INCEPTION
FORENSIC ENGINEERING, LLC

DRAFT
WORK-IN-PROGRESS

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

Edition 000

Collision Management for Electric and Fuel Cell Vehicles

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Acronyms and Abbreviations

ASTM	ASTM International
ANSI	American National Standards Institute
CSA Group	Canadian Standards Association
ERG	Emergency Response Guide
HLDI	Highway Loss Data Institute
HF	Hydrogen Fluoride
HV	High Voltage
IFE	Inception Forensic Engineering, LLC
IIHS	Insurance Institute for Highway Safety
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

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 collision management principles and practices, product information, research reports, journal articles, standards, and other information to develop a collision management system (CMS), which will be utilized to create a training program for first- and second-responders responding to collision incidents involving electric vehicles (EV) and hydrogen fuel cell (FCV) vehicles.

In consideration of vehicle collision management, no two emergency incident responses are the same. There are an infinite number of collision scenarios, involving different vehicles, different speeds, different orientations, different technologies, and obstacles on or off the roadways. As such, readers are advised that statements and opinions made are provided only as guidelines. IFE relies upon other sources of information to provide these guidelines but cannot independently verify that all of the sources are comprehensive and accurate, particularly since research is ongoing in many areas. The recommendations and guidance in this work do not indicate an exclusive course of action, and variations are expected to be taken given the circumstances of the emergency and local protocols. 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.

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 render professional or other services for or on behalf of any person or entity, nor is IFE undertaking to perform any duty owed by any person or entity to someone else.

EV and FCV vehicles 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-collision, 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/collision 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. As such the reader is encouraged to review source information for additional information.

Advisory Committee

Information about the author can be found in Appendix A. The current work is done under an advisory group. The group consists of:

- Jeff Wishart, Ph.D., Science Foundation Arizona, Arizona State University
- Adam Barowy, UL Fire Safety Research Institute
- Christopher Snow, Tempe Fire Department
- Scott Popatia, Tempe Fire Department
- Erik Archibald, Hazard Dynamics
- Don Karner, Electric Applications Inc.
- Jan Swart, Exponent, Inc.
- Nick Christopherson, Emergency Environmental Solutions
- Derick Denis, Clark Sief Clark

0.0 Executive Summary

This section is reserved for future work.

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) Collision 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 collisions are disproportionately exposed to thermal 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 feasible, 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 collision 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 is vast and 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 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 collision damaged vehicles.

Addressing first- and second-responder safety in events involving EVs is becoming more important as more EVs are sold. Additionally, if EVs show similar trends to ICEVs, fires become more frequent as vehicles age and the number of older EVs on the road will continue to increase over time. In either case, most vehicle fires are a result of a collision.[1]

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.

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1 NFPA Fire Protection Handbook, 21st edition, 2023, p21-6,8.

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 collision 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 the highest rate of first-responders with EV-specific training (70%).

First-responders tend 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.

When responding to a traffic incident, first responders need better training 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), and StachD training.

2.2 Modern EV High Voltage Systems

Modern EV high voltage (HV) systems can have voltages up to 900 V. These systems consist of the following:

- 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 consumers, such as air or water heaters
  - Other high output

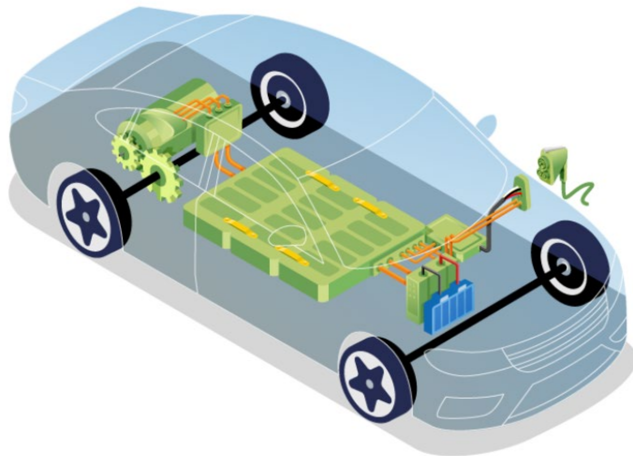

Figure 1 Illustration of the main components of an EVs HV system, per NHTSA.[2]

The HV electrical system is supplied with voltage via contactors (i.e. switches) that are typically integrated into the HV battery pack. 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.[3]

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

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

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

pack is isolated or "floating", single-point faults generally do not result in hazardous situations.[4] 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.[5] Per Bohm, the loss of isolation on EVs is one of the more common failure modes, irrespective of manufacturer.[6]

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.

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

5 FMVSS No. 305.

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

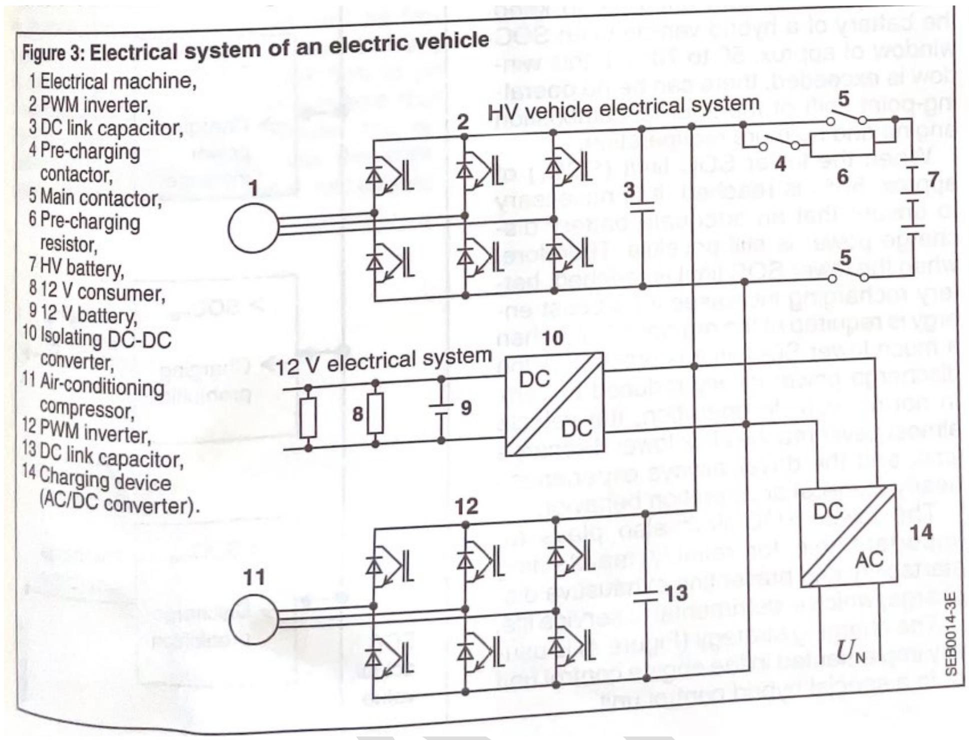

Figure 2 Schematic of an electrical system of an EV.[7]

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 nickel cobalt aluminum oxide (NCA). When charged or discharged, lithium ions are either inserted or extracted from interstitial space between atomic layers of the

7 Bosch, Automotive Handbook, 11th Edition, January 2022, p1563.

electrodes.[8] Much has been written about LIBs, and the reader is referred to other sources for additional information.

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

2.3.2 Battery Pack Styles

This section is reserved for future work.

2.3.3 Abuse Mechanisms and 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 gas 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 is typically associated with a manufacturing defect – the manufacturing process is complex. External sources typically include thermal abuse, electrical abuse, mechanical abuse, and certain types of environmental abuse. In terms of vehicle collisions, mechanical abuse such

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

as impact or crush damage is likely the most common mode of abuse. Thermal abuse may occur if there is a nearby fire or other heat sources. 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. However, for the last three conditions, battery packs are typically designed and manufactured with controls to protect against them.

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 occurs.

