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Crash Management for Electric and Fuel Cell Vehicles: Merging Scientific and Engineering Work with Established Procedures

February 27, 2025

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Acronyms and Abbreviations

ASTM	ASTM International
ANSI	American National Standards Institute
CSA Group	Canadian Standards Association
ERG	Emergency Response Guide
FMVSS	Federal Motor Vehicle Safety Standard
HLDI	Highway Loss Data Institute
HF	Hydrogen Fluoride
HV	High Voltage
IFE	Inception Forensic Engineering, LLC
INL	Idaho National Laboratories
IIHS	Insurance Institute for Highway Safety
LEL	Lower explosive limit
NFPA	National Fire Protection Association
NHTSA	National Highway Traffic Safety Administration
NIOSH	National Institute for Occupational Safety and Health
NTSB	National Transportation Safety Board
PPE	Personal Protective Equipment
SAE	Society of Automotive Engineers
SOC	State-of-charge
UEL	Upper explosive limit
US DOT ERG	U.S. Department of Transportation Emergency Response Guidebook

Disclaimer and Limitations

At the request of the Science Foundation Arizona and Arizona Commerce Authority, Inception Forensic Engineering, LLC (IFE) performed a literature review of established crash management principles and practices, product information, research reports, journal articles, standards, and other information to develop a crash management system (CMS), which will be utilized to create a training program for first- and second-responders responding to crash incidents involving electric vehicles (EV) and hydrogen fuel cell (FCV) vehicles.

In consideration of vehicle crash management, no two emergency incident responses are the same. There are an infinite number of crash scenarios, involving different vehicles, different speeds, different orientations, different technologies, and obstacles on or off the roadways. As such, this report cannot, and does not, address all possible crash scenarios.

Research is ongoing in many of the technical areas discussed in this report. Readers are advised that the information in this document is provided only as current guidelines. In forming the content expressed in this report, IFE has relied upon information created by others, much of which IFE cannot independently verify the comprehensiveness and accuracy of. Furthermore, the information and guidance provided in this document do not indicate an exclusive course of action, and variations are expected to be taken given the circumstances of the incident, local protocols, and equipment utilized. IFE has made every effort to ensure that relevant topics within the scope of work are presented and disclaims any liability or responsibility for the consequences of any action taken in reliance on these statements or opinions. If the reader identifies any information that is incomplete, outdated, incorrect, or unclear, we request that they bring this to our attention immediately so that we may have an opportunity to address.

Anyone using this document should rely on his or her own independent judgment or, as appropriate, seek the advice of a competent professional with actual knowledge of a specific situation in determining the exercise of reasonable care in any given circumstances. IFE is not undertaking or rendering professional or other services for or on behalf of any person or entity besides Science Foundation Arizona & the Arizona Commerce Authority, nor is IFE undertaking to perform any duty owed by any person or entity to someone else.

EV and FCV vehicles, along with traction batteries, are experiencing rapid development and deployment, and the guidance formulated in this report is based on observations and information available at the time of the report. If new information becomes available, this report may be updated. IFE cannot predict the evolution of current technologies; the development of new technologies; the application, implementation, or design of new technologies; the condition of vehicles pre-crash, including conversions to alternative fuel powertrains; and all of the various ways that the technologies or designs will be influenced by the variety of different vehicle/crash scenarios that are possible. Additionally, IFE cannot predict the observations First- and Second-Responders will make, and how those observations influence decision making processes.

The breadth of topics covered in the current work precludes a comprehensive review of all of the supporting material. Additionally, the scope of work in this report does not include recommendations on courses of action, but instead presents information currently available for use by the reader. As such the reader is encouraged to review source information for additional information.

Advisory Committee & Acknowledgements

The current work is done with the assistance and guidance of an advisory group. The group consists of:

- Jeff Wishart, Ph.D., Science Foundation Arizona, Arizona State University
- Adam Barowy, UL Fire Safety Research Institute
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- Scott Popatia, Tempe Fire Medical Rescue Department
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- Jim Barnhart, Mesa Fire & Medical Department
- Erik Archibald, Hazard Dynamics
- Don Karner, Electric Applications Inc.
- Jan Swart, Exponent, Inc.
- Nick Christopherson, Emergency Environmental Solutions
- Jordan Bradley, Emergency Environmental Solutions
- Ryan Campbell, Emergency Environmental Solutions
- Derick Denis, Clark Sief Clark
- Melissa Gambone, Nikola Corporation

Information about the author can be found in Appendix A.

1.0 Introduction, Scope, and Approach

On February 8, 2023, the Science Foundation Arizona (SFAz), in partnership with the Arizona Commerce Authority (ACA), announced the opening of a Request for Proposals to provide Zero-Emission Vehicle (ZEV) Crash Management System (CMS). Inception Forensic Engineering, LLC (IFE) submitted a proposal, and was awarded the contract on May 25, 2023. The ZEV types considered in this work are electric vehicles (EVs) and hydrogen fuel cell vehicles (FCVs).

First-responders and second-responders (e.g. tow vehicle operators) to EV and FCV crashes are disproportionately exposed to hazards of lithium-ion batteries (LIBs). They respond to events which may involve mechanical or thermal damage to a LIB, which can initiate a thermal runaway process, or to a compressed gas tank, which can leak or rupture (other alternative fueled vehicles may also experience boiling liquid expanding vapor explosions). As a community, researching these hazards, communicating them to first- and second-responder communities, and assisting in the development of protocols are important to mitigate risks. The transfer of knowledge from the scientific and engineering communities should occur as quickly as practicable, and this work aims to assist in this manner.

The intended audience for this work is both the first- and second-responder communities as well as the scientific and engineering communities who carry out or support research on the topic. The approach taken for this literature review and CMS development is to take existing first- and second-responder principles and practices and to supplement them with learnings, procedures, and guidance from the scientific and engineering communities. The learnings, procedures, and guidance generated by the scientific and engineering communities is parsed and inserted into the established framework for responders, so responders can see how the process deviates from conventional vehicle crash management. The hope is that the information will be more readily absorbed in this format, and limitations of the guidance will be evident. Based on the literature identified in this work, this approach is needed.

The primary source materials for existing response are *Vehicle Rescue and Extrication: Principles and Practice*, Revised Second Edition, authored by David Sweet, reviewed by publishing partners National Fire Protection Association (NFPA) and the International Association of Fire Chiefs (IAFC), published in 2022; and *Principles of Passenger Vehicle Extrication*, Fifth Edition, written by David Caruana and validated by the International Fire Service Training Association (IFSTA), and published in 2022. The scientific and engineering source material for the various technologies, systems, failure modes, and associated hazards includes information from the Society of Automotive Engineers (SAE), automotive manufacturers, the National Transportation Safety Board (NTSB), journal articles, and more.

In Chapter 2, a status report on the training of responders to EV incidents is provided, along with a background on modern EV systems, LIBs, selected reports, burn tests, and first-responder personal protective equipment (PPE). Chapter 3 is organized by hazards – fire, deflagration/ explosion, toxicity, and electrical shock. Note that hazards do not imply probability or likelihood of the hazard actually causing harm. Chapter 4 includes the CMS, where the established framework for responders is laid out and supplements are made. Additionally, this chapter includes discussion of tools for use in such incidents, along with issues associated with transportation, isolation, and storage of crash-damaged vehicles. The focus of this chapter is on EVs, with unique aspects of FCVs discussed in a specific section. This is because of the higher population of EVs, as well as similarities between FCVs and EVs in that they have battery packs with electric drive units.

Addressing first- and second-responder safety in events involving EVs is becoming more important as more EVs are sold, and as EVs on the road age. If EVs show similar trends to ICEVs, fires become more frequent as vehicles age. At present, according to NFPA, currently available statistics indicate 25.1 EV fires per 100,000 cars sold, and 1,529.9 ICEV fires per 100,000 cars sold.[1]

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[1] NFPA, SFPE conference. Note that this data is not based on national statistical data.

This is the first version of the document. First- and second-responder safety is an active area of research, as research is ongoing by numerous programs including, but not limited to the U.L. Fire Safety Research Institute (FSRI) and the NFPA Fire Protection Research Foundation, among other groups. If feasible, this document will be updated as knowledge on the topic progresses.

2.0 Background

2.1 Progress on Training of First and Second Responders

Liu et al. from the University of Alabama conducted a national survey to better understand whether first-responders are well prepared for traffic incidents that involve EVs and whether there are any organizational and geographic disparities in the level of preparedness. Analysis of the survey was published in November 2022. They found that there are limited training opportunities provided to first-responders, particularly police and emergency medical services (EMS), who are responding to EV crash incidents. The most commonly cited training programs identified in this survey are offered through NFPA and the National Alternative Fuels Training Consortium (NAFTC); however first-responders are also getting information on their own through manufacturer guides and state/local training opportunities. The desert southwest (including Arizona) has a higher-than-average rate of first-responders with EV-specific training (70%).

At the time of the survey, first-responders tended to view both the EV landscape and manufacturer guides as too variable, with both in need of standardization. ISO17840 is a recommended standard for the manufacturer guides, with roughly half of the EV manufacturers adopting (or in the process of adopting) at the time of the study. This standard provides information on formatting (templates) and content for emergency response guides (ERGs) and rescue sheets. First-responders also called for more standardization of vehicle components/systems/color schemes across the industry.

According to the survey, prior to responding to traffic incidents, first responders could be better trained to identify if a vehicle is an EV, and if so, whether the battery has been involved in the incident. This survey also identifies that fire tactics specific to EVs are largely unknown, particularly outside of the fire community. 88% of respondents identified additional training opportunities as the most important recommendation to increase preparedness for a more electrified transportation system.

Additionally, while online training opportunities are very useful given their ease of accessibility, and low or no cost, in-person training and experiential training will benefit first- and second-responders. Experiential training, such as live burn tests, present not only an opportunity for training but also for research that can improve processes in the future.

Training services are also provided by other organizations, such as the Energy Security Agency (ESA), StachD training, and more.

2.2 Modern EV High Voltage Systems

Modern EV high voltage (HV) systems can have voltages up to 900 V. Currently, these systems consist of the following:[2]

- HV battery
- One or more inverters to power the electric drive (a.k.a. electrical machine, or e-motor)
- Isolating DC-DC converter to supply the 12 V system (or 48 V system)
- Potentially:
  - Electric-air conditioning compressors, powered by another inverter
  - Other HV components, such as air or water heaters
  - Other high output system (e.g. power receptacle)

[2] Bosch, Automotive Handbook, 11th Edition, January 2022, p1561.

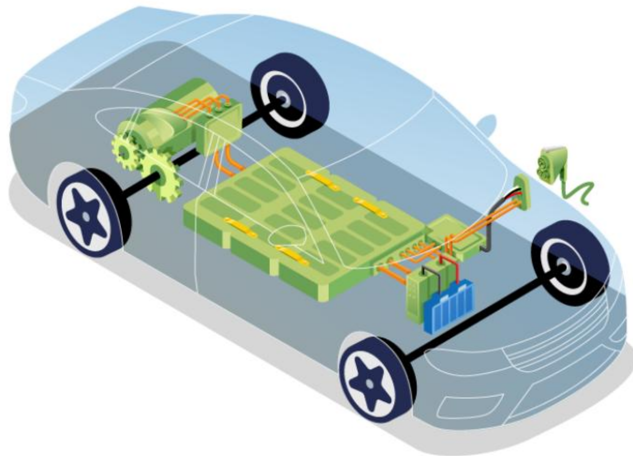

Figure 1 Illustration of the main components of an EVs HV system, per NHTSA.[3]

The HV electrical system is connected to the HV battery, and supplied with voltage via contactors (i.e. switches) that are typically integrated into the HV battery pack assembly. When the vehicle is turned off, or if the vehicle is in an accident of sufficient magnitude, the HV electrical systems are designed to be de-energized at the contactors, so the HV equipment and wires are disconnected from the HV battery pack.[4]

Although the HV electrical systems are disconnected from the HV battery in the above referenced cases, 1) stranded energy likely still remains within the battery pack, 2) there may be stored energy within capacitors in the vehicle, and 3) the electric drive inverters can potentially generate electricity if the wheels are turned. It is also noteworthy that, while many electric vehicles have on/off buttons, some do not and the vehicles will shut down after some elapsed time under normal operation.

The isolating DC-DC converter converts HV to a low voltage, typically 12 V, or commonly referred to as the low voltage system. For safety reasons, the 12 V is isolated from the HV battery pack, and the HV battery pack is isolated from vehicle ground. Because the HV battery

3 https://www.nhtsa.gov/vehicle-safety/electric-and-hybrid-vehicles, accessed 3/9/2024.

4 Bosch, Automotive Handbook, 11th Edition, January 2022, p1561.

pack is isolated or "floating", single-point faults generally do not result in hazardous situations.[5] In such cases, if a single-point fault occurs, then the object touching the fault is simply referenced to the voltage at that point, and current does not flow unless there is a secondary path. HV systems in EVs are greater than 60 volts, so federal government regulations require the OEMs to monitor the body and chassis isolation.[6] Per Bohm, the loss of isolation on EVs is one of the more common failure modes, irrespective of manufacturer.[7]

The schematic of a typical electrical system in an EV is reproduced in Figure 2. The HV battery is identified by #7, and the contactors described earlier are identified by #5. This diagram shows the HV connected to two separate inverters, which run the electric drive motor and air conditioning compressor, respectively, the isolated DC/DC converter to power the low voltage system, and the AC/DC converter which handles the charging.

5 Bosch, Automotive Handbook, 11th Edition, January 2022, p1598.

6 Federal Motor Vehicle Safety Standard (FMVSS) No. 305.

7 Bohn, T., Fundamentals of High Voltage xEV, Safety, and PPE, SAE Course I.D. #C2001, Version: 004, slide 6.

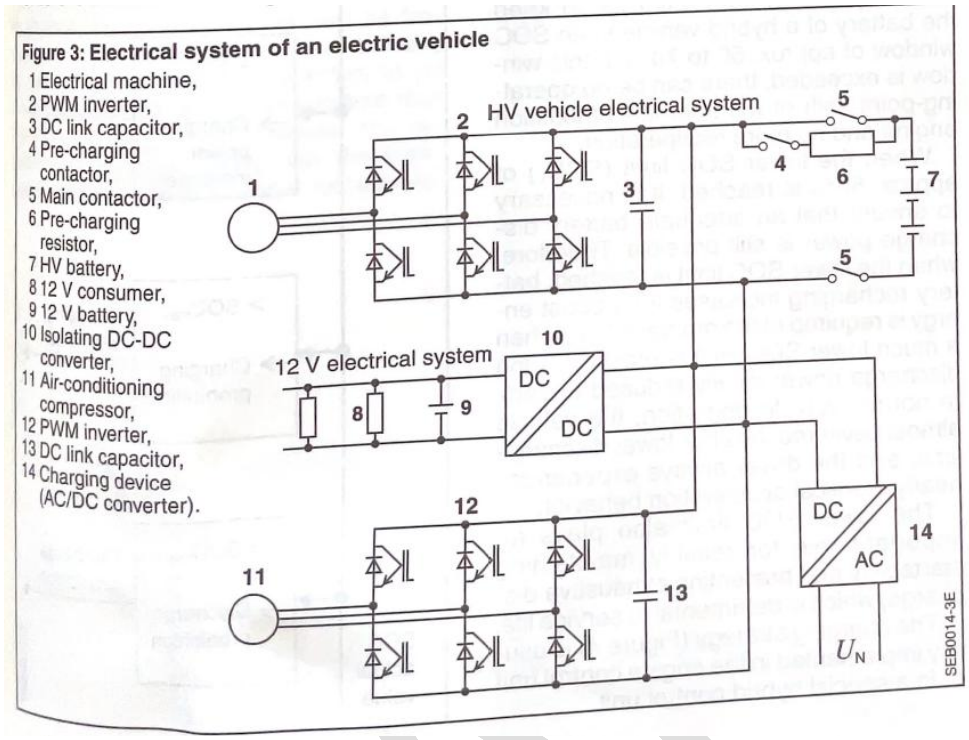

Figure 2 Schematic of a typical electrical system of an EV.[8]

2.3 Lithium-Ion Batteries

2.3.1 Background

The basic operating principle of lithium-ion batteries (LIBs) is that lithium ions (Li^+) pass from one electrode to the other and back during a cycle of charge and discharge. They have been referred to as "rocking chair" batteries because of this behavior. The positive and negative electrodes can store lithium ions. These electrodes are separated by material which is referred to as the *separator*. The negative electrode is typically a graphitic carbon, coated on a copper current collector. The positive electrode can be a variety of different materials, such as lithium iron phosphate (LFP), lithium cobalt oxide (LCO), lithium nickel manganese cobalt oxide (NMC), lithium manganese oxide (LMO), and lithium nickel cobalt aluminum oxide (NCA).[9] When charged or discharged, lithium ions are either inserted or extracted from interstitial space

[8] Bosch, Automotive Handbook, 11th Edition, January 2022, p1563.

[9] Essl et al., Comprehensive Hazard Analysis of Failing Automotive Lithium-Ion Batteries in Overtemperature Experiments, Batteries, MDPI, 2020.

between atomic layers of the electrodes.[10] Much has been written about LIBs, and the reader is referred to other sources for additional information.

Typical electrolytes that are used in cells include:[11]

- Lithium salts, such as $LiClO_4$, $LiPF_6$, $LiBF_4$, and $LiAsF_6$
- Solvents, such as $C_3H_4O_3$, $LiPF_6$, $C_4H_6O_3$, PF_5, $C_5H_{10}O_3$, $C_3H_6O_3$, and $C_4H_8O_3$
- Additives

The collection of electrodes, electrolyte, and lithium ions form a cell, which is on the order of 4.2-4.35V V when fully charged. Cells can have three form factors:

- Cylindrical (i.e. similar to a AA battery, but larger)
- Prismatic, where they are enclosed in a solid rectangular container
- Pouch, where the electrode stack is secured by a flexible cover

Collections of cells may be designed into *modules*, and collections of modules may be designed into an overall battery *pack*. Thus, an EV battery pack is a collection of many (often hundreds) of battery cells, which are encased in an enclosure that also includes a battery cooling system.

2.3.2 Typical HV Battery Pack Locations

Typical battery pack locations in sedans, including "skateboard" style EV battery packs, were shown in Figure 1, and additional examples are shown in Figure 3 and Figure 4. Battery packs in these locations are typically exterior of the vehicle cabin. Sport utility vehicles (SUVs) or light duty trucks may also have battery packs in similar locations. An example of a battery pack in an SUV in the interior of the cabin is shown in Figure 5. An example of a rooftop battery pack on a 35 or 40 ft. electric bus is shown in Figure 6. A schematic of a HV battery pack in a

[10] Beard, K., Linden's Handbook of Batteries, Fifth Edition, 2019, p757.

[11] Gong, C., Crash Safety of High-Voltage Powertrain based Electric Vehicles – Electric Shock Risk Prevention, University of York, December 2020, p29.

class 8 COE 2-door Truck-Tractor is shown in Figure 7, and includes battery packs in typical locations of Diesel fuel tanks in similarly sized ICEVs, along with between the frame rails.

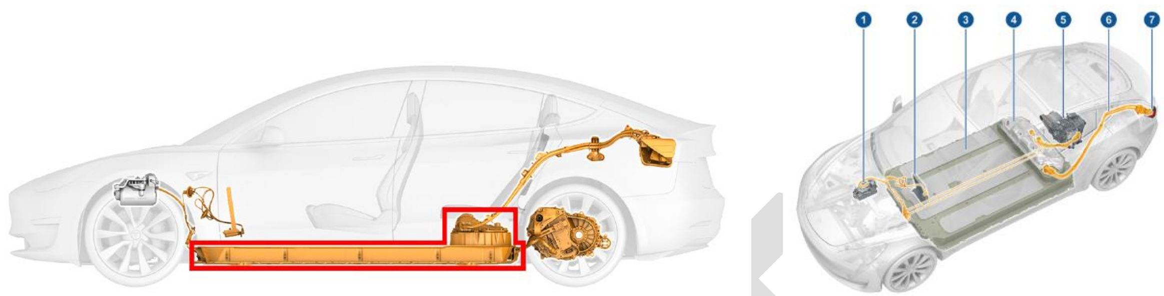

Figure 3 Tesla Model 3 HV battery pack location (item 3 in right schematic).

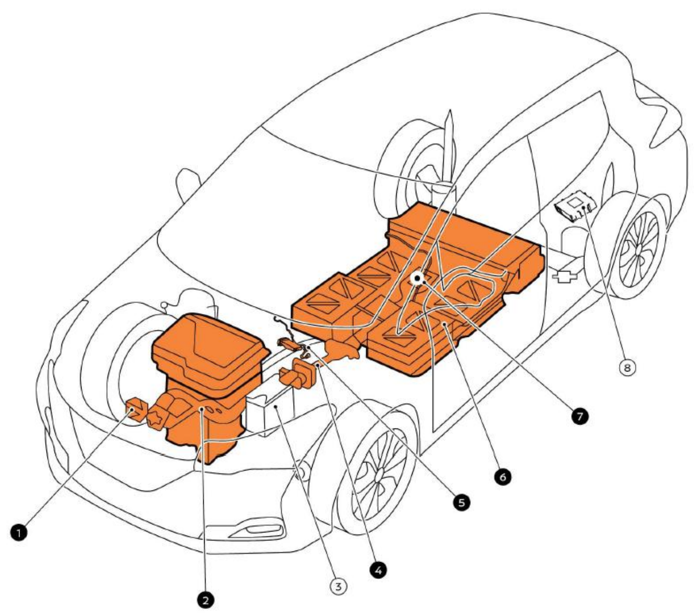

Figure 4 2020 Nissan Leaf EV HV battery pack location (item 6).

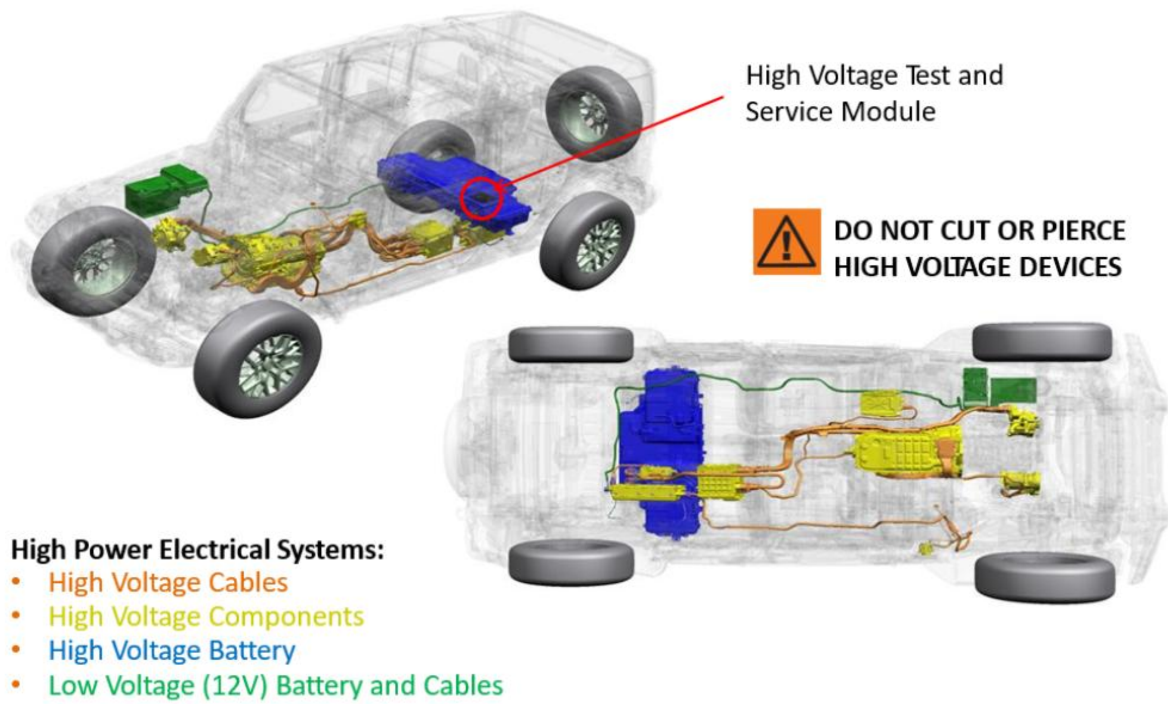

Figure 5 2021 Jeep Wrangler 4xe JL HV battery pack location (blue) in the interior of the vehicle cabin, below the rear seats.

