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

Final Report

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FOREWORD

Fires involving cars, trucks and other highway vehicles are a common concern for emergency responders. Fire Service personnel are accustomed to responding to conventional vehicle fires, and generally receive training on the hazards associated with vehicle subsystems (e.g., air bag initiators, seat belt pre-tensioners, etc). For vehicle fires, and in particular fires involving electric drive vehicles, a key question for emergency responders is: “what is different with electric drive vehicles and what tactical adjustments are required?”

The overall goal of this project is to conduct a research program to develop the technical basis for best practices for emergency response procedures for electric drive vehicle battery incidents, with consideration for certain details including: suppression methods and agents; personal protective equipment (PPE); and clean-up/overhaul operations. A key component of this project goal is to conduct full-scale testing of large format Li-ion batteries used in these vehicles. This report summarizes these tests, and includes discussion on the key findings relating to best practices for emergency response procedures for electric drive vehicle battery incidents.

The Research Foundation expresses gratitude to the report authors R. Thomas Long Jr., Andrew F. Blum, Thomas J. Bress, and Benjamin R.T. Cotts, all with Exponent, Inc. (Bowie, Maryland). Appreciation is expressed to the Project Technical Panelists and all others who contributed to this research effort. Special thanks are expressed to the following project sponsors for providing the funding for this project: Department of Energy; Department of Transportation; and Alliance of Automobile Manufacturers. Gratitude is also extended to Battelle and Idaho National Laboratory, Southwest Research Institute, and Maryland Fire Rescue Institute for their on-going guidance and use of facilities.

The content, opinions and conclusions contained in this report are solely those of the authors.

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Thermal Sciences

Best Practices for Emergency Response to Incidents involving Electric Vehicle Battery Hazards: A Report on Full-scale Testing Results

Best Practices for Emergency Response to Incidents involving Electric Vehicle Battery Hazards

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Acronyms and Abbreviations

AC	alternating current
Ah	Ampere hour
BEV	battery electric vehicle
CAN	controller area network
DC	direct current
DOE	Department of Energy
DOT	Department of Transportation
EDV	electric drive vehicle
EREV	extended range electric vehicle
EV	electric vehicle
FMVSS	Federal Motor Vehicle Safety Standard
FPRF	Fire Protection Research Foundation
FTIR	Fourier transform infrared
gpm	gallons per minute
HCl	hydrogen chloride
HCN	hydrogen cyanide
HEV	hybrid electric vehicle
HF	hydrogen fluoride
HRR	heat release rate
HV	hybrid vehicle
Hz	Hertz
ICE	internal combustion engine
IFSTA	International Fire Service Training Association
kHz	kilohertz
kW	kilowatt
kWh	kilowatt hour
m	meter
MFRI	Maryland Fire and Rescue Institute
MJ	mega joule
mph	miles per hour
ms	millisecond
MW	megawatt
NiMH	Nickel metal hydride
NFPA	National Fire Protection Association
NHTSA	National Highway Traffic Safety Administration
NOx	nitrogen oxides
OEL	occupational exposure limits

PBI	Polybenzimidazole
PBZ	personal breathing zone
PPE	personal protective equipment
PHEV	plug-in hybrid electric vehicle
RESS	Rechargeable Energy Storage System
SAE	Society of Automotive Engineers
SCBA	self-contained-breathing-apparatus
S	Siemens
SOC	state of charge
SRS	supplemental restraint system
SwRI	Southwest Research Institute
UL	Underwriters Laboratories
V	volt
VDC	volts direct current
VFT	vehicle fire trainer
VOC	volatile organic compound
Wh	Watt hour

Limitations

At the request of the Fire Protection Research Foundation (FPRF), Exponent assessed the best practices for emergency response to electric drive vehicle (EDV) battery hazards. This report summarizes a full-scale fire testing and suppression program involving full size hybrid electric (HEV) and extended range electric vehicle (EREV) lithium ion (Li-ion) batteries installed in a vehicle fire trainer (VFT) prop. The scope of services performed during this testing program may not adequately address the needs of other users of this report, and any re-use of this report or its findings, conclusions, or recommendations presented herein are at the sole risk of the user.

The full-scale vehicle mockup test strategy, burner exposure protocol, and any recommendations made are strictly limited to the test conditions included and detailed in this report. The combined effects (including, but not limited to) of different battery types, vehicle types, collision damage, battery energy density and design, state of charge, cell chemistry, etc. are yet to be fully understood and may not be inferred from these test results alone.

The findings formulated in this review are based on observations and information available at the time of writing. The findings presented herein are made to a reasonable degree of scientific and engineering certainty. If new data becomes available or there are perceived omissions or misstatements in this report, we ask that they be brought to our attention as soon as possible so that we have the opportunity to fully address them.

Executive Summary

This report summarizes full-scale heat release rate (HRR) and fire suppression testing of EDV large format Li-ion batteries.

In an effort to bolster preliminary guidance issued by the National Fire Protection Association (NFPA) for fire emergencies involving EDVs, full-scale fire suppression tests were conducted to collect data and evaluate any differences associated with EDV fires as compared to traditional internal combustion engine (ICE) vehicle fires. EDVs may pose new, unknown risks and variables to emergency responders. In particular, members of the emergency response community have questions regarding, (1) personal protective equipment (PPE); (2) firefighting suppression tactics; and (3) the best practices for overhaul and post-fire clean-up. Specifically, questions from the emergency response community regarding these three topics include:

1. Appropriate PPE to be used for responding to fires involving EDV batteries:
    a. Is current PPE appropriate with regard to respiratory and dermal exposure to vent gases and combustion products?
    b. Is current PPE appropriate with regard to potential electric shock hazards?
    c. What is the size of the hazard zone where full PPE, including respiratory protection, must be worn?
2. Tactics for suppression of fires involving EDV batteries:
    a. How effective is water as a suppressant for large battery fires?
    b. Are there projectile hazards?
    c. How long must suppression efforts be conducted to place the fire under control and then fully extinguish it?
    d. What level of resources will be needed to support these fire suppression efforts?
    e. Is there a need for extended suppression efforts?

    f. What are the indicators for instances where the fire service should allow a large battery pack to burn rather than attempt suppression?

3. Best practices for tactics and PPE to be used during overhaul and post-fire clean-up operations.

The scope of work included, but was not limited to, the following six primary tasks:

1. A review of industry best practices for firefighting tactics for ICE and EDVs (see Section 2);
2. Identification, categorization, and prioritization of battery technologies and representative battery types for full-scale testing in conjunction with the Project Technical Panel and their advisory groups (see Section 4);
3. Identification of the key required elements of EDV emergency response PPE, tactics, and overhaul operations (see Section 2);
4. Development of full-scale fire testing program for each battery to be tested (see Section 5);
5. Full-scale fire testing per the full-scale fire testing program developed above, including one unsuppressed HRR test and six suppressed tests (see Section 6); and
6. Report of final results and summary of the best practices for emergency response to incidents involving EDV battery hazards.

In summary, this project involved full-scale HRR and fire suppression testing of EDV batteries alone (HRR test) and installed within a generic VFT prop (fire suppression tests). Fire suppression tests were conducted with and without vehicle interior finishes. All tests subjected the batteries to simulated exposure fires originating underneath the vehicle chassis. All fire suppression activities were conducted by qualified active duty firefighters.

The overriding goal of this research project was to collect data to bolster current guidance provided by NFPA through their *Electric Vehicle Emergency Field Guide*. A full listing of project observations as they relate to the current NFPA guidance is provided in Section 8 of this report.

1 Background

1.1 Project History

In 2009, the National Fire Protection Association (NFPA) began a partnership with the U.S. Department of Energy (DOE) and the automotive industry to develop and implement a comprehensive training program to provide safety training to emergency responders to prepare them for their role in safely handling incidents involving electric drive vehicles (EDVs). Throughout this report, the term EDV is used to describe a passenger road vehicle with an electric drive power system capable of propelling the vehicle solely by electric power or in combination with the internal combustion engine (ICE). This program had a lack of data to draw on to address the potential hazards associated with damaged EDV batteries. EDVs may pose new, unknown risks and variables to emergency responders. In particular, members of the emergency response community have questions regarding, (1) personal protective equipment (PPE); (2) firefighting suppression tactics; and (3) the best practices for overhaul and post-fire clean-up. Specifically, questions from the emergency response community include:

1. Appropriate PPE to be used for responding to fires involving EDV batteries:
    a. Is current PPE appropriate with regard to respiratory and dermal exposure to vent gases and combustion products?
    b. Is current PPE appropriate with regard to potential electric shock hazards?
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2. Tactics for suppression of fires involving EDV batteries:
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    b. Are there projectile hazards?
    c. How long must suppression efforts be conducted to place the fire under control and then fully extinguish it?
    d. What level of resources will be needed to support these fire suppression efforts?

    e. Is there a need for extended suppression efforts?
    f. What are the indicators for instances where the fire service should allow a large battery pack to burn rather than attempt suppression?

3. Best practices for tactics and PPE to be used during overhaul and post-fire clean-up operations.

1.2 Research Objectives and Project Scope

The overall project research objective was to develop a technical basis for the best practices for emergency response for EDV battery incident firefighting, including the necessary PPE for first fire responders, the adequacy of water as a suppression agent, and the best practices for overhaul.

The scope of work included, but was not limited to, the following six primary tasks:

1. A review of industry best practices for firefighting tactics for ICE and EDVs (see Section 2);
2. Identification, categorization, and prioritization of battery technologies and representative battery types for full-scale testing in conjunction with the Project Technical Panel and their advisory groups (see Section 4);
3. Identification of the key required elements of EDV emergency response PPE, tactics, and overhaul operations (see Section 2);
4. Development of a full-scale fire testing program for each battery to be tested (see Section 5);
5. Full-scale fire testing per the full-scale fire testing program developed above, including one unsuppressed combustion test and six suppressed tests (see Section 6); and
6. Report of final results and summary of the best practices for emergency response to incidents involving EDV battery hazards.

A more detailed description of the tasks Exponent performed to fulfill the project objectives is provided below.

1.2.1 Review of Industry Best Practices for Firefighting

Exponent collected, reviewed, and summarized available industry best practices for EDV battery incident firefighting as they relate to hazards, frequency, PPE, suppression tactics, suppression agents, overhaul, and clean-up. This task included a review of firefighting tactics literature, as well as technical discussions with the Maryland Fire and Rescue Institute (MFRI) in regards to industry best practices for fighting ICE and EDV fires (see Section 2).

1.2.2 Identification, Categorization, and Prioritization of Battery Technologies and Representative Battery Types

Exponent, in conjunction with the Project Technical Panel, identified three candidate Li-ion batteries from three different EDV manufacturers for testing. Exponent assisted in analyzing and procuring the candidate batteries. A description of each battery is provided in Section 4.

Li-ion battery technology with an approximate capacity of 5.0 DC kWh or larger if designed for a plug-in hybrid electric vehicle (PHEV) or extended range electric vehicle (EREV) and 15.0 DC kWh or larger if designed for a battery electric vehicle (BEV) was used as a benchmark for the battery selection**.**

Exponent also worked with battery and automotive manufacturers to develop protocols for safe charging and characterization of the batteries prior to testing and safe discharge and removal of the batteries after testing, where required.

1.2.3 Identification of Key Required Elements of PPE, Tactics, and Overhaul Operations

Exponent, in conjunction with the Project Technical Panel and MFRI, identified and summarized the key required elements of emergency response PPE, tactics, and overhaul operations based on a review of EDV fire hazards and traditional responses to vehicle and electrical fires involving energized equipment. This analysis included a review of industry references, as well as discussions with MFRI and automotive resources regarding PPE (see Section 2).

1.2.4 Development of Full-Scale Fire Testing Program

Exponent, in conjunction with the Project Technical Panel and their advisory groups, developed an appropriate program for full-scale fire testing, separated into two categories: (1) HRR testing of a standalone battery pack and (2) full-scale fire suppression testing of battery packs in their correct mounting location positioned inside a vehicle fire trainer prop (VFT), along with other appropriate combustible materials, including vehicle interior finishes and components. The full-scale suppression tests involved a modified VFT prop to simulate typical vehicle fuel loads and ignition and containment of the Li-ion batteries.

1.2.5 Full-scale Fire Testing

The full-scale fire testing involved one standalone HRR free-burn, unsuppressed fire test and suppressed fire tests of Li-ion batteries within a VFT. Instrumentation was provided to monitor fire growth and development, including, but not limited to, heat release rate, temperature, and heat flux. Gas samples and fire suppression water samples were collected for analysis of potential contaminants.

For testing that utilized the VFT, Exponent collaborated with MFRI, who provided expertise in incident command, firefighting tactics, overhaul operations, and firefighter PPE. Their training staff was utilized to identify recommended best practices for emergency response to EDV fire incidents and to facilitate the tests and suppression of the fires.

Active firefighters from MFRI performed all suppression and overhaul operations. Any hazardous events, such as projectile releases, adverse reactions to suppression agents, and electric shock were recorded.

1.2.6 Report and Summary of Best Practices

Exponent collected and processed the test data from the full-scale testing program in this formal research engineering report. This report provides:

1. An overview of the project work to date;
2. A summary of the full-scale test data;

3. Comparison with comments from NFPA interim guidance; and
4. Identification of future potential research.

2 Current State of Emergency Response to ICE and EDV Fires

2.1 Li-ion Overview

Li-ion battery cells are in wide consumer use today. As this technology has evolved and the energy densities have increased, the use of this technology has been applied across many consumer products, including the automotive industry. Li-ion battery cells arranged in large format Li-ion battery packs are being used to power several types of EDVs. As EDVs enter the U.S. marketplace, there is an expectation of a steep increase in the number and size of battery packs in storage and use. A recent study by NFPA's FPRF[1,2] highlights the potential hazards and uses of Li-ion battery cells and packs during the life cycle of storage and distribution. An overview of the Li-ion technology and its failure modes is also included. A brief summary of Li-ion technology is provided here.

Li-ion has become the dominant rechargeable battery chemistry for consumer electronic devices and is poised to become commonplace for industrial, transportation, and power-storage applications. This chemistry is different from previously popular rechargeable battery chemistries (e.g., nickel metal hydride, nickel cadmium, and lead acid) in a number of ways. From a technological standpoint, because of high energy density, Li-ion technology has enabled the powering of EDVs. From a safety and fire protection standpoint, a high energy density coupled with a flammable organic, rather than aqueous, electrolyte has created a number of new challenges with regard to the design of batteries containing Li-ion cells, and with regard to fire suppression.

The term Li-ion refers to an entire family of battery chemistries. It is beyond the scope of this report to describe all of the chemistries used in commercial Li-ion batteries. In addition, it should be noted that Li-ion battery chemistry is an active area of research and new materials are constantly being developed. Additional detailed information with regard to Li-ion batteries is

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[1] Long RT et al. "Lithium-Ion Batteries Hazard and Use Assessment." Fire Protection Research Foundation Report, July 2011. http://www.nfpa.org/assets/files//PDF/Research/RFLithiumIonBatteriesHazard.pdf

[2] Long RT, et al. "Lithium-ion batteries hazards: What you need to know." Fire Protection Engineering Q4 2012.

available in a number of references[3,4] and a large volume of research publications and conference proceedings on the subject.

In the most basic sense, the term Li-ion battery refers to a battery where the negative electrode (anode) and positive electrode (cathode) materials serve as a host for the lithium ion (Li+). Lithium ions move from the anode to the cathode during discharge and are intercalated (inserted into voids) in the crystallographic structure of the cathode. The ions reverse direction during charging, as shown in Figure 1. Since lithium ions are intercalated into host materials during charge or discharge, there is no free lithium metal within a Li-ion cell[5,6], thus, if a cell ignites due to external flame impingement or an internal fault, metal fire suppression techniques are not appropriate for controlling the fire.

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[3] *Linden's Handbook of Batteries*, 4th Edition, Thomas B. Reddy (ed), McGraw Hill, NY, 2011.

[4] *Advances in Lithium-Ion Batteries*, WA van Schalkwijk and B Scrosati (eds), Kluwer Academic/Plenum Publishers, NY, 2002.

[5] Under certain abuse conditions, lithium metal in very small quantities can plate onto anode surfaces. However, this should not have any appreciable effect on the fire behavior of the cell.

[6] There has been some discussion about the possibility of "thermite-style" reactions occurring within cells (reaction of a metal oxide with aluminum, for example iron oxide with aluminum, the classic thermite reaction, or in the case of lithium-ion cells cobalt oxide with aluminum current collector). Even if thermodynamically favored (based on the heats of formation of the oxides), generally these types of reactions require intimate mixtures of fine powders of both species to occur. Thus, the potential for aluminum current collector to undergo a thermite-style reaction with a cathode material may be possible, but aluminum in bulk is difficult to ignite (Babrauskas V, *Ignition Handbook*, Society of Fire Protection Engineers, 2003, p. 870) and thus, the reaction may be kinetically hindered. Ignition temperatures of thermite style reactions are heavily dependent upon surface properties. Propagation of such reactions can also be heavily dependent upon mixture properties. To date, Exponent has not observed direct evidence of thermite style reactions within cells that have undergone thermal runaway reactions, nor is Exponent aware of any publically available research assessing the effect of such reactions on cell overall heat release rates. Nonetheless, even if a specific cell design is susceptible to a thermite reaction, that reaction will represent only a portion of the resulting fire, such that the use of metal fire suppression techniques will remain inappropriate.