As mentioned before, the vent gases are flammable in certain mixtures, and venting cells can also eject extremely hot (glowing) particles and material that can ignite the vent gas. While oxygen may be limited within enclosures such as module cases and battery cases, which will limit the extent of combustion that can occur, streams of vent gases can exit through joints, burst discs, or vents. In some cases, elevated flow rates of vent gases can occur out of certain openings, and if and when these ignite it can result in flame jets. However, many large scale battery pack burn tests have not shown the presence of flame jets, either because of a lower vent gas generation rate, more openings, or potentially other reasons such as relative spatial locations of venting gas and leakage areas. Fire outside of the battery pack can then contribute to thermal abuse of other battery cells which can facilitate propagation.

2.4 Selected Literature Related to Response to EV Incidents

2.4.1 NTSB Report

This section is reserved for future work.

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. 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 ERGs.[9] There are also content recommendations. 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, among with other relevant information. Manufacturers may also produce rescue sheets (also known as quick references guides or rapid response guides (RRGs) which are much shorter and accordingly are more easily reviewed in 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.

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[9] SAE J2990, July 2019, p5

- 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, 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. First- and second-responders that have incomplete collections of ERGs and RRGs, out-of-date information, or information that cannot be accessed during an emergency is a problematic situation.

In order to efficiently transfer these documents to first- and second-responders, and to ensure that they are up-to-date, there should be 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 is not practicable for the various manufacturers to correspond with the more than 29,000+ fire departments in the United States,[10] or vice versa.

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10 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.

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 the abundance of other sources.

2.4.4 RISE Report 2019:50, *Fire Safety of Lithium-Ion Batteries in Road Vehicles*

This section is reserved for future work.

2.4.5 NHTSA Interim Guidance for Electric and Hybrid-Electric Vehicles Equipped with High-Voltage Batteries

This section is reserved for future work.

2.4.6 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 instructions and guidance from automotive and battery manufacturers. It is noteworthy that the current version of SAE J2990, July 2019, was not yet published prior to this guide.

This guide includes some 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.

2.4.7 *Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results*

This section is reserved for future work.

2.5 Review of EV Burn Tests

2.5.1 Heat Release Rate and Total Heat Release

This section is currently under development.

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

Table 1 Ranges of peak HRR and total heat release for burn tests from Kang et al.[11]

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

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

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 grown 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.

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

Hynynen et al. published a study in 2023 involving the burn tests of six vehicles including EVs and ICEVs, and similarly found that the peak HRR and total heat release were not significantly affected by the powertrain type, but were affected by vehicle size and the fire scenario.[12] The authors note that the time to peak HRR was the shortest for ICEVs due to the contribution of the fuel when the fuel tank failed, although this metric would depend heavily on the location of the ignition source, which was selected to involve the traction energy early in the fire.

2.5.2 Evolved Gas, Particles, and Response of Common Gas Monitors

This section is currently under development.

There have been several experimental studies measuring battery vent gases in the past two decades. Baird et al. summarized these studies and created a table (see Figure 3) showing the relative concentrations of hydrogen (H_2), carbon monoxide (CO), total hydrocarbons (THC; 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 events were initiated by heating or overcharging. This data does not capture vent gas composition caused by mechanical damage,

[12] Hynynen, J. et al., Analysis of combustion gases from large-scale electric vehicle fire tests, Fire Safety Journal 139 (2023) 103829.

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 note that 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%. At the time of their analysis, there was insufficient information on testing with NCA cell chemistries.

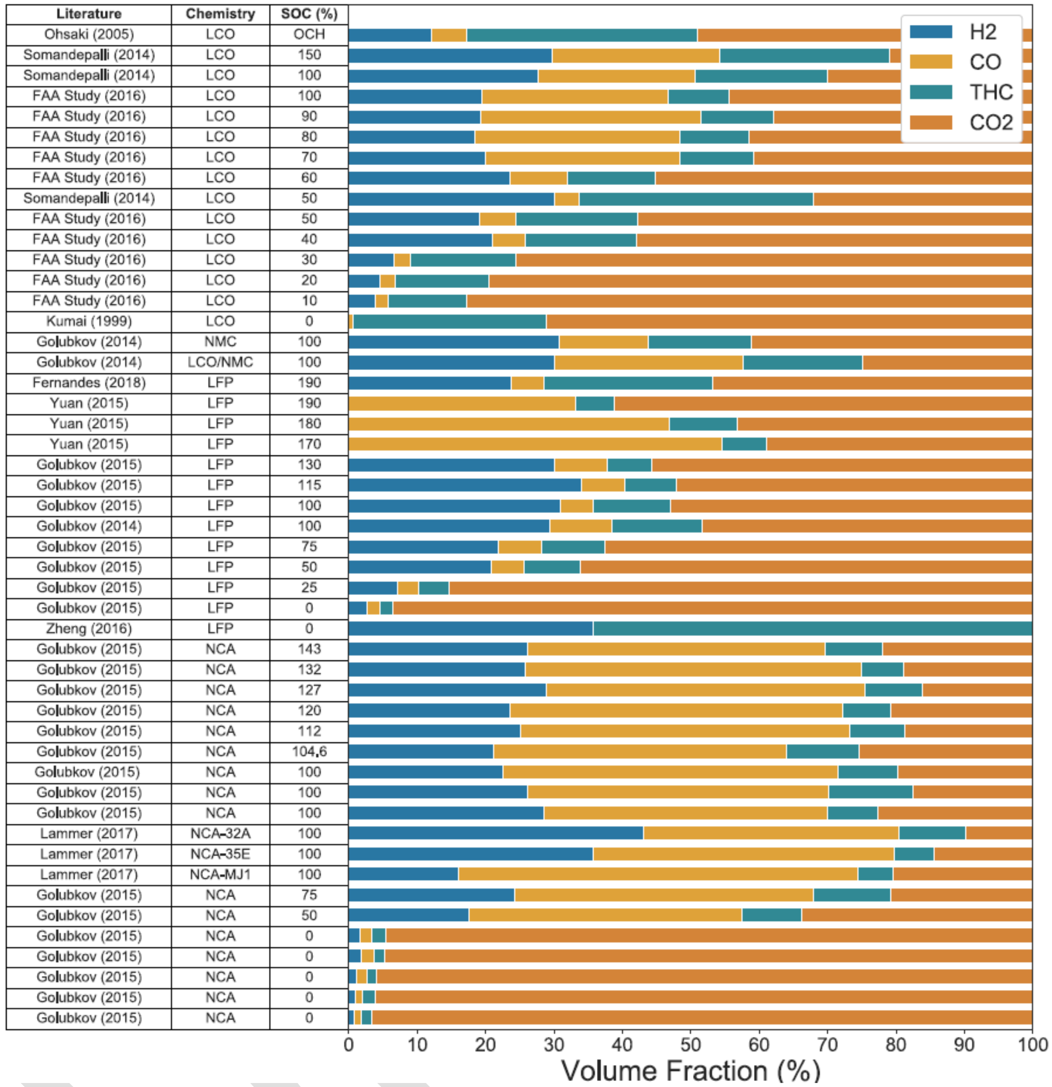

Figure 3 Battery vent gas species compositions from the literature.[13]

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.

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

Table 2 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, event 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. The authors note that

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.

2.6 Personal Protective Equipment (PPE)

This section is currently in development.

The NFPA Fire Protection Handbook lists the specifications for heat- and flame-protective clothing, and the minimum requirements for each of the specifications (see Table 3). Per Sweet et al., most companies wear full structural firefighting clothing, also known as turnout gear, that meets NFPA 1971. However, extrication or technical rescue jumpsuits, per NFPA 1951, may provide additional cut and abrasion resistance and additional mobility compared to typical turnout gear. NFPA 1951 also sets glove standards for technical rescue and recovery. Note that neither of these are required to meet specifications for thermal insulation of electrical arc flashes.