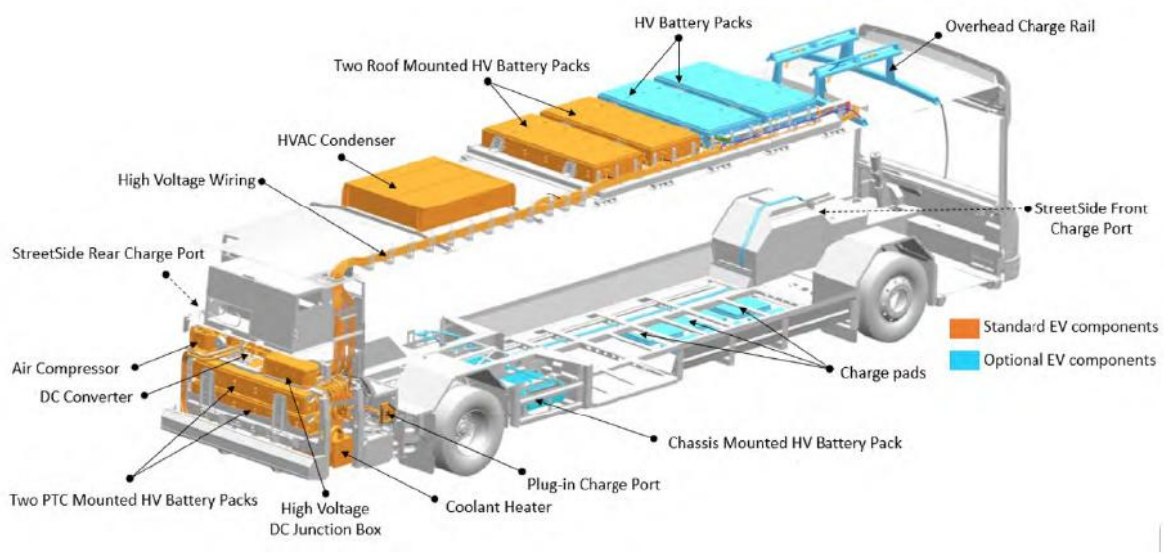

Figure 6 Rooftop HV battery locations (orange, with blue battery packs optional) on a Gillig 35/40 ft. battery electric bus.

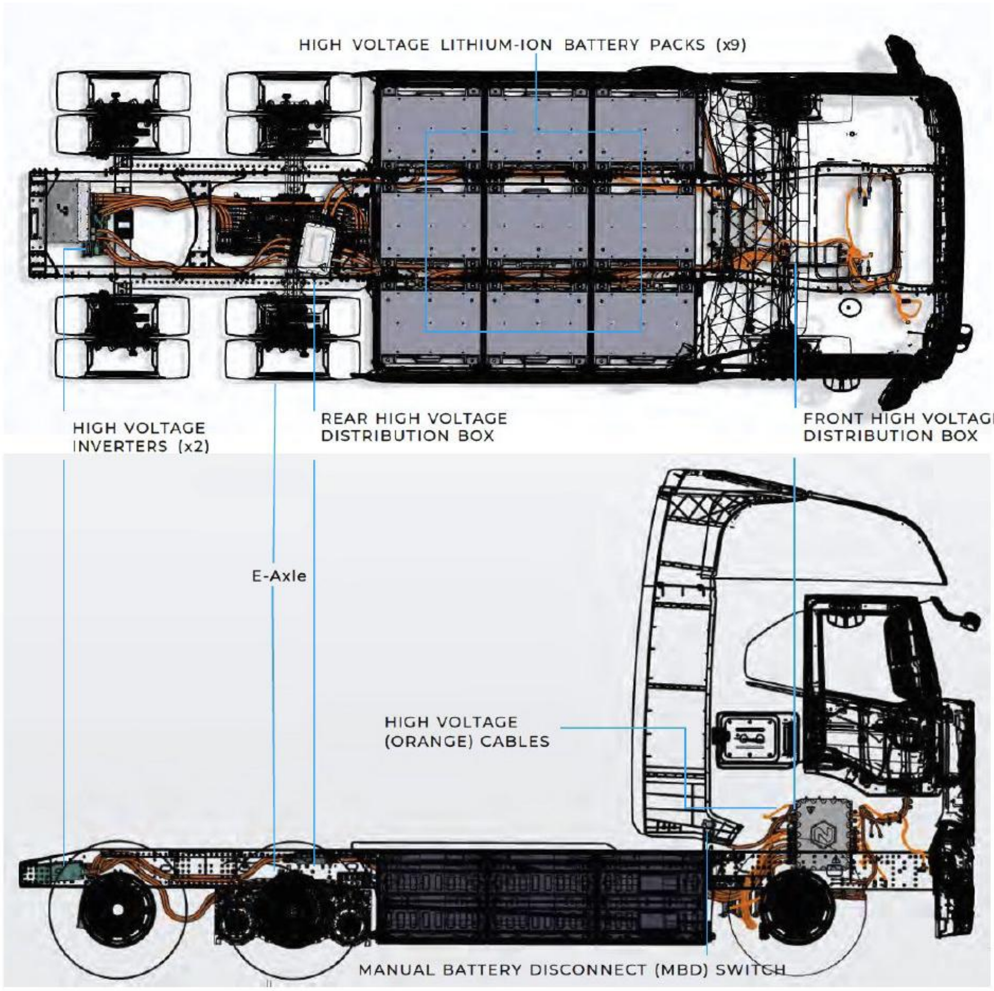

Figure 7 Nikola Tre BEV Class 8 COE 2-Door Truck-Tractor, model years 2022-.

2.3.3 Lithium-Ion Battery Thermal Runaway

LIBs can fail in different ways, some of which are benign, but one of the failure effects is a process called thermal runaway. In this process, from the heat transfer perspective, the heat generated by the cell undergoing thermal runaway is more than the heat that can diffuse from it to the surroundings, so the temperature of the cell rises uncontrollably, chemical reactions occur, and the reaction products vent from the cell. The vent flow contains gases which are flammable in certain mixtures and toxic in certain quantities.

This process can happen as a result of internal cell failure or by external conditions. Internal cell failure can be associated with a manufacturing issue. External factors that can cause thermal runaway typically include thermal abuse, electrical abuse, mechanical abuse, and certain types of environmental abuse. During a vehicle crash, mechanical abuse can occur as a result of the battery pack being impacted or crushed. Thermal abuse may also occur as a result of a nearby fire or other heat sources. Although a less common factor in a crash, environmental abuse may occur at high or low temperatures, e.g. outside of manufacturers specifications, by water ingress (electrical isolation issues), and potentially by other issues such as common mode voltage. Other external, off-nominal conditions include overcharge, multiple over-discharges followed by a charge, or an external short circuit. Battery packs often have controls in place to mitigate risks associated with thermal runaway.

In all of the above conditions, a potential failure effect is thermal runaway of the cell by internal short circuits and heating, or internal cell reactions leading to heating. Given that multiple cells are typically used in a module/pack, thermal runaway of one cell can potentially lead to thermal runaway in adjacent cells, and propagation may occur.

The vent gases that are released from venting cells are flammable in certain mixtures, and venting cells can also potentially eject extremely hot (glowing) particles and material that can potentially ignite the vent gas.

A summary of the decomposition stages of overheated, LIB cells with cell chemistries listed above is shown in Table 1.[12]

[12] Essl et al., Comprehensive Hazard Analysis of Failing Automotive Lithium-Ion Batteries in Overtemperature Experiments, Batteries, MDPI, 2020.

Table 1 Summary of the decomposition stages of overheated, LIB cells with cell chemistries listed above.

Temperature (°C)	Reaction behaviour
>70	Li salt decomposition and reaction with solvent and Solid electrolyte interphase (SEI)
90–130	SEI breaks down leading to anode-electrolyte reaction. Low heat generation.
90–230	Li-electrolyte reaction occurs, leading to gas production e.g. C_2H_4, C_2H_6 and C_3H_6.
120–220	Electrolyte vaporises, leading to additional gas generation, cell pressurisation and initial venting. Separator melts at 130°C to 190°C.
160	Heat generation increases – from “self heating” to “thermal runaway”. Violent gas and particle release (second venting).
200–300	Electrolyte decomposition occurs. At TR there is a rapid temperature rise, the metal oxide cathode decomposes to produce oxygen. O_2 leads to the oxidation of the electrolyte -¿ CO_2 and H_2O

2.4 Selected Literature Related to Response to EV Incidents

2.4.1 NFPA Emergency Field Guide for Hybrid, Electric, Fuel Cell, and Gaseous Fuel Vehicles

NFPA published an Emergency Field Guide in 2018 as part of the Alternative Fuel Vehicles Safety Training Program. This was developed by the NFPA using fire-rescue service best practices at that time and incorporating information from automotive and battery manufacturers. This was published prior to the current version of SAE J2990, July 2019, the latter of which is described in the next section.

This guide includes general or generic response information that are applicable to most vehicles, as well as two-page entries specific to each vehicle that has information to assist with identification, immobilization, disabling, and extrication. The generic information is provided in the case that the vehicle cannot be identified. The guide contains photographs of all of the included vehicles from a 45° perspective relative to the front, which is consistent with first responders approaching from the sides of the vehicle.

This is an excellent resource for first responders, although it is now approximately 6 years old so it does not incorporate the latest research and information for newer vehicles.

2.4.2 SAE J2990

SAE J2990, *Hybrid and EV First and Second Responder Recommended Practice*, was first issued in November 2012, and revised in July 2019. The document covers topics including guidance on inspection of HV systems including batteries in incident vehicles at the scene, as well as after the vehicle arrives at the salvage yard or repair facility. Not all of the information presented is intended for fire departments and tow companies, nor are fire departments and tow companies expected to carry out all of the information themselves. The practice includes some information on transportation, as well as isolation requirements.

SAE J2990, July 2019 encourages automotive OEMs to reference the same for industry design guidance when creating vehicle requirements and emergency response guides (ERGs),[13] and recommends content to be included. These ERGs are developed by individual manufacturers, to be used with their specific vehicles.

2.4.3 Manufacturer's Emergency Response Guides and Rapid Response Guides

Manufacturers produce ERGs specific to their vehicles which have information related to identifying, immobilizing, and disabling their vehicles, along with other relevant information. Manufacturers may also produce rescue sheets, also known as quick reference` guides or rapid response guides (RRGs) which are much shorter and accordingly are more easily reviewed in

[13] SAE J2990, July 2019, p5

the case of an emergency. The contents of ERGs are supplemental in nature. For example, the ERGs are not replacements for HV safety training.

ISO 17840 is a standard that relates to information for first- and second-responders. Sections relevant to ERGs and rescue sheets are as follows. Part 1 includes quick reference rescue sheet templates with a standardized layout, color codes, and standardized pictograms. Part 3 includes a template for ERGs, standardized chapter headings, chapter sequences, color codes, and pictograms. Part 4 standardizes the labels and related colors to indicate the fuel and/or energy used for propulsion of vehicles.

- ISO 17840-1 Road Vehicles - Information for First and Second Responders - Part 1: Rescue Sheet for Passenger Cars and Light Commercial Vehicles
- ISO 17840-3 Road Vehicles - Information for First and Second Responders - Part 3: Emergency Response Guide Template
- ISO 17840-4 Road Vehicles - Information for First and Second Responders - Part 4: Propulsion Energy Identification

There are various locations which collect these ERGs and RRGs. IFE has not performed a comprehensive review of these sources or identified such a review in the literature. The NFPA Emergency Field Guide (discussed in section 2.4.6), vehicle manufacturer websites, the NFPA.org website, commercial platforms (e.g. Moditech) which require purchase/subscriptions, the Energy Security Agency (ESA), Boron Extrication, and smartphone applications have links or include collections of these ERGs and/or RRGs.

A cursory review of two commonly referenced smartphone applications showed either outdated ERGs or only RRGs with no ERG, in some instances. Incomplete collections of ERGs and RRGs, out-of-date information, or information that cannot be accessed during an emergency may be problematic. In order to efficiently transfer these documents to first- and second-responders, and to ensure that they are up-to-date, there may be a benefit to having a singular entity that vehicle manufacturers send up-to-date documents to, and from which first- and second-responders can correspond with to ensure that their ERGs and RRG collections are complete, up-to-date, and available off-line in the case of internet accessibility issues. First- and second-responders would be able to subscribe to a singular service (e.g. update email list, or push notification in the case of an app) and be notified whenever there is a new download. It would be challenging and impracticable for the manufacturers to directly correspond with the more than 29,000+ fire departments in the United States,[14] or vice versa.

It is possible that some commercially available products are available which satisfy the above requirements, but some fire services may be reluctant to purchase them given budgetary constraints, particularly given free sources which appear to be comprehensive and up-to-date.

2.5 Available Electric and Fuel Cell Vehicles

A list of available all-electric and fuel cell vehicles available by manufacturer for the 2021 model year is reproduced in .

[14] As of 2020, per https://www.nfpa.org/education-and-research/research/nfpa-research/fire-statistical-reports/us-fire-department-profile, accessed March 11, 2024.

TABLE 21.4.1 All-Electric* and Fuel Cell Vehicles Available by Manufacturer, Model Year 2021

Model	Drive Type	EPA Size Class	Range (Miles)
Audi e-tron	EV	Standard SUV 4WD	222
Audi e-tron Sportback	EV	Standard SUV 4WD	218
BMW I3 BEV (120 Ah battery)	EV	Subcompact Cars	153
BMW I3s BEV (120 Ah battery)	EV	Subcompact Cars	153
Chevy Bolt (BEV)	EV	Small Station Wagons	259
Ford Mustang Mach-E AWD	EV	Small Station Wagons	211
Ford Mustang Mach-E AWD Extended	EV	Small Station Wagons	270
Ford Mustang Mach-E California Route 1 (RWD)	EV	Small Station Wagons	305
Ford Mustang Mach-E RWD	EV	Small Station Wagons	230
Ford Mustang Mach-E RWD Extended	EV	Small Station Wagons	300
Hyundai Ioniq Electric	EV	Midsize Cars	170
Hyundai Kona Electric	EV	Small SUV 2WD	258
Jaguar I-Pace EV400	EV	Small SUV 4WD	234
Kandi K27	EV	Compact Cars	59
Kia Niro Electric	EV	Small Station Wagons	239
Mini Cooper SE Hardtop 2 Door	EV	Subcompact Cars	110
Nissan Leaf (40 kW-hr battery pack)	EV	Midsize Cars	149
Nissan Leaf (62 kW-hr battery pack)	EV	Midsize Cars	226
Nissan Leaf SV/SL (62 kW-hr battery pack)	EV	Midsize Cars	215
Porsche Taycan Performance Battery	EV	Compact Cars	200
Porsche Taycan Performance Battery Plus	EV	Compact Cars	225
Porsche Taycan 4S Performance Battery	EV	Large Cars	199
Porsche Taycan 4S Performance Battery Plus	EV	Large Cars	227
Porsche Taycan Turbo	EV	Large Cars	212
Porsche Taycan Turbo S	EV	Large Cars	201
Tesla Model 3 Long Range AWD	EV	Midsize Cars	353
Tesla Model 3 Performance AWD	EV	Midsize Cars	315
Tesla Model 3 Standard Range Plus RWD	EV	Midsize Cars	263
Tesla Model S Long Range	EV	Large Cars	405
Tesla Model S Performance (19″ Wheels)	EV	Large Cars	387
Tesla Model S Performance (21″ Wheels)	EV	Large Cars	334
Tesla Model S Plaid (21″ Wheels)	EV	Large Cars	348
Tesla Model X Long Range Plus	EV	Standard SUV 4WD	371
Tesla Model X Performance (20″ Wheels)	EV	Standard SUV 4WD	341
Tesla Model X Performance (22″ Wheels)	EV	Standard SUV 4WD	300
Tesla Model Y Long Range AWD	EV	Small SUV 4WD	326
Tesla Model Y Performance AWD	EV	Small SUV 4WD	303
Tesla Model Y Standard Range Plus RWD	EV	Small SUV 2WD	244
Volkswagen ID.4 1st	EV	Small SUV 2WD	250
Volkswagen ID.4 Pro	EV	Small SUV 2WD	260
Volkswagen ID.4 Pro S	EV	Small SUV 2WD	250
Volvo Polestar 2	EV	Midsize Cars	233
Volvo XC40 AWD BEV	EV	Small SUV 4WD	208
Honda Clarity	FCEV	Midsize Cars	360
Hyundai Nexo	FCEV	Small SUV 2WD	354
Hyundai Nexo Blue	FCEV	Small SUV 2WD	380
Toyota Mirai Limited	FCEV	Compact Cars	357
Toyota Mirai XLE	FCEV	Compact Cars	402

*Fuel cell electric vehicles are just that—electric vehicles. Unlike battery electric vehicles that are plugged into a charger, FCEVs fuel at a hydrogen fueling station and use that hydrogen, with oxygen from the air, in a fuel cell stack to produce their electricity on board, in real time.

EV = electric vehicle; FCEV = hydrogen fuel cell vehicle.

Sources: Davis and Boundy[3]; data from US Department of Energy and US Environmental Protection Agency, Fuel Economy website, Power Search. www.fueleconomy.gov/feg/powerSearch.jsp. Accessed July 29, 2021.

3.0 Hazards to Responders Associated with EV and FCV Incidents

Hazards are defined as a potential source of harm, and not a probable source of harm. Hazards associated with EV and FCV incidents can be related to the more conventional systems and parts of those vehicles (or the environment in which the incident has occurred), or they can be associated with LIBs, H2 tanks, and their associated systems. This chapter includes a discussion of potential fire, explosion, toxicity, and electrical shock hazards associated with EV and FCV incidents.

Additionally, as a starting point, it is noteworthy that many hazards exist in both EVs and ICE incidents. For example, both have the potential for toxic gas release, similar heat release rates (HRRs), and high temperature flames in excess of 1,000°C. The risk of delayed re-ignition is present in both types of vehicles but higher, in certain cases, in EV's than in ICE vehicles. This section, as well as later sections, do not include description or associated analysis of hazards introduced by contents of vehicles, such as other batteries, containers of gasoline or other toxic substances, etc.

3.1 Fire

3.1.1 Fire Involving EVs

The scope of this section includes fires involving LIBs in EVs. This excludes other potential fire causes which may involve different systems and different fuels, such as loose electrical connections.

Fires involving EV LIBs can manifest as free burning fires or as jet-like fires emanating from the pack. In some cases, jet-like fires extending several feet may emanate from specific areas of the pack which have designed venting locations, such as burst discs, or from other parts of the pack that have been breached or damaged. The jet fires can burn for extended periods of time.[15]

There have been several vehicle burn testing campaigns to-date which have involved EVs and ICEVs. The most recent literature review was published in May 2024 by Combustion Science & Engineering, in a project carried out by the NFPA Fire Protection Research Foundation. Many studies report on the heat release rate (HRR), although this can be influenced by test conditions such as the ignition type and location so caution is advised when making comparisons between them. That said, the peak HRR varied across the sixteen recent studies reviewed. Many studies found that the heat release rate (HRR) of comparably sized EV and ICEVs are comparable, although on the whole the peak HRR measured occurred most frequently in EVs. Additionally, the total heat release (THR) measured is about the same, at 5.9 GJ.[16] However, larger vehicles may have higher HRR and THR.

UL FSRI provided an update on their research in June 2024. They noted that the peak HRR can be similar between EVs and ICEVs. They also noted that complete consumption of battery cells occurred if the vehicle was allowed to burn freely (hence the guidance to let it burn if the situation permits, as described in Chapter 4). They also note that vehicle construction is likely playing a role in fire spread and growth rate.[17]

One particular study which made specific observations related to jet-like flames emanating from traction LIBs was done by Kang et al. Kang et al. performed full-scale fire testing of five-door EVs and FCVs and quantitatively compared the results with an ICE vehicle that reportedly used the same platform. All vehicles were allowed to burn out completely, and the EV burns reportedly continued up until 70 mins. A summary of the results is provided in Table 2. Notably, the authors report that the major contribution to the quantity of heat released was associated with the combustion of conventional materials of the EV body, rather than that of the

[15] SFPE June 2024 Conference, Victoria from NFPA?

[16] NFPA Research Foundation, SFPE Conference, June 2024.

[17] SFPE June 2024 Conference, UL FSRI

battery pack. However, a jet fire was noted to accelerate flame spreading, leading to a rapid growth of the fire.

Table 2 Ranges of peak HRR and total heat release for burn tests from Kang et al.[18]

	Peak HRR (MW)	Total Heat (GJ)
EV	6.51-7.25	8.45-9.03
FCV	5.99	10.82
ICEV	7.66	8.08

The difference in fire growth between the jet and non-jet tests were quantified using a generic fire growth equation [1], where the growth parameter is θ. The growth parameter was calculated based on the time needed for the fire to grow to 1 MW of HRR. For the EV that produced jets, the growth parameter was estimated to be 0.020 (fast medium), which was greater than another EV that did not have flame jets (0.0085, slow medium). Fast-medium is described as somewhere between solid wood furniture, or individual furniture items with small amounts of plastic, and high stacked wood pallets, cartons on pallets, or some upholstered furniture.

$$\dot{Q}_f = 1{,}000\left(\frac{t}{t_1}\right)^2 = \theta t^2 \quad [1]$$

Research has also been carried out to evaluate the heat flux from a burning vehicle to adjacent vehicles to assess the potential for fire spread. Representative values of critical heat fluxes for tires, bumpers, and fuel tanks are on the order of 11-17.5 kW/m2.[19] Vehicle fire tests for both EVs and ICEVs produced heat fluxes at nearby targets greatly exceeding 25 kW/m^2.[20] In many conditions, fire can spread from one vehicle to another nearby vehicle within 10 minutes, but it can spread at a faster rate if more vehicles become involved. If an EV has a jet-like flame that is directed towards another vehicle, ignition of the exposed vehicle will likely occur at a faster rate (consistent with Kang et al.'s findings described earlier).

18 Kang, S., Kwon, M., Yoon Choi, J., and Choi, S., Full-scale fire testing of battery electric vehicles, Applied Energy 332 (2023) 120497.

19 SFPR Hutchinson NFPA June 2024

20 Combustion science and engineering p56

3.1.2 Fire Involving Fuel Cell Vehicles with Hydrogen Tanks

Hydrogen (H_2) is an odorless gas. It has an extremely low density, and accordingly it is stored at high pressures – typically much higher than compressed natural gas (CNG). H_2 also has a very broad flammable range at ambient temperature and pressure (4% to 75% in air by volume), although because it is a very light gas it disperses quickly. It is colorless, although releases may involve sufficient cooling of the gas to cause condensation, which may appear as a whitish fog. When pure H_2 ignites, it does not create a typical orange flame, but instead it creates a pale blue flame which may not be visible in certain lighting conditions.

Any liquid hydrogen release will rapidly vaporize (boiling point of -423°F), and accordingly it will likely vaporize prior to reaching or forming a pool on the ground. A liquid H_2 release can cause oxygen to condense out of the air (because of temperature? See AICHE and Center for H2 Safety/hydrogen safety panel for more information).

H_2 tanks may catastrophically fail if they are heated sufficiently or otherwise damaged. However, H_2 tanks in vehicles typically do not store liquid H_2, so they technically are not susceptible to boiling liquid expanding vapor explosions (BLEVEs).

3.2 Flash Fires, Deflagrations, Detonations, and Explosions

These terms are often used interchangeably during recollections of thermal events, so they are described first. As mentioned in section 2.3.3, vent gases from LIBs which have not ignited can be flammable in certain concentrations. If the gas mixture is flammable and it reaches a competent ignition source, ignition will occur.

A flame that travels through a gaseous fuel/air mixture at subsonic speeds is referred to as a deflagration. A deflagration will typically result under conditions that allow for mixing with air and accumulation, such as no wind or slow wind speeds. If there are effectively no damaging pressures, it is more accurately described as a flash fire (a type of deflagration). A deflagration can result in damaging pressure waves, which are characterized by more gradual increases in pressure to a peak, followed by a more gradual decrease. It is a type of explosion, where propagation of the chemical reaction is heat and mass transfer to the unburned material.

When a flame that travels through a gaseous fuel/air mixture at supersonic speeds, it is referred to as a detonation. The propagation mechanism for detonations is different than that described earlier, although they are both considered types of explosions. In detonations, propagation of the chemical reaction is primarily by shock compressive heating. Detonations are characterized by a rapid increase in pressure, to a peak, followed by a more gradual decrease.