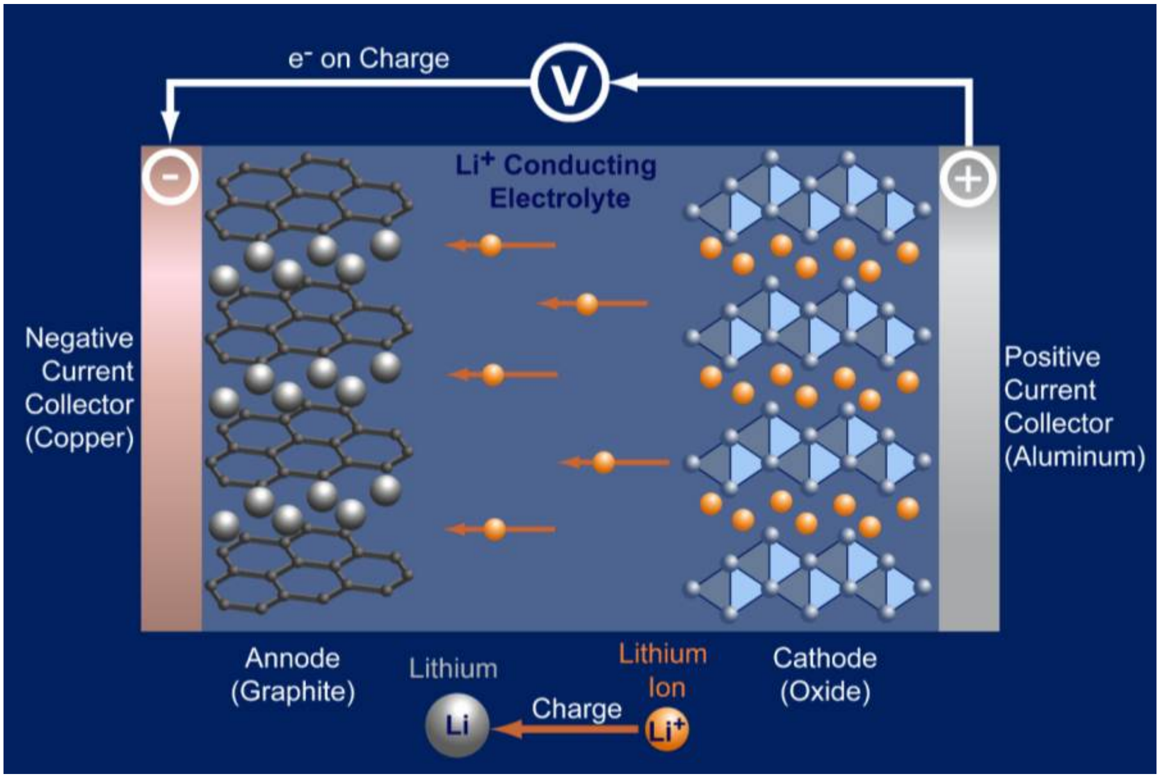

Figure 1 Li-ion cell operation, during charging lithium ions intercalate into the anode, the reverse occurs during discharge

In a Li-ion cell, alternating layers of anodes and cathodes are separated by a porous film (separator). An electrolyte composed of an organic solvent and dissolved lithium salt provides the media for Li-ion transport. A cell can be constructed by stacking alternating layers of electrodes (typical for high-rate capability prismatic cells), or by winding long strips of electrodes into a “jelly roll” configuration typical for cylindrical cells, as shown in Figure 2. Electrode stacks or rolls can be inserted into hard cases that are sealed with gaskets (most commercial cylindrical cells), as shown in Figure 3, laser-welded hard cases, as shown in Figure 4, or enclosed in foil pouches with heat-sealed seams (commonly referred to as Li-ion polymer cells[7]), as shown in Figure 5. A variety of safety mechanisms might also be included in the

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[7] Note that the term “lithium polymer” has been previously used to describe lithium metal rechargeable cells that utilized a polymer-based electrolyte. The term lithium polymer is now used to describe a wide range of lithium-ion cells enclosed in soft pouches with electrolyte that may or may not be polymer based.

mechanical design of a cell, such as charge interrupt devices and positive temperature coefficient switches.[8,9]

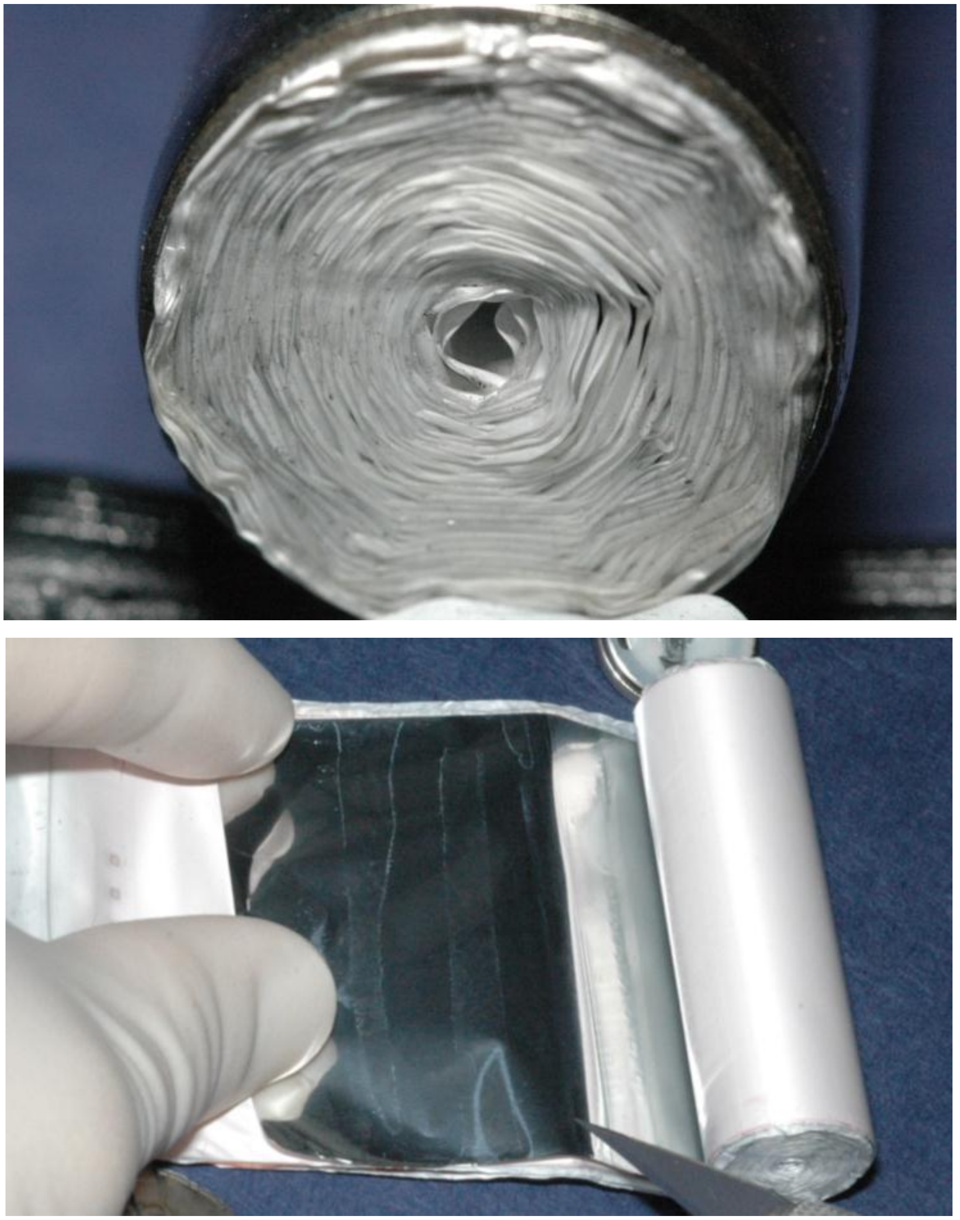

Figure 2 Base of a cylindrical Li-ion cell showing wound structure (top); Cell being unwound revealing multiple layers: separator is white, aluminum current collector (part of cathode) appears shiny (bottom)

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[8] For a more detailed discussion of Li-ion cells see: Dahn J, Ehrlich GM, “Lithium-Ion Batteries,” *Linden’s Handbook of Batteries*, 4th Edition, TB Reddy (ed), McGraw Hill, NY, 2011.

[9] For a review of various safety mechanisms that can be applied to Li-ion cells see: Balakrishnan PG, Ramesh R, Prem Kumar T, “Safety mechanisms in lithium-ion batteries,” Journal of Power Source, 155 (2006), 401-414.

Figure 3 Example of 18650 cylindrical cells (these are the most common consumer electronics Li-ion cell form factor)

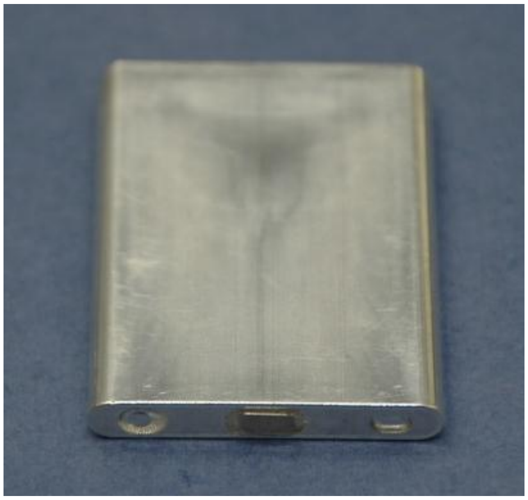

Figure 4 Example of a hard case prismatic cell

Figure 5 Example of a soft-pouch polymer cell

A Li-ion battery is made from multiple individual cells packaged together with their associated control system and protection electronics. By connecting cells in parallel, designers increase pack capacity. By connecting cells in series, designers increase pack voltage. Thus, most battery packs will be labeled with a nominal voltage that can be used to infer the number of series elements and, along with total battery pack energy (in Watt hours [Wh]), can be used to determine the capacity (in Ampere hours [Ah]) of each series element (size of individual cells or the number of cells connected in parallel).

For large format battery packs, cells may be connected together (in series and/or in parallel) in modules. The modules may then be connected in series or in parallel to form full battery packs. Modules are used to facilitate readily changed configurations and easy replacement of faulty portions of large battery packs. Thus, large format battery pack architecture can be complex.

EDV batteries typically utilize many individual cells comprised into modules. The modules are then assembled to form a large format battery pack. Large format packs typically contain an active safeguarding system to monitor electrical current, voltage, and temperature of the cells to optimize pack performance and mitigate potential failures, including fire. Numerous standards and protocols are available for these packs, including, but not limited to:

- Underwriters Laboratories (UL) Subject 2580: Batteries for Use in Electric Vehicles;

- SAE J2464: Electric and Hybrid Electric Vehicle Rechargeable Energy Storage Systems (RESS), Safety and Abuse Testing; and
- SAE J2929: Electric and Hybrid Vehicle Propulsion Battery System Safety Standard – Lithium-based Rechargeable Cells.

It is beyond the scope of this report to discuss all potential standards and protocols; however, a summary of many testing protocols for Li-ion cells has been published previously.[10]

2.2 Electric Vehicle Overview

Different types of EDVs are created by unique combinations of the standard components of a hybrid and/or electric vehicle system, including the battery, electric motor, generator, mechanical transmission, and power control system. There are four primary types of EDVs:

1. Hybrid electric vehicles (HEV);
2. Plug-in hybrid electric vehicles (PHEV);
3. Extended-range electric vehicles (EREV); and
4. Battery electric vehicles (BEV).

The following summarizes the four primary types of EDVs and how they commonly function. Some variances will occur from manufacturer to manufacturer. HEVs use a small electric battery to supplement an ICE. The electric battery is recharged by the gasoline engine and regenerative braking. PHEVs are dual-fuel vehicles, where the electric motor and/or the ICE can propel the vehicle. PHEVs use a larger battery pack than HEVs and are charged directly from the power grid to supplement a smaller ICE. EREVs are propelled by electric motors only. When the propulsion battery is depleted, and ICE is used to power an electric generator that provides electricity to the drive motors. Finally, BEVs have no ICE at all and are full EVs. These vehicles must plug into the power grid to recharge.[11]

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[10] UL: "Safety Issues for Lithium-Ion Batteries," 2012.

[11] http://www.tva.com/environment/technology/car_vehicles.htm

2.3 Current EDV Research and Other Efforts

EDVs involved in collision and fire incidents may present unique hazards associated with the high voltage system (including the battery system). These hazards can be grouped into three distinct categories: chemical, electrical, and thermal. The potential consequences can vary depending on, but not limited to, the size, configuration, and specific battery chemistry. Recently the Society of Automotive Engineers (SAE) International released J2990[12], *Hybrid and EV First and Second Responder Recommended Practice*, which describes the potential consequences associated with hazards from EDVs and suggests common procedures to help protect emergency responders, tow and/or recovery, storage, repair, and salvage personnel after an incident has occurred with an electrified vehicle. Nickel metal hydride (NiMH) and Li-ion batteries used for vehicle propulsion power are the assumed battery systems of this Recommended Practice.

Recently, full-scale fire tests have compared the fire behavior of EDVs with that of conventional ICE vehicles. In the first test series[13], researchers conducted full-scale tests of an electric battery powered EDV and a comparable ICE vehicle. In this test series, the total HRR of the burning vehicles was calculated using the mass loss rates. The peak HRR of the EDV was found to be approximately three times greater than that of the ICE vehicle; however, given that the EDV and ICE were not identical, it is unclear if the peak HRRs can be directly compared. During the EDV test, no projectiles or explosions were observed. It was noted that while the peak HRR was greater, the total energy released for the EDV was approximately 50% more than the ICE vehicle tested, but 15% less than that of a luxury ICE sedan.

In a second test series[14], researchers conducted fire tests on two vehicles. The first was an EDV and the second vehicle tested was an analogous ICE vehicle. A gas burner was used to ignite

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[12] SAE International, Surface Vehicle Recommended Practice J2990 NOV2012, 11-2012, Hybrid and EV First and Second Responder Recommended Practice.

[13] Watanabe, N. et al. “Comparison of fire behaviors of an electric-battery-powered vehicle and gasoline-powered vehicle in a real-scale fire test.” National Research Institute of Police Science, Japan. Presented at Second International Conference on Fires in Vehicles, September 27-28, 2012, Chicago, IL.

[14] Lecocq, A. et al. “Comparison of the Fire Consequences of an Electric Vehicle and an Internal Combustion Engine Vehicle.” INERIS – National Institute of Industrial Environment and Risks, Verneuil-en-Halatte, France. Second International Conference on Fires in Vehicles, September 27-28, 2012, Chicago, IL.

the vehicles and was located on the front driver’s seat. Fire development was similar for both vehicles and no projectiles were observed. The maximum HRR was similar for both vehicles, 4.2 MW for the EDV and 4.8 MW for the ICE vehicle. Gas analysis found that hydrogen fluoride (HF) was emitted in significant quantities in both the EDV and ICE vehicle tests. A distinct area of HF emission was observed during the burning of the EDV that was attributed specifically to the combustion of the EDV battery, however, these peaks were less than the initial and maximum HF peak that was possibly attributed to the air conditioning refrigerant.

Prior work conducted on EDV batteries exposed to pool fires was also reviewed.[15] In this test series, three large format 17 kWh EDV Li-ion batteries were exposed to fuel-fed pool fires in a rack located above an exposure fire. The batteries were not installed in the original host vehicle. The batteries were then extinguished with water and/or water with additives. The battery external temperatures and the total amount of water used were recorded.

The pool fire was placed directly below the battery, was fueled by 45 liters of heptane, and lasted approximately 11 minutes. When exposed to the flames, gases were observed to escape from the battery and produce visible flash fire-like flames and “short circuits” characterized by bright white flames. Water samples collected after extinguishing the batteries showed concentrations of Fluoride and Chloride. Forty (40) to 80 liters of water with various additives were used to extinguish the fire.

The National Institute for Occupational Safety and Health (NIOSH)[16] recently evaluated chemical and particulate exposures to firefighters during vehicle fire suppression training. Smoke samples from engine and cabin fires were collected and analyzed to identify the main chemicals in the smoke. Samples were also collected from the personal breathing zone (PBZ). High levels of hazardous chemicals were found in the smoke samples from the vehicle smoke, however, PBZ samples were below occupational exposure limits (OELs). Recommendations included:

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[15] Egelhaaf, M., Kress, D., Wolpert, D., Lange, T. et al., "Fire Fighting of Li-Ion Traction Batteries," SAE Int. J. Alt. Power. 2(1):37-48, 2013, doi: 10.4271/2013-01-0213.

[16] Fent, K.W. et al. “Evaluation of Chemical and Particle Exposures During Vehicle Fire Suppression Training.” Health Hazard Evaluation Report HETA 2008-0241-3113, NIOSH, Yellow Springs, OH, July 2010.

- Enforcement of the use of self-contained breathing apparatuses (SCBAs) during vehicle fire suppression;
- Attacking fires from upwind positions;
- Parking fire apparatus upwind of the fire;
- Donning SCBA before attacking the vehicle fire; and
- Keeping SCBA on until overhaul is complete.

2.4 Overview of Vehicle Fires

Highway vehicle fires are one of the common types of fires to which fire departments respond. However, the number of highway vehicle fires that occur in the United States has been on a steady downward trend since 1980, when NFPA began tracking such incidents. According to NFPA, between 1980 and 1982, there was an average of approximately 447,000 highway vehicle fires per year; between 2009 and 2011, there was an average of approximately 187,500 highway vehicle fires per year.[17] A highway vehicle is defined as a vehicle intended for highway use and is classified as either a passenger road vehicle or truck/freight road vehicle.[18]

Passenger road vehicles are vehicles designed primarily to carry people on roadways. Passenger road vehicles include cars, buses, recreational vehicles, and motorcycles, but this classification does not include pick-up trucks, which are classified as trucks. Automobiles and cars are the most common highway vehicles involved in fires. Between 2003 and 2007, over 70% of highway vehicle fires involved automobiles or cars.[19,20]

Over the past few decades, changes in automobile structural components and interior elements have made modern vehicle fires more challenging. Modern vehicles contain an increased

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[17] Karter, M. *Fire Loss in the United States 2011*, NFPA Fire Analysis and Research Division, Quincy, MA, September 2012.

[18] Ahrens, M. *U.S. Vehicle Fire Trends and Patterns.* NFPA Fire Analysis and Research Division, Quincy, MA, June 2010.

[19] Ibid.

[20] More detailed information on passenger vehicle fires is available in: Long RT, et al. Passenger vehicle fires. Chapter 1, Section 21. Fire Protection Handbook, 20th Edition. National Fire Protection Association (NFPA), pp. 21-3–21-14, Quincy, MA, 2008.

amount of plastics and also present other hazards, such as compressed gas struts and absorbers that may explode under fire conditions. Modern vehicles can have components constructed from combustible metals that can react when water is applied. In addition, most vehicles now contain various supplemental restraint systems (SRS), i.e. airbags, to protect passengers during a collision and/or rollover. Airbags can deploy during the removal of crash victims, resulting in firefighter injuries if not properly handled.

Currently, the fire service is searching for ways to manage the recent and forecasted increase in the number and type of EDVs and the potential fires that may result. In addition to the hazards described above, these vehicles may present additional challenges for the fire service. Many of these vehicles have operational features with which fire service personnel are currently unfamiliar. For example, EDVs are normally silent when the vehicle is stopped. Thus an EDV can be “on” and ready to propel itself if the accelerator is depressed. Similarly, many HEVs “hibernate” when they come to a stop. These vehicles are also poised to move if the accelerator is depressed. Emergency responders can no longer assume that a vehicle is “off” when they cannot hear the engine running. However, the Department of Transportation (DOT) / National Highway Traffic Safety Administration (NHTSA) recently issued a Notice of Proposed Rulemaking for a minimum noise level to be added to EDVs, which could reduce or eliminate this issue in the future.[21]

EDVs contain high voltage batteries and electrical components that present a risk of shock or possibly electrocution to first responders if not properly handled. These are hazards not typically encountered during responses to fires in conventional ICE powered highway vehicles. Firefighters could be at risk for severe shock/injury/electrocution if they breach an energized high voltage electrical component or the high voltage battery. Firefighters may also be shocked by coming in contact with an energized high voltage component that has been compromised by fire or collision damage.

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[21] US DOT/NHTSA recently issued a Notice of Proposed Rulemaking related to the Minimum Sound Requirements for Hybrid and Electric Vehicles (49 CFR 571; Docket No. NHTSA-2011-0148) based on their Draft Environmental Assessment (Docket No. NHTSA-2011-0100), dated January 2013.

2.5 Conventional ICE Vehicle Fires

Firefighting practices for conventional ICE vehicle fires have not changed significantly over the past 30 years, although the fire service has adapted to the new hazards presented by modern vehicles, as described previously. Vehicle fires were once treated with relative complacency. Often, firefighters would wear only portions of their PPE ensemble when fighting a vehicle fire. Firefighters rarely took measures to protect themselves from inhaling the smoke and gases emitted from burning vehicles. Increased awareness of hazards associated with modern vehicles, coupled with a more highly developed culture of safety have caused the fire service to demand the use of all safety elements in order to prevent injuries and long term chronic illnesses.

The fighting of fires in modern vehicles may place firefighters at risk of injury from projectiles. Modern vehicles are constructed with various sealed, hollow components that may become pressurized when heated. Shock-absorbing bumpers, drive shafts, and the struts used to raise hoods and hatchbacks can rupture and become projectiles during a fire. It is essential that personnel are completely outfitted in structural turn-out gear to limit the potential for injuries from projectiles.

Another factor that has affected tactics in responding to vehicle fires is the use of plastics in vehicle components. Plastic components are found in nearly every compartment of modern vehicles (i.e. engine, cabin, and cargo area) and on the exterior of vehicles. Plastics can have a higher heat release rate than the products used in the construction of older vehicles. In addition, modern vehicles may have components made of metals that can burn and react with water.