Per one PPE provider in or before 2018, nobody in the fire service industry tests PPE for arc flash hazards.[14] The Seattle Fire Department had their PPE tested by Kinectrics Laboratory and reported that their equipment had an arc flash rating of 62 cal/cm^2. This falls into arc flash PPE category 4, the highest rating, with a minimum arc rating of 40 cal/cm^2.

[14] Greene, C., Electrical Arc Flash Hazards and Personal Protective Equipment, December 1, 2018.

Table 3 Specifications for Heat- and Flame-Protective Clothing, per the NFPA Fire Protection Handbook.[15]

TABLE 6.5.12 Specifications for Heat- and Flame-Protective Clothing

			Requirements for Heat- and Flame-Resistance								
Specification	**Application**	**Type of Clothing**	**Flame Resistance**	**Heat Resistance**	**Radiant Heat Resistance**	**Thermal Shrinkage Resistance**	**Thermal Insulation (convection/radiation)**	**Thermal Insulation (conductive)**	**Thermal Insulation (electrical arc)**	**Molten Metal Resistance**	**Steam & Hot Fluids (optional)**
ASTM F1002	Molten metal protection	Primary, secondary	X							X	
ASTM F1506	Electrical arc protection	Secondary	X						X		
ASTM F2302	General heat and flame protection	Secondary	X	X							
CGSB 155.1	Firefighting	Primary	X	X		X	X				
CGSB 155.20	Industrial flash fire protection	Secondary	X	X		X	X				X
CGSB 155.22	Wildland firefighting	Primary	X	X	X	X	X				
ISO 14116	Flame protection	Secondary	X								
EN 469	Firefighting	Primary	X	X	X	X	X				
EN 1486	Specialized firefighting	Primary	X	X	X	X	X				
ISO 11611	Welding protection	Primary	X	X						X	
ISO 11612	General heat and flame protection	Primary, secondary	X		X	X	X	X		X	
ISO 11613	Firefighting	Primary	X	X	X	X	X				
ISO 15384	Wildland firefighting	Primary	X	X	X	X					
ISO 15538	Specialized firefighting	Primary	X	X	X	X	X				
NFPA 1951	Technical rescue operations	Primary	X	X	X	X	X				
NFPA 1971	Structural and proximity firefighting	Primary	X	X		X	X	X			
NFPA 1975	Station/work uniforms	Secondary	X	X							
NFPA 1977	Wildland firefighting	Primary	X	X	X	X					
NFPA 2112	Industrial flash fire protection	Secondary	X	X		X	X				

ASTM = ASTM International
EN = Committee on European Standardization
CGSB = Canadian General Standards Board
ISO = International Standards Organization
NFPA® = National Fire Protection Association®

While this is promising, the results should not be considered applicable to all turnout gear, particularly that which complies with NFPA 1951. Fire and medical response organizations are encouraged to contact their PPE vendors to see if such information is available for their PPE. Per Table 3, the standard that includes minimum requirements for electrical arc resistance is ASTM F1506, *Standard Performance Specification for Flame Resistant and Electric Arc Rated Protective Clothing*. This standard includes, as one part, ASTM F1959, *Standard Test Method for Determining the Arc Rating of Materials for Clothing*, which is a large-scale arc flash evaluation used to determine the Arc Thermal Performance Value (ATPV) of a fabric. Both of these standards relate to clothing. ASTM F2178, *Standard Specification for Arc Rated Eye or Face Protective Products*, specifically addresses eye and face protection during electrical arc exposure.

[15] NFPA Fire Protection Handbook, Volume I, 21st edition, 2023, p6-106.

3.0 Collision 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.[16]

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.

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.

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).

3.1 Approach, Size-Up, and Vehicle Identification

Park apparatus at least 50 ft. from the vehicle in a location that will protect firefighters from vehicle traffic – the "cold" zone.[17,18] Approach the vehicle(s) from sides, from upwind, and from uphill where possible. This is to avoid an incident with an accelerating vehicle,[19] 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

16 Sweet et al. p101

17 Long et al., p18

18 Sweet et al., p44.

19 SAE J2990, July 2019, Appendix C, p40.

lack of engine noise.[20] Anecdotally, inadvertent movement of EVs during an emergency response has resulted in injuries. As with ICEVs, a survey of hazards should be identified such as spilled fluids, traffic, or trapped or injured occupants.

The company officer (or Awareness Level and above[21]) is responsible for the size-up of the incident and reports back to dispatch,[22] 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.[23]

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. Section 2.3.2 shows the location and shapes of different style battery packs. Most passenger vehicles (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 collision 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).

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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[20] Ford Lightning ERG

[21] IFSTA, Principles of Passenger Vehicle Extrication, p14.

[22] Sweet et al., p44; Long et al.

[23] 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,[24] and Long et al. indicate a 1.5" or 1.75" hose from the first arriving pumper.[25] For additional information regarding fire suppression, recommended water additives, and the status of evaluation of novel tools, see sections 3.4 and 3.6.

The next steps would be to identify the vehicle(s). 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.[26] 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 the vehicle should be immobilized before working in or around it.

- Primary indicators:
  - Badging on the front fenders, trunk – may indicate EV, hybrid, zero emissions, e, e-tron (Audi), IMA (Honda), etc.
  - 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
- Secondary visual indicators:
  - Charge port
  - Absence of tailpipe
  - Smaller radiator opening on front

[24] Sweet et al. p194

[25] Long et al., p19

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

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.

Following vehicle identification, it is highly recommended to view manufacturer ERGs for the specific vehicle. To do this, the vehicle model and model year are necessary. This provides vehicle-specific information that can assist with subsequent steps, such as showing high voltage system components, high-strength areas of the body, and .

If a vehicle is already on fire, note where the fire is. Fires involving batteries will often be emanating from the bottom of the vehicle. If fire suppression is deemed necessary, these types of fires should be suppressed with water, or water with encapsulating additive (described in section 3.4). If the HV battery is not involved in the fire, then some manufacturers recommend extinguishing it with an ABC or CO_2 fire extinguisher.[27] 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 response can change. Vehicle incidents are dynamic situations and the response must be dynamic. While the focus of this work is related to EV collision management, per IFSTA, the following potential hazards are identified:[28]

- Environmental hazards (e.g. weather, time of day, terrain)
- Downed power lines/transformer hazards
- Fuel hazards (including batteries)

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

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

- Vehicle contents hazards (one EV fire was reportedly caused by a power tool inside)
- Potential for violent or abnormal behavior
- Vehicle stability (immobilization, section 3.3.1)
- Biohazards
- Incidents with section considerations

3.2 Determination of Safety

Following the survey, hazard control zones (hot, warm, cold, no-entry) should be established and maintained throughout the incident.[29] 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.[30]

There is limited research available to assist in the determination of safety distances based on gases emitted from HV batteries and established exposure limits. 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), 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. This will be well known to first responders.

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 4). The wind speed at the Luke Air Force Base, 11 miles south, was 6

29 Sweet et al., p44.

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

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 4.

Figure 4 Photograph taken during the Surprise, AZ battery energy storage system incident, showing a white fog along the ground. Photograph from UL.[31]

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.

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

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

It is important to note at this stage that, while HF can be absorbed through the skin, the greatest hazard is associated with inhalation.[32] Hazard control zones can be used to define what PPE is required, and that includes whether SCBA's are donned. This suggests that close attention to changing conditions, and strict adherence to hazard control zones is important.

3.2.1 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 6 and Figure 7 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. In the case of fire smoke, arcing, or hot spots, the area around the vehicle should be cleared and vehicle doors and trunk opened to avoid the build-up of flammable gasses. The inspection may be paused if any of the above occurred.

[32] RISE 2020:90, p31.

Steam, fog, or smoke may be observed in collisions 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 electrolyte, which means it may be flammable and toxic. There may be opportunities for confinement of flammable gas in the passenger compartment, or if the collision 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 5).