Finally, there are vapor cloud explosions, which result from ignition of flammable mixtures of air and vapors, gases, aerosols, or mists.

As described later, battery vent gases can have various compounds and particulate matter. Different compounds and particulate matter can affect the accuracy of common LEL sensors and CO sensors, and can in worst cases clog inlet filters, thereby limiting their performance.

There have been several experimental studies measuring the composition of battery vent gases in the past two decades. Baird et al. summarized these studies and created a table (see Figure 8) showing the relative concentrations of hydrogen (H_2), carbon monoxide (CO), total hydrocarbons (THCs; includes various hydrocarbons such as methane, propane, etc.), and carbon dioxide (CO_2). The cathode chemistries most typically analyzed were LCO, LFP, and NCA. Most of these tests were on cylindrical cells, where thermal runaway was initiated by external heating or overcharging. This data does not capture vent gas composition caused by mechanical damage, internal shorts, and fire, nor does it show the behavior of pouch and prismatic cells. Additionally, the techniques used did not measure hydrogen fluoride (HF).

Notably, the authors found that at lower state-of-charge (SOC), the lower the composition of flammable gases and the higher the concentration of CO_2. For LCO and LFP chemistries, there is a significant reduction in flammable gas composition below 40% SOC. At the time of their analysis, there was insufficient information on testing with NCA cell chemistries.

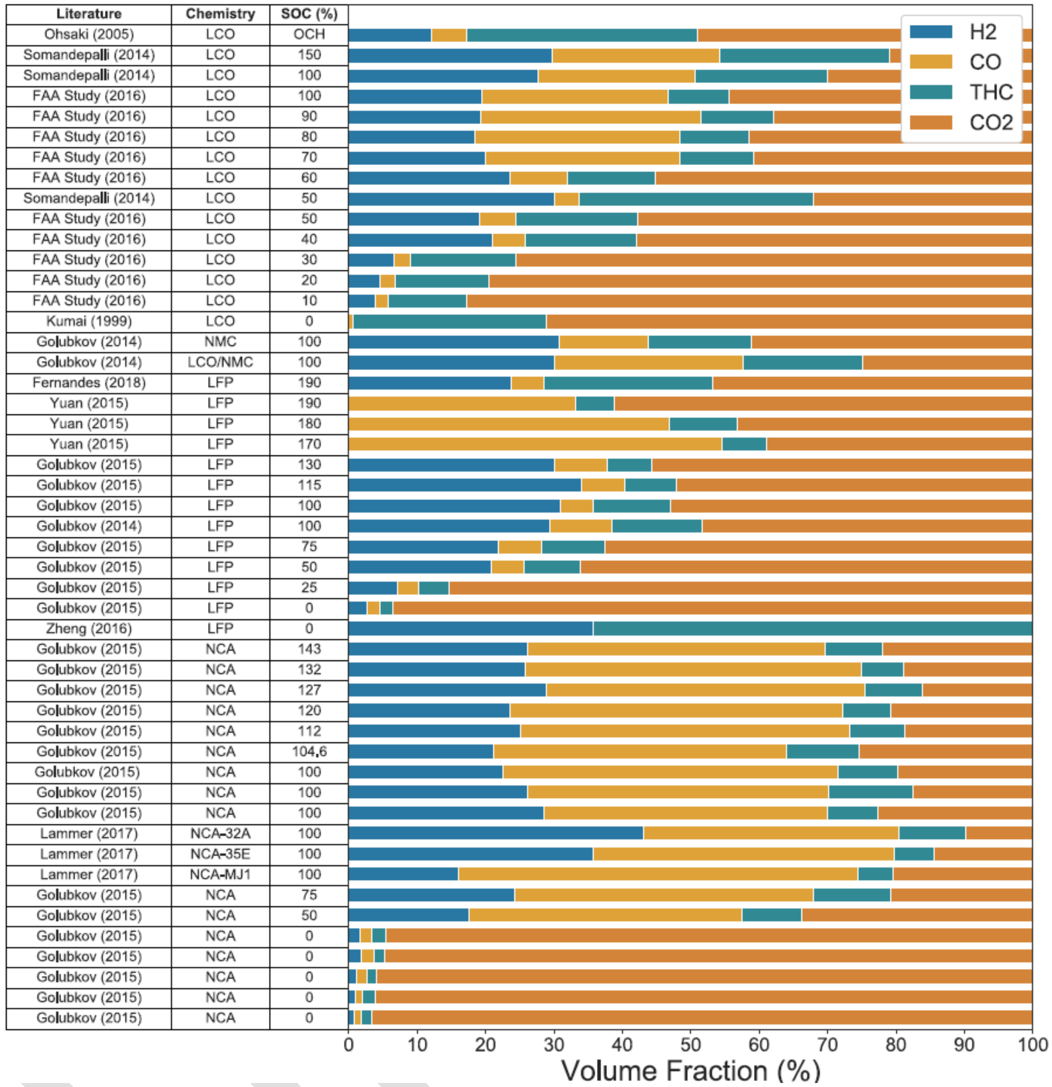

Figure 8 Battery vent gas species compositions from the literature.[21]

It is important to recognize that there is ongoing development of new batteries with new chemistries, and measurements of the composition of vent gases from these systems in various configurations and environments will likely have to be evaluated.

The total volume of gases emitted from LIBs is related to the hazard. Bugryniec et al. collated and analyzed data available in the literature related to LIB battery vent gases. They found that,

[21] Baird, A., Archibald, E., Marr, K., and Ezekoye, O., *Explosion hazards from lithium-ion battery vent gas*, Journal of Power Sources 466 (2020).

as battery capacity increases, the total gas volume emitted increases as well. The authors note that the data suggests cylindrical cells may have a larger range of total volume produced than pouch or prismatic cells, and that there is a lack of analysis of high capacity LFP pouch/prismatic cells. They also found that prismatic cells tend to generate more gas volumes than other cell formats in the studies evaluated. They plotted the results of various battery capacities, chemistries, and form factors, which is reproduced in Figure 9. Note that 1) both scales are log-scales, 2) unfilled points are from tests conducted in air, 3) grey filled points are from tests conducted in an inert atmosphere, and 4) colored filled points are of an unknown SOC but assumed to be 100% for this plot.[22]

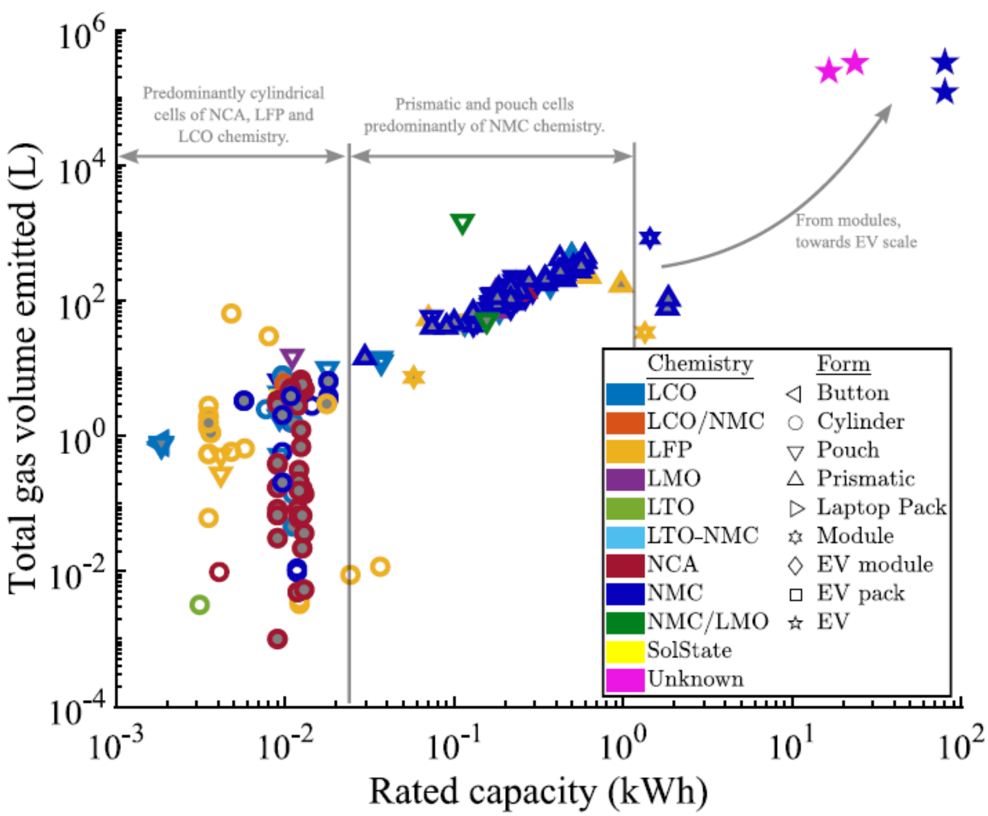

Figure 9 Total amount of gas emitted from LIB failure for batteries at 100% SOC, and with various capacities, chemistries, and form factors.

[22] Bugryniec, P., Resendiz, E., Nwophoke, S., Khanna, S., James, C., and Brown, S., *Review of gas emissions from lithium-ion battery thermal runaway failure – Considering toxic and flammable compounds*, Journal of Energy Storage 87 (2024), p8.

The four EV tests represented in Figure 9 have rated capacities approximately consistent with sedans, and show total volumes of gas produced on the order of 225,000 L.

There has also been limited studies on flammability limits of battery vent gases. The available data shows broader flammability limits than methane or propane, but narrower than hydrogen. Shen et al. measured the gas composition of different LFP and NCM battery chemistries in thermal runaway and calculated the flammability limits using Le Chatelier's equation. The results are reproduced in Figure 10. Similar LFL values on average for LFP and NMC battery chemistries were presented by Bugryniec et al., albeit with significant spread in some of NMC results with tests conducted in an air environment.

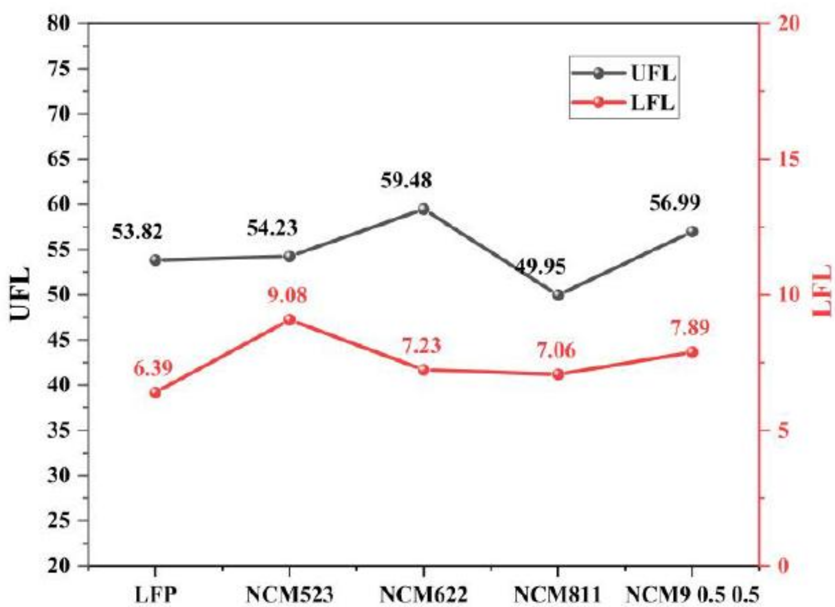

Figure 10 UFL and LFL of lithium ion battery thermal runaway vent gases.[23]

23

3.3 Toxicity

It is important to note that there are various different LIB cell chemistries, including new chemistries in the development phase. These chemistries are developed in the pursuit of improved functional performances. There may be differences in the composition of vent gases released during thermal runaway.

3.3.1 Gaseous and Particulate Matter

Several testing campaigns have been performed which demonstrate that vehicle fires, regardless of if they are an EV powered by a LIB, or an ICE, can release toxic gases.

Testing by Lecocq et al. which involved the burning of complete ICEVs and EVs measured similar levels of toxic compounds produced in the events, including CO_2, oxides of nitrogen (NO_x), hydrogen cyanide (HCN), carbon monoxide (CO), hydrogen fluoride (HF), and hydrogen chloride (HCl).[24] TYPE OF EV CHEMISTRY?

Testing by Long et al. during a heat-release-rate (HRR) test showed only CO and CO_2 present, and no HF or HCN was detected. However, water samples collected during some tests found chloride and fluoride, which the authors believe were a result of HF and HCl being present during suppression activities.[25] This supports the concept of "knockdown" of HF and HCl using water.

RI.SE noted that the toxic components of main concern include those noted above, but also include sulfur dioxide (SO_2).[26]

[24] Lecocq, A, et al., *Comparison of the fire consequences of an electric vehicle and an internal combustion engine vehicle*, INERIS, International Conference FIVE – Fires in Vehicles, Chicago, IL, September 27-28, 2012.

[25] Long et al p188.

[26] …

Bugryniec et al. noted that the most significant difference in the toxicity of EV fires and ICEV fires is the quantity of HF produced. However, ICEVs were found to emit more lead than EV fires in one study.[27]

Hynynen et al. published a study in 2023 involving six large-scale fire tests including battery EVs and ICE vehicles. For the ICEVs, a higher concentration of lead was identified. For EVs, HF, Ni, Co, Li, and Mn accounted for the largest difference in the combustion gases between EVs and ICEVs. Table 3 shows the relative levels of lead and HF for EVs and ICEVs.

Table 3 Summary of measured released of lead and HF from EV and ICEV burns.

	Lead	HF
EV	2.5 – 5g	120 – 859 g
ICEV	7 – 18g	11 – 15 g

Hynynen et al. reported that the variation in reported concentrations of HF found in literature is vast, even for cell level tests. This could be a result of HF being highly reactive, and reacting with surfaces that it collides with, which was referred to as "wall losses." This could also be attributed to the origin and amount of fluoride ions that can be released from a cell. Because of the wall losses, extrapolation from near field measurements of cells to large-scale events may result in the overprediction of the HF produced.

Franqueville et al. aggregated toxic gas data and used it to predict the range of safety distances for a variety of conditions, including different battery state of charge and wind conditions. Additionally, they compared the downwind toxicity hazard in an EV and ICEV fire. Their analysis showed that HF exposure could be the greatest toxicity hazard in LIB fires. They also noted that there was significant variance in the reported quantities evolved in different studies, and this highlights the importance of collecting more data to allow for more precise safety distance guidelines. The input data used in the simulations originated from cell-only experiments.

27 …

Sodium-ion battery chemistries (which do not use lithium/lithium-ion) have recently been launched in a Volkswagen-backed Chinese vehicle manufacturer in December 2023.[28] While IFE is not aware of any production EVs in the United States that utilize sodium-ion battery chemistries, they may come in the future. There is currently very little published data on sodium-ion battery safety. Current sodium-ion batteries utilize flammable organic electrolytes, although the use of different cathode and anode materials in the future may allow different electrolyte solvents to be used which may have higher safety, according to Lander.[29] It is expected that, similar to LIBs, various materials for electrodes and electrolytes will be investigated to improve performance, and the thermal characteristics and emissions for cells/packs with these materials under different failure mechanisms will have to be studied.

Particulate matter (PM) generated during LIB thermal runaway events has also been researched. Premnath et al. analyzed the PM of four LFP modules and one NMC module and found that the PM2.5 and total PN emissions were 5-6 orders of magnitude higher than what is emitted from a modern heavy-duty Diesel engine. They found that the particle and gaseous emissions may be a function of the way thermal runaway was initiated (e.g. nail penetration vs. overcharging), battery chemistry, and cell arrangement, among other variables. They also noted that particle emissions from thermal runaway of identical modules induced by the same mechanism could be highly variable.[30]

Zhang et al. analyzed the particle size distribution and elemental composition of settled solid particles after thermal runaway from a large-format NMC cell and found the total mass of scattered particles was 11.2 % of the total cell weight, and was primarily comprised of carbon, nickel, copper, cobalt, manganese, aluminum, and lithium (although several other elements were present). The metallic portions of the samples were between 30% - 50%. The potentially toxic

[28] https://electrifynews.com/news/batteries/volkswagen-backed-chinese-oem-rolls-out-first-sodium-ion-battery-electric-car/, accessed 10/23/2024.

[29] https://www.accure.net/battery-knowledge/sodium-ion-batteries-role-in-energy-storage#Sodium_ion_safety, accessed 10/23/2024.

[30] Premnath, V., Wang, Y., Wright, N., Khalek, I., & Uribe, S. (2022). Detailed characterization of particle emissions from battery fires. Aerosol Science and Technology, 556(4), 337-354.

elements identified were Al, Li, F and Sn, with mass percentages of 6.9 %, 3.9%, 0.002 %, and 0.001 %, respectively.[31]

Contaminants may bond to fibers or damage materials such as PPE. While there is not currently a well-established method for cleaning PPE that has been exposed to battery vent gases, this is currently an active area of research.[32] Avoiding unnecessary exposure and prevention (i.e. staying upwind) is considered the current best practice.

3.3.2 Water Runoff

A comprehensive review of the fire water runoff composition and any resulting consequences of it are outside of the scope of the current work. However, some general observations are noted.

In fire suppression tests with a battery module, elevated levels of cobalt, nickel, and manganese were measured in the extinguishing water collected (30-50 mg/l).[33] Separately, Bisschop et al. noted that measured concentrations of fluoride and chloride that were higher than permissible to discharge directly into the environment according to German regulations.[34] If feasible, runoff should be redirected away from storm drains and other water sources using dikes or other techniques to limit the remediation that must be done. The more water that is used, the more water runoff there will be and the further it may travel.

The testing by Long et al. mentioned in the previous section included analysis of collected fire suppression water. They noted that the concentration of chloride was only 2-3 times greater than normal detected levels, while the concentration of fluoride was more than 100 times greater than normal detected levels.[35]

31 Zhang, Y., Wang, H., Li, W., Li, C, & Ouyang, M. (2019a). Size distribution and elemental composition of vent particles from abused prismatic Ni-rich automotive lithium-ion batteries. Journal of Energy Storage, 26, 100991.

32 Preliminary research indicates that LCO2 may be a suitable cleaning method.

33 See 53 in 2020 RISE REPORT

34 Bisschop, R., Willstrand, O., Amon, F., Rosengren, M., Fire Safety of Lithium-Ion Batteries in Road Vehicles, RISE Report 2019:50.

35 Long et al p188.

Particulates from venting LIBs can also accumulate when there is containment of vented gases – and this includes if LIBs are venting into the cabin of a crash-damaged vehicle. Following thermal events in grid-scale battery energy storage systems or after incidents involving EVs that occur indoors, particulate matter is often observed on flooring and other surfaces (overhead wiring, piping, I-beams, etc.). IFE has seen particulate accumulations on the order of 5mm deep in untouched areas, or as deep as 1 cm or more in areas where the particulate has been disturbed. If disturbed, this particulate matter can get suspended in the air and potentially inhaled. Per Mr. Derrick Denis, an expert in industrial hygiene, health and safety, and indoor environmental quality, "the best way to clean the air is to clean the floor."

Given that fire water runoff from LIB fires has contaminants and given airborne particulate residue, first- and second-responders are advised that tools utilized, including turnout gear and water hoses with fabric exterior, may absorb the contaminants in runoff, enabling the transfer to first-responders. First departments are advised to clean their equipment according to NFPA 1851, *Standard on Selection, Care, and Maintenance of Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting*, 2020 edition.

Note that there have been significant changes to this standard from the previous edition.[36] Additionally, initial results are showing that conventional cleaning techniques are not removing etched heavy metal particulate matter in turnout gear during lithium-ion battery fires. [37] Available techniques are not yet mainstream, and some fire companies are budgeting for increased costs associated with disposal of contaminated turnout gear.

3.4 Electrical Shock and Arc Flash

IFE is not aware of any electrical shocks to vehicle occupants, first responders, or second responders as a result of a crash involving an EV at the time of this report. However, the hazard of electrical shocks may still exist in some cases and is discussed here. Additionally, arc flashes

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36 https://www.firerescue1.com/fire-products/firefighting-gear/articles/what-firefighters-should-know-about-nfpa-1851-2020-edition-Bc7jmSrBTyp0Xagf/, accessed 3/9/2024.

37 Michael Abraham, Alcohol, Tobacco, and Firearms; *Lithium-Ion Batteries, Fire Investigations, and Keeping Pace with Emerging Technologies*, Fire Engineering, recorded January 24, 2024, 32:39.

are discussed as they relate to first responder and second responder activities (i.e. not arc flashes created as a result of a crash or internal to a battery pack).

In this section, electrical isolation faults are discussed first, followed by potential electric shock hazards. Note that, per SAE J2990, evaluating the isolation of the HV battery pack is done during the second HV system inspection when OEMs or other responsible parties have been engaged. Nevertheless, general information is provided here to support the general guidance to first and second responders to avoid contact with or interaction with HV batteries or HV components. The information provided is general in nature and variability in vehicle design may affect operational characteristics.

Hazards to first responders and second responders associated with electrical shock and arc flash are largely associated with interaction with and/or damage to the HV battery or HV components. At a high level, hazards to first responders and second responders involves interacting with the HV electrical system at two different locations or voltage potentials.

There are certain system failure modes associated with crashes that are possible but not described in detail here because they will present differently to first and second responders. For example, if an EV experiences damages which results in multiple isolation faults, and/or an arc flash, it may initiate a fire which will influence tactics which are deployed upon arrival by first and second responders.

A response to a vehicle crash that is not on fire should therefore assume that an isolation failure has already occurred, and avoid contact with the HV battery, components, and wires.

Note that Federal Motor Vehicle Safety Standard (FMVSS) 305 specifies requirements for vehicles post-crash to protect vehicle occupants, rescue workers, and others who may contact the vehicle after a crash.

For background, IEC 62368-1:2018 defines safe voltage and safe current as 60 V DC, 2 mA DC, respectively, and 30 V AC, 0.5 mA AC, respectively.

3.4.1 Electricity Transmission Through Water Spray

To-date, IFE is not aware of evidence that spraying water from a distance at EVs, inclusive of HV battery packs, has resulted in electricity transmission back through water spray which is hazardous to first responders.

Exponent reported on voltage and current measurements for tests involving batteries placed in a VFT prop. For noninvasive suppression operations, they reported no significant current or voltage readings at the discharge of the nozzle in any of their tests. The authors noted that they did not test complete vehicles with electrical distribution systems or evaluate offensive firefighter tactics involving cutting, piercing, manipulating the vehicle for extraction purposes to gain better access for suppression purposes.[38]

Although IFE is not aware of this phenomenon occurring in EV fire suppression activities, there is anecdotal evidence indicating that this phenomenon is possible and has occurred in a residential structure fire when a firefighter was directing a hose stream at a fire in a laundry room and attic space above it, and was reportedly shocked due to 220 VAC electrical service.[39] As such, fire departments are advised to avoid touching vehicles, or standing close to vehicles, while simultaneously holding a nozzle directing water spray into the vicinity of the battery pack or inverter.

Additional information regarding some specialized tools that are sold for use to suppress fires involving HV EV battery packs is discussed in more detail in section 4.6.

3.4.2 Isolation Faults

Typical polymer wire insulation or air gaps have a very high electrical resistance, which is referred to as isolation. If an isolation (or insulation) fault occurs between the HV system and another electrically conductive object, such as a metal enclosure and/or chassis, it can result in a

[38] Long Jr., R. T., Blum, A., Bress, T., and Cotts, B., Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results, The Fire Protection Research Foundation, June 2013, p192.

[39] Fire Engineering, Podcast: Sons of the Flag: Life After Being Injured on the Job, https://www.fireengineering.com/firefighting/podcast-sons-of-the-flag/#gref, July 23, 2019, accessed 10/23/2024.

potential electrical pathway with a particular resistance that can be characterized as a leakage resistor. Isolation faults can occur between the enclosure and/or chassis and the negative terminal, positive terminal, or at some intermediate location within a HV battery pack. As noted before, a single point isolation fault generally does not result in hazardous situations.

If, after the initial isolation fault, a hypothetical second isolation fault occurs such as a person touching a battery terminal or other energized part and the same object noted above (metal enclosure and/or chassis), this may result in a hazardous situation. The significance of the hazard would depend on voltages at each of the fault locations, magnitude of the leakage resistors, and other factors. The potential hazard is shown graphically in Figure 11 by Milios et al. The red resistors indicate leakage resistors (i.e. faults), which connect some portion of the HV battery pack, to other objects such as the chassis or a human.