The high heat release rate characteristics of the plastics necessitate the deployment of higher flow rates than might typically have been used in years past. These higher flow rates facilitate faster suppression of the fire and provide a higher level of protection to firefighters. It was common 30 years ago for firefighters to deploy ¾-inch to 1-inch booster lines to combat vehicle fires. Currently, firefighters deploy attack lines of at least 1.5 inches in diameter on vehicle fires, as recommended by the International Fire Service Training Association (IFSTA). IFSTA also recommends not relying on booster lines as they, "…do not provide the protection or rapid cooling needed to effectively and safely fight a vehicle fire." In addition, IFSTA encourages the deployment of a back-up line as soon as possible.[22]

The increased use of plastics and other materials, combined with a much clearer understanding of the detrimental health effects associated with vehicle fires has also resulted in changes to tactics. In the past, it was uncommon for firefighters to wear an SCBA while extinguishing a vehicle fire. A rising awareness of the vast array of volatile organic compounds (VOCs) and other gases emitted during a vehicle fire and their associated potential health effects have made the donning of SCBAs essential at every vehicle fire.[23]

2.6 Current Conventional ICE Vehicle Fire Tactics

In order to examine how the prevalence of EDVs should influence tactical operations at vehicle fires, it is important to look at how, in general, fires in conventional ICE vehicles are being extinguished currently. The following is a list of tasks in chronological order, typically performed at a vehicle fire. The operations described below assume there are at least four fire service personnel on scene. If fewer personnel are present, all of the tasks still must be performed by those personnel on scene.[24]

1. Upon arrival of the pumper(s), the apparatus is parked at least 50 feet from the burning vehicle, in such a position as to protect firefighters from vehicular traffic.
2. Firefighters (FF1 and FF2) and officer wear full PPE and SCBA. The pumper operator (FF3) is usually not in full PPE.
3. The officer performs a 360-degree size-up to identify hazards and determine if there are trapped occupants or injured civilians. The officer directs the firefighters throughout the extinguishment.

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[22] IFSTA. Essentials of Fire Fighting. Stillwater, OK: Fire Protection Publications. 2008.

[23] Fent, K. and Evans, D. Assessing the risk to firefighters from chemical vapors and gases during vehicle fire suppression. 2010.

[24] These tactics are the basic vehicle fire operations known to MFRI.

4. The firefighters stretch an attack line (1-1/2” or 1-3/4”) from the first arriving pumper. At this point, they don their SCBA (attach facemask to face and begin breathing off cylinder air), if they had not already done so.
5. The officer advises the firefighters of any observed hazards, victims, etc.
6. FF3 charges the attack line with water from the pumper’s water tank.
7. FF1 opens the nozzle’s bale and adjusts the stream of the nozzle. FF1 advances toward the vehicle with a wide pattern (60° fog) from uphill/upwind if possible, approaching toward one of the vehicles corners or the side of the vehicle, but not from the front or rear of the vehicle. The main priority of FF1 is to protect anyone who may be trapped in the vehicle.
8. FF2 or the officer chocks a wheel of the vehicle to prevent it from rolling as FF1 approaches the vehicle.
9. If the fire is in the passenger compartment and the window(s) have already failed, FF1 narrows the pattern to a 30° fog and directs the stream at close range into the cabin of the burning vehicle. If the windows have not failed, FF2 attempts to open the vehicle’s door with the door handle. If the doors are locked, FF2 uses a forcible entry tool to smash the vehicle’s window(s). FF1 can then direct the stream into the cabin.
10. If the fire is in the engine compartment, FF1 may direct the 30° fog stream up through the wheel-wells, through the grill, or under the hood from the base of the windshield. FF2 attempts to release the hood latch from the cabin of the vehicle and raise the hood. If the hood release will not work, FF2 may use a prying tool to create a gap between the hood and the fender through which the stream can be directed. Some departments utilize piercing nozzles that can be spiked though the hood to flow water into the engine compartment.
11. As fire in the engine compartment is knocked down, FF2 begins to force entry into the engine compartment by smashing/prying the hood lock/clasp or by using other tools to pry the back corners of the hood up and cut through the hood’s hinges. Some departments use powered saws to cut a hole in the hood.

12. Access to a fire burning in the trunk area may be gained using methods similar to those described for forcing entry to the hood. In some instances, a firefighter may be able to drive-in the trunk lock with a forcible entry tool and pick the disabled locking mechanism with a screwdriver.
13. FF1 moves around the vehicle with the attack line to access all burning areas of the vehicle. All visible fire is extinguished.
14. FF2 accesses the compartment housing the vehicle battery and cuts or disconnects the negative (ground) cable from the battery terminal (or both cables from both terminals), to prevent a shorted electrical system from reigniting a fire. This step is repeated if the vehicle has a second battery.
15. The firefighters and officer overhaul the vehicle to ensure the fire is completely extinguished by opening areas where fire may be hidden and/or smoldering; these areas are thoroughly soaked.
16. The officer does an investigation to determine the fire's origin and cause. The officer may call for a fire investigator if the cause is undetermined, incendiary, or suspicious.

2.7 Current EDV Fire Tactics

Firefighters are confronted with additional hazards and challenges when dealing with EDVs. The following best practices address EDV fires.[25,26,27] The operations described below do not state how many fire service personnel will be on scene. However many are present, all of the tasks still must be performed by those personnel on scene. These tasks include:

1. Identify the vehicle;
2. Immobilize the vehicle;
3. Disable the vehicle;

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[25] National Fire Protection Association. Electric Vehicle Emergency Field Guide. Quincy, MA. 2012.

[26] National Highway Traffic Safety Administration. Interim Guidance for Electric Vehicle and Hybrid-Electric Vehicles Equipped With High Voltage Batteries. Washington, D.C. 2012.

[27] SAE International, Surface Vehicle Recommended Practice J2990 NOV2012, 11-2012, Hybrid and EV First and Second Responder Recommended Practice.

4. Extrication;
5. Extinguishment; and
6. Overhaul operations.

2.7.1 Identify the Vehicle

Identification of a vehicle as an EDV is the first challenge firefighters face upon arriving at a vehicle fire. It must become part of every firefighter's size-up operations to determine if a burning vehicle is an EDV. In many instances, it may be readily apparent from the vehicle make/model or from exterior badges/logos. In other instances, it may not be so apparent. Damage sustained by the vehicle by either a collision/roll-over or the fire and smoke itself may make identification very difficult. During size-up of the incident, firefighters should look for warning labels on the EDV that warn of high voltage. Some labels may be less direct at communicating the fact that the vehicle in question is an EDV.

If the fire is confined to the engine compartment or trunk, a firefighter may be able to get a clear view of the instrumentation on the vehicle's dashboard. In this case, firefighters should look for words and symbols that indicate the vehicle is an EDV. If the vehicle is "on", the firefighter may be able to see dash symbols indicating charge status of the battery, or that there isn't a fuel gauge.

Whatever method is used to identify the vehicle, all personnel operating at the scene must be made aware if the vehicle on fire is an EDV.

2.7.2 Immobilize the Vehicle

As with conventional ICE vehicles, it is important to place chocks to the front and rear of one of the wheels to prevent the vehicle from rolling. EDVs can hibernate; although it may not be obvious that the engine is running, the vehicle may be poised to move as soon as the accelerator is depressed. EDVs should be chocked to prevent any inadvertent movement of the vehicle as soon as possible. Although a good preventative measure, chocking alone may not prevent movement if the drive system is engaged. If possible, setting the emergency brake and placing the vehicle in park can add additional protection against inadvertent movement.

2.7.3 Disable the Vehicle

Determine the status of the vehicle by viewing the dash display, the position of the key in the ignition, and/or the power button to see if it has a lit indicator light. If the vehicle is “on”, turn the key to the “off” position. Some new EDVs operate with a proximity key. If the proximity key is within range of the vehicle (usually less than 16 feet), the vehicle is powered “on” by a button on the dash. Turn the vehicle “off” by pressing this button. Then remove the key from the ignition and place it beyond the range of the vehicle (typically greater than 16 feet).

In addition to the high voltage battery that powers an EDV motor, there is a conventional 12-volt battery located somewhere on the vehicle. The 12-volt battery powers many of the vehicle accessories and is used to control high voltage contactors. Severing the 12-volt battery’s ground cable will prevent the vehicle from powering up. Cutting the 12-volt battery in a vehicle that is “on”, however, will not turn the vehicle “off”, as power supplied by the DC/DC convertor may keep the contactor closed. After the vehicle has been powered down by the key/ignition button, firefighters should further disable the vehicle by severing the 12-volt battery’s negative ground cable. The officer should refer to NFPA’s *Electric Vehicle Emergency Field Guide* or other appropriate guides for vehicle specific information on the location of the 12-volt battery and fuses that can be pulled to disable the high voltage system.

If firefighters are unable to gain access to the area housing the 12-volt battery or fuses, they may attempt to isolate the high voltage system by removing or switching off the high voltage main disconnect (or “high voltage service disconnect”). Firefighters will need a guide, such as NFPA’s *Electric Vehicle Emergency Field Guide*, in order to determine the location of the high voltage main disconnect and identify the proper method for de-energizing the system. Firefighters may not be able to complete this step until after the fire is extinguished.[28] Further detail on recommendations for high voltage system disabling can be found in SAE International Recommended Practice J2990. J2990 recommends that vehicle manufacturers provide a

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[28] Delphi Corporation. Hybrid Electric Vehicles for First Responders. Troy, MI. 2012.

minimum of two methods of initiating the disconnection of the propulsion system from the high voltage sources. Utilizing more than one method increases the likelihood that the high voltage sources have been disconnected. SAE recommends the following methods of initiating the disconnection in their preferred order:

1. Automatic shutdown of the high voltage system based on the detection of a prescribed level of vehicle impact;
2. Switching the ignition switch or power button to the "off" position (assuming there is no damage to the shutdown circuits or high voltage discharge circuits;
3. Cutting or disconnecting the negative and positive 12-volt battery cables to discharge the 12-volt system while also cutting or disconnecting the DC/DC converter's 12-volt output cable; and/or
4. Removing the manual disconnect. However, this was listed as not being a primary method for first responders to disable the vehicles high voltage circuits, as there are a variety of manual disconnect designs and locations.

Firefighters assigned the task of disabling the high voltage system via the main should consider wearing Class 0/1000v high voltage safety gloves with outer leather covers. However, a review of a selection of automotive manufacturer requirements for electrical PPE showed significant variations according a recent NFPA workshop.[29] This workshop also highlighted that there are significant differences between PPE used by the fire service and electrical professionals when handling energized electrical equipment.

It may take up to ten minutes for a high voltage system to dissipate its energy after the main has been pulled/switched off. However, it should be noted that high voltage will still be present within the battery pack and on the battery pack side of the high voltage main disconnect switch.

Should the EDV be plugged into a charging station at the time of a fire, the best practice would include isolating the electrical supply to the charging station at a safe location by trained professionals prior to any attempts at disabling the high voltage system within the vehicle.

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[29] Emergency Responder Personal Protective Equipment (PPE) for Hybrid and Electric Vehicles May 1, 2012.

2.7.4 Extrication

Upon arrival at an incident involving the extrication of victims from an EDV, response personnel should use the steps identified above to immobilize and disable the vehicle. Due to the degree of damage to the vehicle and/or the physical aspect of the vehicle, responders may have to employ secondary methods for disabling the vehicle, as described above. The supplemental restraint systems in most vehicles will remain active if the 12-volt batteries are not disconnected.

A damaged high voltage battery may emit corrosive, toxic, and flammable fumes. If responders become aware of unusual odors and/or sense irritation of their eyes, nose, or throat, they should don PPE and SCBA. In addition, responders should use ventilation techniques to protect the occupants of the vehicle and prevent the build-up of flammable vapors in the trunk or passenger compartment.

A charged attack line should be staged in close proximity to the vehicle during extrication. Responders should constantly monitor for indications that a damaged battery may be overheating, such as sparking, smoking or making bubbling sounds.

Throughout stabilization and extrication, response personnel must avoid inadvertent contact with all high voltage cabling and high voltage components. Response personnel should never cut through any high voltage electrical component. Personnel performing the extrication should visually check for the presence of high voltage electrical cabling and components of the supplemental restraint system prior to initiating every cut or displacement (e.g. pry). The location and routing of high voltage components may prevent some advanced extrication techniques, such as trunk tunneling and gaining access through the underside or floor pan of the vehicle.

2.7.5 Extinguishment

Fires confined to the cabin or trunk of an EDV can be extinguished using tactics associated with conventional vehicles. EDVs contain the same polyvinyl chlorides, polyurethanes, and reactive metals as conventional vehicles, as well as the previously discussed projectile hazards. Firefighters should be in full PPE with SCBA donned.

Firefighters must avoid contact with any orange electrical cables and components that have high voltage warning labels. If a fire has burned warning labels or rendered them otherwise illegible, firefighters should not touch any electric drive or drive system component. Firefighters should never attempt to breech a high voltage battery or its casing for any reason.

Fires in the engine compartment of an EDV may require different tactics. Many high voltage components are directly accessible from the engine compartment. Defensively applying a fog stream through existing openings in the wheel-wells and grill can be done safely to knock down the fire. Firefighters should not attempt to force entry into the engine compartment with prying tools, nor should they attempt to spike or cut the hood or fenders with a piercing nozzle, cutting tool, or prying tool. Performing any of these tasks could result in a firefighter being severely shocked or electrocuted.

It may be the case that firefighters are unable to gain access to the engine compartment. In this instance, defensive fire suppression tactics should be employed until the fire is completely extinguished.

If there are no exposures and the fire involves the high voltage battery, currently defensive tactics are recommended. Because of the potential difficulty of applying a sufficient amount of extinguishing agent to a burning high voltage battery, the incident commander may allow the vehicle to burn itself out. If the high voltage battery is involved in the fire, an offensive attack may be recommended if there are exposures (other vehicles, buildings, etc.). If the high voltage battery is not involved in the fire, an offensive attack may be mounted regardless of whether there are exposures.

2.7.6 Overhaul Operations

Following extinguishment, the EDV must be properly overhauled. Responders should first verify the vehicle has been properly immobilized and disabled, and take appropriate steps to accomplish these tasks if they have not been completed. As during all phases of any response to incidents involving an EDV, responders must avoid contact with any high voltage component during the overhaul phase of the incident. Responders should never attempt to cut, breach or remove the high voltage battery or any high voltage component. Diligent thought and care should be exercised before manipulating the EDV in any way with any forcible tools.

During overhaul, firefighters will verify that the fire has been completely extinguished. Firefighters should not drive prying tools into any area that may house or cover high voltage components. Firefighters should also carefully observe the high voltage battery compartment to ensure it is not smoking, sparking, or making bubbling sounds. A thermal imaging camera may be used to assess the temperature of the battery and to assist in determining if it is producing heat.

Responders should contact a dealer/manufacturer representative to de-energize the high voltage battery (if possible) and to determine the final disposition of the vehicle. Responders should advise the company recovering the vehicle that it is an EDV, and advise them not to store the vehicle inside a structure or within 50 feet of a structure or other vehicle in accordance with current NFPA guidance. EDVs should be recovered on a flatbed truck.

2.8 High Voltage Battery Fires

Fires may occur in an EDV high voltage battery, or a fire may extend to the battery. Most EDV batteries currently on the road are NiMH.[30] However, the number of cars powered by Li-ion batteries is increasing. These batteries may exhibit different burning characteristics and react differently to heat exposure. There is very little literature concerning recommended tactics for EDVs in which the battery is burning. Some literature encountered during this review is contradicted by other literature, demonstrating that further testing and research, such as in this testing program, is needed.

To show the variation in reviewed literature regarding high voltage battery fires, some excerpts of the literature are quoted below.

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[30] Delphi Corporation. Hybrid Electric Vehicles for First Responders. Troy, MI. 2012.

The NFPA's *Electric Vehicle Emergency Field Guide*[31] states the following:

> *The use of water or other standard agents does not present an electrical hazard to firefighting personnel.*
>
> *If an HV battery catches fire, it will require a large, sustained volume of water.*
>
> *If Li-ion HV battery is involved in fire, there is a possibility that it could reignite after extinguishment. If available use thermal imaging to monitor the battery. Do not store a vehicle containing a damaged or burned Li-ion HV battery in or within 50ft. of a structure or other vehicle until the battery can be discharged.*

The Fire Protection Research Foundation report, *Fire Fighter Safety and Emergency Response for Electric Drive and Hybrid-Electric Vehicles*[32] states:

> *Dry chemical, CO_2, and foam are often the preferred methods for extinguishing a fire involving batteries, and water is often not the first extinguishing agent of choice.*
>
> *Another important consideration with an EV or HEV fire is that the automatic built-in protection measures to prevent electrocution from a high voltage system may be compromised. For example, the normally open relays for the high voltage system could possibly fail in a closed position if exposed to heat and if they sustain damage. Further, short circuits to the chassis/body may become possible with the energy still contained in the high voltage battery or any of the high voltage wiring still connected to the battery.*

Delphi Corporation's, *Hybrid Electric Vehicles for First Responders*[33] states:

> *Firefighting techniques for vehicles using Li-ion battery packs should be treated like any electrical fire by using Class C extinguishing agent.*
>
> *Initial attack on hybrid HEV battery pack fires: perform a fast aggressive attack.*
>
> *Should a fire occur in the NiMH high voltage battery, attack crews should utilize a water stream or fog pattern to extinguish any fire within the trunk. The incident commander*

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[31] National Fire Protection Association. Electric Vehicle Emergency Field Guide. Quincy, MA. 2012.

[32] Grant, C. Fire Fighter Safety and Emergency Response for Electric Drive and Hybrid Electric Drive Vehicles. Quincy, MA. 2010.

[33] Delphi Corporation. Hybrid Electric Vehicles for First Responders. Troy, MI. 2012.

> *should make the call on whether to perform an offensive or defensive fire attack in the area around the HEV battery pack.*

The National Highway Traffic Safety Administration's publication, *Interim Guidance for Electric and Hybrid Electric Vehicles Equipped with High Voltage Batteries*[34] states:

> *If the fire involves the lithium-ion battery, it will require large, sustained volumes of water for extinguishment. If there is no immediate threat to life or property, consider defensive tactics, and allow the fire to burn out.*

Based on the above, currently there is no consensus on best practices for extinguishing EDV battery pack fires. Preliminary results[35,36] indicate that water can be an effective extinguishing agent on both NiMH and Li-ion batteries; however, none of the literature reviewed indicated the level of shock/electrocution hazard from directly applying a water stream to an energized high voltage battery that has been compromised by heat and fire. Furthermore, some of the testing was conducted by applying water directly on EDV batteries that were free standing (not installed in vehicles). While these test showed that water was an effective extinguishing agent, it may be difficult to flow large volumes of water on a battery that is actually installed in/under the vehicle.

2.9 Summary

Current versions of various firefighting guidelines are consistent with each other regarding first responder firefighting tactics to immobilize/disable the vehicle. However, a new step for first responders has been identified when comparing tactics for conventional ICE vehicles and EDVs. This involves identifying whether or not the vehicle is an EDV. Firefighters typically will not know what type of vehicle is involved before they arrive at the scene of the incident or the type of vehicle may not be obvious once they arrive and begin their tactics. As such,

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[34] National Highway Traffic Safety Administration. Interim Guidance for Electric Vehicle and Hybrid-Electric Vehicles Equipped With High Voltage Batteries. Washington, D.C. 2012.

[35] Egelhaaf , M. and Kreß, D. Fire Fighting of Li-Ion Traction Batteries, DEKRA Automobil GmbH, SAE International, 2012

[36] Delphi Corporation. Hybrid Electric Vehicles for First Responders. Troy, MI. 2012.

performing the same practices for all vehicle fires would ensure that first responders are acting safely and appropriately regardless of the type of vehicle involved in the incident.

In regards to suppression, in most instances, available literature suggests that the application of water can extinguish EDV fires, as is the case with most fires in conventional ICE vehicles. However, it may be difficult to apply a sufficient flow of water to a burning battery installed in/under a vehicle with the tools currently available to the fire service.

In most EDVs, the battery is located in the chassis, housed in a plastic or metal shell. In these cases, water may not be sufficient to achieve full extinguishment, but rather the water may serve as a medium to transfer heat and cool the battery and cell components as thermal runaway subsides and or is interrupted by the application of water.

Based on a review of the literature, the final topic that requires further research is the electrical hazard presented by burning vehicle batteries. Some of the literature[37] reviewed suggests that a burning EDV battery has the potential to discharge electrical energy to the frame and body of the vehicle. Furthermore, the application of water streams to burning EDVs at close range may also become recognized as an unacceptable practice, if it is found that the potential for high voltage shock exists.[38]

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[37] Grant, C. Fire Fighter Safety and Emergency Response for Electric Drive and Hybrid Electric Drive Vehicles. Quincy, MA. 2010.