Figure 5 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.[33]

One electrolyte, DMC, has a sweet smell, and if it is smelled that would mean exposure to failing batteries[34] in potentially toxic concentrations. In this case, if unusual odors are detected or eye, nose, throat, or skin irritation are observed, don full PPE with SCBA. 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 and vehicle doors opened to avoid build-up of gasses. These sounds may be indicative of cells venting. There is EV burn research that

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

[34] Ezekoye, NFPA 52:00

has attempted to record various noises and identify battery related noises during fires, and such material may become available for training purposes at a later date. 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. If sufficient information is not available, review the U.S. Department of Transportation/Transport Canada Emergency Response Guidebook for Lithium-ion (Guide 147) or NiMH (Guide 171).

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. 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.[35]

Properly trained and equipped personnel (including HV PPE) are required to collect and dispose of damaged battery components. 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. The tow driver/operator should be notified of the damage and associated hazards.

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

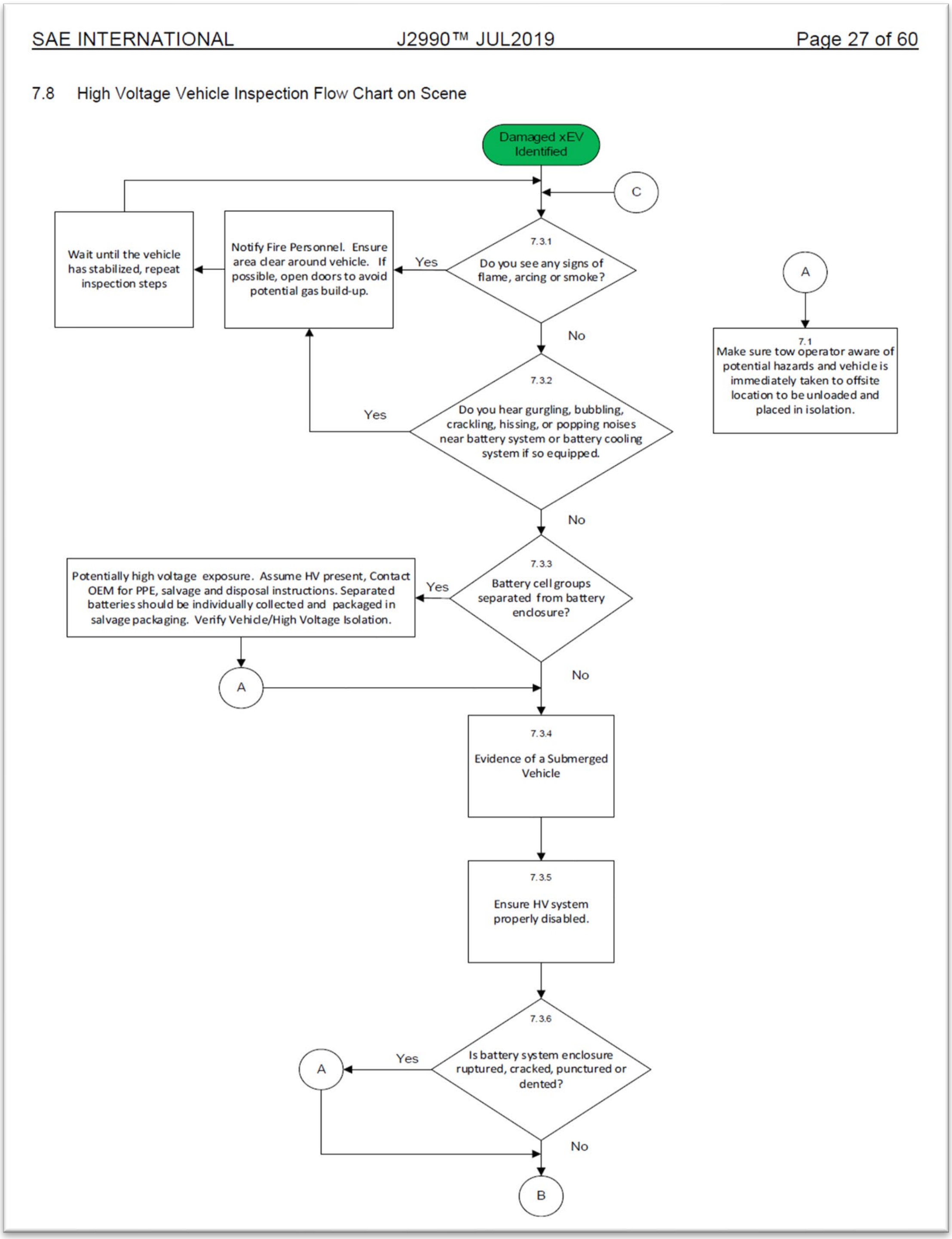

Figure 6 First HV vehicle inspection flow chart, page 1.[36]

36 SAE J2990, July 2019, p27.

DRAFT – WORK IN PROGRESS – SIGNIFICANT CHANGES MAY OCCUR FOLLOWING REVIEW BY ADVISORY COMMITTEE AND OTHERS

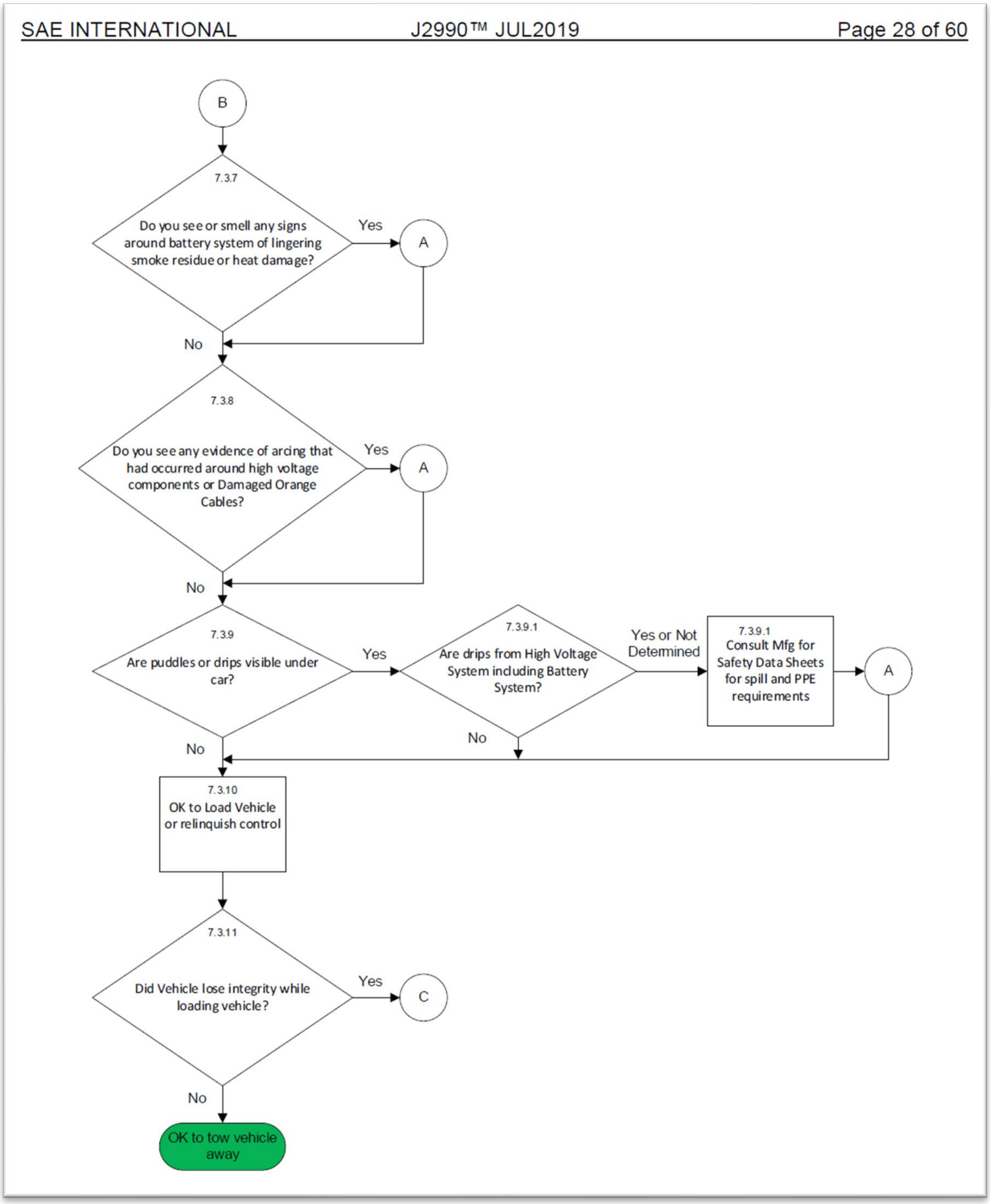

Figure 7 First HV vehicle inspection flow chart, page 1.[37]

[37] SAE J2990, July 2019, p27.