Practically speaking, it will be difficult to access battery terminals that are inside of the pack. Additionally, as described in section 2.2, when the vehicle is turned off, or if the vehicle is in an accident of sufficient magnitude, the HV electrical systems are designed to be de-energized at the contactors, so HV equipment and wires exterior to the battery pack are disconnected from the HV battery pack.[40]

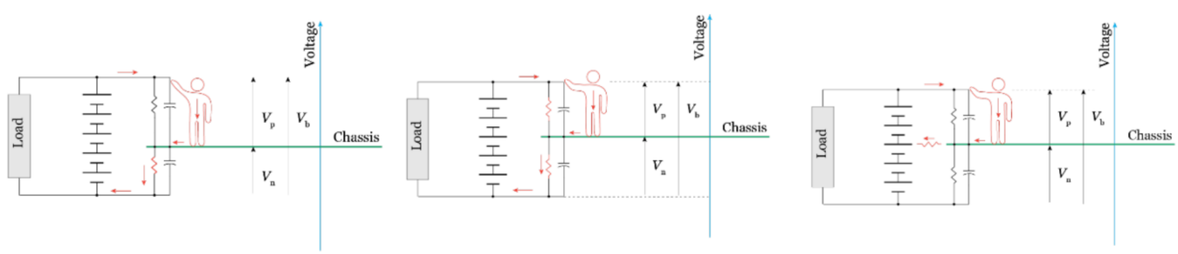

Figure 2: An isolation fault may occur in one side, two sides or in any place in the power system. Resistors in red represent leakage resistors.

Figure 11 Schematics showing an isolation fault in one side (left), two sides (center), or at an intermediate location within the pack (right).[41]

[40] Bosch, Automotive Handbook, 11th Edition, January 2022, p1561.

[41] Milios, J., Clauvelin, N., Safety of electric vehicle high voltage systems, 33rd Electric Vehicle Symposium (EVS33), Portland, Oregon, June 14-17, 2020.

If somehow the HV battery pack contactors do not operate as intended, or physical damage as a result of a crash precluded their successful operation, then the potential hazards associated with isolation issues can be found in IEC 61557-8. This standard indicates that a potential hazard exists if the isolation resistance drops below the threshold of 100 Ohms/volt. The actual resistance encountered in a situation where an emergency responder contacted two different areas at different voltage potential (and potentially a second fault occurred if the responder was not touching energized battery parts directly, such as the chassis), would depend on numerous factors such as the nature of the electrical fault, PPE of the emergency responder, contact locations, etc.

Actual analysis methods on the effects of electrical current on human beings, including information about body impedances under certain conditions, can be found in IEC TS 60479-1, *Effects of current on human beings and livestock, Part 1: General aspects*. As an example, and not necessarily representative of typical conditions: for a current path hand to hand, with large surface areas of contact in dry conditions, the impedance at 400 V touch voltage at the 50th percentile is 950 Ω.[42]

Separate from the electrical shock hazard, there is reportedly a potential for arc flashes to occur as a result of battery vent gases passing between terminals or bus bars with different voltage potentials. This could explain, for example, why some EV thermal events have created holes in the floorboard.

3.4.3 Capacitance Faults

AC motor drives typically used in EV systems require a capacitor (the “DC-bus capacitor”) at the input to the inverter which powers the motor. While this capacitor stores significantly less energy than the battery pack, an uncontrolled discharge is still an electrical shock hazard. The capacitors are outside of the battery pack, so the actuation of a HV disconnect or contactors on the battery pack does not necessarily mitigate capacitive fault hazards. HV capacitor locations, along with locations and routing of cables connected to them, may be found in manufacturer

42 IEC TS 60479-1, Effects of current on human beings and livestock, Part 1: General aspects, Fourth edition, 2005-07, p43.

ERGs in the diagrams. The pictogram for the HV capacitors in ISO 17840 is shown in Figure 12.

Figure 12 Pictogram showing a HV capacitor as defined in ISO 17840.

After a crash or incident, residual energy is designed to be dissipated to reduce the DC bus voltage. The residual energy is also dissipated under normal operation when the vehicle is turned off, although the time duration of the discharge may be different. Per Gong et al., the techniques employed generally fall into two categories: external bleeder-based methods and internal power device-based methods.

For the bleeder-based method, a circuit in parallel with a resistor is used to bleed off the DC-bus capacitor energy in the form of heat. There can be active or passive modes, with different sized resistors, and the resistors that are in use can determine how long it takes to drain the DC-bus capacitor. In the example of a permanent magnet synchronous motor (PMSM) driven system, when a crash is detected, the six transistors are sealed off and current flows through six free-wheeling diodes to either of the aforementioned resistors.

The second method, instead of using bleeder resistors, uses the motor and inverter to dissipate the energy. In one technique, current flows from the DC-bus capacitor through two transistors on two different bridge arms of the inverter. Mechanical energy in the motor is first converted into electrical energy and then consumed by both of the transistors and the machine windings. In a second technique, referred to as a current-injection based discharge, all of the transistors are turned on, and the motor windings are the bleeder. The residual energy is dissipated primarily by the machine windings as heat.[43,44]

It is noteworthy that systems designed to discharge the DC bus can theoretically be damaged during a crash event. First and second responders are generally advised to avoid contacting HV systems and components, but this is especially true if there is crash damage to those systems.

43 Gong, C., Liu, J., Han, Y., Hu, Y., Yu, H., and Zeng, R., Safety of Electric Vehicles in Crash Conditions: A Review of Hazards to Occupants, Regulatory Activities, and Technical Support, IEEE Transactions on Transportation Electrification, Vol. 8, No. 3., September 2022, p3878.

44 Gong, C., Crash Safety of High-Voltage Powertrain based Electric Vehicles – Electric Shock Risk Prevention, University of York, December 2020, p43-45.

4.0 Crash Management System

No two emergency incident responses are the same and the circumstances of the event may dictate the course of action. Some steps may be done sequentially or concurrently. Per Sweet, the goal of the process is the safety of everybody involved, and procedures are not intended to be overly rigid and non-flexible.[45]

Given that no two emergency incident responses are the same, it is not surprising that available literature and guidance for first- and second-responders does not cover all possible situations. In cases where topics are addressed by some literature but not others, IFE provides the available information but note that the reader is cautioned that it may not be universally applicable. The circumstances of the incident will dictate the specific procedure involved.

It is also important to note that recommended procedures for EV incident response are changing as the community learns from unique incidents, research, and as vehicle and LIB battery designs evolve. This makes it critical for first and second responders to access manufacturer ERGs, from a source that is comprehensive and up-to-date.

First and second responders are also encouraged to utilize service providers which can help with different aspects of incident management. For example, there are organizations which can assist with collection and handling, packaging, transportation, and disposal or recycling aspects of the incident, or they can assist with environmental, health and safety aspects such as evacuation, shelter-in-place, PPE requirements, or management of environmental impacts.

Generally, the approach provided below assumes that a fire has not yet ignited, and additional comments are added to describe how the steps are different if the vehicle has already ignited prior to arrival.

[45] Sweet, D., National Fire Protection Association, International Association of Fire Chiefs, *Vehicle Rescue and Extrication: Principles and Practices*, 2022, p101.

The following information is guidance and is not meant to take the place of vehicle manufacturer ERGs, rescue sheets, or local standard operating procedures (SOPs).

NOTE: The Energy Security Agency (ESA) offers a guidance and response center service 24 hours per day, 7 days per week to assist with responding to incidents involving LIBs. Their phone number is 855-372-7233.[46]

4.1 Approach, Size-Up, and Vehicle Identification

Initial observations regarding the incident can include identifying the location of the incident and nearby exposures, as this may significantly influence decision making in managing the incident. If the incident occurs in an open area, such as an uncongested roadway or parking lot, the handling strategies may be very different than if the incident occurs in an area with exposures, such as parking garages, tunnels, on bridges, or in congested parking lots or roadways.

Park apparatus at least 50 ft. from the vehicle in a location that will protect firefighters from vehicle traffic – the "cold" zone.[47,48] Approach the vehicle(s) from sides, from upwind, and from uphill where possible. This is to avoid an incident with an accelerating vehicle,[49] contact with HV battery vent gases, and to avoid interacting with spilled fluids, respectively. As the vehicle is approached, note that it may be difficult to determine if the vehicle is running due to a lack of engine noise.[50] Anecdotally, inadvertent movement of EVs during emergency responses has occurred on multiple occasions, which has resulted in injuries on at least one occasion. As with ICEVs, a survey of hazards should be identified such as spilled fluids, traffic, or trapped or injured occupants.

[46] IFE is not endorsing ESA or any guidance that they offer.

[47] Long et al., p18

[48] Sweet, D., National Fire Protection Association, International Association of Fire Chiefs, *Vehicle Rescue and Extrication: Principles and Practices*, 2022, p44.

[49] SAE J2990, July 2019, Appendix C, p40.

[50] Ford Lightning ERG

The company officer (or Awareness Level and above[51]) is responsible for the size-up of the incident and reports back to dispatch.[52] In addition to typical survey elements – types of vehicles, number of victims, possible ejections, level and type of entrapment, need for additional resources – the size-up should include some additional information as described below that will assist in the operation. However, although certain personnel are responsible for the size-up, all responders must be responsible for performing a size-up.[53]

As part of the initial outer survey, responders should evaluate whether there is any crush damage in the area where a typical battery would be (and re-assess after the vehicle has been identified and ERG consulted). Section 2.3.2 shows the location and shapes of different style battery packs. Most passenger EVs (e.g. sedans, pick-up trucks) have skate-board style battery packs that are typically found between the wheels and the side frame members. Damage in these areas, or extensive damage to the front or rear can damage HV systems and potentially the HV battery pack. In crash events, the HV battery may vent or become involved in the fire if HV battery cells are mechanically damaged, thermally abused (heated by fire), or potentially by electrical faults (e.g. short circuiting, or resistive connections creating heat). Note that the use of odor is not a recommended assessment approach, as that could potentially mean exposure to battery vent gases. It is worth noting that some manufacturers use LIBs as their auxiliary batteries, as opposed to the more conventional lead-acid batteries. For instance, Tesla uses LIBs for their auxiliary batteries (12V or 48V), and Mercedes Benz uses 48V LIB auxiliary batteries in their EQ boost hybrid powertrains.

The initial survey, which begins from afar, should also include a survey of debris in the area. Driving over debris or objects could have damaged a battery pack on the underside of a vehicle, or in some circumstances could have caused the battery pack or portions of the battery pack to dislodge from the vehicle – which has happened before. In either of these two cases, this flags a HV hazard, as discussed in section 3.2.1.

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51 IFSTA, Principles of Passenger Vehicle Extrication, p14.

52 Sweet, D., National Fire Protection Association, International Association of Fire Chiefs, *Vehicle Rescue and Extrication: Principles and Practices*, 2022, p44; Long et al.

53 IFSTA, Principles of Passenger Vehicle Extrication, p14.

A charged hose line should be deployed. Sweet indicates one 1.75" hose for scene and personnel protection.[54] For additional information regarding fire suppression and the status of evaluation of novel tools, see sections 3.4 and 3.6.

The inner survey is then conducted in a defensive posture, remaining approximately 3-5 ft. away from the vehicle while being cognizant of potentially sudden forward or rearward lurching of the vehicle.[55] This survey is intended to identify immediately dangerous to life and health (IDLH) hazards, the type of vehicle, status of vehicle (on/off/gear), number of occupants, degree of entrapment (if any), obvious injury to occupants (if any), and status of SRS airbag system (deployed/undeployed airbags), primary access plans, secondary access plans, and emergency escape plans.

The NFPA Emergency Field Guide indicates that the vehicle should always be assumed to be some type of hybrid, electric, or alternatively fueled vehicle until proven otherwise.[56] If, after evaluation, the vehicle is confirmed to be an EV then this should be reported back to dispatch such that other responders can tailor their response or prepare as needed (e.g. reviewing emergency response guides (ERGs)). First-responders and second-responders should use all available cues to determine if a vehicle is *not* an EV – there is not yet a singular indicator that broadly applies to all makes/models. The following should be considered. Note that the vehicle should be immobilized before working in or around it.

- Primary external indicators:
    - License plate identifiers in certain states.[57]
    - Badging on the front fenders, trunk – may indicate EV, hybrid, zero emissions, e, e-tron (Audi), IMA (Honda), etc.

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[54] Sweet, D., National Fire Protection Association, International Association of Fire Chiefs, *Vehicle Rescue and Extrication: Principles and Practices*, 2022, p194.

[55] Sweet, D., National Fire Protection Association, International Association of Fire Chiefs, *Vehicle Rescue and Extrication: Principles and Practices*, 2022, p106.

[56] NFPA Emergency Field Guide, 2018, p11.

[57] Igleheart, A., Electric Vehicle (EV) and Alternative Fuel Vehicle (AFV) License Plate Requirements, National Conference of State Legislatures, February 2024, https://leg.mt.gov/content/Committees/Interim/2023-2024/Transportation/Meetings/031424-March-14-2024/06.020-Electric_Vehicle-AFV_Special_License_Plates_and_Decals_February_2024.pdf, accessed June 26, 2024.

  - Some makes/models only exist as EVs – e.g. Ford Mach-e, Tesla vehicles.
  - VIN – in some cases, one or more characters in the VIN will identify the vehicle as an EV; see ERGs.
  - Orange cables – typically on the underbody or in front/engine compartment
  - License plate or lower corner windshield stickers (per SAE J3108; see Figure 13)
- Secondary visual indicators:
  - Absense of exhaust pipes (note: hybrid vehicles may have exhaust pipes and large LIBs)
  - Charge port
  - Smaller radiator opening on front

Figure 13 Slide showing an example of the SAE J3108 window sticker location and selected examples (courtesy of Bob Swaim).[58]

Existing telematic systems, such as OnStar (GM), BMW Assist, and Blue Link (Hyundai) can also notify dispatch of the location and nature of the call, as well as the type of vehicle involved. In the future, machine vision and the use of roadway cameras may also be able to identify the vehicles involved and notify first-responders.

[58] https://howitbroke.com/downloads-%26-links, downloadable images, accessed June 26, 2024.

Following vehicle identification, it is highly recommended to view manufacturer ERGs for the specific vehicle. To do this, the vehicle make, model and typically the generation (model year range) are necessary. This provides vehicle-specific information that can assist with subsequent steps, such as showing high voltage system components, and high-strength areas of the body or chassis. If there are vehicle occupants entrapped and extricating involves more than door release/removal, then the location of HV equipment can assist in identifying entry/exit points and suitable vehicle stability approaches.[59]

If a vehicle is already on fire, note where the fire is. Fires involving the HV LIB on most passenger vehicles will often emanate from the bottom of the vehicle. If fire suppression is deemed necessary, these types of fires should be suppressed with water. If the HV battery is not involved in the fire, then some manufacturers recommend extinguishing the vehicle with an ABC or CO_2 fire extinguisher.[60] Fires in the passenger compartment or rear/trunk area may be considered for this approach. Fires that appear in the front area may or may not be associated with the HV battery pack – there is likely no floorboard to serve as a fire barrier in the front compartment so a venting battery pack towards the front of the vehicle may show as a front compartment fire. However, note that some packs, such as Acura hybrid vehicles or some Jeeps have HV batteries that are located in the interior of the vehicle.

The size-up is an ongoing process throughout the incident. As conditions change, the tactics can change. Vehicle incidents are dynamic situations, and the response must be dynamic. While the focus of this work is related to EV crash management, per IFSTA, the following potential hazards are identified:[61]

- Environmental hazards (e.g. weather, time of day, terrain)
- Downed power lines/transformer hazards
- Fuel hazards (including batteries)
- Vehicle contents hazards (one EV fire was reportedly caused by a power tool inside)

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[59] Sweet, D., National Fire Protection Association, International Association of Fire Chiefs, *Vehicle Rescue and Extrication: Principles and Practices*, 2022, p105.

[60] NFPA 1901 requires that fire apparatus be equipped with handheld fire extinguishers.

[61] IFSTA, Principles of Passenger Vehicle Extrication, p16.

- Potential for violent or abnormal behavior
- Vehicle stability (immobilization, section 3.3.1)
- Biohazards
- Incidents with section considerations

4.2 Determination of Safety

Following the survey, hazard control zones (hot, warm, cold, no-entry) should be established and maintained throughout the incident.[62] Per NFPA 1500, section 8.7, these zones should delineate operational boundaries. Per Caruana, no standard distance or specific area size meets the needs of every vehicle incident; personnel determine the needs for each scene.[63] The U.S. Department of Transportation/Transport Canada Emergency Response Guidebook (hereafter referred to as the US DOT ERG), which is primarily designed to be used at hazardous materials incidents occurring at highways, railroads, and pipelines, provides some information in this context. Guide 147 applies to battery-powered vehicles with LIBs and sodium ion batteries.[64] As an immediate precautionary measure, the evacuation distance is 75 ft. (25 m) in all directions, and that distance should be increased in the downwind area (this does not apply to rail car incidents). The US DOT ERG also provides initial isolation distances (all directions) for various other materials. For compressed hydrogen or propane/liquified petroleum gas (LPG), the initial isolation/evacuation distance is 330 ft. (100 m) in all directions (see Guide 115),[65] increased in the downwind area. As discussed in section 4.9, larger vehicles may require larger isolation zones.

62 Sweet, D., National Fire Protection Association, International Association of Fire Chiefs, *Vehicle Rescue and Extrication: Principles and Practices*, 2022, p44.

63 Caruana, *Principles of Passenger Vehicle Extrication*, verified by the IFSTA, 2022, p22.

64 U.S. Department of Transportation/Transport Canada Emergency Response Guidebook, 2024 edition, p69, 86.

65 U.S. Department of Transportation/Transport Canada Emergency Response Guidebook, 2024 edition, p30, 160.

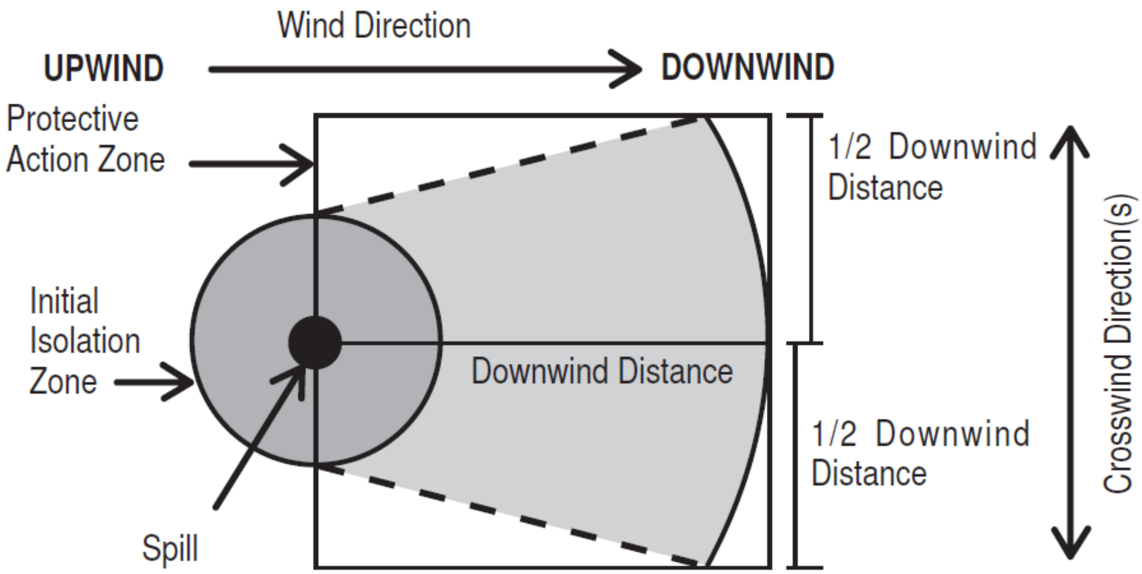

Figure 14 Initial Isolation and Protective Action Distances figure, showing the spill location, initial isolation zone, and downwind areas.

There is limited research available to assist in the determination of safety distances based on gases emitted from HV batteries and established exposure limits, although this is an active area of research by U.L. FSRI and potentially others.

Long et al. performed testing on VFT props with batteries and measured certain gases and noted that, based on the data collected, the hazard zone where full PPE, including respiratory protection must be worn was comparable to that of traditional ICEV fires.[66]

As described in section 2.5.2, Franqueville et al. utilized data in the literature and associated databases to perform a computational study on exposures in plumes emitted from vehicles.

Generally, for burning EV cases, the safety distances increase as wind speed increases. At wind speeds less than 5 mph, safety distances were below 50 ft. At high wind speeds (20 mph),

[66] Long Jr., R. T., Blum, A., Bress, T., and Cotts, B., Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results, The Fire Protection Research Foundation, June 2013, p192.

safety distances increased to 177 ft. As EVs burn, hot gases will tend to rise (hence the shorter safety distance), but strong winds can push them horizontally.

For non-burning cases, they estimated the highest safety distance at 5 mph (167 ft.). This wind speed was just high enough to move the gases away from the vehicle without causing substantial dilution, and at higher wind speeds more dilution occurs. Recall that firefighters responding to the Surprise, Arizona battery energy storage system thermal incident observed a white fog along the ground (see Figure 15). The wind speed at the Luke Air Force Base, 11 miles south, was 6 mph shortly after the alarm. Note that the quantity of vent gas from an EV event may be smaller than that what is seen in Figure 15.

Figure 15 Photograph taken during the Surprise, AZ battery energy storage system incident, showing a white fog along the ground. Photograph from UL.[67]

The above estimations were based on battery cell data (not full EV burn data), and the variation in the emissions data were significant. The safety distances they estimated were approximately a factor of 10 higher than a computation with full vehicle burn data. Franqueville et al. utilized data published by Willstrand et al. to compare safety distances for a burning EV and burning ICEV and found the safety distances to be approximately the same, at 13-17 ft. in moderate winds. This was attributed to buoyant hot gas plumes created by combustion.

NOTE: the authors of this study importantly note that other make/model/model year vehicles may have different rates of toxic gas emissions (and accordingly higher safety distances). The

67 McKinnon, M., DeCrane, S., Kerber, S., Four Firefighters Injured In Lithium-Ion Battery Energy Storage System Explosion – Arizona, UL FSRI, 2020.

authors also note that because the uncertainty in the emitted gas volumes was large, care should be taken when making policy decisions based on single-point estimates.

When the hazard control zones are established, evacuation orders or road closures orders should be given, entry to the area should be denied to people not directly involved in emergency response operations, and if necessary shelter-in-place considerations made.[68] The U.S. DOT Emergency Response Guidebook provides information on these protective actions, and consultation with EHS consultants may also be advisable.

At a very high level, people should be evacuated keeping in mind that wind direction can change and affect different areas at different times. If evacuating the public would cause a greater risk to the public than staying where they are, or if the evacuation cannot be safely performed, shelter-in-place may be done inside a building. For the latter, various steps may be necessary such as shutting doors, shutting off all ventilating, heating and cooling systems, etc. If a building is exposed to smoke or combustion products, the building owner or operator may wish to consult with EHS professionals.

It is important to note at this stage that, while HF can be absorbed through the skin, the greatest hazard is associated with inhalation.[69] Hazard control zones can be used to define what PPE is required in each zone, and that includes when SCBA's are donned and air flowing. This suggests that close attention to changing conditions, and strict adherence to hazard control zones is important. Anecdotally, some fire departments in Arizona don SCBA and turn on air as soon as they get out of the truck when responding to EV incidents. With this strategy, attention should be paid to the quantity of air in the tanks, as they could empty during longer responses. SCBAs are typically available in 30-60 minute versions.[70] SEE GUIDE 125 US DOT ERG P224The above discussion relating to isolation zones would be the *hot* zone (also known as the "action" zone). Outside of this area is the *warm* zone, which is intended for properly trained

68 Emergency Response Guidebook, 2024 edition, p283-5.

69 RISE 2020:90, p31.

70 Sweet, D., National Fire Protection Association, International Association of Fire Chiefs, *Vehicle Rescue and Extrication: Principles and Practices*, 2022, p56.

and equipped personnel only, where equipment decontamination and hot zone support take place, including a debris area for material that is removed from the vehicle.