[38] Backstrom, R. et al. “Firefighter Safety and Photovoltaic Installations Research Project.” Underwriters Laboratories, Northbrook, IL, November 29, 2011.

3 Testing Program Summary

Exponent, in conjunction with the Project Technical Panel and their advisory groups, identified three different battery assemblies for full-scale testing. The three batteries procured were different in size and vehicle installation position to simulate the varying hazards emergency responders could face in the field depending on the automobile manufacturer. A more detailed description of each battery is provided in Section 4.

The full-scale fire tests were separated into two categories: (1) free burn, unsuppressed HRR testing of a standalone battery pack and (2) full-scale suppression testing of a battery pack in its correct mounting location positioned inside a VFT, along with other appropriate combustible materials, including vehicle interior finishes.

Once the battery fire self-extinguished, as in the case of the unsuppressed fire, or extinguished, as in the suppressed fires, Exponent continued to monitor the batteries visually and through a combination of thermal imaging and thermocouple temperature measurements. This was performed to provide data on the safe handling of post-fire batteries for fire responders and those involved in overhaul and storage.

The free burn, unsuppressed HRR test was performed on one standalone battery. Data collected during this test included:

- HRR;
- Products of combustion (gas sampling);
- Temperatures;
- Heat fluxes;
- Projectile observations;
- Battery internal temperature;
- Battery internal cell voltage measurements;

- Thermal imaging;
- Still photography; and
- High definition video.

The full-scale fire suppression tests were performed in conjunction with MFRI and their firefighter training staff. Data collected included:

- Temperatures;
- Heat fluxes;
- Projectile observations;
- Suppression water sampling;
- Volume of suppression water flow;
- Nozzle voltage and current measurements;
- Chassis voltage and current measurements;
- Battery internal temperatures;
- Battery internal cell voltage measurements;
- Thermal imaging;
- Still photography;
- High definition video; and
- MFRI staff / firefighter observations.

Battery packs were tested in the configuration and arrangement as they would be located within the actual vehicle. To ignite the battery packs, an external gas burner system was used. The gas burners were located under the vehicle to simulate a moderate size gasoline pool fire underneath the battery pack.

A detailed description of these measurements, the test setups and the test protocols for each test series is provided in Section 5.

4 Battery Descriptions

In conjunction with NFPA's FPRF and the Project Technical Panel, Exponent procured batteries from two car manufacturers for testing, designated Battery A and Battery B.[39] Both of the batteries procured were based on a Li-ion technology are currently being used in production vehicles in the United States. Battery A is a 4.4 kWh battery that is installed under the rear cargo compartment of the vehicle. Battery B is a 16 kWh battery that is installed under the vehicle floor pan and spans nearly the length of the vehicle from the rear axle to the front axle in a T-shaped configuration. Battery A and Battery B span a wide spectrum of battery sizes and vehicle installation positions to simulate the varying hazards emergency responders could face in the field during actual EDV fire incidents.

As part of the agreement with the vehicle manufacturers who graciously donated batteries, the EDV batteries were not opened, altered, or manipulated prior to, during or after the fire tests. The designs, descriptions, and details of the batteries in the following sections were provided to Exponent by the vehicle manufacturers, as well as from publically available information sources.

4.1.1 Battery A

Battery A is designed for a PHEV and features a large capacity high voltage hybrid vehicle (HV) battery assembly that contains sealed Li-ion battery cells. The 4.4 kWh HV battery pack is enclosed in a metal case (see Figure 6) and is rigidly mounted in the lower portion of the rear cargo area behind the rear seat, as shown in Figure 7. The metal case is isolated from high voltage and concealed and separated from the passenger compartment by a molded plastic cover with carpeting, as shown in Figure 8. The electrolyte used in the Li-ion battery cells is a flammable organic electrolyte.

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[39] Three (3) approximately 10 kWh Li-ion batteries were procured in addition to Battery A and Battery B from a third manufacturer. However, once procured, the battery packs were found to have significant anomalies and damaged cells, which presented significant safety hazards associated with handling and charging the battery packs. Therefore, these batteries were not included in the test program.

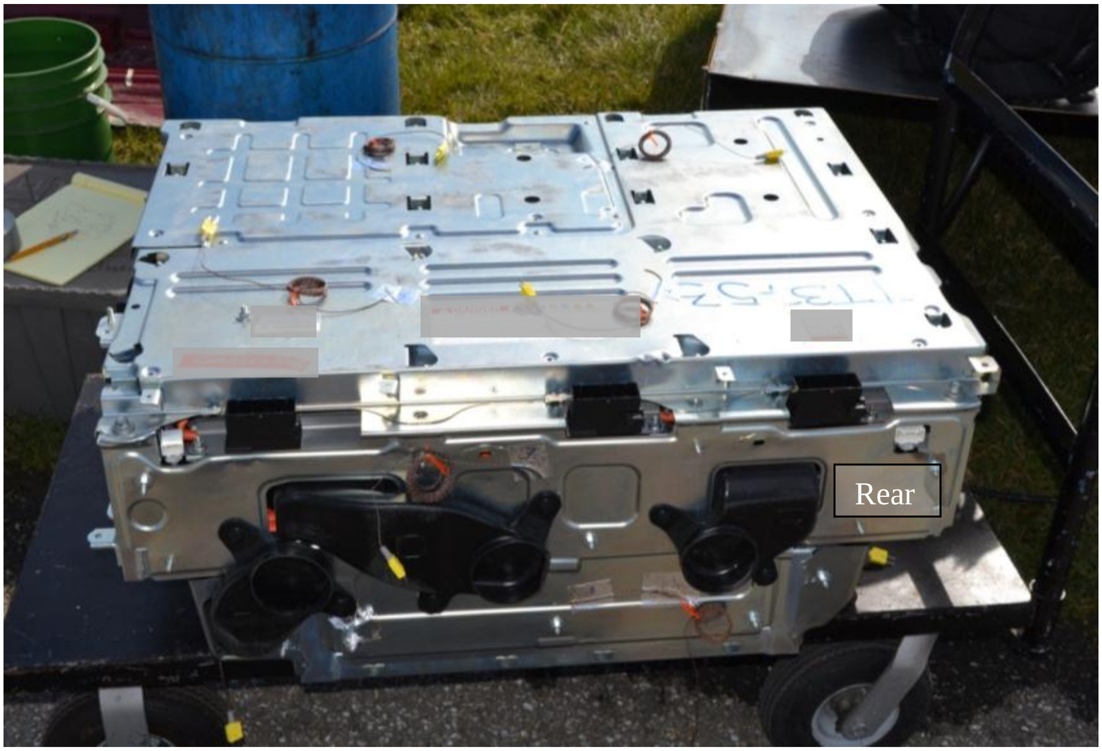

Figure 6 Battery A

Figure 7 Battery A cargo area over the battery compartment

Figure 8 Battery A compartment in cargo area with carpet and molded plastic cover removed

4.1.2 Battery B

Battery B is designed for an EREV and features a battery assembly that contains sealed Li-ion battery cells. The 16 kWh battery pack sits on top of a steel plate and is enclosed in a fiberglass case, as shown in Figure 9. The T-shaped battery spans nearly the length of the vehicle from the rear axle to the front axle and is rigidly mounted underneath the vehicle floor pan, as shown in Figure 10. A vehicle passenger compartment floor pan separates the battery assembly from the passenger compartment. The electrolyte used in the Li-ion battery cells is a flammable organic electrolyte.

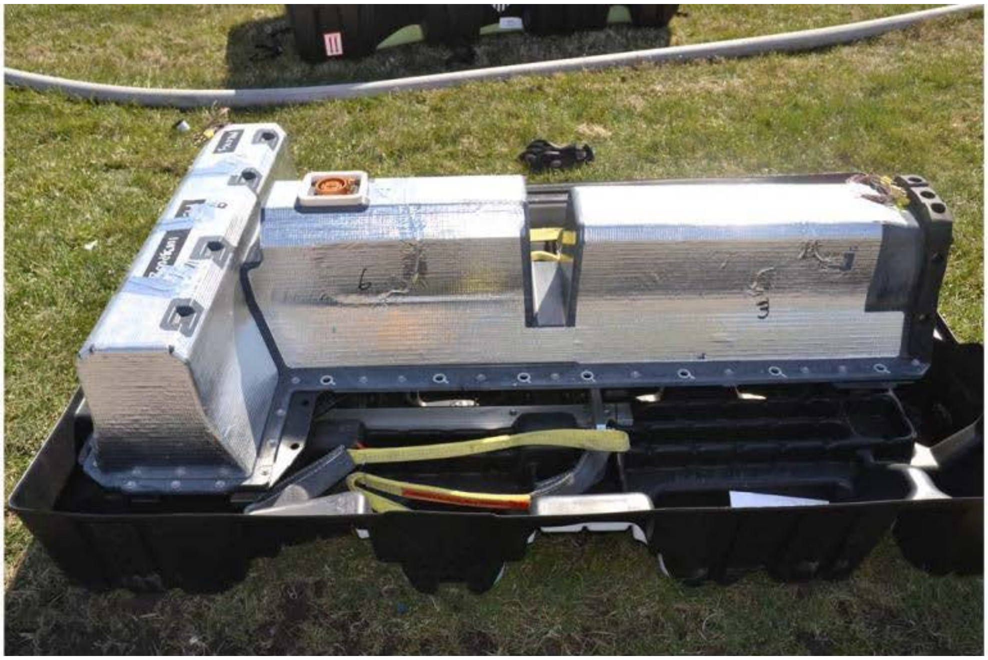

Figure 9 Battery B

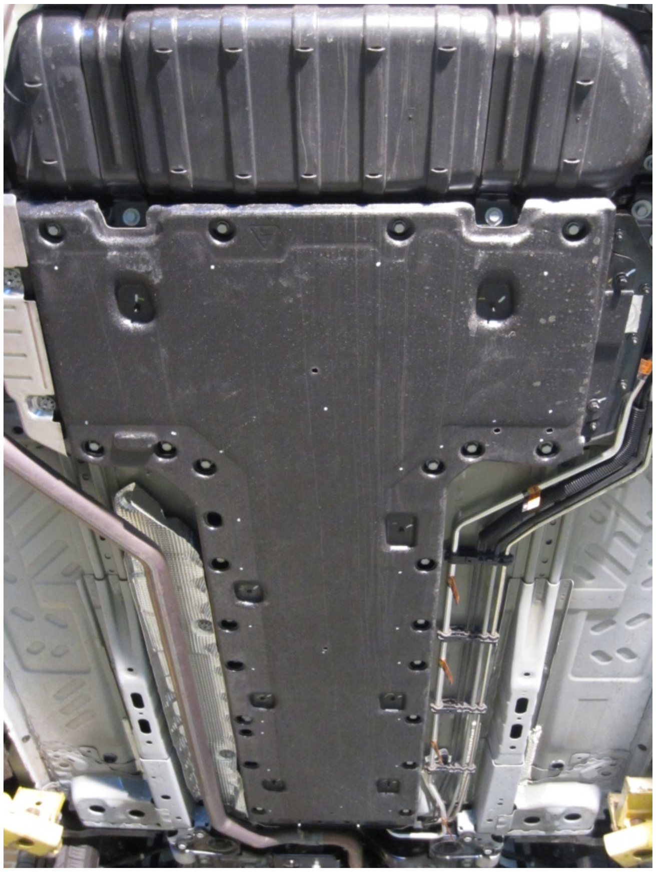

Figure 10 Battery B installed in vehicle

5 Test Setup

The full-scale fire tests were separated into two categories: (1) HRR testing and (2) full-scale fire suppression testing. The test setup for each phase of the project is described herein.

The overall intent of the testing is to provide a repeatable scientific experiment that evaluates water-based suppression of an EDV fire. The data generated will then be used to answer many of the questions first responders have regarding EDV fires. In addition, the data will facilitate any necessary revision to the NFPA training materials for first responders regarding how to safely and efficiently extinguish EDV fires while highlighting how these fires are different from those involving traditional ICE vehicles. The following are key assumptions related to the testing:

- The EDV batteries were tested at a 100% SOC.
- The suppression tests were conducted in a modified VFT capable of housing the different manufacturer battery packs.

5.1 HRR Testing

The full-scale HRR testing was performed at Southwest Research Institute (SwRI) in San Antonio, Texas.[40] The objective of the HRR testing was to determine the amount of energy released from the battery alone when it was ignited by an external ignition source. The secondary objective of the testing was to verify the battery could be induced into thermal runaway with the external ignition source (propane fueled burners positioned beneath the battery) for use during the full-scale fire suppression tests and to collect data as to the indications that the battery was experiencing thermal runaway. Due to a limited number of batteries available for the project, only one standalone battery pack was designated for HRR testing from the Battery B sample set. Data collected during this test included:

- HRR;

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[40] SwRI is one of the oldest and largest independent, nonprofit, applied research and development organizations in the United States. The Fire Technology Department is one of the world's largest organizations dedicated to fire research and testing.

- Products of combustion (gas sampling);
- Temperatures;
- Heat fluxes;
- Projectile observations;
- Battery internal temperature;
- Battery internal cell voltage measurements;
- Thermal imaging;
- Still photography; and
- High definition video.

SwRI was responsible for providing the facility for the fire test and performing the following analyses:

- HRR measurements using oxygen calorimetry;
- Products of combustion by collecting gas samples and analyzing the gas using Fourier transform infrared spectroscopy (FTIR);
- Temperature measurements using thermocouples;
- Heat flux measurements using heat flux gauges;
- Test observations;
- Still photography; and
- High definition video recording.

The full SwRI report detailing these measurements is provided in Appendix A.

Exponent was responsible for the following:

- Test observations;
- Still photography;

- High definition video recording;
- Providing and controlling the external burner assembly;
- Internal battery cell voltage and temperature measurements through direct communication with the battery; and
- Thermal images of the battery during and after the test.

5.1.1 Battery Positioning

Battery B was centered under a 20 foot by 20 foot hood supported by five stainless steel legs, as shown in Figure 11 and Figure 12. The leg supports held the battery in place, twenty inches above the ground to provide a viewing angle to the bottom of the battery during testing.

Figure 11 Battery B configuration and burner locations for HRR testing

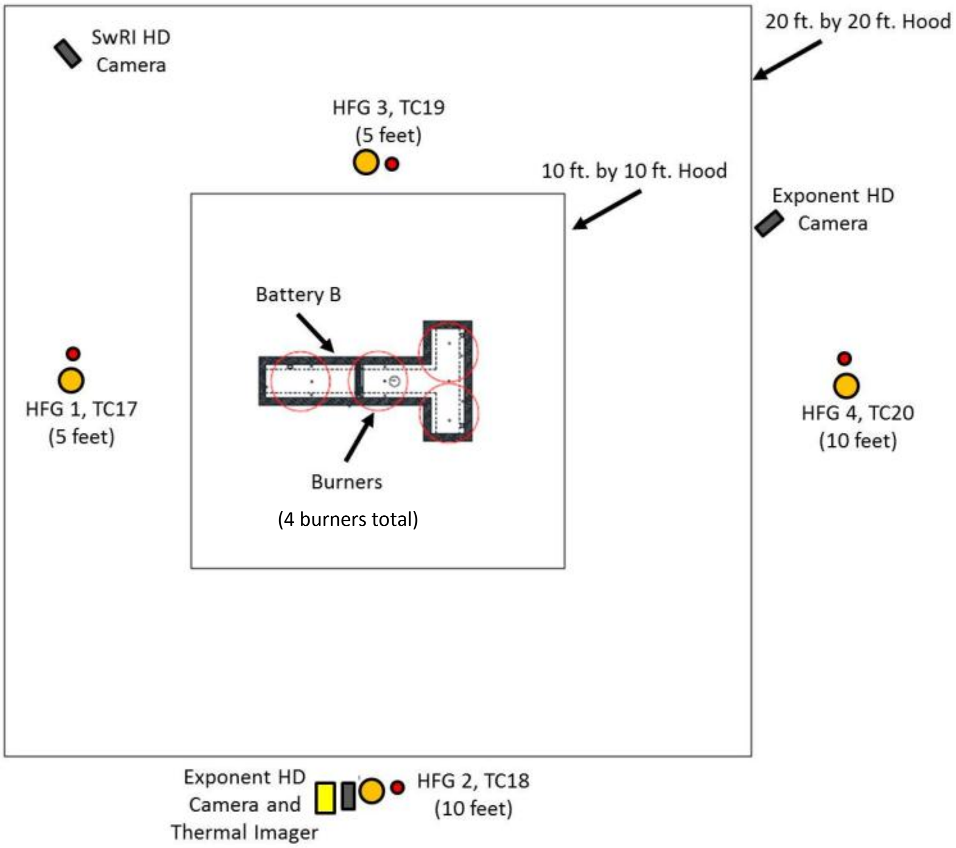

Figure 12 Layout and arrangement of the HRR testing perimeter instrumentation

5.1.2 Burner Description

As part of the agreement with the vehicle manufacturers, the EDV batteries were not to be opened, altered, or manipulated internally prior to, during, or after testing. This included ignition of the batteries during testing. As such, an external ignition source was chosen. Fires occurring from some type of internal cell fault are therefore outside the scope of this project. Given that EDVs are still a small percentage of the marketplace, a collision involving an EDV and an ICE vehicle was considered a possible scenario. Based on a review of NFPA data on vehicle fire risk[41], flammable or combustible liquids or gases were the first item ignited in 31% of U.S. highway vehicle fires, resulting in 70% of civilian deaths, 58% of civilian injuries, and 31% of the direct property damage. As such, a pool fire scenario under the EDV was selected

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[41] Ahrens, M. “U.S. Vehicle Fire Trends and Patterns.” National Fire Protection Association, Quincy, MA; June 2010.

as the likely ignition scenario where the batteries become near fully involved and "burning on their own."

While previous tests were successful in burning the batteries with a pool fire exposure, a pool fire ignition source is not easily "throttled" or "turned off." As such, four propane-fueled gas burners were utilized as the external ignition source in this test series to induce the batteries into thermal runaway. Propane fueled burners were chosen to allow for definitive control of the exposure and repeatability, as well as to allow for turning off the exposure once the battery was in thermal runaway so that the "battery only" scenario fire could be evaluated.

The burner assembly comprised three main sections: fuel supply, fuel control, and burners, as shown in Figure 13 and Figure 14 and listed in Table 1. Propane gas was supplied from two 100-gallon (400 lb.) capacity cylinders and regulated to a working pressure of up to 35 psi. The gas cylinders were connected to the fuel control section via 9/16-inch hoses, which fed into a 1-inch stainless steel pipe section, a 1-inch manual shutoff valve and a 1-inch electric-powered solenoid valve (ASCO Model HV285926002), respectively.

Table 1 Burner Assembly Components

Burner Assembly Component	Figure 13 / Figure 14 Number
Fuel Supply: 100 gallon (400 lb.) propane cylinders 9/16-inch diameter hoses 1-inch diameter stainless steel piping	1
Fuel Control:	
1-inch manual shutoff valve	2
1-inch solenoid valve	3
1-inch mass flow controller	4
DAQ	8
Burners:	
1/4-inch manual burner isolation valve	5
Second stage regulator and 1/4-inch stainless steel braided hose	6
19-inch diameter burners	7

Downstream of the solenoid valve, a mass flow controller (Bronkhorst M+W Model D6383, with ±2% accuracy) was instrumented to allow for measurement and control of the LP-gas mass supply rate. The solenoid valve and the mass flow controller were controlled by a data acquisition system (DAQ), which is discussed in Section 5.1.7. All sections of pipe between the manual shutoff valve, solenoid valve and mass flow controller were 1-inch and constructed of stainless steel.

From the outlet of the mass flow controller, LP-gas continued via 1-inch stainless steel piping to a four-outlet manifold, allowing for simultaneous operation of up to four (4) burners. From each of the manifold outlets, a ¼-inch manual isolation valve and a second stage regulator are instrumented, respectively. A ¼-inch flexible stainless steel braided hose 40 feet in length was used to connect the outlet of the second stage regulator to a circular, 19-inch diameter gas burner containing eighty-eight (88) 0.30-inch diameter nozzles. Exponent utilized four burners positioned under the span of the T-shaped battery to provide an even heat source to the entire battery pack, as shown in Figure 15 and Figure 16. The burners were placed six inches under the battery, as measured from the top of the nozzle tip to the bottom of the battery frame to allow for optimal flame development from the burners.