3.2.2 Submersion

This section is reserved for future work.

3.2.3 Use of Common Four Gas Monitors

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

- All of the devices tested had a minimal time delay in response, relatively good repeatability, and relatively good characterization of the lower explosive limit (LEL).
- 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.

This study is an important step 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 be underreported. 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.

3.3 Onsite Handling

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.[38] 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 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)…*"[39] 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).

3.3.1 Immobilize

Per the NFPA Emergency Response Field Guide, all vehicles should be immobilized prior to working around them.[40]

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 that is typically pushed to engage the parking brake. It is typically a rocker switch 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.[41] In some vehicles, the word BRAKE appears in red on the instrument cluster when the brake is engaged. For some Audi and BMW vehicles, pulling up on the parking brake rocker switch activates the parking brake,[42] whereas in other vehicles the rocker switch may need to be pushed down.

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

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

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

[41] Porsche Taycan, ID no. EN-01-710-0078, version no. 1, p2.

[42] Guideline for Rescue Forces, Vehicles with Alternative Drives, e-tron, g-tron, p31.

It is important to set the parking brake at this stage. For some vehicles 12V cables are cut to disable them and this will render the parking brake (and other systems, as described later) nonfunctional.[43]

3.3.2 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 windows, seats, 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.

For many vehicles, the disable process is similar to conventional ICEVs and is as follows:

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

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.[44]

Note that ERGs can be referenced to locate the 12V batteries, as this can vary from vehicle to vehicle. Table 4 provides some guidance, although ERGs should always be referenced, particularly since some vehicles have HV batteries or HV battery disconnects under the rear seats, or HV batteries behind the rear seats:

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[43] 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 4-6.

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

Table 4 Location of 12V batteries in various EVs.

Front hood/Frunk	. 2019-2021 . .	Tesla Model 3 Porsche Taycan Audi e-tron Ford Mustang Mach-E
Under Rear Seat	. . .	Chevrolet Bolt EV Nissan Leaf Hyundai Kona EV
Trunk	. . . . . 2019-2021 2019-2021	BMW i3 Volkswagen ID.4 Kia Soul EV Jaguar I-PACE Mercedes-Benz EQC Audi Q5 TFSI Audi A8 TFSI e

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.

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 8 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 will 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.

Disabling the 12V system will also disable the SRS airbag systems.

Tesla notes that, after deactivation, the HV circuit requires 2 minutes to de-energize.[45] 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.[46] Some models have capacitors that retain HV energy for up to 10 minutes.[47]

Figure 8 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.

45 Tesla Model 3 ERG, no model years listed,

46 Kia Niro ERG, p11

47 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.

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.[48]

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.[49] However, first-responders should attempt to assess the reliability of statements made by people who were recently in a collision.

3.3.3 Extrication

Vehicle Rescue and extrication consists of three phases: stabilization of the scene, stabilization of the vehicle(s), and stabilization of the victim(s).[50]

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.[51]

The scene and vehicle should always be stabilized before beginning extrication.[52] 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. HV batteries cables are typically routed along the underbody of vehicles and are not found in typical

[48] Idaho NL paper, Table 2.

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

[50] Sweet, D., *Vehicle Rescue and Extrication: Principles and Practices*, 2022, p##.

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

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

extrication cut locations. Note that in some cases, such as in Nissan Altima HEVs, the orange cabling is not always visible and can be behind plastic paneling.[53]

Solar panels are currently not commonly installed in production vehicles. However, they are available as options in some vehicles (e.g. Hyundai Sonata Hybrid,[54] Fisker Ocean), and the only way to shut them down when there is daylight is to cover them with a solid, opaque tarp. These cables will likely be routed down one of the pilars. 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 collision 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 collisions will actuate this system (or airbags) and it may be possible for collision 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 collision scene involving an EV.

Per the NFHA Emergency Field Guide, if batteries are venting and fumes are present, immediate removal of patients is not possible. If equipment is available, set up positive pressure ventilation or a smoke ejector to direct vapors away from the interior of the vehicle. If possible, provide patients with oxygen by a non-rebreather at a minimum.[55]

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53 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.

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

55 NFPA Emergency Field Guide, 2018, p30.

3.4 Fire Suppression and Extinguishment

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, vaporizes to interfere with gaseous reactions. Anecdotally, suppressing EV fires with water could require in the range of 300 gallons to over 20,000 gallons of water.[56] At the lower range, a rupture in the battery case between the front seats allowed water into the case which helped extinguish the fire. 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. Some manufacturers indicate that salt water should not be used, as this may generate a large volume of H_2 gas due to electrolysis.[57]

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.[58]
- 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.
    - Areas where the nozzle can be directed area areas with polymeric floor plugs/gaskets or where the HV disconnects are.

[56] NTSB Report, p54

[57] Kia Niro EV 2023 ERG, p24

[58] Kia Niro EV 2023 ERG, p19

- 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 EV 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. As may be expected, larger vehicles will generate more heat.

If there is no immediate threat to life or property, consider defensive tactics and allow fire to burn out.[59]

Testing 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 accelerated the production/release of HF.[60] This suggests that strict adherence to hazard control zones and attention to wind direction during water 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 its incipient stages and does not include the battery, conventional firefighting approaches are appropriate.[61]

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[59] 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.

[60] RISE Report 2020:90, p31

[61] Thomas Barth, FSRI, 23:45

Fire services should consider using water mist with F-500 encapsulator additive, as it has shown to better suppress a battery pack fire than water mist alone[62] as well as reduce potential exposure to HF. An external inductor could be used to introduce F-500 for use in an EV fire. NFPA 18A, *Standard on Water Additives for Fire Control and Vapor Mitigation*, section A.4.3, states the following:[63]

> **A.4.3** Lithium-ion battery and lithium-ion battery energy storage system (BESS) fires are unique electrochemical fire hazards that involve multiple fire classes (Class A, Class B, Class C, Class D) within one entity. While BESS are covered by NFPA 855, it should be noted that lithium-ion battery fires as a stand-alone hazard are not currently addressed in any NFPA standard. According to NFPA research reports, copious amounts of plain water are required to extinguish lithium-ion battery fires, and they can still exhibit thermal runaway up to 72 hours after initial extinguishment.
>
> Water additive based on spherical micelle technology (encapsulator agents) conforming to Section 7.7 has been tested extensively by independent third-party testing organizations, including Kiwa, Dekra, Daimler, Dutech, Bosch, Fraunhofer University, and TU Clausthal. This testing has been controlled, scientific, and highly instrumented, documenting fire suppression, control and elimination of thermal runaway, and encapsulation of both flammable electrolyte and other explosive off-gases, rendering them nonexplosive. Encapsulating technology reduces the toxicity of HF gas exposure to humans.
>
> In addition, the copious amounts of water used to suppress lithium-ion battery fires create copious amounts of run-off containing hydrofluoric acid, creating an environmental issue and expensive HAZMAT disposal cost. Compared to water, water additive solution uses a reasonable amount of solution and has been documented to modify the chemistry of the run-off, making it suitable for additional dilution and disposal in a municipal water treatment plant. Testing documentation can be found in the NFPA Research Library and Archives.