The no-entry zone relates to areas where no one is permitted to enter because of an IDLH exposure, or the need to preserve the scene for evidence for a post-investigation team.[71]

4.2.1 First HV System Inspection

SAE J2990 Surface Vehicle Recommended Practice, *Hybrid and EV First and Second Responder Recommended Practice*, July 2019, includes a flow chart to assist with decision making at incident locations. This flow chart is reproduced in Figure 17 and Figure 18 below. This document is not intended to be referenced by first and second responders in the field but can be used for training purposes and also can assist manufacturers in developing vehicle requirements and ERGs.

The scene HV system inspection begins during the size-up, as described earlier. The inspection should include looking and listening for signs of fire including flames, smoke, arcing, or hot spots. A thermal camera or IR temperature probe may be useful for identifying hot spots, although this should be interpreted with caution because the view of hot objects can be obstructed by relatively cool objects. If the temperature measurements are taken in the same locations, then such data can still be useful to identify trends, so make a mental note of the measurement values and locations. In the case of fire, smoke, arcing, or hot spots, the area around the vehicle should be cleared. The inspection may be paused if any of the above occurred. Vehicle doors and the trunk can be opened to dissipate any flammable gasses, although this should be done with the caution that fresh air can affect the concentration of flammable gases inside of the cabin and accordingly could result in a flash fire or explosion. For example, fresh air can provide oxygen to an oxygen starved fire, or alternatively it may dilute a gas mixture that is too fuel-rich to burn such that it is in the flammable range.

[71] Sweet, D., National Fire Protection Association, International Association of Fire Chiefs, *Vehicle Rescue and Extrication: Principles and Practices*, 2022, p110.

Steam, fog, or smoke may be observed in crashes in conventional ICE vehicles, but interpreting such observations is different for an EV. If there is a whiteish fog or smoke present, it may be LIB battery vent gases, which means it may be flammable and toxic. There may be opportunities for confinement of flammable gas in the passenger compartment, or if the crash involves a structure or parking garage. In one case, vent gases were confined in a vehicle cabin, and after the vehicle was ventilated an explosion occurred (see Figure 16).

Figure 16 Screenshot of a video showing white fog emanating from a vehicle (left), followed by a screenshot after an explosion occurred where the roof of the cab has been pushed off of the vehicle (see red arrow). First-responders opened a window or door prior to the incident to ventilate the cabin.[72]

In almost all cases, structural firefighting PPE should already be donned when approaching an EV with a venting LIB. One electrolyte, DMC, has a sweet smell, and if it is smelled that would mean exposure to failing batteries[73] in potentially toxic concentrations. Battery electrolyte gases that are emitted from batteries may be hot and buoyancy may be observed. However, as in the Surprise, Arizona BESS event, a fog along the ground may also be observed if the gases have cooled and there are low winds.

Gurgling, bubbling, crackling, hissing, or popping noises are evidence of an unstable battery system. The area around the vehicle should be cleared. These sounds may be indicative of cells venting. There is EV burn research that has attempted to record various noises and identify

[72] https://www.youtube.com/watch?v=aLtkTp4GVuE, 3:11/5:09

[73] Ezekoye, NFPA 52:00

battery related noises during fires, and such material may become available for training purposes at a later date. If there is no evidence of smoke inside the cabin, the vehicle doors, windows, and/or trunk can be opened to avoid build-up of gasses. However, if the cabin is full of smoke, then the tactics used may be different. Ventilating the cabin may introduce oxygen which can bring a fuel-rich concentration of gases below the upper flammability limit, or it can potentially participate in other reactions and create an ignition source. Some smoke may also emanate from air extractors, wiring or equipment penetrations, or other areas as vehicle cabins are not hermetically sealed.[74] As noted before, the inspection may be paused if any of the above observations are made and restarted at a later time.

During the size-up, the officer is instructed to look for battery cell groups separated from the enclosure. In this case, modules/terminals, bus bars, cables, and/or enclosures have likely been compromised and there is a potential for arcing and exposure to HV. Also, the likelihood of reignition of a fire may be higher for the same reasons. The vehicle manufacturer or other responsible organization should be contacted for their ERG, depowering recommendations, packaging instructions, and disposal instructions in this case.

Note that damaged LIBs are colloquially referred to as DDR batteries (damaged, defective, or recalled batteries). DDR LIBs are at a higher risk of undergoing thermal runaway. Signs of DDR LIBs may include leaking electrolytes, swollen or discolored battery casing, odor or corrosion, burn marks, known conditions of use or misuse, or being recalled.[75]

Modern HV EV batteries have a very limited amount of electrolyte and are considered dry batteries. It is unlikely that pure electrolyte will be leaking out of a battery. However, batteries commonly use coolants that are similar to coolants used in ICEVs, so coolant may be observed and the coolant may be contaminated with electrolyte.

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[74] In *UL 9540A Installation Level Tests with Outdoor Lithium-ion Energy Storage System Mockups*, April 12, 2021, by Barowy et al., they also noted gases emanating from door seals in a large scale battery energy storage system. This may also be possible in vehicles.

[75] Emergency Response Guidebook, 2024 edition, p356.

It is also noted that many types of coolants (e.g. glycols) are combustible fluids and readily burn when sufficiently heated. Additionally, many coolants currently used are not dielectric and, if released in certain locations, may cause electrical faults. Cooling systems and/or coolants with dielectric properties are currently being developed for use in future vehicles.

As such, wear SCBA and appropriate PPE to avoid inhaling fumes from ruptured LIB cells. Follow departmental standard operating procedure (SOP) for common automotive fluids.[76]

Properly trained and equipped personnel (including HV PPE) are required to collect, transport, dispose, or recycle DDR LIBs. Separated battery parts should be individually collected and packaged in salvage packaging with non-conductive inner packaging, and surrounded by a non-conductive and non-combustible, absorbent cushioning material (e.g. sand or vermiculite; see SAE J2950 for further recommendations for packaging of damaged battery systems). Any leaked battery materials should be collected and disposed of per their safety data sheets or ERGs. First responders are encouraged to seek assistance from outside vendors trained and equipped to collect, transport, dispose, or recycle DDR LIBs if they do not have a vetted program in place to accomplish these tasks.

The tow driver/operator should be notified of the damage and associated hazards prior to handling the damaged vehicles (discussed further in section 4.5).

It is generally not currently recommended that first or second responders remove the traction LIB battery pack, or attempt to open the battery pack in an attempt to mitigate hazards. The procedure for doing so may be developed by qualified personnel based on the scope and extent of damage, accessibility, system design and condition, environment, available equipment (including PPE), etc.

[76] NFPA Emergency Field Guide, 2018, p29.

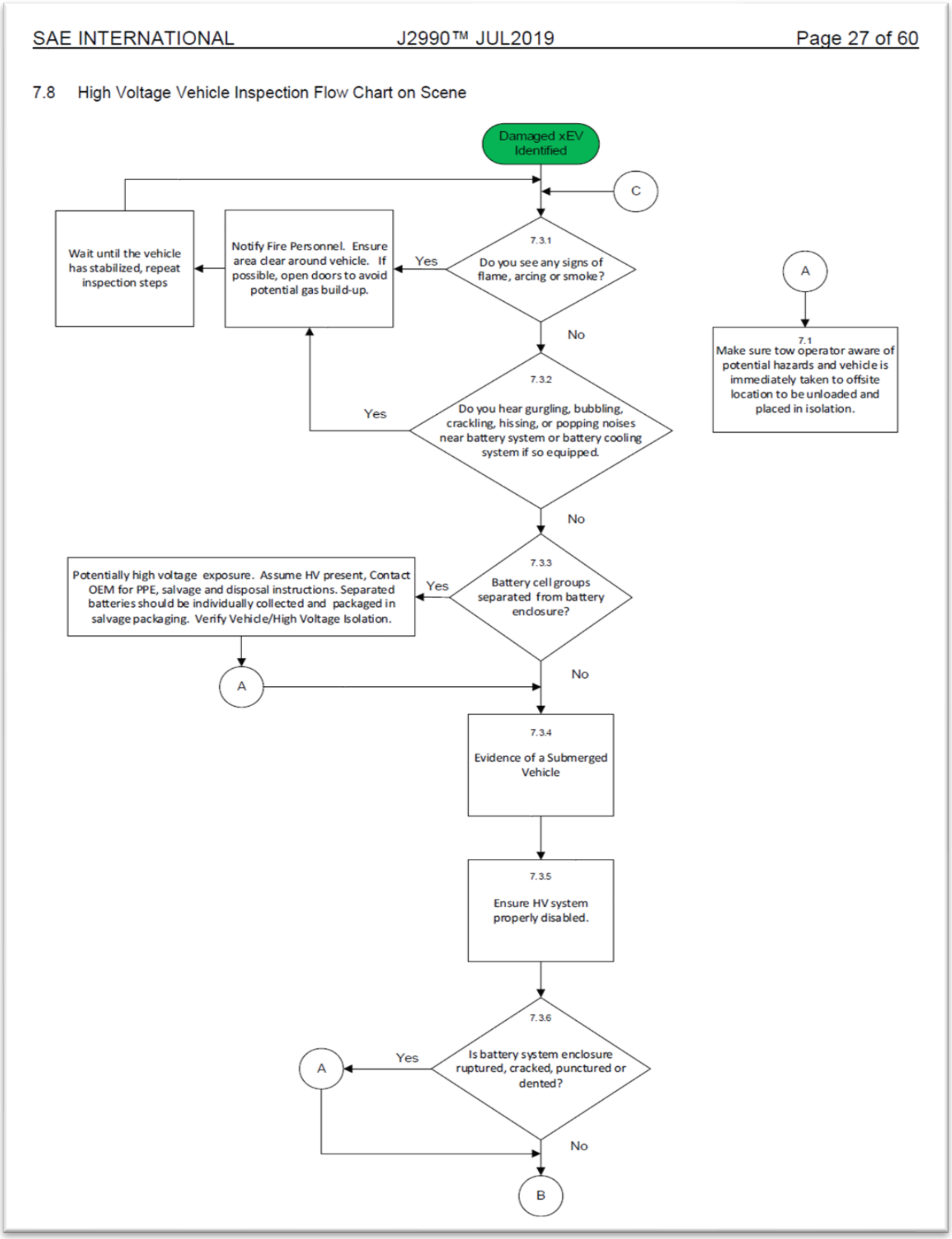

Figure 17 First HV vehicle inspection flow chart, page 1.[77]

[77] SAE J2990, July 2019, p27.

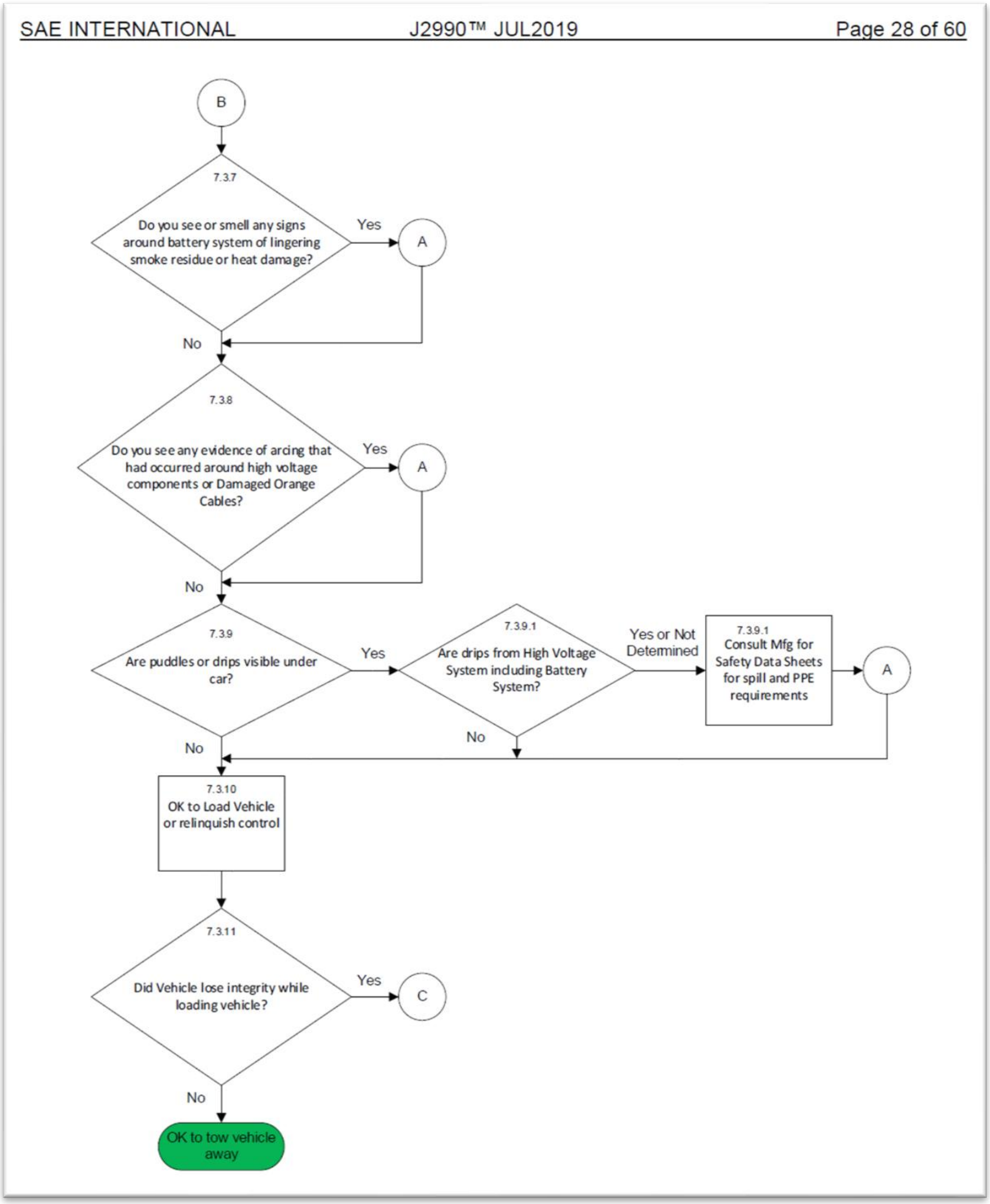

Figure 18 First HV vehicle inspection flow chart, page 1.[78]

[78] SAE J2990, July 2019, p27.

4.2.2 Use of Common Four Gas Monitors

Commonly used four gas monitors measure for the lower explosive limit (LEL) for combustible gases, carbon monoxide (CO), oxygen (O_2), and volatile organic compounds (VOCs). LEL sensors are typically of the catalytic bead type. For these sensors to measure combustible gas within the accuracy specifications provided by the manufacturer, the device must be configured to measure for a specific gas (e.g. methane (CH_4), propane (C_3H_8), or hydrogen (H_2)), and be exposed to that specific gas, in the absence of other species that may be cross-sensitive[79] (and assuming it is calibrated, etc.). The devices can be configured to measure for a specific gas by by selecting the appropriate correction factor, which in some cases must be done via connection to a computer. As such, they are not designed to accurately measure the LEL of mixtures of combustible gases, which is often the case with unburned LIB vent gases. However, such devices may still be useful in a qualitative fashion by first and second responders responding to incidents involving LIBs.

The sensors for these devices typically have particulate filters installed. For gas monitors with pumps, there may be a singular, user replaceable filter. Depending on the gas composition that is sampled, along with the duration, and the frequency of use, these filters may become clogged and require replacement. Fire companies are advised to examine filters after each use (or even during use) to see if there is heavy discoloration and potentially blockage. Some gas monitors will give some variation of a "pump clogged" error message, and they may stop sampling at that point. Fire companies are advised to understand how to identify when a filter/pump is clogged and gas monitor can no longer draw in gas to test.

It is important to note that some of the particulate matter that can be ejected during thermal runaway from battery cells such as nickel, cobalt, manganese, aluminum, magnesium, etc., are

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[79] Some gas monitor manufacturers publish information about their sensors, including cross-sensitivity information.

not measured by these devices. Per Michael Abraham, heavy metals are not easily measured in real-time at incident scenes.[80]

U.L. evaluated the use of commonly available combustible gas and hydrogen monitors during their testing related to large-scale battery energy storage systems (BESS). They found that, while these gas monitors were effective for indicating that a thermal runaway event had occurred, they were not reliable for an ongoing assessment of hazard conditions given the harsh operating environment. They note that heat, high quantities of particulate, reduced oxygen concentration, high concentrations of battery vent gases, and possibly water or other suppression agents make the environment harsh. The report also notes that halocarbons may poison (i.e. damage) the sensor based on exposure duration, and they also noted relatively high levels of soot during their tests.[81]

In a separate study, U.L. evaluated the use of multi-gas monitors to see if they could be used to identify whether LIBs were in thermal runaway inside of a garage, when measuring outside of the garage, with a residential size BESS. They found that the sensor measurements between the various tests, including a baseline test with no LIB, could not be used to determine that a LIB was involved in a garage fire when the garage door was closed.[82] However, the gas monitors were at least 1 ft. away from the structure during these tests. Pumped gas monitors placed directly in the gap between the garage or man door and the structure, perhaps with a small diameter probe, may be able to pick up more gases from the interior, but future work is needed to evaluate the efficacy of this approach. Additionally, such a tactic would need to be balanced with the potential explosion hazard of a venting LIB in a confined space.

Ezekoye et al. studied the response of some commonly used four-gas monitors by the fire service. They studied the response time, cross-sensitivity, and accuracy of the devices.

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80 Michael Abraham, Alcohol, Tobacco, and Firearms; *Lithium-Ion Batteries, Fire Investigations, and Keeping Pace with Emerging Technologies*, Fire Engineering, recorded January 24, 2024, 1:08:08.

81 Barowy et al., April 2021, p180.

82 Barowy et al., 2023, piii,64.

Regarding the cross-sensitivity, this is an important assessment given the multiple compounds that are found in battery vent gas. They found the following:

- For the LEL, all of the devices tested had a minimal time delay in response, relatively good repeatability, and relatively good characterization.
- CO concentration measured by the four-gas monitors was approximately 1/3 to 1/2 of that measured by a more accurate method, Fourier transform infrared spectroscopy (FTIR).
- The VOC sensor drastically underreported the concentration of the electrolyte, DMC, by a factor of 25 or more.

These studies are important steps in understanding whether four-gas monitors that fire departments commonly utilize work in situations involving failing LIBs. More work should be done to understand if the same trends are observed in different battery formats, and with different electrolytes.

Based on the performance of the variety of four-gas monitors tested, these devices can still be utilized to assess the *presence* of flammable gases and CO, with the assumption that the values may not be accurate. This assumes that the devices are in good working condition prior to use – properly calibrated, sensors not poisoned, and filters are not clogged. Regarding the VOC signal in the presence of gases evolved from the electrolyte, the values were significantly underreported compared to FTIR measurements, so those particular sensors do not appear to respond adequately in this environment. As noted before, these devices do not measure for other compounds that may be emitted when battery cells enter thermal runaway.

4.2.3 Submersion

Many ERGs have information regarding what to do if an EV is encountered submerged in water. Many of these ERGs indicate that the vehicles should be handled the same way as non-submerged vehicles, although with added notes and cautions. Typically, the ERGs note that there is no electric shock hazard when the vehicle is inside or outside of the water when touching the bodywork, although they note that the hazard may exist if the vehicle is severely damaged. The procedures generally indicate to remove the vehicle from the water prior to shutting down the HV system. Some ERGs indicate that noises may emanate from the battery due to discharging and shorting. Some ERGs indicate that water should be allowed to drain from the vehicle and appropriate PPE be donned. Some ERGs note that power supplies should not be turned on while submerged or partially submerged.

Several ERGs warn about potential explosion hazards associated with electrolysis of water into hydrogen and oxygen. The propensity for this to occur may be related to the salinity of the water. Some ERGs note that chlorine or chlorinated gas may also be created if chlorine is in the water. Therefore, explosion and corrosion hazards may be developed, particularly in confined spaces such as the vehicle cabin or structures.

Idaho National Laboratories (INL) performed a teardown study of seawater flood damaged electric vehicles associated with hurricanes in Florida. In the 2022 Hurricane Ian event, 600 EVs were a total loss, and approximately 36 caught on fire. In several cases, ignition occurred while EVs were being towed on flatbed trailers. In their study, INL identified leak paths into HV batteries, but they were not enough to cause catastrophic damage to the batteries studied. They identified one isolation fault, although indicated it probably would not violate FMVSS-305 (>500 Ohms/volt). The authors noted that additional efforts were ongoing to obtain a more comprehensive understanding of the flood-induced events, including more teardowns and controlled immersion tests with instrumentation.[83]

4.2.4 Incidents in Tunnels

There is currently limited research studying characteristics of EV fires in tunnel environments.

Strum et al. from the University of Gratz in Austria performed five burn tests in tunnels. In their analysis, they concluded that the HRRs of EVs and ICEs are similar, so the tunnel structural response is not really an issue for most passenger vehicles. However, this might be different for buses or similar vehicles that have HV batteries on the roof, closer to the roof of the

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tunnel. They also determined that the combustion products tended to stratify and stay in an upper layer by the ceiling with their tunnel ventilation systems, and that concentrated, undiluted streams of combustion products may have elevated concentrations of various species when compared to free-burn tests described earlier. Therefore, if layers are observed during a tunnel fire, it is advisable to avoid the upper smoke and hot gas layer if possible. The tunnel ventilation systems in the U.S. may be different than those involved in the tests, so stratification may or may not occur in U.S. tunnels.

4.3 Onsite Handling

In some cases, it may be desirable to move an EV from a directly dangerous situation, such as a highway construction site. Manufacturer ERGs may have information related to this purpose. Per some ERGs, as described below, moving them short distances and at very slow speeds may be acceptable if there is minimal risk of fire or high voltage exposure. Spinning wheels that have motor generators may generate electricity which could potentially be stored in the inverter capacitor. Note that the capacitors may have stored energy from driving prior to the incident, and per the manufacturer disabling procedures described later this section this capacitor will discharge over the course of minutes after disabling the vehicle.

Selected related manufacturer notes are provided below (NOTE: the ERG of the vehicle involved in the incident should be referenced). Additionally, note that these do not apply to towing or relocating vehicles outside of emergency situations:

- Mercedez-Benz notes that, to remove a vehicle from a directly dangerous situation such as a highway construction site, a tow bar or tow rope can be used to move their vehicles a short distance, no faster than walking speed.[84]
- Lexus similarly notes in some hybrid ERGs that "*if a tow truck is not available, in an emergency the vehicle may be temporarily towed using a cable or chain secured to the*

[84] Mercedez Benz, Guidelines for car towing services, Vehicle with electric drive, p38.

emergency towing eyelet or rear tow hook. This should only be attempted on hard, paved roads for short distances at low speeds (below 18 mph)…"[85]

- Tesla notes that, in situations where there is a minimal risk of fire or high voltage exposure, and 12V power is present, the Model 3 can be quickly pushed in order to clear the roadway. However, a driver needs to be present to keep the vehicle in neutral, or *transport mode* needs to be activated if no driver is present (see ERG).
- Nikola notes that the vehicle can be pushed at speeds below 3 mph for up to a total of 1 mile to clear it from the roadway. The vehicle must be placed in *neutral*, and the parking brake must be disengaged prior to pushing.

4.3.1 Immobilize

Per the NFPA Emergency Response Field Guide, all vehicles should be immobilized prior to working around them.[86] Anecdotally, there have been incidents resulting in damage and/or injuries which have involved inadvertent movement of EVs during emergency responses.

Generally, the steps to immobilize the vehicle are to chock the wheels, set the parking brake, and place the vehicle in park. In many modern vehicles, the parking brake is a switch or button that is typically pushed to engage the parking brake. It is typically a rocker switch or button to the left of the steering wheel, on the center console, or at the end of the steering column stalk on the right side (some Tesla and Mercedes Benz vehicles). In some vehicles, putting the vehicle in park automatically engages the parking brake.[87] In most vehicles, the word BRAKE appears in red on the instrument cluster when the brake is engaged.

It is important to set the parking brake at this stage because many parking brakes require that the low voltage system be operative in order to engage the parking brake.

Up-to-date manufacturer ERGs should be checked before attempting to disable vehicle. The use of cut loops to disconnect low voltage systems appears to be an evolving subject. Per the US

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85 Lexus LS 600hL Hybrid, 2008-2013, Emergency Response Guide, REV B (08/28/12), p35.