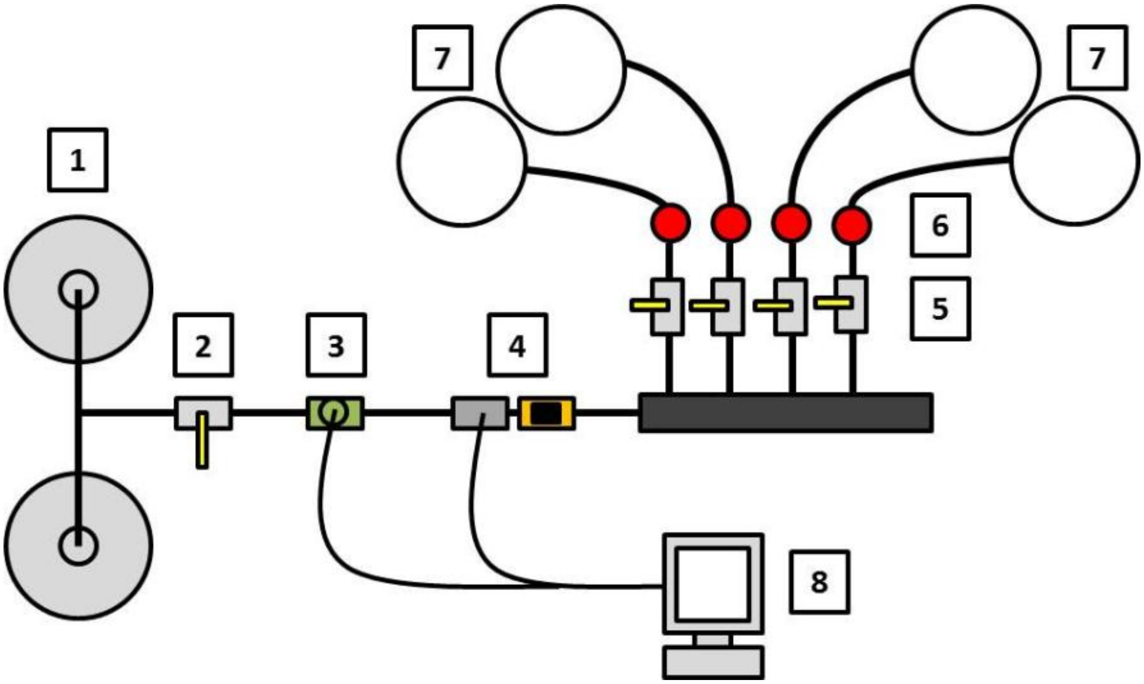

Figure 13 Layout of burner assembly

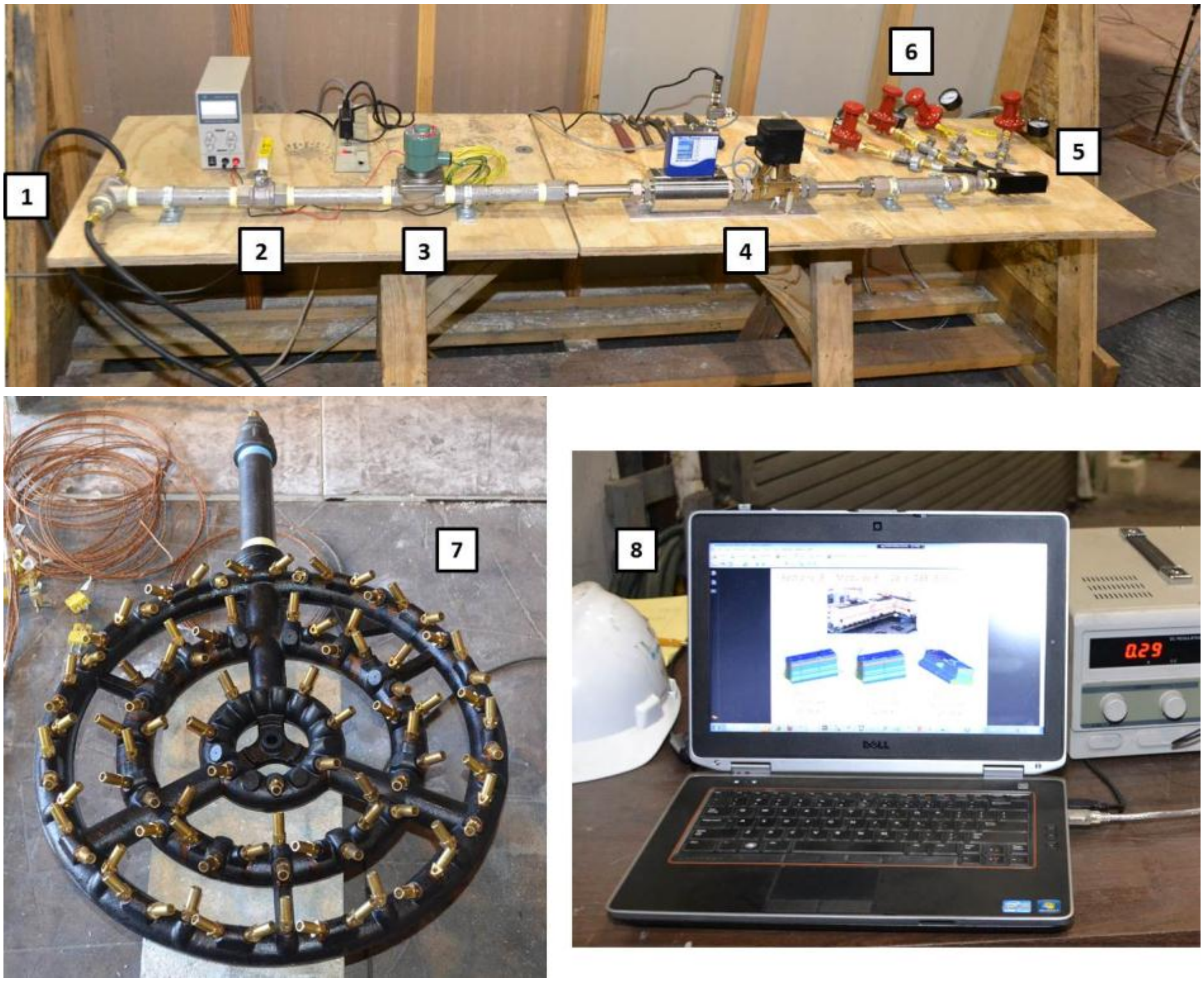

Figure 14 Burner assembly (top); single burner (bottom left); and DAQ (bottom right)

Figure 15 T-shaped burner arrangement comprised of four burners

Figure 16 Four burners positioned under Battery B

5.1.3 HRR Measurements

The HRR was measured during the test by SwRI using oxygen consumption calorimetry. This requires the measurement of gas concentrations, namely oxygen (O_2), carbon dioxide (CO_2), and carbon monoxide (CO) in the exhaust duct and the volumetric flow of these gases. The products of combustion and entrained air were collected in a hood and extracted through a duct by an exhaust fan. A sample of the gas was drawn from the exhaust duct through a sample line by a pump and analyzed for O_2, CO_2, and CO concentrations. The gas temperature and differential pressure across a bi-directional probe were also measured to determine the mass flow rate of the exhaust gases. In addition, smoke production and smoke temperature measurements were taken throughout the duration of the test.

5.1.4 Products of Combustion Gas Sampling

Product of combustion gas sampling was performed by SwRI using FTIR spectroscopy to analyze the byproducts of the battery fire. SwRI performed these measurements by positioning a smaller 10-foot by 10-foot steel truncated cone hood above the battery pack, as shown in Figure 17. The hood was positioned in this manner to concentrate the products of combustion for FTIR sampling. The top of the hood was open to allow the products to temporarily collect within the smaller hood but ultimately escape into the large hood setup for HRR measurements. A gas sampling tube with nine (9) 1-mm holes was located across the top of the smaller hood and was connected to a heated sample line. A pump drew the gases through the 1-mm holes and heated sample line and filled Tedlar grab bags at five minute intervals during testing.

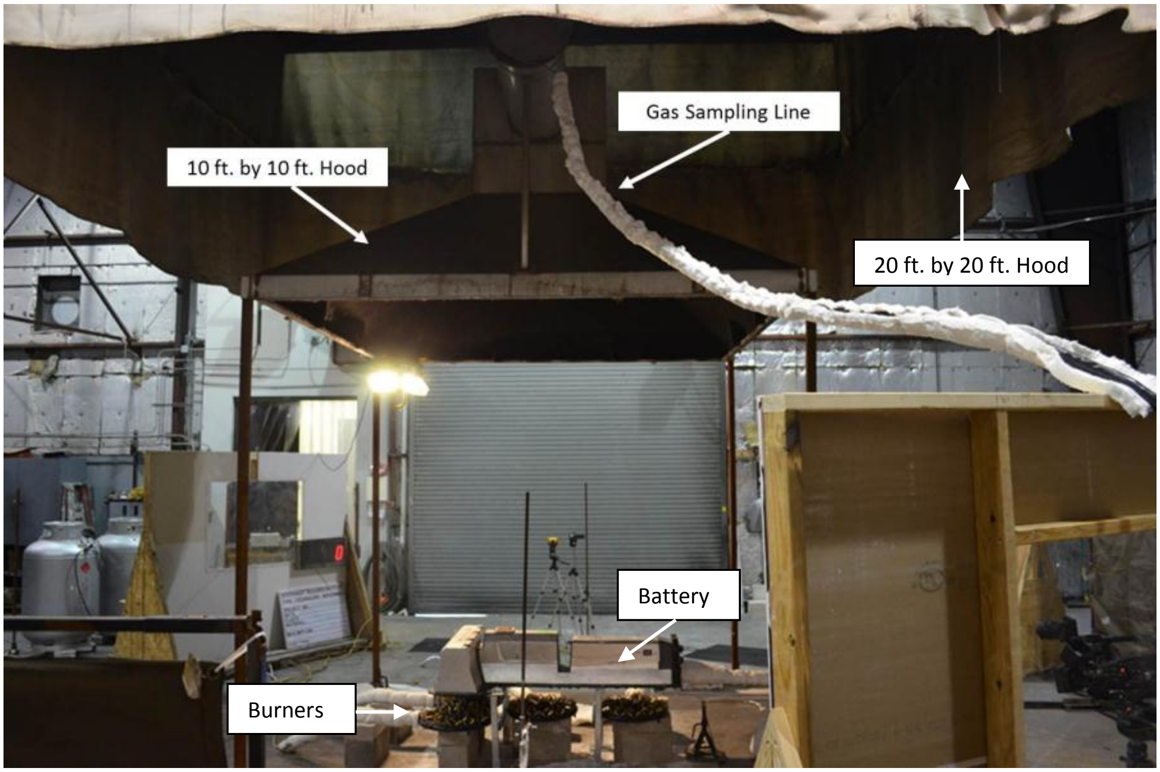

Figure 17 SwRI hood and test arrangement

5.1.5 Temperature and Heat Flux Measurements

The temperature and heat flux measurements were performed by SwRI using a total of twenty Type K thermocouples (TCs) and four Schmidt-Boelter HFGs, as shown in Figure 12 and Figure 18. The location and measurement description of the TCs and HFGs are listed in Table 2 and Table 3.

Table 2 Summary of TC Locations

TC	Measurement	TC	Measurement
1	Battery exterior	11	Battery exterior
2	Battery exterior	12	Battery exterior
3	Battery exterior	13	Battery interior
4	Battery exterior	14	Battery interior
5	Battery exterior	15	Battery interior
6	Battery exterior	16	Flame temperature
7	Battery exterior	17	Air temperature (5 ft)
8	Battery exterior	18	Air temperature (10 ft)
9	Battery exterior	19	Air temperature (5 ft)
10	Battery exterior	20	Air temperature (10 ft)

Table 3 Summary of HFG Locations

Heat Flux Gauge	Measurement	Thermocouple	Measurement
1	Heat Flux (5 ft)	3	Heat Flux (5 ft)
2	Heat Flux (10 ft)	4	Heat Flux (10 ft)

TCs 1 through 12 were fixed to the exterior surface of the battery using Omega Bond CC High Temperature Bonding cement. The cement was located over the TC bead and was allowed to dry for at least 24 hours prior to testing. TCs 13 through 15 were located inside three vents on the battery, as shown in Figure 19. The TCs were placed through the vent opening to measure the internal air temperature within the battery casing. The vent hole was covered with the appropriate self-adhesive covers provided by the manufacturer. TC 16 was positioned 1-inch under the bottom steel plate of the battery pack, just above the burners to measure the approximate flame temperature. TCs 17 through 20 were positioned around the perimeter of the battery pack to measure the air temperature at five and ten foot standoff distances. HFGs 1 through 4 were also positioned at the same five and ten foot standoff distances and were capable of measuring a radiant heat flux between 0 and 50 kW/m^2.

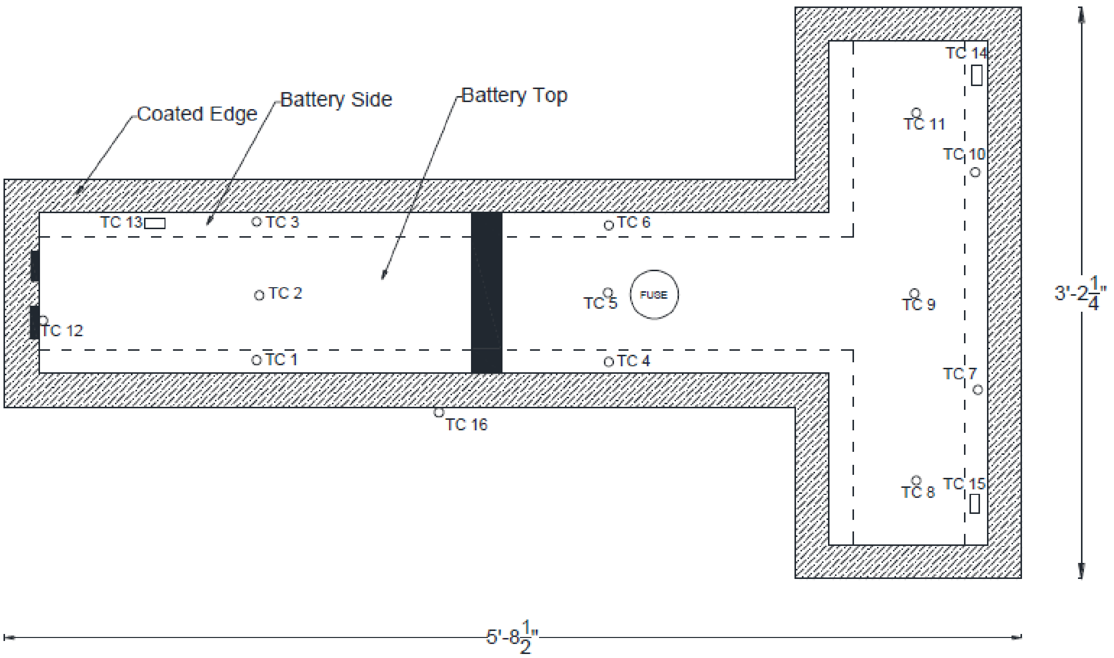

Figure 18 TC locations around Battery B during HRR testing (see Figure 12 for TC and HFG positions around the perimeter of the battery pack)

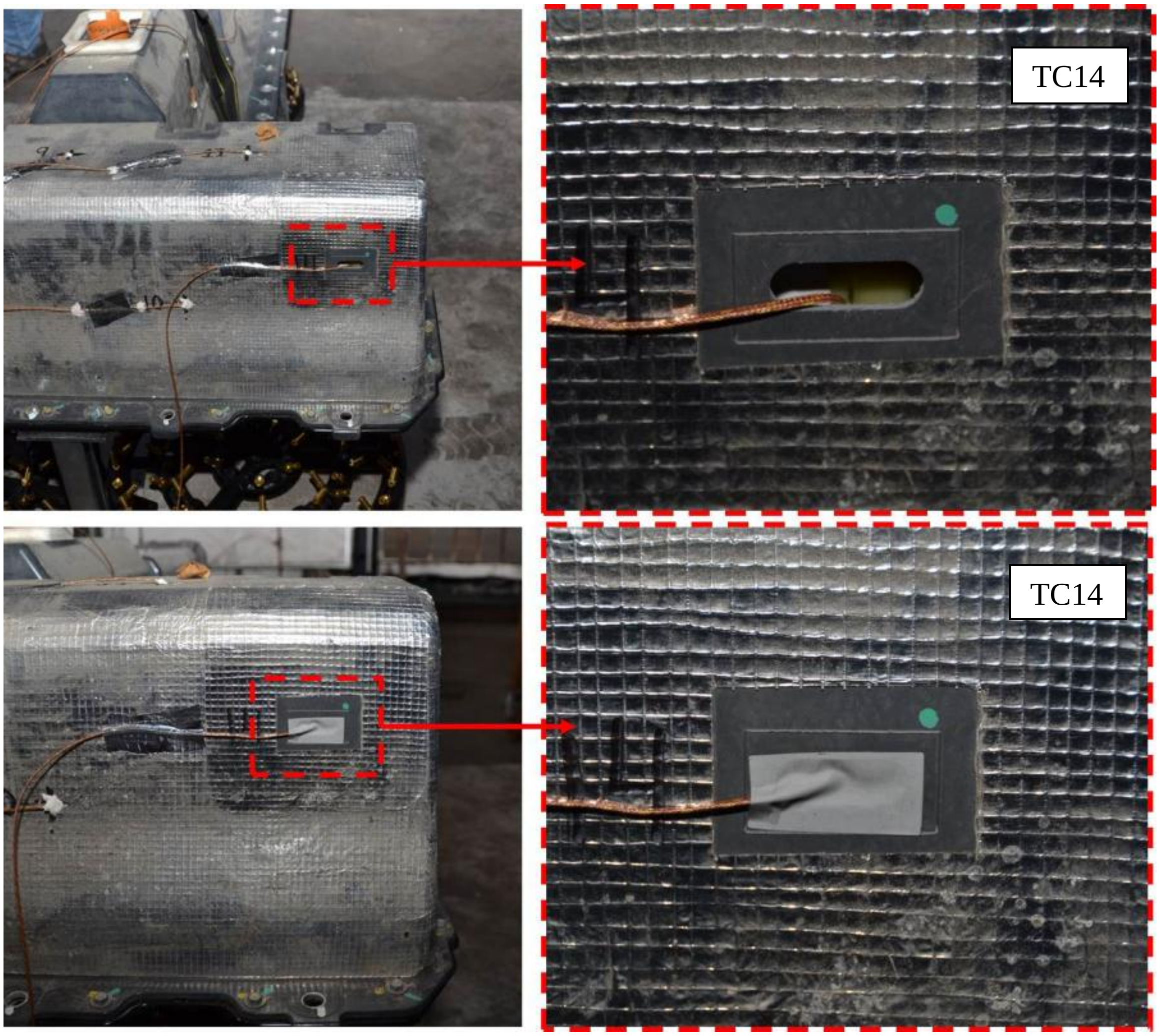

Figure 19 Installation of typical TCs inside Battery B

5.1.6 Internal Battery Sensor Measurements

During the fire test, Exponent collected internal battery temperatures and individual cell voltages from the battery’s own sensors, including 96 cell voltages and nine temperature sensors as possible. To collect this data, Exponent communicated directly with the battery through its own CAN bus protocol utilizing a custom Lab VIEW software program. This allowed Exponent to retrieve internal battery temperatures and cell voltages as the battery was being exposed to an external heat source. The CAN bus protocol is a serial bus standard that allows automotive components to communicate with each other. The custom Lab VIEW code used the National Instruments (NI) XNET protocol in combination with the NI 9862 CAN bus module and a 7-port NI CAN breakout box, which allowed Exponent to send and receive individual data frames to and from the battery. The NI 9862 is a single-port high-speed CAN bus module and the 7-port NI CAN breakout box provided a means to power the CAN port and to set the termination resistance. The NI 9862 bus module and CAN breakout box are shown in Figure 20. The NI 9862 was connected to the breakout box using an NI CAN high-speed cable. The breakout box was in turn connected to the battery using a custom interface cable provided by the manufacturer. In addition, the manufacturer provided the necessary binary codes to Exponent to use in its custom Lab VIEW program so that communication could occur. This cable connected directly to the battery, as shown in Figure 21. To protect these connection points and the cables, a calcium silicate board assembly was installed just below the connection points to shield the area from direct flame impingement by the burners below. In addition, Kaowool insulation ceramic fiber blankets were wrapped around these connection points and cables to insulate them from heat, as shown in Figure 22.