Anecdotally, some fire services are using a pick-axe to puncture the pack such that they can flood it with water and facilitate discharge. 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

[62] Tang, W., Yuan, L., Thomas, R., and Soles, J.; *Comparison of Fire Suppression Techniques on Lithium-Ion Battery Pack Fires*; Mining, Metallurgy & Exploration, 2023.

[63] NFPA 18A, *Standard on Water Additives for Fire Control and Vapor Mitigation*, section A.4.3, p18A-23, 2022.

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. [64] Additionally, pick-axe heads are typically metal, and by puncturing the battery enclosure both the battery enclosure and the pick-axe may be pushed into the battery cell area. This could cause a number of potential failures, as shown in Figure 9: 1) compromising HV battery isolation at one location, 2) compromising HV battery isolation at two locations and resulting in arcing, and/or 3) mechanically damaging a cell and initiating thermal runaway. MSB did recommend the use of a water lance with an extension, which is described further in section 3.6.1.

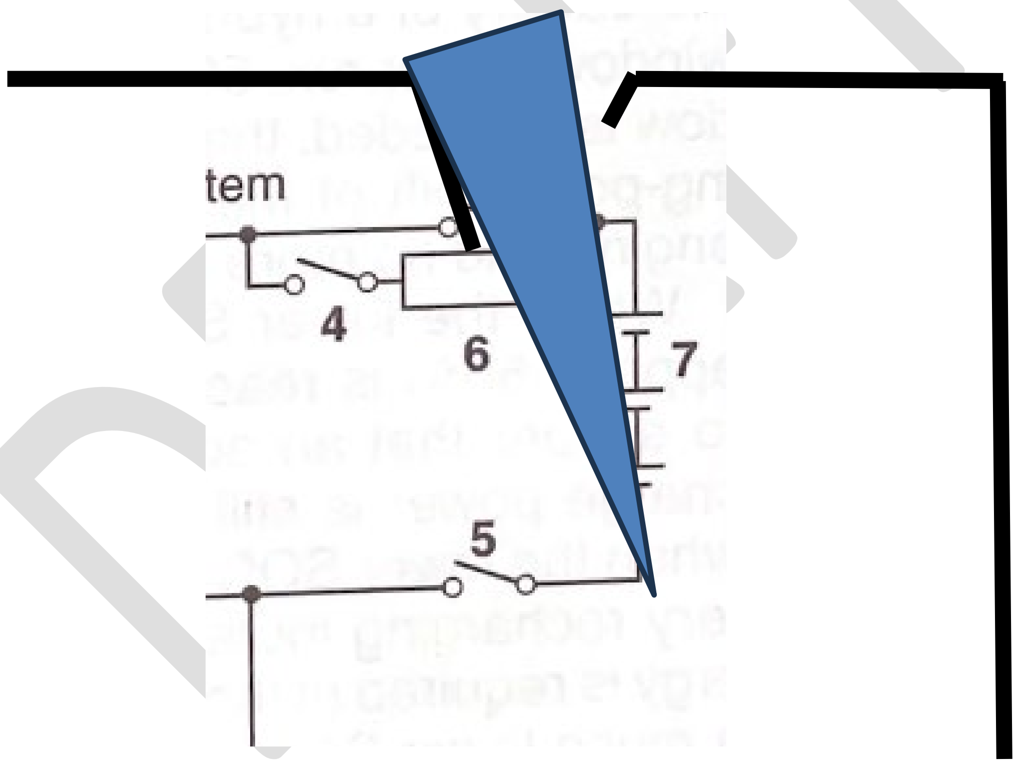

Figure 9 Potential failures that may occur if a pick-axe is used to open a HV battery pack in order to flood it with water. The enclosure and/or pick-axe may fail the HV battery isolation, the pick-axe may short different voltage potentials and cause an arc, or the pick-axe may mechanically damage cells and induce thermal runaway.

[64] 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.

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

3.4.2 Fire Water Runoff & Particulate Residue

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).[65] 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.[66]

Given that fire water runoff from LIB fires has contaminants, first- and second-responders are advised that tools utilized, including 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.[67]

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 collision 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.

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65 See 53 in 2020 RISE REPORT

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

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

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."

3.5 Transportation, Storage, and HV System Inspection

Per Ezekoye, fire departments should consider services available to provide safe decommissioning and transport of vehicles with damaged batteries.[68] These services may include discharging battery packs using resistor loads, as has been done for recovery of grid-scale battery energy storage system thermal events.

3.5.1 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 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.[69]

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, IFE recommends that fire apparatus escort the tow vehicle to the location where it will be stored, whether that is a salvage yard or repair facility. Jostling or movement of vehicles may cause 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.

Per manufacturer ERGs, 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, ensuring that all of the wheels are off of the ground and cannot spin is sometimes offered as an option (see Figure 10). Towing vehicles where the wheels can spin can

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

69 Tesla Model 3 ERG, p23; note that the Tesla Model Y ERG indicates 45 minutes.

lead to significant damage and overheating.[70] Many ERGs advise against using a sling-type tow.

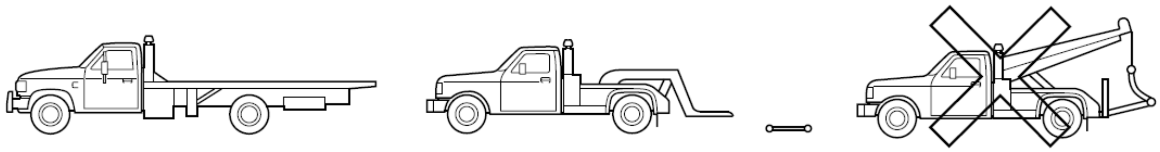

Figure 10 Graphic illustrating that flatbed tow vehicles and tow vehicles using dollies to keep the towed wheels off of the ground are acceptable, whereas sling-type tow vehicles are not acceptable.[71]

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 collision.[72] For this reason, the author prefers using an open top shipping container with doors (also referred to as a 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 be taken. If possible, avoid passing through tunnels or over bridges.

3.5.2 Storage

Initially, the vehicles should be isolated until a second inspection has been carried out of the damaged vehicle or unless the battery has been discharged according to an approved procedure. The second inspection is described in the following section.

70 Tesla Model 3 ERG

71 2021-2023 Ford Mustang Mach-E ERG, 4/2023

72 SAE J2990, July 2019, p22.

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.

Some ERGs recommend that passenger and cargo compartments remain ventilated during storage. However, some also state that if the HV battery is damaged, it should be protected from rain and water accumulation, so a tarp may be necessary for storage to satisfy both criteria.

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. The use of odor is not a recommended assessment approach, as that could potentially mean exposure to battery vent gases.

3.5.3 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.[73] This recommendation is supported by one reported incident where a vehicle caught fire, was extinguished, a fire watch

[73] SAE J2990, July 2019, p21.

was conducted for 6 hours including speaking with a manufacturer representative, followed by a tow, and the vehicle ignited again. [74]

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 top of the vehicle to preclude re-ignition. If sufficient sand is placed on top of the vehicle, including the hood and trunk areas, in the interior, and around the sides of the vehicle it would serve to absorb heat from any vent gases, mitigate ignition sources (e.g. sparks, hot particles), and protect/absorb heat when on top of combustibles any fire that could ignite. 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 move, particularly since not all of the sand is easily removed. Following such a procedure, the sand may need to be treated as industrial waste.

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. [75] 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.

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[74] 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

[75] SAE J2990, July 2019, p21.