86 NFPA Emergency Field Guide, 2018, p11.

87 Porsche Taycan, ID no. EN-01-710-0078, version no. 1, p2.

DOT ERG, 2024 edition, *most electric vehicles have emergency cut loops which are low voltage wire loops that can be cut to disconnect the high voltage system from the rest of the vehicle. If it is safe to do so, follow the manufacturer's directions to disconnect the 12-volt battery. This will isolate the power to the high voltage battery and reduce risk of electric shock*.[88] However, as of June 2024 some manufacturers such as Tesla and General Motors reportedly are advising to use the cut loops only if necessary.[89]

As part of the immobilization process, a few other considerations may be made. If or when low voltage cables are cut, this may preclude use of powered seat adjustments, trunk release buttons, etc., so adjusting or actuating those systems first may be considered.

Following immobilization of the vehicle, and if there is no pressing emergency (e.g. medical or extrication), first-responders should consider approaching the vehicle from the side and looking at the underbody to see if a battery pack has been damaged by road debris, driving off-road, crush damage, etc.

4.3.2 Disable

Following immobilization, trained personnel should plan to access the interior of the vehicle and shut down the vehicle's ignition/HV system to help isolate the HV wiring and components from the HV battery.

As noted before, some electrical appliances, like power, seats, windows, or electronic trunk releases may not function after disabling the vehicle, so it may be desirable to use these before disabling. Additionally, in the Tesla Model 3, if the low voltage power is disabled, the door cannot be opened from the outside and must be opened from the interior, per the ERG. Disabling the 12V system will also disable the SRS airbag systems.

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[88] Emergency Response Guidebook, 2024 edition, p225, 356.

[89] SFPE Conference, June 2024.

The disable procedures for specific vehicles can be found in their ERGs, and those ERGs should be the primary point of reference for disable procedures. That said, if a vehicle cannot be identified, the primary disable process is similar to conventional ICEVs and is as follows:

- Shut off the vehicle ignition (button or key).
- Disconnect the 12V DC battery

When disconnecting the 12V DC battery, the negative terminal can be removed, or a gap cut can be made if there are space or time limitations. A gap cut is a 2-point cut in the same cable a couple inches away,[90] such that the "memory" of the cable cannot re-establish a connection.

Many ERGs note to remove the key fob from the vehicle and move it away from the vehicle – 20+ ft. is the longest distance seen in the ERGs.[91]

Note that ERGs can be referenced to locate the 12V batteries, as this can vary from vehicle to vehicle. These batteries can be under the front hood/frunk, under one of the seats in the passenger compartment, or in the trunk.

The secondary method includes the following:

- Disconnecting 12V battery -- some Teslas do not have on/off buttons, and the disabling starts with doubling cutting 12V battery cables in the frunk area.
- Pull the HV system disconnect, main fuse, or relay.

Still, these two procedures do not cover all vehicles, so the ERGs must be referenced. For example, the Polestar 2 (2020-) is disabled by 1) pull disconnect/safety mode switch on the floor between the passenger front and rear seats, and 2) disconnect 12V battery in frunk.

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90 Caruana, Principles of Passenger Vehicle Extrication, verified by the IFSTA, 2022, p196.

91 This is the longest distance specified in ERGs by a manufacturer. Some may have shorter distances (e.g. 2023 Kia Niro is 7+ ft.).

In the continued effort to ensure that the HV system is disabled, responders may look for cues that the vehicle is in ready mode. Figure 19 shows the instrument panel of a Kia Niro, as viewed from the driver's side doorway. Note the green "READY" in the upper left corner, indicating that the HV system powertrain is engaged and the vehicle may move if the accelerator pedal is depressed. Also note the light blue charger plug in the lower left corner, showing 185 miles. Acknowledging this can be helpful in assessing risk during the activities. Vehicles may also show state-of-charge (SOC) as a percent. The instrument cluster may also say "AUTO STOP" if the system is still engaged.

Tesla notes that, after deactivation, the HV circuit requires 2 minutes to de-energize.[92] Kia notes that the wait should be 5 minutes before engaging in any emergency response procedures to allow the capacitor in the HV system to discharge to avoid electrocution.[93] Some models have capacitors that retain HV energy for up to 10 minutes.[94]

[92] Tesla Model 3 ERG, no model years listed,

[93] Kia Niro ERG, p11

[94] Electric Vehicle Safety for Emergency Responders, Module IV: Initial Response, Identify, Immobilize, and Disable, accessed from https://www.mass.gov/doc/nfpa-electric-vehicle-mod-iv-initial-response/download on March 1, 2024, p SM 4-8.

Figure 19 Instrument panel of a Kia Niro, as viewed from the driver's side doorway. Note the green "READY" indicating that the HV battery can supply power to the inverter/wheels, air conditioning, or other HV consumers.

When in the vehicle at this time, if time permits, then take note of indications of remaining miles or battery SOC. Many vehicles (e.g. Testla Model 3, Hyundai Ioniq 5, Nissan Leaf, Ford Mustang Mach-E, Porsche Taycan, etc.) have this information in the EV instrument displays.[95]

If possible, ask the vehicle drivers or occupants for state of charge/battery percent or remaining miles. If the SOC is less than 40%, studies indicate that there is a lower fire hazard as a result of less flammable gases and more CO_2 in the venting gas[96] (although this does not necessarily mean a lower toxicity hazard if battery vent gases are not burned). However, first-responders should attempt to assess the reliability of statements made by people who were recently involved in a vehicle crash.

95 Idaho NL paper, Table 2.

96 Baird, A., Archibald, E., Marr, K., and Ezekoye, O., *Explosion hazards from lithium-ion battery vent gas*, Journal of Power Sources 466 (2020), p3.

4.3.3 Extrication

Vehicle Rescue and extrication consists of three phases: stabilization of the scene, stabilization of the vehicle(s), and stabilization of the victim(s).[97]

If entrapment is involved, fire and rescue personnel would fully complete the identification, immobilization, and disabling of the HV system before beginning forcible entry and extrication activities.[98]

The scene and vehicle should always be stabilized before beginning extrication.[99] Before cutting or prying, visually check to determine the location of the following:

- HV components and cabling (always assume "hot")
  - Includes solar panel cabling.
- SRS and occupant protection systems

This information is typically shown in the ERG and Quick Response Guides. With this information, vehicle stabilization measures can be taken. If and when cribbing is used, avoid placing it under high voltage wiring or battery packs (or fuel supply lines, or fuel cylinders).

HV batteries cables are typically routed along the underbody of vehicles and are not found in typical extrication cut locations. If a vehicle roll-over has occurred, HV cables may be more readily accessible, and any cut locations should be made considering vehicle stabilization measures. Note that in some cases, the orange cabling is not always visible and can be behind plastic paneling.[100]

[97] Sweet, D., National Fire Protection Association, International Association of Fire Chiefs, *Vehicle Rescue and Extrication: Principles and Practices*, 2022, p4.

[98] SAE J2990, July 2019, Appendix C, p40.

[99] NFPA Emergency Field Guide, 2018, p13.

[100] Electric Vehicle Safety for Emergency Responders, Module IV: Initial Response, Identify, Immobilize, and Disable, accessed from https://www.mass.gov/doc/nfpa-electric-vehicle-mod-iv-initial-response/download on March 1, 2024.

Solar panels are currently not commonly installed in production vehicles. However, they are available as options in some vehicles (e.g. Hyundai Sonata Hybrid,[101] Fisker Ocean), and the only way to shut them down when there is daylight is to cover them with a solid, opaque tarp. Additionally, whereas many electrical systems may be de-energized by disconnects, fuses, circuit breakers, relays, or other means, photovoltaic panels may continue generating electrical power after a fault, albeit in a current and voltage limited manner.[102] These cables will likely be routed down one of the pillars. If they are orange, that means they have more than 60V. Disabling solar panels should be covered in ERGs and quick summary sheets.

First- and second-responders are advised to always consider that the HV system is still engaged when responding to a vehicle incident. As described in section 2.2, vehicles are designed such that in the event of a crash of sufficient magnitude, that the contactors at the HV battery pack will open and isolate the HV electrical system from the battery pack. However, since not all crashes will actuate this system (or airbags) and it may be possible for crash damage to affect the operation of the contactors, the assumption should be that the HV system is live.

Modern EVs commonly use high strength steel in the construction of the cabin. First responders are advised to test their cutting equipment on a salvaged vehicle prior to attempting to use them at a crash scene involving an EV.

Per the NFPA EVFG, fire companies should not blindly pierce through the hood with tools such as a Halligan bar, as this could damage HV components.

[101] ALLDATA Repair, 2020 Hyundai Sonata (DN8) L4-2.0L Hybrid, Solar Roof Ssystem, SD816-3

[102] For additional information regarding firefighter response to PV system incidents, see, e.g., https://fsri.org/research-update/firefighter-safety-and-photovoltaic-installations-research-project-released, https://fsri.org/research-update/updated-course-firefighter-safety-and-photovoltaic-systems-now-available

4.4 Fire Suppression and Extinguishment

4.4.1 Fire Suppression

If a fire ignites during the incident, it is important to note the location and environment of the vehicle(s), as that may affect the strategy. Additionally, noting what fuels are involved in the fire, to the extent possible, may influence suppression tactics.

If there is no immediate threat to life or property, first responders should consider defensive tactics and allow fire to burn out.[103] For example, for incidents in open areas such as uncongested roadways or parking lots, letting the vehicle burn may be a preferred approach if feasible. By allowing the fire to propagate through the battery pack, the potential for stranded energy which could facilitate re-ignition goes down. UL FSRI noted in a June 2024 presentation that complete consumption of battery cells occurred when the vehicles were allowed to free burn.

For incidents in other areas, such as parking garages, congested roadways or parking lots, tunnels, or on bridges, the preferred approach would be to attempt to suppress the fire. Anecdotally, fire suppression of an EV takes approximately 60 to 90+ minutes, whereas suppression of an ICEV fire takes approximately 30 minutes.[104]

Many studies and experiential knowledge indicate that water can suppress EV fires, although copious amounts may be necessary since it is often difficult to apply the water directly to the battery cells – the packs themselves are designed to keep water out. Water has a cooling effect, has high specific heat, and vaporizes to interfere with combustion reactions. Anecdotally, suppressing EV fires with water could require in the range of 300 gallons to over 20,000 gallons

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[103] U.S. Department of Transportation, National Highway Traffic Safety Administration, *Interim Guidance for Electric and Hybrid-Electric Vehicles Equipped with High Voltage Batteries*, January 2012, DOT HS 811 574, p9.

[104] NFPA, SFPE Conference, June 2024.

of water.[105] One of the challenges with suppressing EV fires is that it can often take more water than one apparatus can supply.

At the lower range, a rupture in the battery case between the front seats allowed water into the case which helped extinguish the fire. At the upper range, it is highly unlikely that all of the water is actually going to suppress the fire, as opposed to attempts to cool the battery and/or mitigate re-ignition hazards. In many cases, the flames were extinguished rather quickly but it took sustained water application to stop the battery from venting. In one case, the firefighters could not extinguish the fire until they elevated the vehicle and applied large quantities of water directly to the battery on the underside of the vehicle.

As described in section 3.4.1, IFE is not aware of electricity transmission through hose streams in EV fire suppression, but this phenomenon has been reported in structure fire(s) involving directing hose streams at areas where 220 VAC was present. Fire departments are therefore advised to avoid touching vehicles, or standing close to vehicles, while simultaneously holding a nozzle directing water spray into the vicinity of the battery pack or inverter.

Some manufacturers indicate that salt water should not be used. This may generate a large volume of H_2 gas due to electrolysis,[106] Depending on the damage to the vehicle and the condition of the vehicle, the use of salt water may also result in unintended electrical current flow, which may have implications for thermal runaway propagation and electrical shock hazards.

The following methods are offered for consideration for cooling skateboard-style packs. Note that there have been no studies or research done to prove that these are effective methods:

- Consider putting water through any holes that might be made due to the accident or fire.[107]

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[105] NTSB Report, p54

[106] Kia Niro EV 2023 ERG, p24

[107] Kia Niro EV 2023 ERG, p19

- Applying water from the ground level and up into the wheel well area to try to get water on the front, rear, and top of the battery packs.
- Applying water in the interior (particularly for vehicles where the battery is in the interior). This may not work well in the incipient stages of an event, or if the battery pack just started venting, and it may be more effective if there is already some heat damage to the interior.
    - There may be polymeric floor plugs/gaskets, wire pass-throughs with grommets, or HV disconnect access points which can potentially allow water to reach the battery pack.
- Applying water to any damaged areas of the battery pack, including areas where gas is venting, while maintaining a safe distance.

When considering the potential for fire spread to adjacent vehicles or structures, note that vehicle burn testing to-date has shown that peak heat release rate (HRR) and total heat released in EVs, FCVs, and ICEs with vehicles of approximately the same size are comparable.[108] As may be expected, larger vehicles will generate more heat.

Testing by RI.SE has shown that applying water mist to LIB fires increases the production of HF significantly during the application process, but it did not change the total amount of HF produced. Essentially, applying water mist accelerated the production/release of HF.[109] The authors did not note if this applies to hoseline flow. This suggests that strict adherence to hazard control zones and attention to wind direction during water mist application would limit exposure to HF – larger hazard control zones may be considered if the wind is variable.

Electric vehicles have a lot of fuels that are common and similar to fuels in conventional modern vehicles, such as plastics, foams, and wire insulation. Additionally, there may be glycols (heat transfer fluids/coolants), and flammable refrigerants. In hybrid vehicles, additional fuels associated with internal combustion engines will be present, such as gasoline or Diesel fuel, motor oil, power steering fluid, etc. In circumstances where the fire is isolated or in

[108] UL FSRI, June SFPE Conference

[109] RISE Report 2020:90, p31

its incipient stages and does not include the LIB, conventional firefighting approaches will likely be appropriate.[110] It may be challenging to understand if the HV battery has become involved. Note, however, that the use of cooling agents (e.g. CO_2) can affect the temperature of areas that may eventually be observed with a thermal camera.

As recently as June 2024, water remains the primary suppression method for EV fires per NFPA. There is some literature indicating that a water mist with encapsulator additive such as F-500 may, facilitate suppression of a battery pack fire more than water mist alone (see NFPA 18A-2022, section A.4.3). However, as a point of reference, in the 2023 version of NFPA 855, Annex G — Guide for Suppression and Safety of Lithium-Ion Battery (LIB) Energy Storage Systems (ESS), there is no preference shown for the use of encapsulator agents.

Anecdotally, some fire services are using a pick-axe to puncture the pack such that they can flood it with water and facilitate discharge. Pick-axes can introduce thermal and arc flash hazards when used in this manner. The Swedish Agency for Community Protection and Preparedness (MSB) noted in their testing program that when battery packs were punctured without water, jet flames emerged, whereas when the pack was punctured with simultaneous water injection, no jet flames emerged. The MSB did not recommend using a pack axe approach because it may be difficult to carry out in a real vehicle fire where access to the battery is limited and it may require working inside of a burning vehicle. [111]

Additionally, pick-axe heads are typically metal, and by puncturing the battery enclosure then both the enclosure and pick-axe may be pushed into the battery cell area. This could result in or initiate, thermal runaway in the LIB, or create an arc flash. The potential failure modes, as shown in Figure 20, are as follows:

[110] Thomas Barth, FSRI Symposium, 23:45

[111] The Swedish Agency for Community Protection and Preparedness (MSB); Unit: Fire and rescue; Demonstration of quench method for lithium ion batteries, method application at different levels of aggregation – module, sub-battery, electric car pack and vehicle level; MSB2184 – March 2023.

1) compromising HV battery isolation at one location,

2) compromising HV battery isolation at two locations and resulting in arcing,

3) compromising HV battery isolation at one location when it was already lost elsewhere as a result of damage, and/or

4) mechanically damaging a cell and initiating thermal runaway.

As described earlier, EV HV systems are isolated from the chassis (at the positive terminal, negative terminal, and at all of the intermediate voltages; the total voltage of EV LIB packs is achieved by putting individual battery cells in series, so there are multiple intermediate voltages within a pack). Regarding potential failures 2 and 3, if the battery isolation has already been lost at one location, either as a result of a strike or crash crush damage, then creating a second isolation failure at a different voltage potential can potentially create a short circuit and arc flash if both isolation failures are with the same electrically conductive material, such as a metallic enclosure. In other words, if crash crush damage occurs and results in a metal battery enclosure touching a bus bar at 300 VDC, and if a pick axe pushes a different part of that same metal battery enclosure into a different bus bar at 100 VDC, then there is a short circuit with a 200 VDC potential.

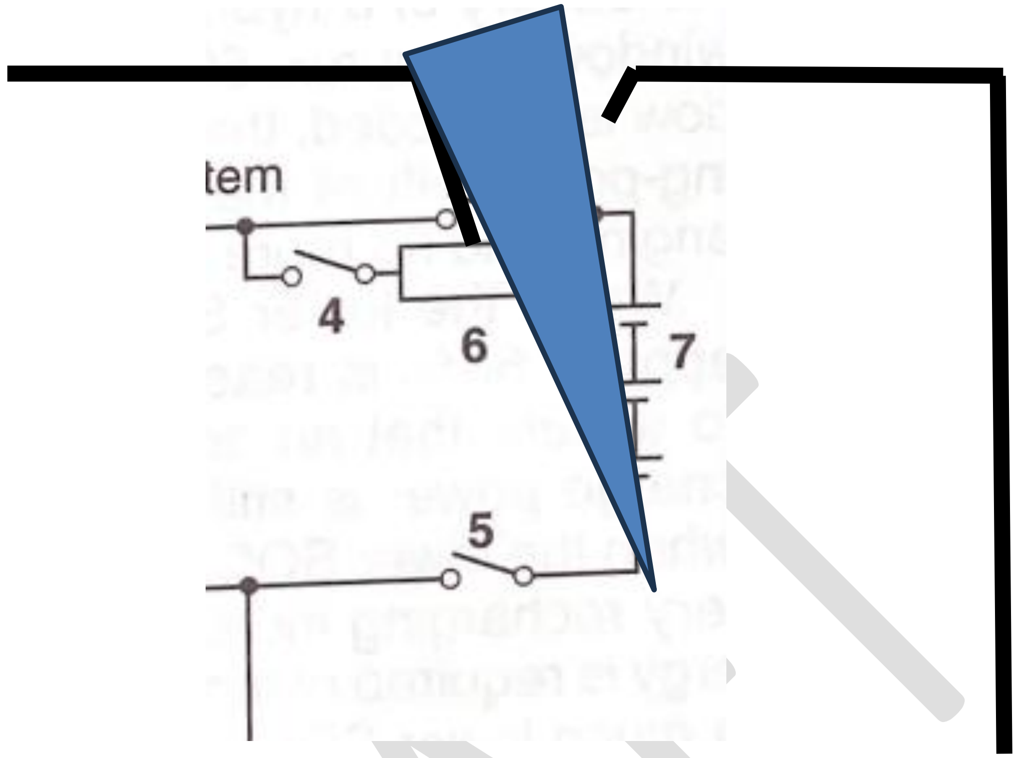

Figure 20 Potential failures that may occur if a pick-axe is used to open a HV battery pack in order to flood it with water. The enclosure and/or pick-axe may fail the HV battery isolation, the pick-axe may short different voltage potentials and cause an arc, or the pick-axe may mechanically damage cells and induce thermal runaway.

Note that fires involving the HV battery pack may reignite following extinguishment if there is sufficient stored energy in the pack, as described in section 4.5.

4.4.2 Fire Water Runoff & Particulate Residue

Hazards associated with fire water runoff are described in more detail in section 3.2.

Fire water runoff may contain elevated levels of cobalt, nickel, manganese, chloride, fluoride, and potentially other contaminants. If feasible, runoff should be redirected away from storm drains and other water sources using dikes or other techniques to limit any remediation that must be done.

Generally, as more water is used during suppression efforts, there is the potential for runoff to travel further.

4.5 Transportation, Storage, and HV System Inspection

Fire departments should consider services available by vendors to provide safe decommissioning and transport of vehicles with damaged batteries.[112] These services may include handling, collection, packaging, transportation, and disposal or recycling. The process may involve discharging battery packs using resistor loads, as has been done for recovery of grid-scale battery energy storage system thermal events.

4.5.1 Transportation

First-responders must convey any known information regarding hazards or risks to second-responders. Batteries must be completely cooled prior to towing activities. Per Michael Abraham at the ATF, the general guidance is for the batteries to be at ambient temperature.[113] Per Tesla ERGs (Model 3, Model S 2016+), there must not be fire, smoke, or heating present in the high voltage battery for at least one hour before the vehicle can be released to second responders.[114]

In cases where there is suspected or known damage to the vehicle HV system (e.g. smoke, fog, popping, gurgling), or if the vehicle had caught fire, it is recommended that fire apparatus escort the tow vehicle to the location where it will be stored, whether that is a salvage yard or repair facility. There is a risk of ignition or re-ignition of an EV with damaged HV systems due to jostling or movement of vehicles. This may be a result of short circuiting or high resistance connections/heating to form, so a vehicle that is showing no signs of heat generation may begin to do so during handling.

Vehicle manufacturer ERGs should be consulted to determine the approach to transportation. Flatbed trucks are typically the recommended tow vehicle option, and in some cases the only permitted option (e.g. Acura RLX Sport Hybrid, 2014, 2016-2020). Towing with dolly's,

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[112] Ezekoye, O., *Firefighter Safety on Firegrounds Involving Lithium-ion Batteries*, November 21, 2023, Fire Protection Research Foundaation 2023 Webinar Series.

[113] Michael Abraham, Alcohol, Tobacco, and Firearms; *Lithium-Ion Batteries, Fire Investigations, and Keeping Pace with Emerging Technologies*, Fire Engineering, recorded January 24, 2024, 1:20:00.

[114] Tesla Model 3 ERG, p23; note that the Tesla Model Y ERG indicates 45 minutes.

ensuring that all of the wheels are off of the ground and cannot spin is sometimes offered as an option (see Figure 21). Towing vehicles where the wheels can spin can lead to significant damage and overheating.[115] Many ERGs advise against using a sling-type tow.

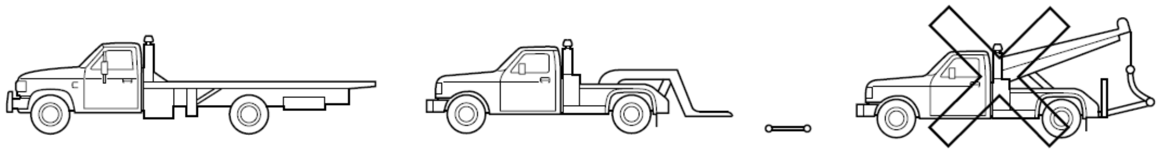

Figure 21 Graphic illustrating that flatbed tow vehicles and tow vehicles using dollies to keep the towed wheels off of the ground are acceptable, whereas sling-type tow vehicles are not acceptable.[116]

Some hybrid and EVs have pedestrian warnings that may begin to emit sound if the vehicles are moved with the ignition in the *on* position.

Note that reignition(s) can occur during loading, transportation, unloading, or after arrival – even several days later if the HV system was damaged in the crash.[117] For this reason, the author prefers using an open top shipping container with doors (or roll-off dumpster with doors or conex) for transportation. This container can also double as the isolation/storage unit, permissible in SAE J2990, July 2019.

The shortest and safest route to the repair facility or salvage yard should generally be taken. Planning the route prior to departure can be helpful to avoid passing through tunnels, over bridges, through congested or heavily populated areas, HAZMAT restricted routes, etc.

4.5.2 Storage

Initially, the vehicles should be isolated until a second inspection has been carried out on the damaged vehicle or unless the battery has been discharged according to a procedure approved

[115] Tesla Model 3 ERG

[116] 2021-2023 Ford Mustang Mach-E ERG, 4/2023

[117] SAE J2990, July 2019, p22.

by the vehicle manufacturer or other qualified organization. The second inspection is described in the following section.

Isolated vehicles should be placed outside, in a well-ventilated area, and not inside of a structure. Per SAE J2990, July 2019, two methods are permissible for isolation:

1) Open perimeter – a minimum 50 ft. separation between the vehicle and all combustibles or structures.
2) Barrier isolation – vehicle is separated from all combustibles and structures by a barrier constructed of earth, steel, concrete, or solid masonry designed to contain a fire and prevent propagation. Examples include an open top steel shipping container with doors for loading (not enclosed; needs to be ventilated; also referred to as conexs); or a three sided solid masonry bay of suitable height to prevent fire propagation, where the fourth side has a 50 ft. separation distance as described above.

Consideration should also be given to accessibility of the vehicle to emergency responders should reignition occur.