The custom Lab VIEW program was part of the same DAQ system that was used to control the burner assembly discussed previously in Section 5.1.2. The DAQ will be discussed in more detail in Section 5.1.7.

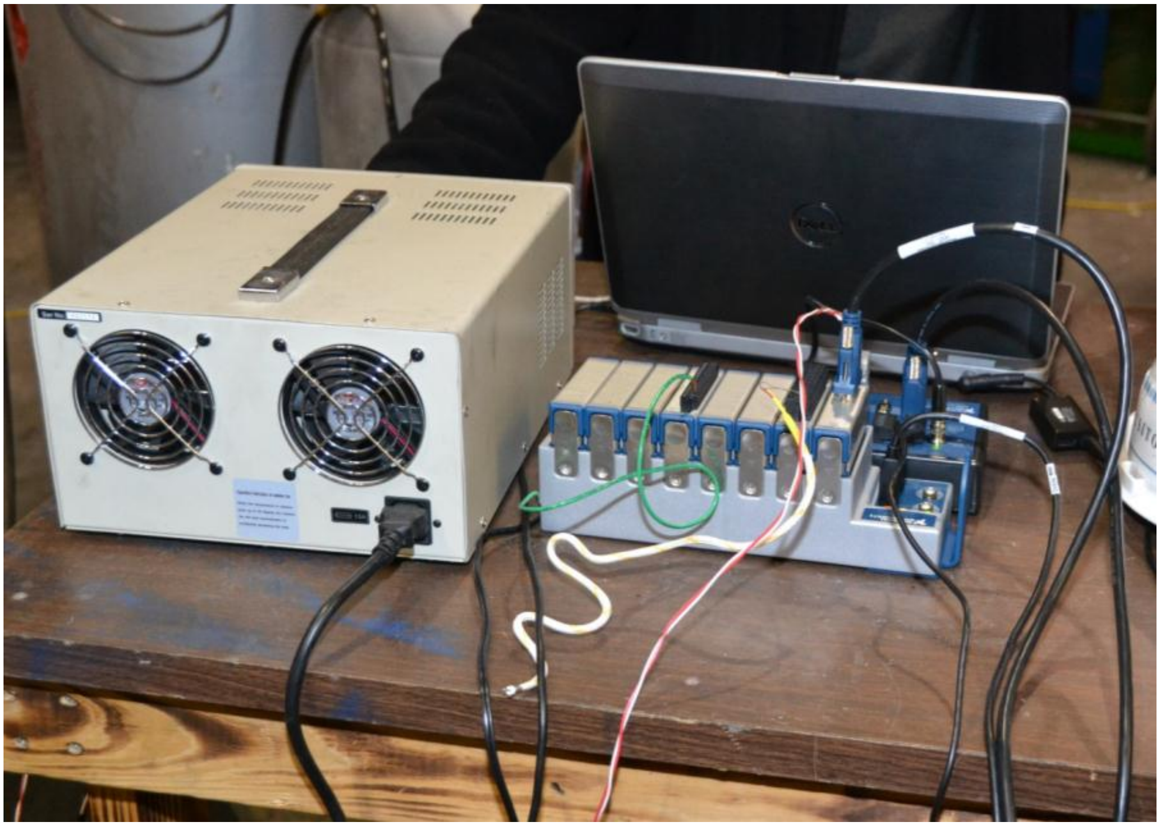

Figure 20 NI 9862 CAN bus module and 7-port NI CAN breakout box

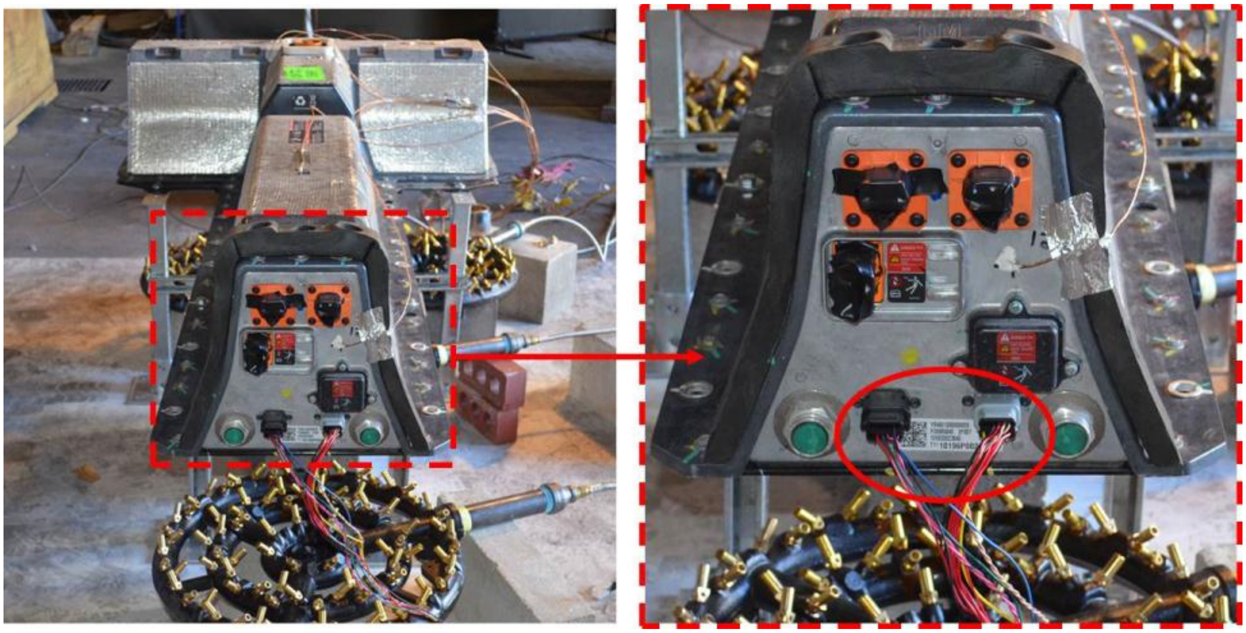

Figure 21 Location of the connection points to the internal battery sensors (circled right)

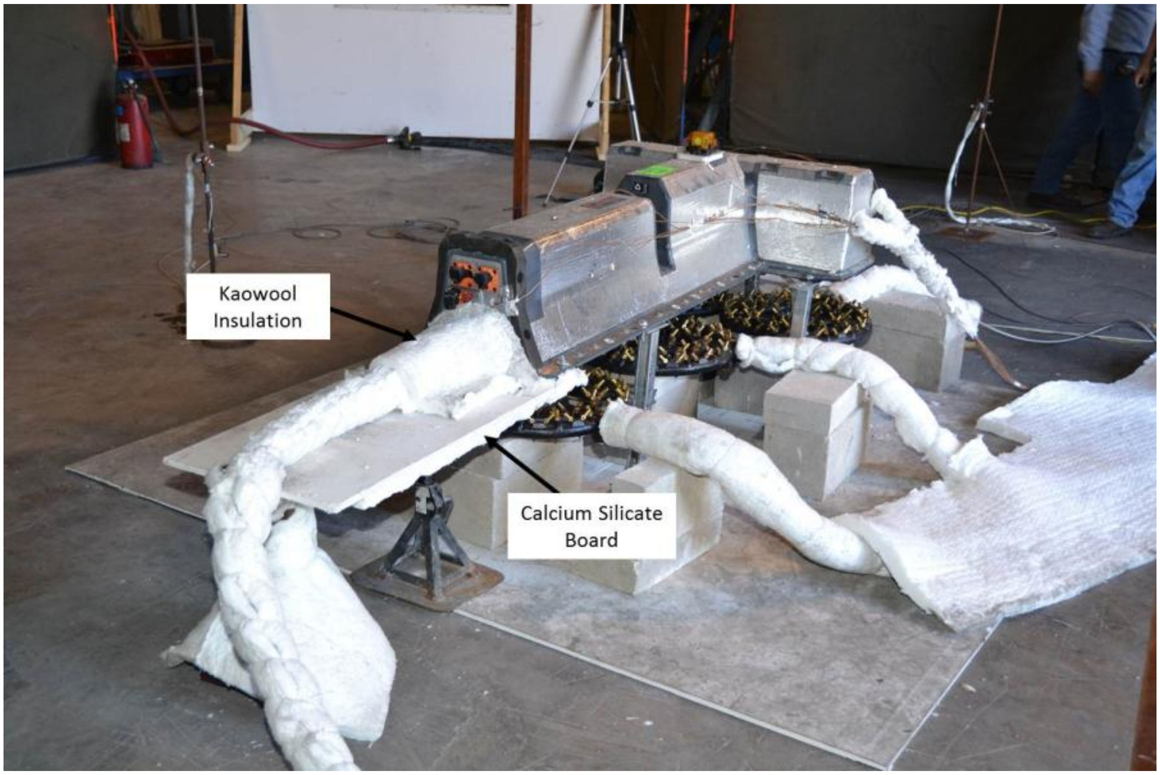

Figure 22 Protection scheme for the connection points and cables

5.1.7 DAQ System

The data acquisition was performed by a custom Lab VIEW code. The code performed three simultaneous tasks during the HRR testing:

- CAN bus communication with internal battery cell voltage and temperature sensors;
- Digital output to the relay module to control the burner; and
- Serial input and output to the mass flow meter.

These tasks were performed by a modular data acquisition system, a NI cDAQ 9178, which is an eight-slot USB-based data acquisition chassis. To communicate with the battery, the DAQ requested data at one-second intervals. However, communication with the battery through the CAN bus was asynchronous, meaning data is transmitted intermittently rather than in a steady stream. Communication with the battery consisted of broadcasting a request for a particular piece of information and then waiting for a response. Requests for all voltages and temperatures were made at a rate of one per second, however not all of the data would be received during that same second due to the asynchronous nature of the CAN bus. To circumvent this issue, each data frame received from the battery included identification bytes and a timestamp, so the data that was received could be properly identified and synchronized.

To communicate with the burner controls, a ±60 VDC, 750 mA NI 9485 8-channel switching relay module and a serial cable was connected to the cDAQ 9178 chassis. The relay module was used to switch the burners on and off during the test. The serial cable was used to communicate with the mass flow controller during the test.

The remainder of the data collected during the HRR tests, such as O_2, CO_2, and CO concentrations for oxygen calorimetry, TC, and HFG measurements performed by SwRI were also recorded at one-second intervals.

5.1.8 Thermal Imaging, Still Photography and High Definition Video

Thermal imaging, still photography, and high definition video were also recorded during the HRR testing by SwRI and Exponent. The thermal imager is a Fluke TI32 infrared camera with a temperature measurement range up to 1112°F. Infrared images were captured at 1-minute intervals during the test and after test completion to monitor the battery post fire. Still photography was captured using a Nikon D3100 digital camera. Representative images of the test were captured as possible during the test. High definition video was captured using a Canon Vixia HFS10 high definition camcorder. Three camcorders were used during testing (one by SwRI and two by Exponent) to ensure all angles of the battery were captured. The positioning of the high definition camcorders and thermal imager during testing is shown in Figure 12.

5.2 Full-scale Fire Suppression Testing

The full-scale suppression testing was performed at MFRI in College Park, Maryland.[42] The objective of the suppression testing was to evaluate the following when dealing with an EDV battery fire:

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[42] MFRI is Maryland's comprehensive fire and emergency response training and education agency. MFRI plans, researches, develops, and delivers quality programs to enhance the ability of emergency services providers to protect life, the environment, and property.

- Tactics and procedures for first responders;
- PPE of first responders;
- Adequacy and amount of water as a sole suppression agent; and
- Procedures for overhaul and post-fire clean-up.

Six tests were conducted; three for Battery A and three for Battery B. For each battery type, two of the tests were performed with only the battery pack positioned inside the VFT as they would be positioned in the host vehicle and one test was performed with typical interior finishes/upholstery (i.e., car seats, carpeting, dashboard, etc.). The additional interior finishes were installed within the VFT to simulate a fuel load more typical of a vehicle fire. Data collected during this test included:

- Temperatures;
- Heat fluxes;
- Projectile observations;
- Suppression water sampling;
- Volume of suppression water flow;
- Nozzle voltage and current measurements;
- Chassis voltage and current measurements;
- Battery internal temperatures;
- Battery internal cell voltage measurements;
- Thermal imaging;
- Still photography;
- High definition video; and
- MFRI staff / firefighter observations.

MFRI was responsible for providing the facility for the fire testing, the gear and equipment required for suppression efforts, all PPE and SCBA required for the firefighters, as well as the personnel to perform the fire suppression activities. Exponent was responsible for providing and controlling the external burner assembly used to ignite the battery pack and for providing all other instrumentation relating to data collection, still photography, and video recording.

5.2.1 VFT and Battery Positioning

In lieu of procuring fully intact production vehicles for the full-scale suppression tests due to the extreme costs, Exponent, in conjunction with an outside contractor, Tactical Incident Systems[43], designed and manufactured a VFT that could be outfitted with the two different battery assemblies. This allowed for multiple tests of different battery sizes, dimensions, and installation locations all while using the same VFT.

The VFT was constructed to resemble a modern EDV both in size and design, as shown in Figure 23 and Figure 24. It stands approximately 57 inches tall, 70 inches wide, and 15 feet long. The VFT was designed to open in the back, similar to a hatchback, to allow for the installation of the batteries as well as to facilitate firefighter access. The batteries were placed on top of a ¼-inch steel plate simulating the floor pan of the vehicle. The floor pan had two holes cut out to allow the burners, positioned below the VFT, direct access to the bottom of the battery assemblies, as shown as the shaded areas in Figure 23. Each of the battery assemblies weighed over 400 pounds, as such, two carriages, one for each battery type, were constructed for the battery assemblies to sit inside the VFT. The carriages were placed inside the VFT and rolled into position, either in the cargo compartment for Battery A or the middle of the VFT for Battery B, as shown in Figure 25 through Figure 27. The carriages rolled on wheels in two (2) 3-inch wide welded channels installed on top of the steel floor pan. The passenger compartment was framed of 2-inch by 2-inch by ¼-inch welded steel tube. The exterior of the VFT was formed of ¼-inch steel plates and was painted black. The frame was supported by four “peg legs” hidden behind fixed steel tire assemblies. The fixed tires were not operational and were for aesthetic purposes only. Two (2) 8-inch by 4-inch by ¼-inch steel tubes were installed

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[43] Tactical Incident Systems, 9130 Flint Overland Park, Kansas 66214

under the floor pan such that the VFT could be moved with a forklift. Drawings of the VFT and the battery carriages are provided in Appendix B.

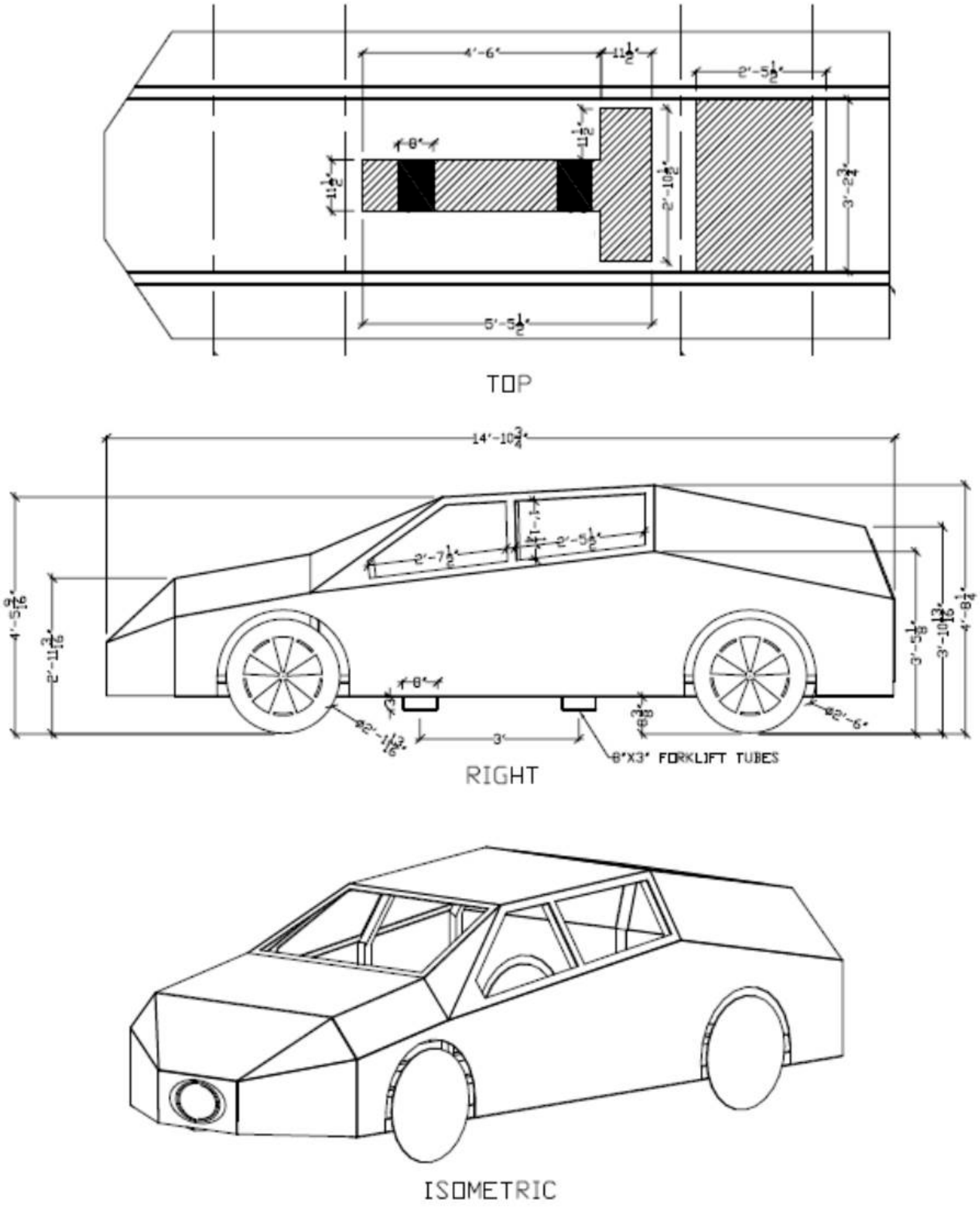

Figure 23 VFT design drawing

Figure 24 VFT: Side profile (top); rear profile with hatchback open (bottom left); and front profile with hood open (bottom right)

Figure 25 Carriage installed inside the VFT positioned above the four burners located in the rear test position

Figure 26 Battery A positioned on the carriage above the burners and inside the VFT

Figure 27 Battery B positioned on the carriage above the burners inside the VFT; burners located in the center test position

The VFT was placed on a concrete burn pad at MFRI, as shown in Figure 28. The burners slid under the VFT and into position depending on the battery type and had direct access to the bottom of the batteries through the holes cut out in the VFT floor pan. For Battery A, the four burners were centered six inches under the rectangular battery, as shown in Figure 25 and Figure 26. For the first two tests, Tests A1 and A2, the battery was installed alone within the VFT, as shown previously in Figure 26. For test A3, typical interior finishes/upholstery, including car seats, a dashboard, and a carpet layer above the battery (used to separate the battery from the cargo compartment) were also installed within the VFT, as shown in Figure 29 through Figure 33. The car interiors were procured from vehicles that were of a similar size as the VFT. These additional vehicle interior finishes were installed to better simulate the fuel load of a typical vehicle.