7.9 High Voltage Vehicle Inspection Flow Chart Post-Incident

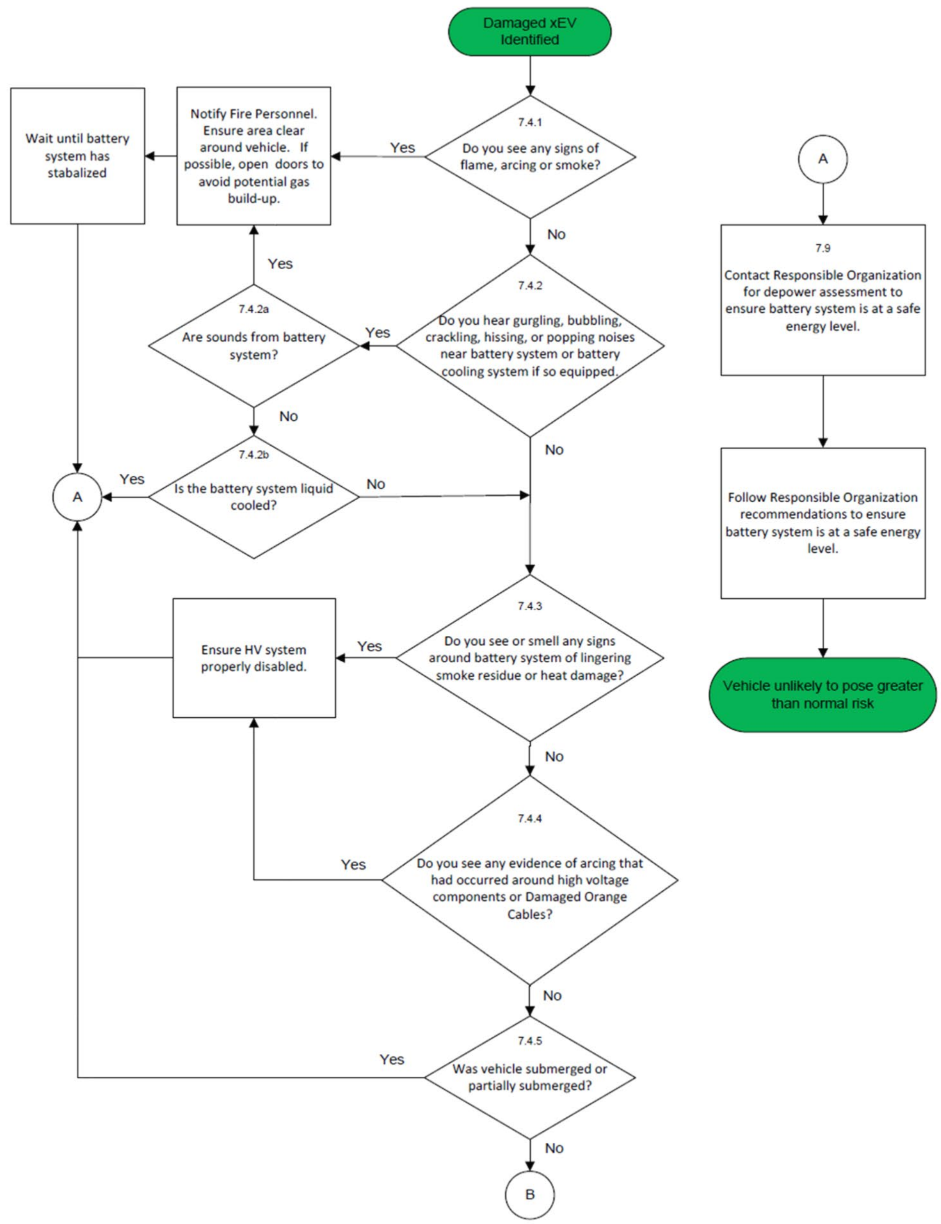

Figure 11 Second HV System Inspection, page 1.

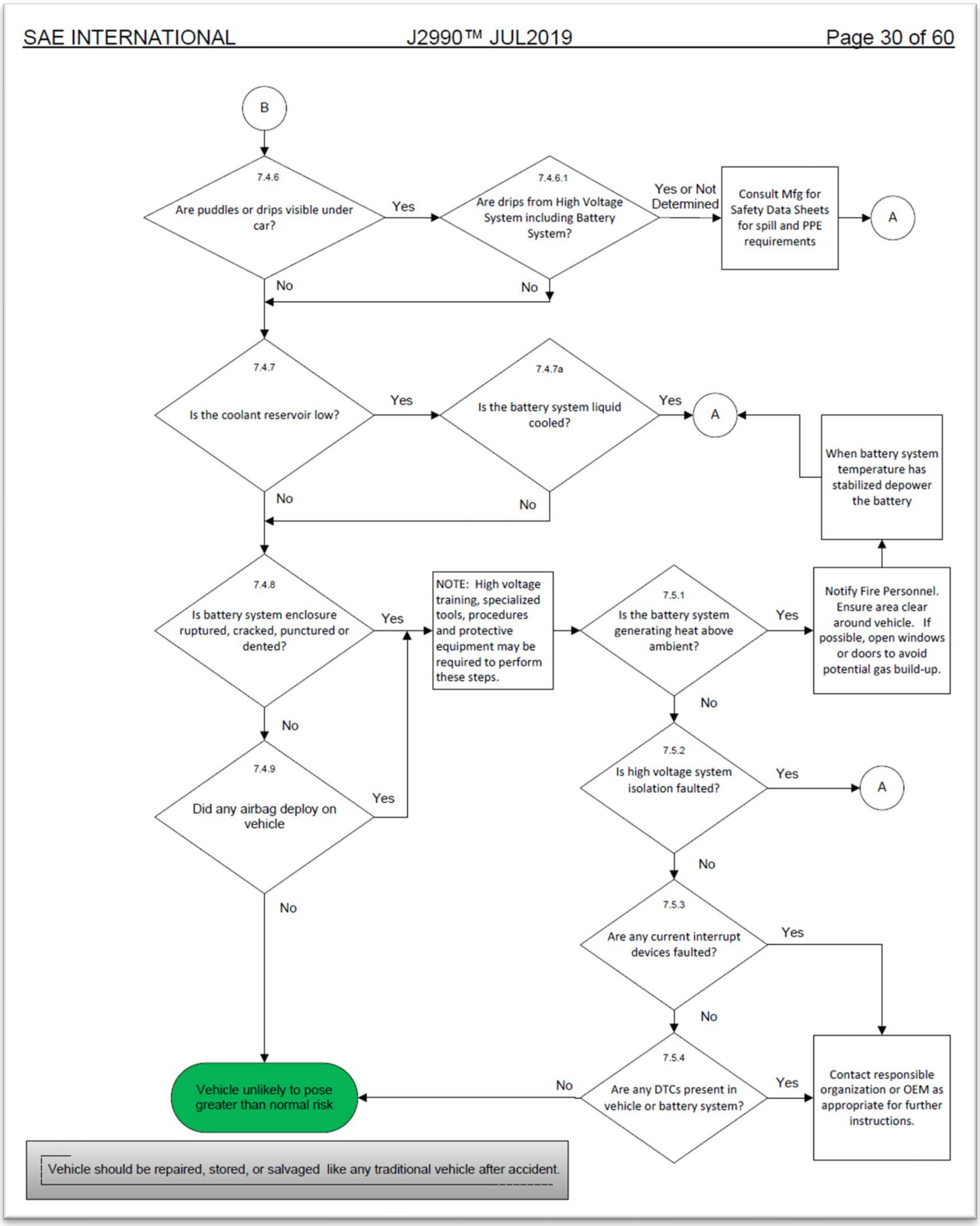

Figure 12 Second HV System Inspection, page 2.

3.5.4 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. Contact information from the ERGs is supplied in Appendix B.

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. This method is also used for discharging battery packs that have been abuse tested for research and development purposes. The water and residue left which contains metals such as phosphorus and lithium, it should be disposed of as an industrial waste according to local regulations.[76] 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.[77] 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
- Maintain water level for 90+ hours, adding water if necessary

[76] 2017-2020 Acura MDX Sport Hybrid ERG, p34

[77] 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

3.6 Specialized Tools

Tools that may be used in the management of collisions 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

3.6.1 Water Penetrating Nozzles

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*.[78] However, it must be noted that MSB only currently offers

[78] 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.