Some ERGs recommend that passenger and cargo compartments remain ventilated during storage to limit the accumulation of battery vent gases, should any venting occur while in storage. However, some also note that if the HV battery is damaged, it should be protected from rain and water accumulation. While battery packs are typically designed to prevent water intrusion, if they are damaged then openings may be created. The specific approach taken will depend on the vehicle design and nature of the damage. A fire blanket may be utilized, or in some cases adhesive backed plastic or tarps may be utilized to control water or rain ingress.

After the vehicle is placed at the storage site, a weatherproof placard or some other identifier should be placed on the roof and hood of the vehicle to identify and warn others that it is a HV vehicle with suspected damage. Periodic visual inspections can be made for elevated temperatures using a thermal camera, smoke/fog, or fire. As mentioned earlier, the use of odor is not a recommended assessment approach, as that could potentially mean exposure to battery vent gases.

Note that vehicles placed in storage may reignite. Anecdotally, a vehicle ignited 3 months and 3 hours after it was placed in storage.[118]

4.5.3 Second HV System Inspection

In addition to inspection of the HV system at the scene, SAE J2990 July 2019 recommends inspections at the storage location as well within 24 hours of unloading.[119] This recommendation is supported by one reported incident where a vehicle caught fire, was extinguished, a fire watch was conducted for 6 hours including speaking with a manufacturer representative, followed by a tow, and the vehicle ignited again. [120]

Some OEMs have indicated in their ERGs that the batteries may be discharged by placing the vehicle in a water bath (see section 3.5.4). This may preclude the need for carrying out a second HV System Inspection, provided that the instructions are correctly carried out.

Anecdotally, some fire departments are using sand or dirt piled on and around the vehicle to preclude re-ignition. In at least one case, the roof was cut off so that sand could be dumped in the interior. If sufficient sand is placed in areas where battery vent gases may emerge from the pack, it would serve to absorb heat from any vent gases, potentially mitigate some ignition sources (e.g. sparks, hot particles), protect/absorb heat when on top of combustibles, and limit mixing with ambient air/oxygen. The limitations of this are 1) anecdotally, one vehicle has re-ignited after the sand was removed, and 2) examinations as part of a fire investigation campaign are made more difficult when there is sand to remove, particularly since not all of the sand is easily removed. Following such a procedure, the sand may need to be treated as industrial waste.

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[118] Michael Abraham, Alcohol, Tobacco, and Firearms; *Lithium-Ion Batteries, Fire Investigations, and Keeping Pace with Emerging Technologies*, Fire Engineering, recorded January 24, 2024, 1:00:10.

[119] SAE J2990, July 2019, p21.

[120] Tesla Model S, Los Gatos, California, on or about December 19, 2018, reported by ABC7, https://abc7.com/tesla-fire-los-gatos-model-s-catches-fremont-tsla/4930766/, https://www.bing.com/videos/riverview/relatedvideo?q=tesla%20fire%20jet&mid=E9C204148789A4EE51DAE9C204148789A4EE51DA&ajaxhist=0

If the submersion approach is not taken, SAE J2990 recommends that the OEM or other responsible organization should then be contacted to determine additional inspection and diagnostic steps prior to removing the vehicle from isolation. [121] Contact information provided in the ERGs is supplied in Appendix B. Fire services may already be aware of other organizations who can perform this work based on experience with incidents to-date.

Since SAE J2990 recommends OEMs or other responsible parties be contacted at this stage, details of the second HV system inspection are not provided in this document.

[121] SAE J2990, July 2019, p21.

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7.9 High Voltage Vehicle Inspection Flow Chart Post-Incident

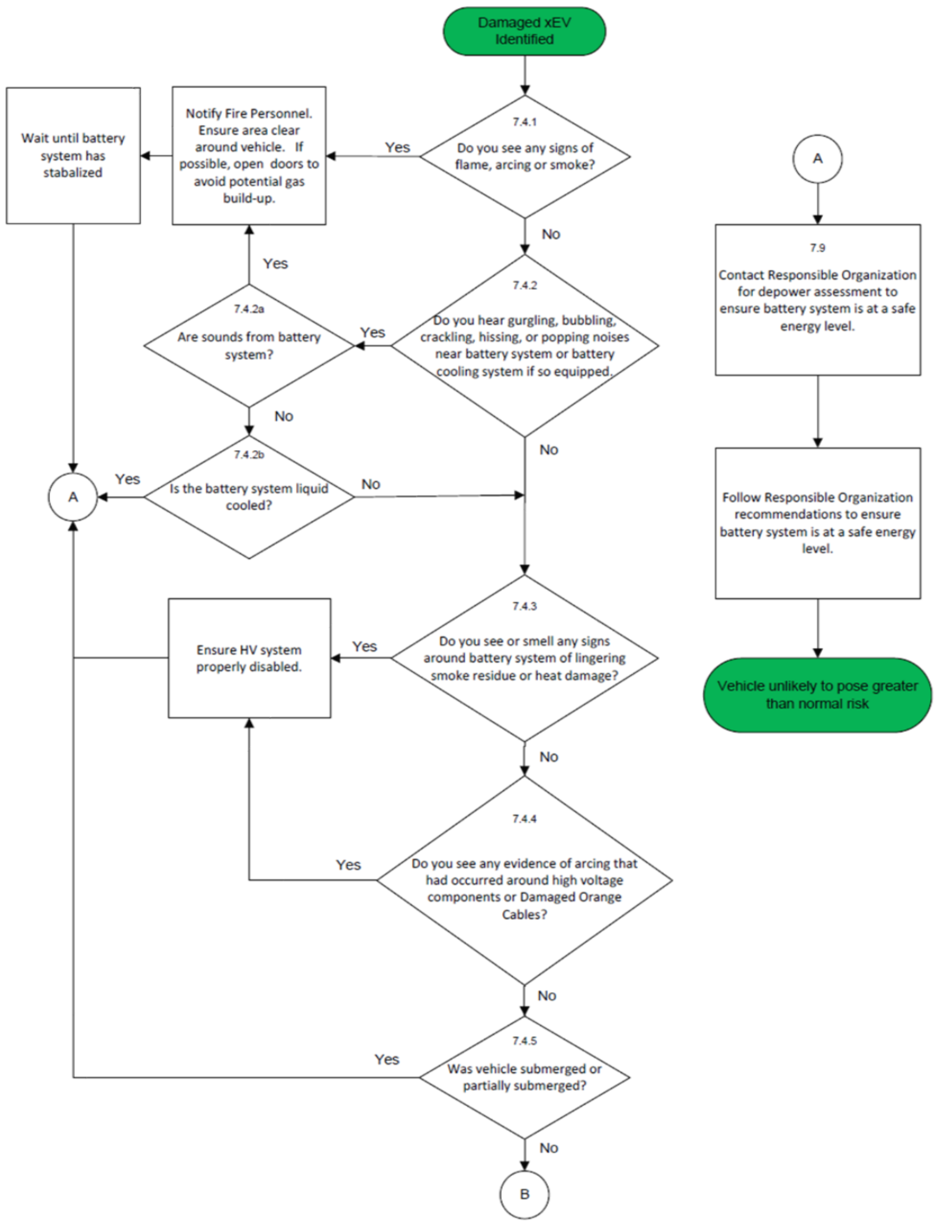

Figure 22 Second HV System Inspection, page 1.

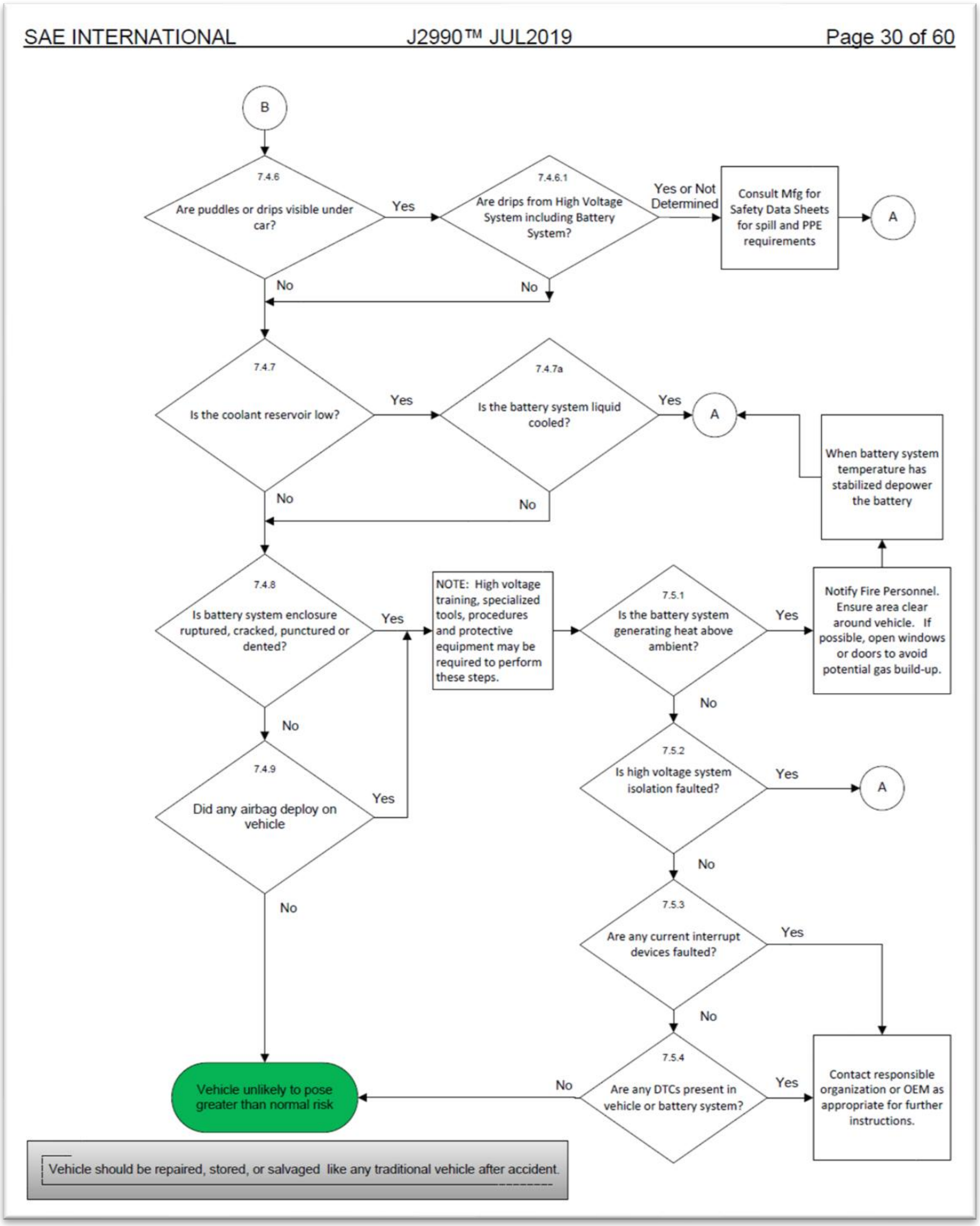

Figure 23 Second HV System Inspection, page 2.

4.5.4 Discharge

Some vehicle manufacturers explicitly state in their ERGs to contact experts at the vehicle manufacturer rather than attempting to discharge a HV battery pack. Most vehicle manufacturers do not recommend submerging vehicles – including Tesla, as of June 2024. However, as described in the prior section, some OEMs have indicated in their ERGs that the batteries may be discharged by placing the vehicle in a water bath. Separately, this method is also used for discharging battery packs that have been abuse tested for research and development purposes. Per one ERG, the water and residue left after submerging a vehicle may contain metals such as phosphorus and lithium, and it should be disposed of as an industrial waste according to local regulations.[122] If the battery is discharged using this method, it may preclude the need for carrying out a second HV System Inspection, provided that the instructions are correctly carried out.

Multiple ERGs include a specific procedure to discharge the HV battery. A simplified procedure generated using two different ERGs is below.[123] This procedure may be slightly different for other vehicles, so the ERG for the specific vehicle at issue should be referenced.

- Open windows or doors
- Disconnect 12 V battery
- Remove the manual HV disconnect service plug
- Set up a pool large enough to fit the vehicle, and contain at least 3 ft. deep water, in a well-ventilated area
- Use a forklift or other equipment to place the vehicle in the center of the pool
- Add water until the pool completely submerges the HV battery. Do not use salt/sea water to start
- Maintain water level for 90+ hours, adding water if necessary

[122] 2017-2020 Acura MDX Sport Hybrid ERG, p34

[123] 2017-2020 Acura MDX Sport Hybrid ERG, 2023 Kia Niro ERG

- Add salt to make 3.5% salt/water ratio and maintain water level for an additional 48 hours

It is a noted that, at the time of this report, an SAE technical committee named Battery Field Discharge and Disconnect Committee is in the process of being formed.

4.6 Specialized Tools

Tools that may be used in the management of crashes in traditional ICE vehicles may also be used in EV and FCV incidents. However, various tools have been designed and marketed for the purposes of managing EV incidents. These tools could conceivably be used to discharge a damaged pack that is not venting or on fire, or to extinguish a fire that involves the battery pack. Additionally, other tools are discussed in this section. This section includes a discussion on the following:

- Water penetrating extinguishers
- Pack-puncture and water injection
- Underbody nozzles
- Fire blankets
- Non-sparking tools
- Non-conductive tools
- Placards
- Charging plugs for disabling purposes

IFE is not recommending, providing guidance on the use of specific tools, or commenting on the efficacy of the use of specific tools unless explicitly noted. However, information identified during IFEs research at the time of this report regarding these tools is presented here. It is important to note that no manufacturer ERG currently recommends tools which puncture or penetrate the traction battery. However, a discussion of these tools is presented, including a discussion of available technical published information as evaluated by third parties. Information from the manufacturers is not included, in part because some manufacturers would not respond to requests to discuss their tools. Additionally, some preliminary questions that relate to potential issues when using the equipment are presented.

4.6.1 Water Penetrating Nozzles

Water penetrating nozzles, also referred to as water lances, have been used to fight fires in containers but are also now being considered for use in EV fires. Water penetrating nozzles utilize water to cut the battery enclosure, and subsequently to inject water into the battery pack. These have been studied by a third party, the Swedish Civil Contingencies Agency (MSB) in their report, titled *Demonstration of Quench Method for Lithium-Ion Batteries: Method application at different aggregation levels – module, sub-battery, electric car pack and vehicle level*.[124] However, it must be noted that MSB only currently offers this publication in Swedish on their website, and that available copies online are not translated to English by the authors.

The authors note that they tested cells that contain a maximum of 60% nickel content in the cathode, and that more nickel-rich and energy-dense electrode systems have higher reactivity and must be investigated separately. The study also includes prismatic cells and pouch cells. They used water as the extinguishing medium. All tests were performed at 100 % SOC.

In their complete EV test, they initiated thermal runaway and a countdown of 15 minutes was started to mimic the response time of emergency services. By that time, a fully developed fire was noted and the extinguishing attempt was started. They utilized a water lance with a water pressure of 300 bar (4400 psig), flow rate of 58 liters per minute (15 gpm), and an abrasive was added to the water to facilitate cutting.

They used the cutting extinguisher to knock down the flames in the cabin, and then they opened the rear door and scanned the interior of the vehicle to look for hot spots in the battery pack. Wind and the use of a positive pressure ventilation (PPV) fan made it difficult to access one side of the vehicle due to thick smoke and flames. The cutting extinguisher was eventually used

[124] The Swedish Agency for Community Protection and Preparedness (MSB); Unit: Fire and rescue; Demonstration of quench method for lithium ion batteries, method application at different levels of aggregation – module, sub-battery, electric car pack and vehicle level; MSB2184 – March 2023.

above the drive-shaft and lance extenders were used to facilitate access and avoid contact with the bodywork (see Figure 24).

Figure 24 Photograph showing the application of the water lance with extension on an EV fire.

During this process, a conventional firehose was used as personal protection for the fire extinguisher operator. This firefighter's primary focus was to protect the water lance operator from flash and flames.

The test was terminated when the thermal imager showed a stable temperature below 50°C (122°F). This was approximately 10 minutes after the water flow began. They estimate that approximately 200 gallons of water were utilized.

To simulate activities by tow vehicle personnel, they lifted the vehicle with a forklift approximately 1.5 ft. off of the ground and dropped it to the ground. The authors note that no re-ignition occurred. However, there was not a simulation associated with prolonged vibration that a vehicle may experience when being transported from the site of an incident to a salvage yard or repair shop.

Two and three days after the test, they measured voltages of all battery modules in this test. The voltage of the module where the fire extinguisher had been installed had no residual voltage. Of the remaining modules, 22 out of 27 had residual voltage. This is referred to as *stranded energy*, which may have the potential to cause a reignition. The authors noted that it is difficult to determine the extent of thermal propagation within the battery pack based on externally observable factors such as thermal imaging, smoke, and sound.

The authors concluded that a static flow of water through the battery using the water lance can be effective in suppressing thermal runaway. When they made holes in the batteries while flowing water, no flame jets appeared, whereas when they made holes without flowing water flame jets did appear.

The authors did not mention the nature of the hole that was created in the battery pack enclosure – if they cut a circular hole and liberated a piece of conductive material that was pushed into the pack, or if they cut a small hole large enough only for the water stream and a trivial amount (if any) of conductive material was introduced into the battery pack.

A photograph of a water lance being pointed by a firefighter at the location on a vehicle where skateboard-style battery pack may reside, taken from the Cold Cut Systems website, is reproduced in Figure 25.

While this study is promising and it demonstrations the equipment used, the methodology followed, and the results, more research is needed to understand if this equipment successfully suppresses a fire and thermal runaway in a battery pack that has higher reactivity cells, if different battery pack designs and different penetration locations result in different results, and if any hazards are introduced during different conditions related to the vehicle, environment, or incident characteristics.

It is also noteworthy that other water lances exist which do not appear to penetrate the surface of the battery pack (or container) by water (or water with abrasives) alone – e.g. a mallet is used on the back of a piercing tool. As a cursory assessment, such tools may function with typical water pressure which is a benefit, but penetrating the pack with a metal object may create hazards. For instance, thermal runaway may be induced, jet flames may emerge, and battery isolation may be lost. If battery isolation has already been lost at another location in the pack, then a second isolation fault at a different voltage potential may result in an arc flash.

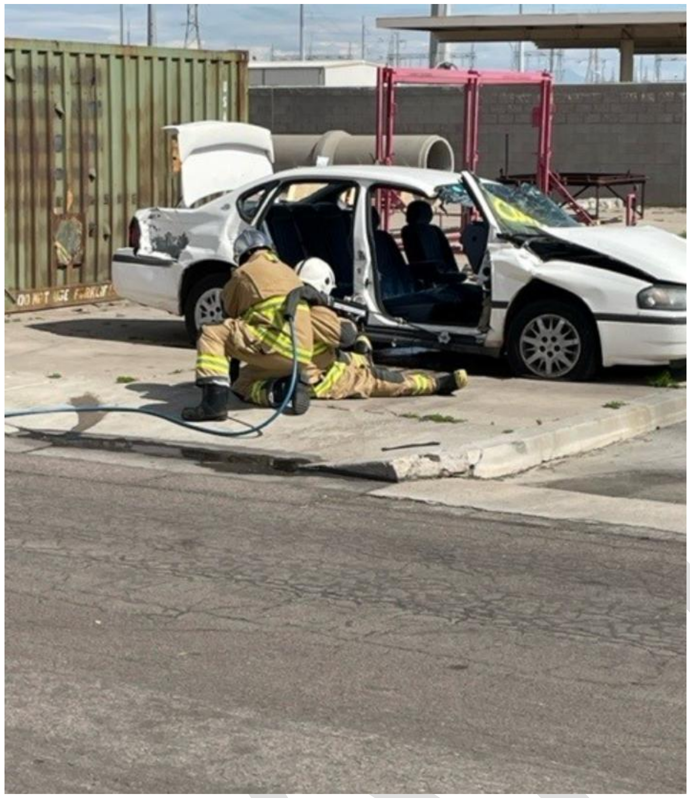

Figure 25 Photograph from the Cold Cut Systems website labeled Tempe-2024-02-29-8.[125]

4.6.2 Pack Puncture Tools

Pack-puncture and water injection tools are intended to solve the challenge of getting water into the battery pack and circulating amongst the battery modules and cells too cool them, limit cell-to-cell heat transfer, and stop thermal runaway. These tools reportedly limit the amount of water required, and accordingly the resulting runoff. They could conceivably be used in an attempt to discharge a pack of a damaged vehicle that is not on fire, or to suppress a fire that involves the HV battery pack.

IFE has not seen a third-party evaluation of these tools, including an assessment of any potential hazards that may be created by using these tools. IFE reached out to the manufacturer of one of these devices, but they did not reply. A study such as the one done by MSB described in section

[125] https://www.coldcutsystems.com/news/a-week-in-tempe/

3.6.1 would be helpful for the community. Additionally, such a study could serve a dual purpose by allowing first- and second-responders an opportunity to:

- Observe batteries in thermal runaway
- Use thermal cameras to observe batteries in thermal runaway
- Observe data such as temperature evolution, and measurements of electrical isolation
- Observe the effectiveness of the tool
- Practice using the tool
- Understand the construction of complex battery packs

Some of the pack puncture tools are intended to be placed below the vehicle, and others are intended to be placed inside of the cabin to puncture the battery pack from the top. Some questions and considerations that can be addressed prior to use with the manufacturer of the equipment (currently, vehicle manufacturer ERGs do not recommend puncturing the pack) are as follows:

- Does the device have sufficient travel to reach cells in battery packs that have cooling systems below the cells, and vehicles with high clearance height?
- Does the device successfully penetrate the pack on every occasion?
  - If it does not, then does it cause deformation of the pack, potentially resulting in mechanical damage to cells and initiation of thermal runaway, without the ability to flood the pack? Or could it potentially result in lost isolation?
  - Anecdotally, one of these tools reportedly did not puncture the pack and just lifted the vehicle. However, IFE has no information on the make/model of the tool, the water pressure, vehicle make/model/model year, or whether the tool was in adequate condition (i.e. plunger movement, edge sharpness, etc.).
  - Does the device penetrate skid plates on vehicles that are designed for off-road use, or will it be required to remove them to enable puncture?
- How is the device removed from the battery pack?
  - As observed in the MSB study, after flooding a battery pack with water there still may be stranded energy. Can removing the device contribute to reignition?

    - Removing the device requires direct interaction with the vehicle battery pack. Can this result in a shock hazard?
    - Can the device get stuck in the battery pack, and if so, what hazards may be introduced in removing it?
- Can the tool itself be damaged during the puncture process, and what are the effects of using a damaged tool (e.g. will it fail to puncture the pack on the next use, but instead deform the pack and induce thermal runaway?)?

4.6.3 Underbody Nozzles

Specialized nozzles are manufactured to facilitate spraying water onto the underside of the battery pack, which would facilitate getting water onto skateboard-style battery packs. IFE is aware of one demonstration between the UL FSRI and Boston Fire Department where nozzles such as these were utilized. In one instance, the nozzle failed, and in the other instance, the nozzle worked with limited success. Generally, these nozzles should be considered to have limited effect on cooling individual battery cells because the water is expected to be sprayed onto a skid plate or the battery enclosure.

4.6.4 Fire Blankets

First responders who are handling an EV or EVs in a crash are advised to develop a plan to use fire blankets during each incident with an understanding of the potential exposure, deflagration, explosion, and re-ignition risks that may be created.

Fire blankets are available for sale that are intended to be used with damaged EVs. These blankets could conceivably be used in different ways. It could be pulled over a damaged vehicle that has not yet ignited as a risk mitigation measure. It could also be pulled over a vehicle that is already on fire to suppress the fire. In either case, the goal would be to starve the fire of oxygen and slow the heat release rate. Applying a fire blanket should not be expected to stop thermal runaway.

These blankets can be valuable tools in certain circumstances. For example, if an EV fire occurs in parking garages, tunnels, or other areas not easily accessible by fire apparatus, fire blankets may be a useful tool. However, there may be consequences of their use that users should be aware of and consider prior to their use.

A review of demonstrations online shows that pulling a blanket over a vehicle that is fully involved in fire visually appears to control the fire (i.e. it is not seen), and a significant amount of smoke is generated and flowing out from underneath the blankets. In one demonstration, after the blanket was removed approximately 45 minutes after it was originally placed on, the vehicle quickly re-ignited.[126] This could be because of a smoldering fire that was not extinguished when the blanket was on, venting LIB cells which include hot particles or ejecta capable of ignited the gases, or venting LIB cells generating just enough oxygen to sustain a flame and allow for a rapid re-ignition.