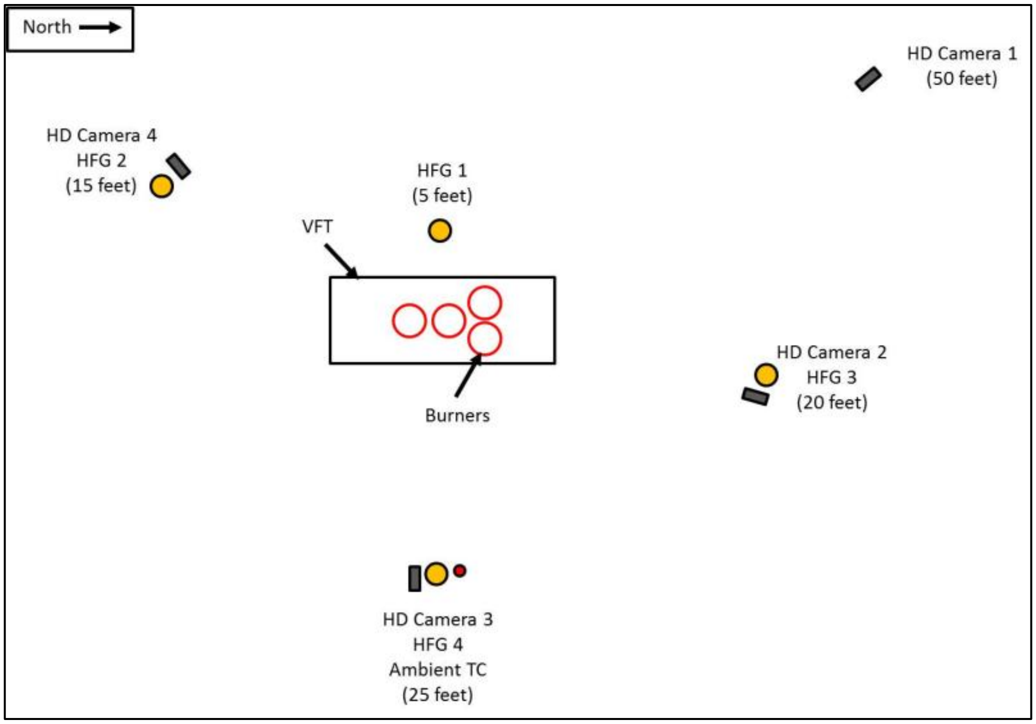

Figure 28 Layout and arrangement of the suppression testing perimeter instrumentation

Figure 29 Overall view of the VFT with interior finishes for Test A3

Figure 30 Dashboard and front seats installed inside the VFT for Test A3

Figure 31 Front seats installed inside the VFT for Test A3

Figure 32 Back seats installed inside the VFT for Test A3

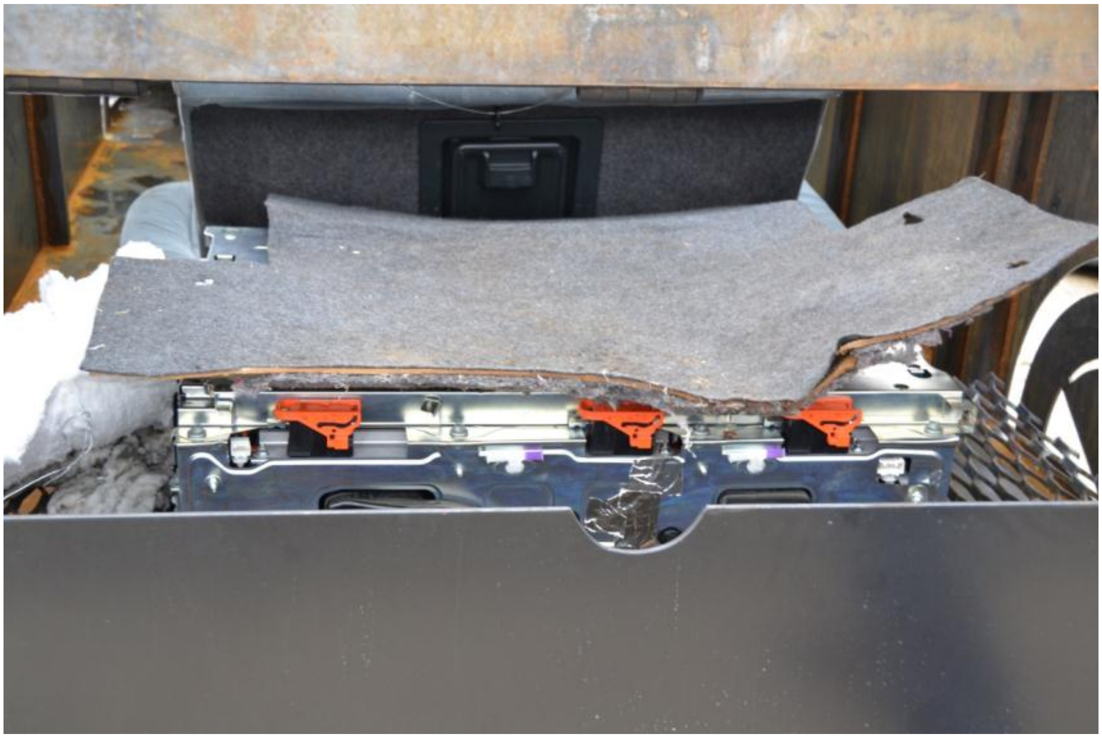

Figure 33 Carpet installed on top of the battery for Test A3

For Battery B, the four burners were positioned under the span of the T-shaped battery to provide a uniform heat source to the entire battery pack, as described in Section 5.1.2 for the HRR test. Inside its production vehicle, a steel floor pan is positioned on top of the battery, separating it from the passenger compartment. As such, the vehicle manufacturer that donated Battery B also donated a steel floor pan from an actual vehicle to be placed above the battery during testing. This configuration provided a more realistic vehicle fire scenario, as shown in Figure 34 and Figure 35. For the first two tests, Tests B1 and B2, the battery and the steel floor pan were installed within the VFT. For Test B3, typical interior finishes/upholstery, including car seats, a dashboard, and carpeting were added to the VFT along with the battery and steel floor pan, as shown in Figure 36 through Figure 40. The car interiors were procured from vehicles of a similar size to the VFT. These additional vehicle interior finishes were installed to better simulate the typical fuel load expected in a vehicle fire.

Figure 34 View of Battery B inside the VFT without the floor pan (top) and with the floor pan (bottom); the blue tank at the rear of the battery is the empty gasoline tank for the production vehicle, which blocks direct access to the rear of the battery

Figure 35 Top view of Battery B inside the VFT without the floor pan (top) and with the floor pan (bottom); the yellow fuse in the middle of the red floor pan is the only hole within the pan that allows for access to the battery

Figure 36 Overall view of the VFT with interior finishes for Test B3

Figure 37 Dashboard, front seats, and carpet installed inside the VFT for Test B3

Figure 38 Front seats and carpet installed inside the VFT for Test B3

Figure 39 Back seats installed inside the VFT for Test B3

Figure 40 Back seats and carpet installed inside the VFT for Test B3

5.2.2 Burner Description

The components, design, and function of the burner assembly utilized during the full-scale fire suppression testing were the same as those used during the HRR test, as described previously in Section 5.1.2. The only difference between the two setups, Battery A and Battery B, was the positioning of the burners under the VFT, as described in the previous section.

5.2.3 Electrical Measurements during Fire Suppression

One of the objectives of this test series was to evaluate the potential electric shock hazards associated with fighting EDV fires. Literature was reviewed on the subject of electric shocks and the physiological response to touch potentials, as well as the impedance of the human body.[44,45,46,47] In addition, literature was reviewed to investigate methodologies of fire

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[44] Backstrom, R. and Dini, D.A., “Firefighter Safety and Photovoltaic Installations Research Project” November, 29, 2011.

[45] NFPA 15, 2007 edition, Chapter 6.

suppression of electrical fires[44,48,49,50,51,52,53], as well as literature discussing previously-used testing methodologies for measuring voltage and current through a water stream and the effect of PPE.[44,48,54] These previous studies provided guidance as to how to best measure and collect electrical data during the test to (1) protect the firefighters suppressing the fires and (2) provide useful data to the firefighting community in regards to potential electrical hazards during suppression of an EDV fire.

Electrical measurements were recorded to investigate the possibility of electric shock by a firefighter while suppressing an EDV fire. While both voltage and current measurements were recorded, the parameter important for characterizing the potential shock hazard is current. While simultaneous voltage measurements can provide an indication as to the presence of a shock hazard, the effects of voltage on different individuals can vary substantially. Conversely, the current magnitude can be directly related to physiological effects ranging from a slight tingling sensation to cardiac arrest and probable death.[55]

Another important parameter is the conductivity of water used for the suppression of the fire. Electrical conductivity is a measure of the ability of a material to conduct (or allow the flow) of electricity and is measured in units of Siemens per meter (S/m). Good conductors, such as copper, have a very high conductivity (5.96×10^7 S/m), whereas poor conductors (or insulators),

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[46] OSHA Construction eTool, “How Electrical current Affects the Human Body”, http://www.osha.gov/SLTC/etools/construction/electrical_incidents/eleccurrent.html

[47] Olsen, G. R., Schneider, J.B., Tell, R. A., “Radio Frequency Burns in the Power System Workplace” IEEE Transactions on Power Dleivery, Vol. 26, No. 1, January, 2011.

[48] Bolander, G.G., Jughes, J. T., Toomey, T. A., Carhart, H.W., and J.T. Leonard. “Use of Seawater for Fighting Electrical Fires” Navy Technology Center for Safety and Survivability, Chemistry Division. May 25, 1989.

[49] “Electrical Conductivity of Extinguishing Agents”, Factory Mutual Handbook of Industrial Loss Protection,

[50] Thorns, J., “Feuerwehreinsatz an Hochvoltfarzeugen,: Aubau, Funktion und Einsatzhinweise” BrandSchutz, Zeitschrift fuer das gesamte Fuerwehrwesen, fuer Rettungsdienst und Umweltschutz. (English translation: Firefighting on High Voltage Vehicles: Structure, Function, and Application notes), March 2011

[51] Electric Vehicle Safety Training Online Blog, 08/14/2012

[52] Firehouse World, online firefighter blog, http://www.firehouse.com/forums/t20745/

[53] conEdison 2010 Sustainability Report downloaded from: http://www.conedison.com/ehs/2010annualreport/print-template.asp

[54] Sprague, C.S. and C.F. Harding. “Electrical Conductivity of Fire Streams” Research series no. 53. Engineering Experiment Station, Purdue University Lafayette, Indiana, January 1936

[55] OSHA http://www.osha.gov/SLTC/etools/construction/electrical_incidents/eleccurrent.html.

such as glass, have a very low conductivity (approximately 1 x 10^{-11} S/m or less). The conductivity of water is typically much lower than good conductors and is, therefore, often measured in units of microSiemens per centimeter (μS/cm). The conductivity of water is, however, highly dependent on the amount of other material (minerals, salts, etc.) dissolved in the water. For example, deionized water is a poor conductor (0.055 μS/cm), while seawater (with a high salt content) is a much better conductor (58,000 μS/cm). In order for a firefighter to experience an electrical shock during fire suppression efforts, the firefighter must either make physical contact with something held at an elevated voltage potential (thereby providing a path for the electricity to ground) or the electricity must pass through the water stream back to the firefighter in order to complete the circuit. The conductivity (or ability of the water to conduct electricity) will, therefore, play a role in determining the potential shock hazard. A sample of water was collected from the suppression water source used for the tests and its conductivity was tested by Microbac Laboratories, Inc.[56] The conductivity of the water used during the suppression tests was found to be 190 μS/cm, which is a very low conductivity. The full Microbac Laboratories report is provided in Appendix C.

Previous tests[57] have characterized the shock hazard of alternating current (AC) electricity at a variety of voltage levels, nozzle patterns, and distances, as well as water conductivities. In these tests, a metal screen or plate was intentionally energized to a specified voltage and then the voltage and/or current level was measured as a function of distance from the energized source. The effect of water conductivity was also assessed in these tests, with water ranging from well water (185 μS/cm) to seawater (58,000 μS/cm). Finally, these previous tests performed measurements where the nozzle was connected through a short circuit to ground (no additional resistance) or, optionally, through a 500 Ohm resistor to simulate the resistance of an average person to the flow of electricity (under wet conditions).

Following a similar methodology to previous studies, the electrical measurements performed in Exponent's full-scale fire suppression tests were conducted by measuring both the voltage and current at the nozzle. In addition, the voltage and current at the body of the chassis in which the

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[56] Microbac Laboratories, Inc. 2101 Van Deman Street . Baltimore, MD 21224

[57] Sprague and Harding, 1936; Bolander 1989

battery was placed were also measured. For the electrical measurements at the nozzle, 14 AWG stranded copper wire was securely soldered to a hose clamp and affixed to the nozzle's exterior housing, as shown in Figure 41. Continuity tests confirmed that the front of the nozzle from which water was expelled was electrically connected to the discharge portion of the nozzle. The wire was then routed back to the DAQ system utilized to collect the voltage and current measurements, as shown in Figure 42. Similarly, at the chassis, a separate 14 AWG stranded copper wire was securely connected to the body of the chassis and run along the ground to the DAQ system, where it was connected to the measurement circuit shown in Figure 42. Inside the chassis, additional metallic components, such as the sliding chassis and the VFT body components were also connected using a 14 AWG stranded copper wire to the same measurement wire such that all conductive items, including the sliding chassis and the VFT body components, were electrically connected. Due to the high temperatures expected inside the VFT, the internal wires were protected using aluminum foil and Kaowool. Though in most tests the wire insulation nearest the most intense portion of the fire was found to be degraded in post-test assessment, continuity after each test was confirmed to verify all conducting objects in the chassis remained electrically connected throughout the test.

Figure 41 14 AWG stranded copper wire soldered to a hose clamp and affixed to the nozzle's exterior housing

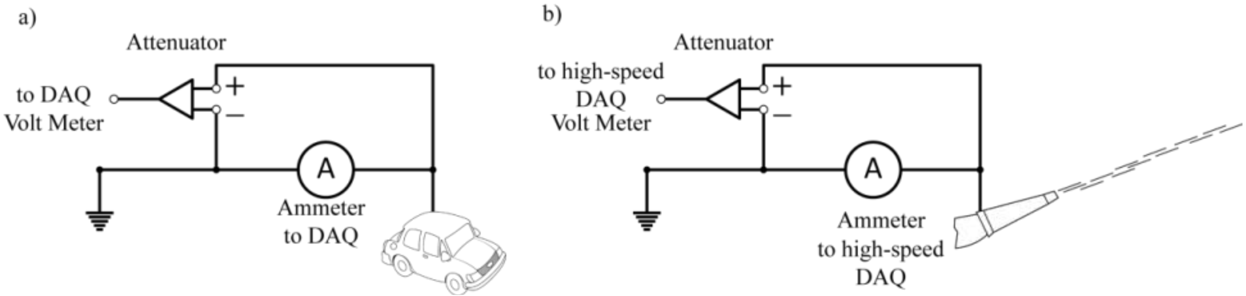

Figure 42 Simplified circuit diagram for the electrical measurements

Due to the likely transient nature of the electrical connection from the EDV battery to the nozzle through the water stream, a high-sampling-rate of 2 kilohertz (kHz) was performed to identify any brief electrical connection of the EDV battery voltage to the nozzle. This allowed for the detection of any electrical activity at the nozzle such that the hazard could be relayed to the firefighters as quickly as possible and data could be collected and subsequently analyzed regarding the potential electrical hazards involved with suppressing an EDV fire. For the chassis measurements, the transitory nature of voltage/current flow was not expected; therefore, measurements were recorded at one-second intervals, or 1 Hertz (Hz). These measurements were collected for as long as fire suppression activities were being performed.

In both measurement cases, the maximum voltage level of the battery was approximately 400 VDC, while the maximum input voltage of the DAQ was limited to ± 10 V. In order to ensure that the full voltage range was covered, a voltage attenuator was incorporated into the voltage measurement circuit, as shown in Figure 42. In addition, due to the long wires necessary in connecting the nozzle and chassis to the DAQ system, external sources of noise were present. The most prevalent noise was from power lines at 60 Hz and their harmonics. The 1 Hz sampling used for the chassis measurements was too low to be affected by the power-line noise, however, the nozzle measurements sampled at 2 kHz were significantly affected by not only the 60 Hz fundamental frequency of the power-line, but also the first 15 harmonics (120 Hz, 180 Hz,… 960 Hz). Post-test analysis confirmed that the noise from these power-line sources was seen in the voltage measurements. As such, a comb-filter comprising each of these frequencies was applied to the recorded data to mitigate these effects.

Current measurements for both the nozzle and chassis were performed through the use of Hall-effect probes. The magnitude of current conducted to ground through either the nozzle or from the chassis were expected to be relatively low, therefore a relatively high-gain setting (100 mV/A) was selected for both probes. While this selection is more likely to detect relatively low current levels on the respective wires, the higher gain also contributes to relatively higher noise levels, which were addressed by post-test filtering and processing of the data, including background noise subtraction and averaging.

The four measurements described here, the high-speed 2 kHz sampling rate current and voltage measurements of the nozzle and the 1 Hz sampling measurements of the chassis current and voltage were performed using the DAQ described in Section 5.2.7.

5.2.4 Water Sampling

Contaminated water runoff created by suppression of an EDV fire is an environmental concern, as well as a concern to first responders in regards to their PPE. To evaluate this potential hazard, Exponent collected water samples after each test to analyze what, if any, potentially harmful byproducts may be present in the water. Approximately one pint of water was collected in a sealed glass jar after each test. The water was collected off the ground approximately two feet in front of the VFT after suppression efforts had ceased by one of the firefighters, as shown in Figure 43. This collection method was utilized, as opposed to collecting water from directly underneath the battery through a collection pan or trough, to better sample from a location that first responders would be performing activities, possibly standing in the water, during and immediately after suppression activities. The chemical analysis of the water samples was performed by Analyze, Inc.[58]

Once received by Analyze, Inc., the test samples were filtered of any particulates (debris) prior to analysis. Each sample was analyzed for pH using a Fisher Scientific Accumet Excel XL15 pH meter and screened for cations and anions using a Dionex ICS-2000 Ion Chromatograph. In addition, elemental analysis was performed to survey the amount of organic and inorganic

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[58] Analyze, Inc. 318 South Bracken Lane, Chandler, Arizona, 85224.

carbon present in the samples. The full water sampling report from Analyze, Inc. detailing the measurement techniques is provided in Appendix D.

Figure 43 Water sample collection during test A1 just in front of the VFT

5.2.5 Temperature and Heat Flux Measurements

The temperature and heat flux measurements were performed using sixteen 0.10-inch diameter Type K TCs and four Schmidt-Boelter HFGs, as shown in Figure 28. The location and measurement description of the TCs and HFGs are provided in Table 4 and Table 5. These measurements were collected for at least one hour after testing or until external battery temperatures had dropped to near ambient levels, whichever was first.

During Battery A tests, TCs 1 through 12 were fixed to the exterior surface of the batteries using Omega Bond CC High Temperature Bonding cement, as shown in Figure 44. The cement was located over the TC bead and allowed to dry prior to testing. An ambient TC was placed 25 feet east of the VFT, as shown in Figure 28.

During Battery B tests, TCs 1 through 15 were installed in the same locations around the exterior of the battery and within the interior of the battery through the vent holes, as described in Section 5.1.5 and as shown in Figure 45.

During all six of the Battery A and B tests, HFGs 1 through 4 were positioned at 5, 15, 20, and 25 foot standoff distances from the VFT. The HFGs were capable of measuring a radiant heat flux between 0 and 50 kW/m^2.