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, flow rate of 58 liters per minute, and an abrasive as 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 in the gimbal tunnel and lance extenders were used to facilitate access and avoid contact with the bodywork (see Figure 13).

Figure 13 Photograph showing the application of the water lance with extension on an EV fire.

During this process, a "conventional jet pipe" 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 imaged 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. No re-ignition occurred.

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 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 14.

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, and if different battery pack designs and different penetration locations result in different results.

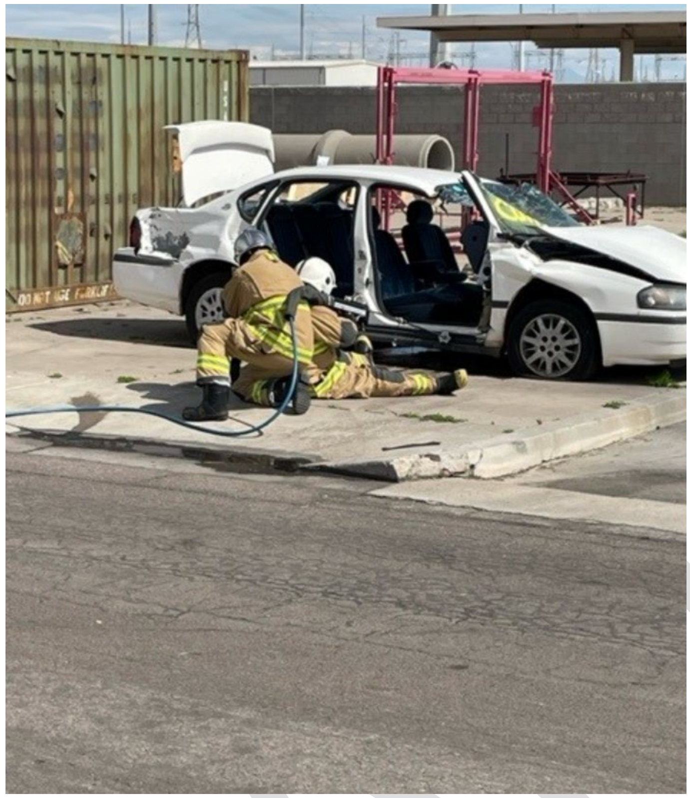

Figure 14 Photograph from the Cold Cut Systems website labeled Tempe-2024-02-29-8.[79]

3.6.2 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

[79] 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. Questions regarding the use 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.).
    -
- 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?

3.6.3 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 not aware of any third-party evaluation of these tools to assess their effectiveness.

3.6.4 Fire Blankets

Fire blankets are available for sale that are intended to be used with damaged EVs. These blankets could conceivably 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.

While these blankets may be useful in certain circumstances, there may be consequences of their use that users should be aware of. IFE is not aware of any third-party evaluation or systematic testing of the blankets to understand what hazards they may create, under what conditions the blankets should be used, who should make the decision of when to use the blanket and when to take the blanket off, and what the criteria should be of when it is sensible to take it off.

A cursory 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.[80] This could be because of a smoldering fire that was not extinguished when the blanket was on, or venting LIB cells generating just enough oxygen to sustain a flame and allow for a rapid re-ignition. A few questions raised by these demonstrations are as follows:

1) Does the blanket create a concentrated plume of toxic smoke?

[80] 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.

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 flash fire hazard created?
4) How long does the blanket need to be kept on so that the fire does not re-ignite?
5) What is the criteria to know when the blanket can be removed?
6) 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.).
7) How does the performance of different fire blankets on the market compare with one another?
8) Can the ones that are specified as re-usable be re-used without performance degradation?
9) What is the criteria to decide if a blanket is no longer usable?

Given these questions, responders who are handling an EV or EVs in a collision are advised to follow the isolation requirements set forth in SAE J2990, July 2019, as described in section 3.5.2. If readers wish to use the blankets in other circumstances – and there may be good reasons to do so – they are advised to develop a plan to do so safely with an understanding of the potential risks. Additionally, fire blankets exposed to heat should not be re-used unless there is substantial evidence to support re-use.

3.6.5 Non-sparking Tools

Battery vent gases can generate flammable gas clouds, and in cases where there is confinement such gas clouds can result in vapor cloud explosions. Vapor cloud explosions 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. A photograph of a vehicle with battery vent gases accumulated in the cabin is shown in Figure 15.

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 the author has been unable to identify any study describing the efficacy, limitations, and practicality of using such tools for first- and second-responders tasks, particularly tasks involving high-strengh steel frame members.

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 amount of sparks but is effective at cutting through hardened steel.[81] Such a tool would need to be used with caution to extricate a person from a vehicle. If there was any sign of smoke or fog, another tool would be recommended.

Figure 15 Example of a vehicle that has filled with battery vent gases – note the white smoke.

3.6.6 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.

3.6.7 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.

[81] Sweet et al., p67

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.

3.6.8 Charging Plugs

Specialized charging plugs are available for purchase which are intended to immobilize the vehicle by "tricking" the vehicle into thinking that it is charging. Based on 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.

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 manufacturers claims or understand unintended effects of using them, if any, in the circumstances of EV collisions.

One manufacturer has indicated that when their device is used the vehicles 12 V system still works, allowing the use of windows, seats, etc. The use of windows and seat functions are important to facilitate ventilation and prevent buildup of flammable gases, and the use of seat functions may be necessary for extrication.

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.

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. If the reader's department currently owns and utilizes one of these plugs, the reader is advised to check with the manufacturer and understand if their device will work on all EVs. Additionally, the reader is advised that these devices are not considered to be an alternative to emergency procedures.

3.6.9 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.

3.7 Fuel Cell Vehicle Collision Management

This section is reserved for future updates.

3.8 Gap Analysis

This section is reserved for future work.

3.9 PPE, Don and Doff

This section is reserved for future work.

4.0 Hands-on Training Scenarios

This chapter is reserved for future work.

5.0 Summary and Future Work

This section is currently under development.

A. Collisions involving EVs are increasing in number. Because EV collisions 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.

B. There are recently published, detailed textbooks which describe vehicle rescue principles and practices, but these references do not incorporate some of the latest learnings, research, and guidance from the scientific and engineering communities. Alternatively, the latest learnings, research, and guidance from the scientific communities generally does not integrate the aforementioned vehicle rescue principles and practices in great detail. This work aims to close that gap.

C. Fire departments will need hands-on training, and the scientific and engineering communities will need to study various aspects of the EV collision events and fire events. There is an opportunity for dual purpose 1) training on battery failure and 2) research, such as third party scientific evaluation of specialized tools, e.g. pack puncture water nozzles.
    - A study should be carried out similar to the MSB work using pack puncture tools to evaluate their effectiveness at discharging and/or stopping thermal runaway, limitations of the equipment, and potential failure modes and effects for the equipment and the process of using it.

D. In-person trainings with vehicles allow for the following:
    - Vehicle identification and disabling exercises while under time pressure
    - Size-up exercises while under time pressure
    - Burn testing and evaluation of fire suppression tactics

E. Response scenarios could be developed based on a review of reported incidents, crash testing, and discussions with experts in the vehicle accident reconstruction field.

F. 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.

G. The utility and practicality of non-sparking cutting tools for use by first- and second-responders should be studied and published to the broader community.

H. Fire & Medical Responders are encouraged to request performance data for their PPE from the following standardized tests:

  - ASTM F1959, *Standard Test Method for Determining the Arc Rating of Materials for Clothing*, which is a large-scale arc flash evaluation used to determine the Arc Thermal Performance Value (ATPV) of a fabric.
  - ASTM F2178, *Standard Specification for Arc Rated Eye or Face Protective Products*.

I. 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.

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-collision 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.

Appendix B: Contact Information From Emergency Response Guides