In another study involving vehicle burn tests in tunnels, the authors found that the use of a fire blanket in one test was unsuccessful after it was applied after the LIB was involved in the fire. The vehicle had been burning for approximately 10 minutes prior to application of the blanket to simulate an emergency response. While the fire blanket did significantly reduce the HRR, strong flames near the ground made it difficult to cover the entire vehicle (a compact car). The authors also suggested that oxygen release from the battery limited the suffocating effect of the blanket.[127]

A few questions raised by these demonstrations are as follows:

1) Does the blanket create a concentrated plume of toxic smoke and flammable gases, and where will it travel?
2) What are the constituents of the plume, how do the concentrations compare with established exposure limits, and does this change hazard control zones?
3) Is a deflagration or explosion hazard created in semi-confined areas?
4) How long does the blanket need to be kept on so that the fire does not re-ignite?
5) What are the criteria to know when the blanket can be removed?

[126] Prosol, UK; https://electricvehiclefireblanket.co.uk/, accessed March 7, 2024; note that this blanket is used to quarantine vehicles in a suspected pre-fire condition.

[127] Sturm et al., Fire tests with lithium-ion battery electric vehicles in road tunnels, Fire Safety Journal 134 (2022)

6) Can flammable gases accumulate underneath the blanket, and subsequently ignite, resulting in a flash fire or explosion which pushes the blanket and potentially projectiles away?
7) What are the safety risks of using the fire blankets in order to transport a vehicle on fire out of an environment where it can spread or cause damage (e.g. parking garage, residential garage, etc.).
8) How does the performance of different fire blankets on the market compare with one another? Do under-performing fire blankets result in additional hazards, such as flaming embers?
9) Can the ones that are specified as re-usable be re-used without performance degradation?
10) What are the criteria to decide if a blanket is no longer usable?
11) If such a blanket is reused, what decontamination measures, if any, should be made?
12) Will the blanket size be big enough for the vehicles encountered and how will it function if there is extensive thermal runaway propagation in the traction LIB?

IFE is not aware of any third-party evaluation or systematic testing of the blankets to understand many of these questions. Additionally, there is currently no standard that governs performance or design requirements for EV fire blankets. Fire companies who are researching fire blankets are advised to ask suppliers what standards their products have been tested to, why they have tested to those particular standards, and to research those standards to understand the meaning of the results. The only related standard identified in this work that specifically relates to the performance or design criteria for fire blankets in the American markets is ASTM F 1989-05 *Standard Specification for Cooking Suppression Blankets*, last updated in 2020.

Fire blankets exposed to heat should not be re-used unless there is substantial evidence to support re-use.

Fire blankets are also being used for storage of vehicles damaged in crashes. The effectiveness of various fire blankets following environmental exposure, including light exposure and rain, is not well understood.

4.6.5 Non-sparking Tools

The use of non-sparking cutting tools could potentially mitigate some of the risk involved when performing cutting operations in the presence of damaged batteries, but IFE has been unable to identify any study suggesting their use, or describing the efficacy, limitations, and practicality of using such tools for first- and second-responders tasks.

Battery vent gases can generate flammable gas clouds, and in cases where there is confinement such gas clouds can result in overpressure events (explosions). Overpressure events have been observed in vehicles with HV battery packs, which is relevant to the current work, but they have also been observed in garages and trailers (i.e. ISO containers). A photograph of a vehicle with battery vent gases accumulated in the cabin is shown in Figure 26.

One popular tool used by first responders is a pneumatic cut-off tool, or "whizzer," which uses a small carbide disk which generates a significant number of sparks but is effective at cutting through hardened steel.[128] Such a tool would need to be used with caution to extricate a person from an EV. If there was any sign of smoke or fog, another tool would be recommended. Ignition of flammable gases by sparks is probabilistic in nature, and the available energy of each particle depends on a variety of factors including materials involved, angle of impact, etc.

[128] Sweet, D., National Fire Protection Association, International Association of Fire Chiefs, *Vehicle Rescue and Extrication: Principles and Practices*, 2022, p67.

Figure 26 Example of a vehicle that has filled with battery vent gases – note the white smoke.

UL Solutions carried out research relating to the fire service response to residential battery energy storage system incidents which has applicability to EV fires within garages. As part of their work, they documented a cutting operation using a rotary rescue battery-powered saw on a metal garage door.[129] As can be seen in Figure 27, this process generated a considerable amount of sparks.

[129] Schraiber, A., Barowy, A., Gaudet, B., Kimmerly, V., Considerations for Fire Service Response to Residential Battery Energy Storage System Incidents, December 4, 2023, p67.

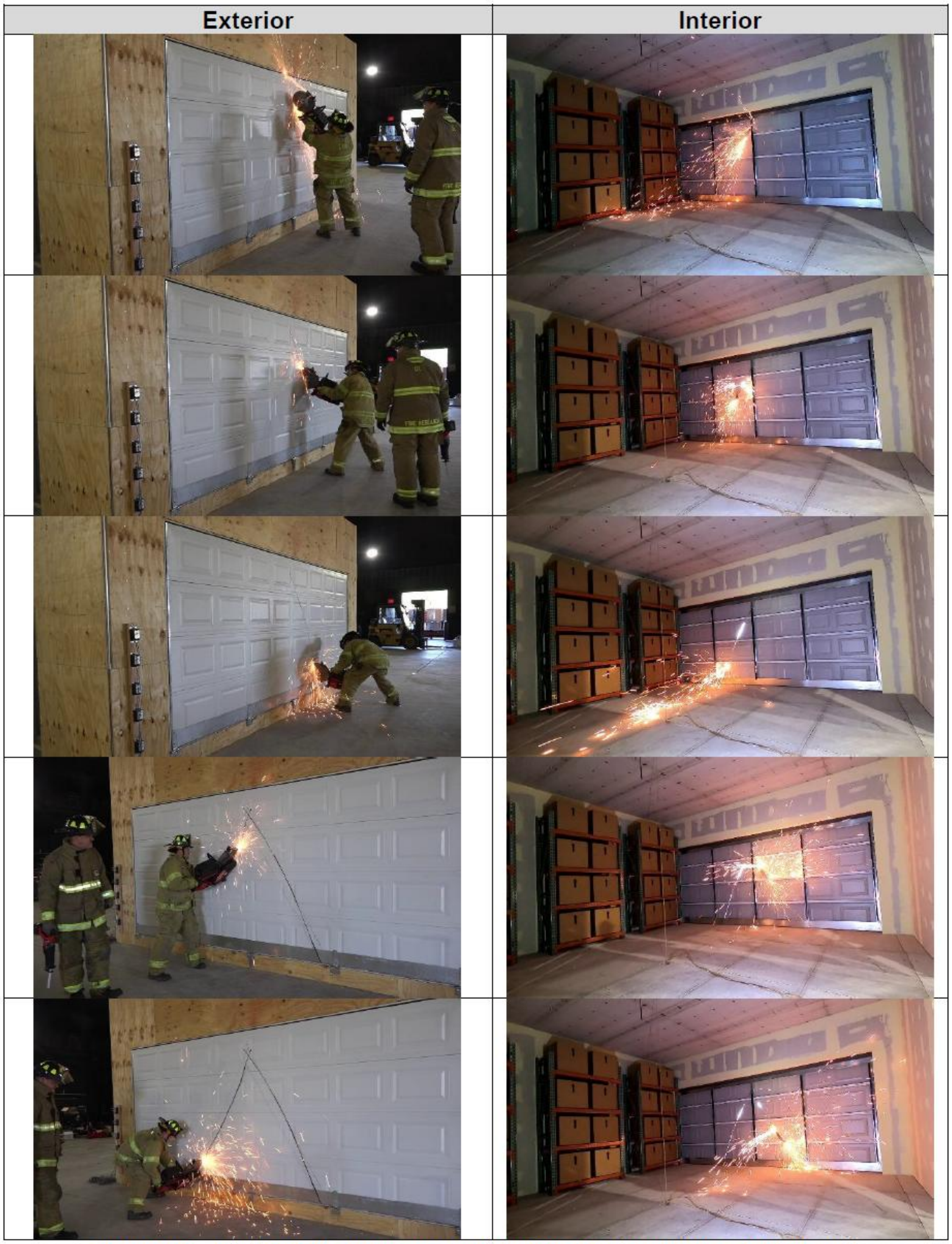

Figure 53 – Inverted-V cutting operation with rotary rescue powered saw.

Figure 27 Figure courtesy of UL Solutions visually documenting sparks created with a rotary rescue battery powered saw.

4.6.6 Non-conductive Tools

One vehicle manufacturer recommended having a 5 ft. long non-conductive rod available during an EV vehicle rescue. This could potentially be used to remove a person potentially receiving an electrical shock.

4.6.7 Placards

SAE J2990, July 2019 recommends the use of placards to identify damaged EVs. These should likely be applied as soon as the vehicle reaches the repair facility or salvage yard. Some ERGs contain pages that can be printed and used as placards.

It may be beneficial to standardize this placard design such that vehicles with damaged HV battery systems can be easily identified by various employees of repair facilities, salvage yards, tow vehicle drivers, and first responders, regardless of the vehicle type and the location.

4.6.8 Immobilizing Charging Plugs

Specialized immobilizing charging plugs (absent cables) are available for purchase which are intended to immobilize the vehicle by "tricking" the vehicle into thinking that it is charging. Based on immobilizing charging plug manufacturer literature, these devices are useful for a variety of uses, including immobilization for law enforcement, medical assistance, vehicle repair, roadside assistance, or by fire departments.

Anecdotally, one large fire department uses these plugs on vehicles without significant mechanical damage to immobilize them in certain situations. They opted to use these devices after an incident occurred where an occupant experiencing a medical issue hit the accelerator pedal, and the vehicle moved forward and over wheel chocks.

At the UL FSRI Lithium-Ion Battery Symposium: Challenges for the Fire Service on March 30, 2023, this was described as: *not an alternative to emergency procedures*. IFE is not aware of any third-party evaluation of the plugs to confirm the immobilizing charging plug manufacturers claims or understand unintended effects of using them, if any, in the circumstances of EV crashes.

One immobilizing charging plug manufacturer has indicated that when their device is used the vehicles 12 V system still works, allowing the use of windows, seats, etc. The same manufacturer indicates that it will not expose the user to HV. However, if the vehicle is "tricked" into thinking that it is charging it would seem that the vehicle would try to keep the HV battery pack contactors closed, and it is unclear if following the manufacturer's instructions on disabling the HV system will actually work with this plug – *on all EVs*.

If fire companies expect that this device will immobilize the vehicle(s) and not expose them to HV, this may affect their tactics following insertion. This would become problematic if it does not, in fact, immobilize the vehicle and open the HV battery contactors.

It is noteworthy that, at the time of this report, one charging plug manufacturer has recently learned that their plug will not disable two vehicles, and that the manufacturer is working on a solution.

The reader is advised that these devices are not considered to be an alternative to vehicle manufacturer ERGs.

4.6.9 12V Battery or Extended Length Jumper Cables

Some vehicles (e.g. Tesla Model 3) may require that a 12V battery is connected to jump start the vehicles auxiliary 12V battery.

4.7 Fuel Cell Vehicle Crash Management

Per Sweet, emergency procedures for vehicles that use H_2 as a fuel are generally similar to those for CNG and LNG.[130] Sweet recommends that two 1.75" (44 mm) charged hose lines be

[130] Sweet, D., National Fire Protection Association, International Association of Fire Chiefs, *Vehicle Rescue and Extrication: Principles and Practices*, 2022, p182.

deployed to protect personnel, and disperse any release of vapor.[131] This is one more than is recommended for EVs. Responders are advised to view the ERGs for vehicles when responding to incidents.

As discussed in section 4.2, in the U.S. D.O.T. ERG, the initial isolation/evacuation distance for an incident involving compressed hydrogen is 330 ft. (100 m) in all directions (see Guide 115),[132] increased in the downwind area.

The direction of approach remains the same as described above. In passenger vehicles, H_2 tanks are typically stored in the trunk area or on the underbody towards the rear of the vehicle.[133] In some class 8 vehicles, there may be several tanks located behind the cabin.

H_2 can often be measured using catalytic bead LEL sensors in common multi-gas meters. However, as described earlier, in order to provide accurate values these monitors must be configured for the specific fuel that they are measuring, so while the gas monitors can be used to alert to the presence of flammable gas the specific measurements should be used with caution.

As part of the onsite handling (immobilization, disabling, extrication process), manual valves associated with the H_2 tanks should be closed if practicable. The locations of these are identified in ERGs. The ERGs will also identify if the disabling process involves removal of main fuses, the use of service disconnects, cut loops, or other operation.

Hydrogen (H_2) is a colorless, odorless, and non-toxic fuel. It is approximately 14 times lighter than air, so once released it will tend to rise and disperse. Per Sweet, no odorant is added because of its inability to adequately follow the H_2 gas.

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[131] Sweet, D., National Fire Protection Association, International Association of Fire Chiefs, *Vehicle Rescue and Extrication: Principles and Practices*, 2022, p182.

[132] U.S. Department of Transportation/Transport Canada Emergency Response Guidebook, 2024 edition, p30, 160.

[133] Sweet, D., National Fire Protection Association, International Association of Fire Chiefs, *Vehicle Rescue and Extrication: Principles and Practices*, 2022, p182.

Hydrogen is relatively buoyant, being 14 times lighter than air; it rises and disperses at a rate of 44 mi/h (71 km/h) at approximately 66 ft/s (20 m/

Wide flammability range, with an lower flammability limit (LFL) and upper flammability limit (UFL) of 4-75%.

Per Caruana, fire companies are advised not to try to extinguish hydrogen vehicle fires, but instead to try to protect exposures and allow the fuel to burn off.[134] In the daylight, it may produce a nearly invisible flame, but which can be detected by a thermal camera.

During an extrication effort, fire companies are advised to avoid contact with fuel delivery systems to prevent the release of pressurized fuel.

4.8 Incidents Involving Structures

Management of incidents involving EVs and structures are outside of the scope of this document. However, some information is provided here.

IFE is not aware of any literature that specifically relates to management of incidents involving EVs or FCVs and structures. However, UL carried out research related to energy storage systems in typical residential garages that has some utility.[135]

In cases where LIBs are venting but not burning, flammable gas clouds may be developing or have developed prior to arrival by first responders. As a result, the risk of explosion may be unknown and fire companies should consider not entering and taking a defensive posture. Explosions within residential garages have been observed as a result of gases from an EV thermal runaway event. Confinement may also affect the concentration of toxins present. Fire companies are advised that some methods of entering garages, such as cutting an inverted V,

[134] Caruana, *Principles of Passenger Vehicle Extrication*, verified by the IFSTA, 2022, p51.

[135] Schraiber, A., Barowy, A., Gaudet, B., and Kimmerly, V., *Considerations for Fire Service Response to Residential Battery Energy Storage System Incidents*, UL Solutions, Prepared for the International Association of Fire Fighters, December 4, 2023.

may create sparks inside of the garage which can potentially serve as an ignition source (see section 4.6.5).

Limited testing of total gas emitted from EV LIBs with rated capacities approximately the size of sedan batteries indicate that approximately 225,000 L of gas may be emitted. A typical two-car garage measures 20 ft. wide by 24 ft. deep,[136] and a typical ceiling height is 8 ft (110,000 L). Thermal runaway initiating in an EV LIB pack in a garage, developing gases which do not ignite, may therefore result in accumulation up to the LEL, through the explosive limit, and above the upper explosive limit (UEL). Convection and diffusion could then bring the mixture to back within the flammable range. This could happen, for example, if doors are opened. However, note that thermal runaway in one or more cells in a LIB pack does not necessarily mean that it will propagate to all cells within the pack.

The UL report also notes that typical LEL sensors were not effective in distinguishing between an ordinary garage fire and one where LIBs were venting. The gas monitors were placed approximately 1 ft. away from the structure – additional research may show that pumped gas monitors with probes can detect flammable gas. This may require getting near the structure in the same way that they are used when investigating natural gas leak or propane leak.

Following the incident, fire companies may consider either retaining, or recommending to building owners or operators to retain EHS experts to handle PPE requirements for clean up, and assess decontamination needs. The latter may include remediation of water runoff; measurement of airborne contaminants (including flammable gases if LIBs are still present); addressing particulate matter accumulating on flooring, I-beams, and other surfaces; etc. Additionally, structural engineers may be retained to analyze the integrity of structural components.

[136] Schraiber, A., Barowy, A., Gaudet, B., and Kimmerly, V., *Considerations for Fire Service Response to Residential Battery Energy Storage System Incidents*, UL Solutions, Prepared for the International Association of Fire Fighters, December 4, 2023, p41.

4.9 Heavy Duty Vehicles

Heavy-duty vehicles, such as class 8 tractors, have significantly larger battery packs and more stored energy. For example, one class 8 truck may have the equivalent of six Tesla Model 3 batteries contained within. This potentially means higher total heat release and longer burn durations, among other factors. Batteries on class 8 vehicles may be located in the same areas as Diesel fuel tanks on similarly sized vehicles, and they may also have additional battery packs between the fuel rails.

As discussed in section 3.2, a literature survey on the total volume of gas produced from LIBs increases with the rated capacity. Heavy duty vehicles will have larger battery packs, so more battery vent gas can potentially be created and accordingly isolation zones likely need to be increased. Limited testing on EVs and EV packs (with NMC and another unidentified chemistry) shows that the total mass of HF and CO emitted increases with increasing battery capacity.[137] Note that HF production seems to be closely related to battery chemistry.

Per Sweet, fire companies responding to heavy duty vehicles incidents which need to move the heavy duty vehicle should consider towing service providers. Specialized equipment may be able to lift or move the heavy duty vehicles faster than fire apparatus.[138]

Heavy duty vehicles which have enclosed cargo areas that are transporting LIBs may develop flammable mixtures which are confined in the cargo area.

4.10 Automated Vehicles

If a jurisdiction has automated vehicles operating on the roadways, there are some proactive steps that can be taken that may be useful when responding to an incident involving the same.

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[137] Bugryniec, P., Resendiz, E., Nwophoke, S., Khanna, S., James, C., and Brown, S., *Review of gas emissions from lithium-ion battery thermal runaway failure – Considering toxic and flammable compounds*, Journal of Energy Storage 87 (2024), p11,14.

[138] Sweet, D., National Fire Protection Association, International Association of Fire Chiefs, *Vehicle Rescue and Extrication: Principles and Practices*, 2022, p333.

In the case of fleet-managed automated driving system-dedicated vehicles, the fleet-manager may provide training for first responders, based in part on the Automated Vehicle Safety Consortium (AVSC) Best Practice (AVSC-I-01-2024) which provides a framework of recommended procedures and protocols automated driving system developers, manufacturers, and fleet operators can follow to facilitate first responder interactions in multiple use cases.

The Best Practice includes considerations of direct and indirect interactions by first responders. For direct interactions, examples include checking a vehicle door handle to see if it is locked, a first responder entering a vehicle to provide aid to a passenger, or a tow vehicle operator connecting a tow apparatus to a vehicle. For indirect interactions, this may include an emergency vehicle using lights or sirens while moving through traffic or while stationary on or near the roadway, a police officer using temporary traffic control devices (e.g. cones, signs, flares) to alter the flow of traffic or cordon off an area, or a first responder positioning an ambulance to protect first responders or patients from other vehicles or hazards.

Some automated vehicle operators provide phone numbers and email addresses so that they can be contacted to address certain situations. One operator reportedly can disable their vehicles, or implement geo-fencing to keep their vehicles away from certain areas upon request.

5.0 Potential Hands-On Training Exercise

There is important information in vehicle manufacturer ERGs, and there are also many different vehicle makes and models. If, as part of first and second responder training programs, ERG information for a variety of vehicles is conveyed in a practicable manner, it may increase familiarity with different vehicle designs and assist responders in making observations and the development of tactics during an incident.

An event including multiple vehicle manufacturers and/or their partners (dealers) and first and second responders could be organized so that relevant details of vehicles can be visually shown to first and second responders. This effort is intended to facilitate uptake of information of many popular vehicles so that it is more easily absorbed when responding to an incident. Information from ERGs can be discussed while visually observing relevant aspects of the vehicles. Information may include:

- Identifying features of vehicles
- Understanding observations related to disabling procedures
- Battery pack location, including vent locations
- Identify lift points
- General routing and vicinity of high voltage cables
- General vicinity of inverter and other HV components

6.0 Summary and Future Work

A. Crashes involving EVs are increasing in number. Because EV crashes have unique risks to property and safety, and the rescue tactics can vary compared to conventional vehicles, effective training of first- and second-responders is important. Per Liu et al.'s national survey, 88% of respondents identified additional training opportunities as the most important recommendation.
   - Per Liu et al., police and EMS are not receiving as much training on response to EV incidents as fire personnel, and police and EMS may arrive first. Police and EMS may benefit from targeting training on vehicle identification and assist in gathering data relating to HV system safety.

B. Recently published textbooks aimed to train first responders on vehicle rescue principles and practices do not incorporate some of the latest learnings, research, and guidance from the scientific and engineering communities. Similarly, the latest learnings, research, and guidance from the engineering and scientific communities generally do not integrate vehicle rescue principles and practices in great detail. This work aims to close that gap.

C. The utility and practicality of non-sparking cutting tools for use by first- and second-responders should be evaluated for efficacy in cutting vehicle bodies and published to the broader community.

D. It may be beneficial to standardize the design of placards used to identify vehicles with damaged HV battery systems, so they can be easily identified by various employees of repair facilities, salvage yards, tow vehicle drivers, and first responders, regardless of the vehicle type and the location.

E. Well-performing fire blankets may be valuable in certain circumstances (e.g. parking garages, tunnels, ferries, storage). However, their use may create hazards such as smoke plume exposure, flash fire, accumulation and ignition of flammable gases, and re-ignition hazards, in part because they may not stop thermal runaway.
   - Anecdotally, the performance of fire blankets from different manufacturers used for EV fires is varied. This can have implications for durability during and after heat exposure.

- IFE was unable to identify a standard that specifies performance-based or design-based requirements for fire blankets to be used with EV fires, such as thermal performance, cut and abrasion resistance, criteria for re-usability, etc.
- A standard developed for this purpose could potentially mitigate hazards associated with the use or attempted re-use of fire blankets.

F. There are various sources of information made available to first and second responders which may be misleading, which presents a challenge to training.

G. Continued research on thermal characteristics and emissions characteristics of existing and new battery chemistries may improve our understanding of the hazards.

- LEL and UEL research on different chemistries.
- Larger pack testing, dispersion analysis, and guidance on isolation distances.
- Additional full EV emissions measurements, including with different battery chemistries.

Appendix A: Author

Dr. Cundy is the President and Principal Engineer at Inception Forensic Engineering, LLC (IFE), an engineering firm which he founded in 2021. Prior to founding IFE, he was employed by Exponent, Inc. for over nine years, working in the Thermal Sciences Practice and the Electrical Engineering & Computer Science Practice. He is a registered professional engineer in the State of Arizona (#55526). He is a Certified Fire Protection Specialist (#5501), certified by the National Fire Protection Association. He is also a Certified Fire & Explosion Investigator (#21707-12362), certified by the National Association of Fire Investigators. He is a member of the Society of Automotive (SAE) Hybrid and EV First and Second Responder Task Force. He has also developed and teaches a Failure Analysis & Prevention course at Arizona State University.

During the course of Dr. Cundy's career, he has specialized in the application of engineering principles to the investigation of complex mechanical and electrical systems, with an emphasis on thermal and fluid events such as the investigation of fires, explosions, carbon monoxide exposures, water/fluid losses, and burn injuries.

As part of his engineering experience, he has performed a variety of investigations of thermal events on electric and hybrid vehicles, post-crash vehicle fires, and grid-scale battery energy storage systems, including the Surprise, Arizona incident. He has carried out hundreds of burn tests, including bench scale tests up to full-scale vehicle burns and room-burns, and explosion testing using various fuels, including hydrogen. He has carried out and observed a variety of lithium-ion battery testing campaigns, including the development and use of an oxygen depletion calorimeter to measure heat release rate and total heat release from large format lithium ion battery cells. He also has specific experience investigating vehicle systems including airbag inflators, ignition switches, and fires in various types of on-road and off-road vehicles.