment and personnel should stage away from the vehicle.

Once the cabin fire has been suppressed, suppression efforts should shift towards the battery.

C.5 Battery Fire Management

Managing the battery fire is the most challenging, and the only truly unique aspect of EV fire response. However, while fires involving the battery system behave differently from ICEVs, results from this study show that contrary to high-profile news reports, they can often be managed with modest volumes of water and time, without requiring any specialized equipment or training.

The most reliable way to extinguish an EV traction battery is to let it burn out. Complete burnout of the battery will reduce the risk of reignition and presence of stranded energy. Furthermore, the electrical hazard will be reduced, as the highest risk is posed by batteries that have been damaged enough to lose electrical isolation while being intact enough to retain a dangerous charge. While the risk cannot be eliminated, the risk is reduced if all cells are destroyed.

Applying copious amounts of water to the battery in an attempt to externally cool it and interrupting thermal runaway propagation will consume significant resources, produce a lot of runoff and is unlikely to stop thermal runaway propagation. Furthermore, thermal runaway exhaust gases may appear similar to steam, making the identification of ongoing TR difficult under continuous water application. Instead, firefighters should use restrained, intermittent water application with a narrow fog pattern to cool the vehicle chassis to prevent (re-)ignition of the passenger compartment and supervise the battery while it burns out. This will significantly reduce resource expenditure while upholding a comparable incident resolution timeline. If necessary, a fog stream can be used to cool the flaming vent gases, and hydraulic ventilation can be used to direct the flames away from adjacent exposures. Introducing water into openings burned into the battery casing marginally increases the cooling rate of the battery, but under no circumstances should the battery be manually breached.

Once the flames have been suppressed, the vehicle should be reassessed for risk of battery reignition using the scheme outlined in Figure C.5. The assessment should include listening for audible signs of thermal runaway such as hissing or popping, production of smoke and vapor from the battery pack and temperatures that are higher than ambient and/or increasing. The use of a thermal imaging camera (TIC) may be useful to identify temperature differences, but firefighters should be aware that this tool has limitations as well. Temperature readouts may vary by 50 % or more and auto-ranging may make small temperature differences appear more significant than they are. In any case, responders should be familiar with the operation and limitations of their TICs. The battery may take a long time to cool to ambient temperatures. The vehicle may be removed from scene at incident command's discretion once the battery has cooled enough that it can be handled safely by responders and poses no thermal hazard to the tow truck. It is emphasized that actions such as moving the vehicle may cause short circuits which can reignite the battery without warning.

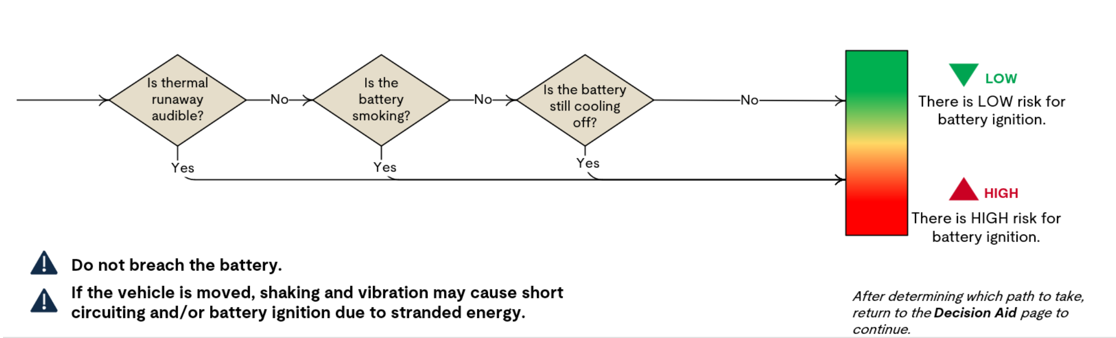

Figure C.5: Indications for high battery reignition risk.

Due to the unpredictable nature of battery reignition, and the potentially severe chemical exposure that may result, any personnel operating close to the vehicle during the observation period should use an SCBA, even if there appears to be no active fire or acute respiratory hazard.

Once the battery has been determined to have a low risk of reignition, the vehicle can be released to second responders and the incident can be terminated.

C.6 Incident Termination

Termination of the incident involves performing a post-incident inspection to confirm the EV reignition risk is low enough for transport. Second responders should be informed about EV hazards and storage requirements in accordance with local policies. Any movement of the vehicle increases the risk of short circuits and associated reignition and incidents have been documented where firefighters were exposed to thermal runaway vapors without respiratory protection during such activities. For this reason, it is prudent that all personnel operating in the vicinity of the vehicle use an SCBA and that a charged hoseline be staged during loading operations.

Once the vehicle is handed over to second responders, a preliminary exposure reduction and decontamination should take place. All firefighters that came into contact with smoke and/or debris should be brushed clean and rinsed with water before going off air. PPE should be removed and immediately bagged for transport separately from the crew compartment. Firefighters should remove their PPE before going to firefighter rehabilitation and do so well away from the rehab site.

Experience has shown that the movement associated with loading the vehicle onto a flatbed truck and unloading it at the tow lot can increase the reignition hazard. In order to allow for early recognition and easy access, the vehicle should be transported uncovered. Furthermore, a suppression unit with tank water should escort the tow truck to the salvage yard to allow for rapid recognition and suppression, should reignition occur.