Table 4 Summary of TC Locations

Thermocouple	Measurement	Thermocouple	Measurement
1	Battery exterior	9	Battery exterior
2	Battery exterior	10	Battery exterior
3	Battery exterior	11	Battery exterior
4	Battery exterior	12	Battery exterior
5	Battery exterior	13	Battery interior (B only)
6	Battery exterior	14	Battery interior (B only)
7	Battery exterior	15	Battery interior (B only)
8	Battery exterior	16	Ambient temperature

Table 5 Summary of HFG Locations

Heat Flux Gauge	Measurement	Thermocouple	Measurement
1	Heat Flux (5 ft)	3	Heat Flux (20 ft)
2	Heat Flux (15 ft)	4	Heat Flux (25 ft))

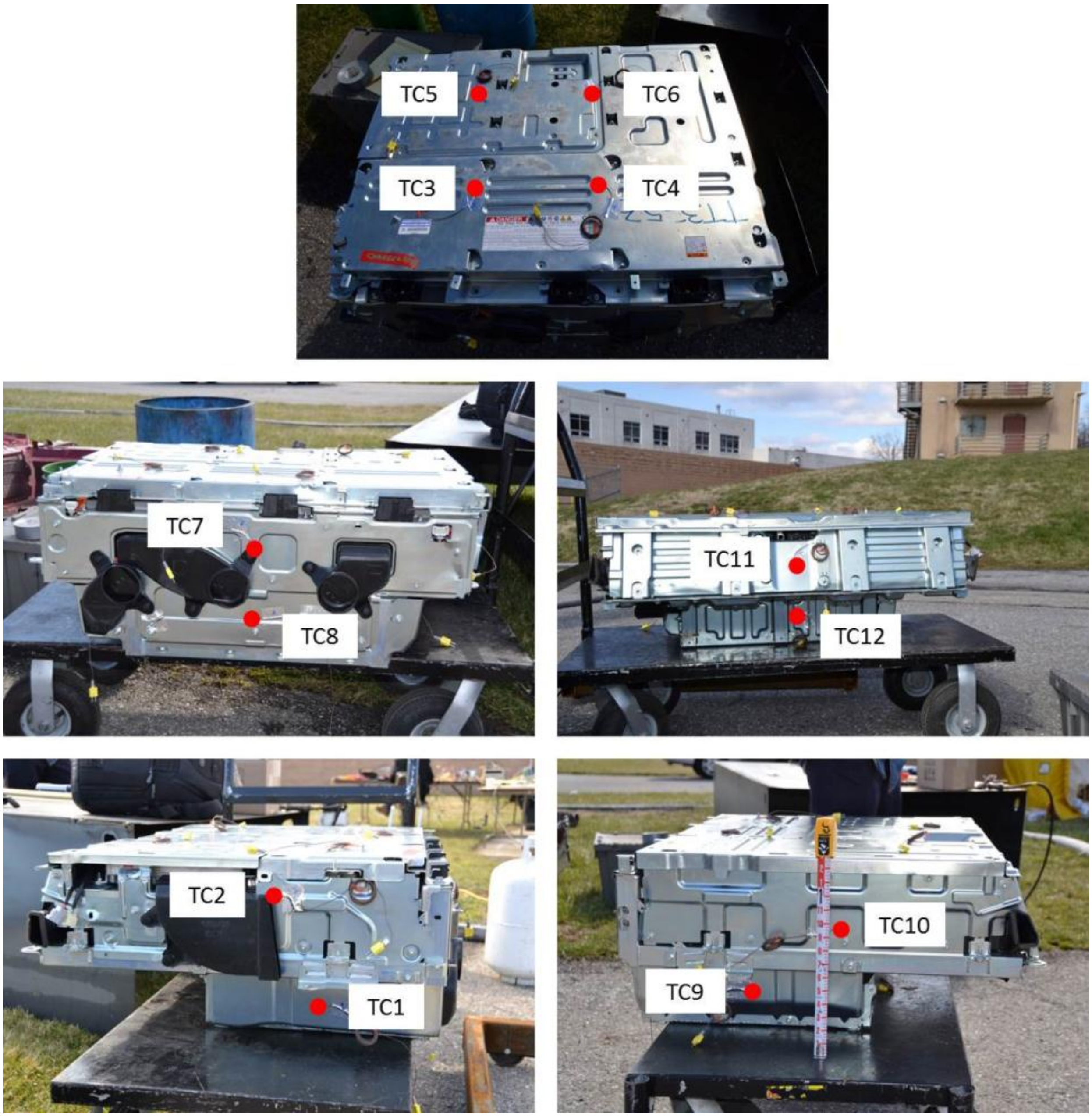

Figure 44 TC locations (red circles) on battery exterior for Battery A tests

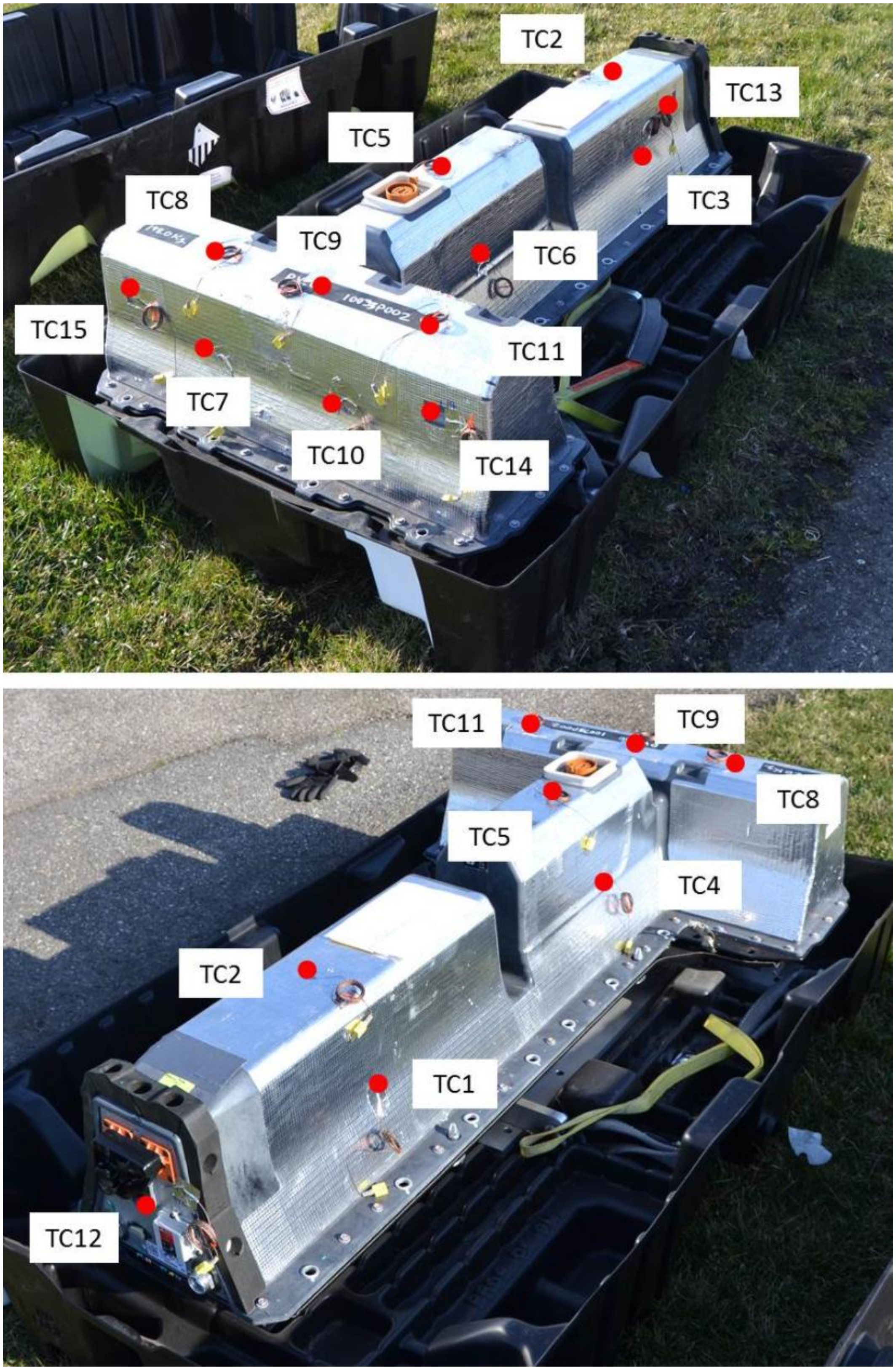

Figure 45 TC locations (red circles) on battery exterior/interior for Battery B tests

5.2.6 Internal Battery Sensor Measurements

During the Battery B tests, Exponent collected internal battery temperatures and individual cell voltages from the battery’s own sensors. Exponent was not provided with the necessary supporting information to communicate with the A series batteries. These measurements were collected for as long as the connection between the battery and the DAQ system would allow (i.e., that is until fire exposure conditions compromised the communication paths). To collect this data, Exponent communicated directly with the battery using the same software programs, cables, equipment, sensors, and connection points to the battery described in Section 5.1.6. Prior to the suppression tests however, the battery was installed within the VFT, which required a slightly modified protection scheme for the battery’s connection points. To protect these connection points, a modified calcium silicate board structure was erected around the front end of the battery once it was positioned within the VFT, as shown in Figure 46 and Figure 47. This structure shielded the connection area from direct flame impingement by the burners below, as well as any flames licking around the bottom edge and sides of the battery. In addition, Kaowool was inserted into the structure to insulate the connection points further and wrapped around the cables running to the battery from the DAQ system.

Figure 46 Connection points to Battery B once installed inside the VFT (before protection)

Figure 47 Protection scheme for the connection points and cables running to Battery B

5.2.7 DAQ System

Data acquisition was performed by a custom Lab VIEW code. The code performed five simultaneous tasks during the suppression testing:

- Analog input at a rate of 1 Hz for the TCs, HFGs, and chassis electrical measurements;
- Analog input at a rate of 2 kHz for the nozzle electrical measurements;
- CAN bus communication with individual internal battery cell voltage and temperature sensors;
- Digital output to the relay module to control the burner; and
- Serial input and output to the mass flow controller.

The temperature measurements consisted of up to sixteen Type K TCs and four calibrated Schmidt-Boelter HFGs. The TCs were monitored by an NI 9213 16-channel, 24-bit resolution TC module with built-in cold-junction compensation, as shown in Figure 48. The HFGs were monitored by an NI 9207 8-channel current/8-channel voltage module and a 24-bit resolution module with 50/60 Hz noise rejection. The TCs and HFGs were monitored continuously at a sampling rate of 1 Hz, or once per second.

The electrical measurements were performed at two different sampling rates by two data acquisition modules. The chassis voltage and current were monitored at a sampling rate of 1 Hz by the NI 9213 module described above. The nozzle voltage and current were continuously sampled at a rate of 2000 Hz by an NI 9239 module, a high-speed 4-channel analog input module with 24 bits of resolution, channel-to-channel isolation and anti-aliasing circuitry.

CAN bus communication and burner control were performed using the same software programs, cables, equipment, and connection points to the battery described in Section 5.1.7.

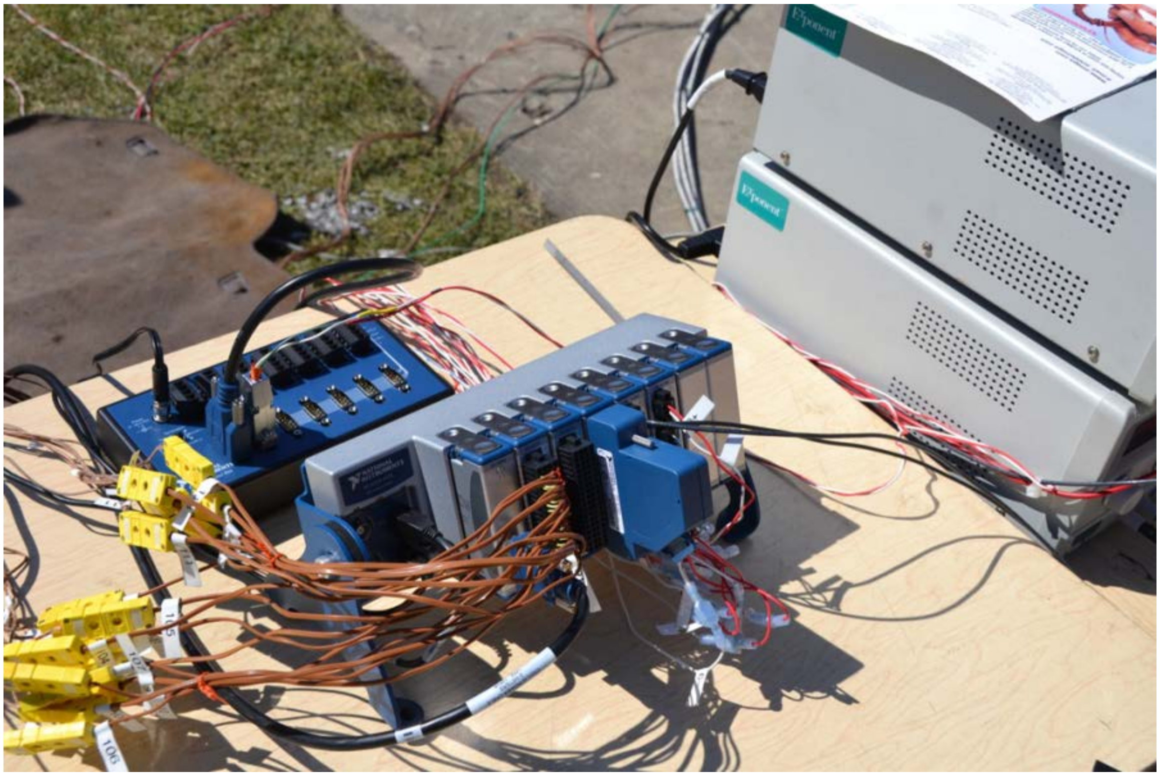

Figure 48 NI 9213 TC module and NI 9207 voltage module (for HFGs) plugged into the NI cDAQ 9178 data acquisition chassis

5.2.8 Thermal Imaging, Still Photography and High Definition Video

Still photography and high definition video was recorded during the suppression testing by Exponent using the same cameras as described in Section 5.1.8. Images of the tests were captured as the situation warranted and/or important events occurred. Four high definition camcorders were used during testing to ensure all angles of the VFT and battery were recorded. The positioning of the high definition camcorders during testing is shown in Figure 28.

Due to the position of the batteries within the VFT, it was not possible to take thermal images that could provide meaningful data during the suppression tests given that direct access was obstructed by the VFT or floor pan components. However, thermal images were recorded after test completion to supplement the TCs in monitoring the battery post fire. The thermal imager used during the suppression tests was the same as described in Section 5.1.8.

5.2.9 Suppression Activities

Suppression activities were handled by MFRI. No guidance was given to the firefighters regarding what they could and could not do tactically to suppress the fires. They were instructed to fight the fire as they would normally approach a vehicle fire with an offensive attack. Any tactics or modifications to those tactics during the fire tests were at the sole discretion of the MFRI staff and based on their many years of firefighting and training experience. The suppression team was restricted from using any forcible tools to access the VFT or the battery for safety reasons.

However, due to the setup of the tests, there were two limitations regarding how MFRI could attack the fires: (1) they were not able to fight the fire from the east side of the VFT, as the instrumentation wires and cables in that area posed a tripping hazard and (2) they were not able to fight the fire from underneath the VFT (i.e. shooting water up to the undercarriage of the batteries) due to the presence of the four propane burners.

These two limitations did not greatly affect MFRI's tactics, as the VFT was designed to provide ample access to the interior of the VFT. Each VFT window was open to air, mimicking a more involved vehicle fire, where all of the windows would be broken prior to fire department arrival or by first responders once on scene, as shown in Figure 49. In addition, the top section of the back hatch was left open to provide better access to the batteries during the test. The MFRI firefighters stated that they would normally attempt to open the back hatch or trunk as one of their first actions if this were a real fire scenario. As such, for safety reasons, as a means to limit the touching, moving, and manipulating of the VFT as the firefighters are standing within a few feet of a potentially fully involved battery, the top portion of the back hatch was kept open from the beginning of the test. Ultimately, having the hatch open also greatly aided in the video recording and still photography captured during the tests.

All tests were conducted with a defacto incident commander and assistant and two active firefighters; one on the nozzle and one on the hose. This is equivalent to one company, as defined by NFPA 1710, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career*

Fire Departments, 2010 edition. All staff outside of the suppression team was kept behind a 50-foot perimeter around the VFT. A 1.75-inch diameter hose line fed by a private hydrant was used to supply the Elkhart Brass - Chief nozzle (model no. 4000-10, variable fog 30 degree, 60 degree, and 90 degree), which discharged approximately 125 gallons of water per minute (gpm) at 75 psi. The water usage was tracked by Exponent staff (time of application estimates) during the tests so that an estimate of the total water used for suppression could be determined. Final data was cross checked with video recording for accuracy. In addition, interviews with the firefighters after the tests were conducted to, among other things, gain insight into:

- What they saw;
- How they attacked the fire;
- How the fire differed from a conventional vehicle fire;
- What they may have learned from the test regarding tactics; and
- General observations.

The two firefighter suppression team donned full SCBA and firefighting turnout gear prior to the beginning of the test and only removed their SCBAs if they needed to swap out a cylinder or once the fire was deemed “out.” The turnout gear consisted of:

- Polybenzimidazole (PBI) coat (Globe G-Extreme or Lion Apparel Janesville);
- PBI pants (Morning Pride);
- Polycarbonate helmet (Morning Pride Ben Franklin II or MSA 660);
- Kangaroo skin (Honeywell) or leather (Shelby) gloves;
- PBI (Firecraft) or lanzing (PAC II) hood; and
- Leather boots (Warren Pro or HAIX).

Figure 49 VFT windows were all open to air and the top portion of the back hatch was kept open to during the tests

5.3 Full-scale Fire Protocols

Exponent created two protocols for the full-scale fire tests; one for the HRR test and one for the suppression tests.

5.3.1 HRR Testing

The test protocol for the HRR test was as follows:

1. The battery was positioned and the test equipment was setup as described in Section 5.1.
2. The following background data was collected for 2 minutes:
    a. Gas concentrations for oxygen calorimetry;
    b. Thermocouples;
    c. Heat flux gauges; and

    d. Internal battery sensor measurements.

3. High definition video recordings were started simultaneously with data collection.
4. Thermal images were recorded at 1 minute intervals starting at an elapsed time of 1 minute.
5. After 1 minute and 45 seconds, the pilot lights to the propane burners were ignited with a torch.
6. After 2 minutes, the propane supply to the burners was turned on at a propane mass flow rate of 67 liters per minute (approximately 100 kW exposure) and ignition of the burners via the pilot lights occurred.
7. After all of the nozzles on the four burners were verified to be lit (at 3 minutes and 30 seconds), the mass flow rate of propane was increased to 267 liters per minute (approximately 400 kW exposure).
8. Gas samples were collected at five minute intervals starting at 5 minutes.
9. The burners were allowed to run until visible signs of battery involvement occurred. These visible signs included:
    a. Arcing, visible flames, or projectiles emanating from battery;
    b. 80 °C measured at internal temperature sensors;
    c. Individual cell voltages decreasing; and
    d. Venting of electrolyte and/or combustion.
10. Still photographs were recorded throughout the test as necessary.
11. All data collection equipment was turned off once visible signs of combustion had ceased.
12. The battery was continuously monitored with the thermal imager to verify safe handling temperatures had been reached before overhaul.

5.3.2 Suppression Testing

The test protocol for the suppression tests was as follows:

1. The battery was positioned and the test equipment was setup as described in Section 5.2.
2. The following background data was collected for 1 minute:
    a. Thermocouples;
    b. Heat flux gauges;
    c. Internal battery sensor measurements (if applicable); and
    d. Electrical measurements at the VFT chassis and nozzle.
3. High definition video camera recordings were started simultaneously with data collection.
4. After 1 minute, the propane supply to the burners was turned on at a propane mass flow rate of ~267 liters per minute (~400 kW exposure) and the propane burners were ignited with a torch.
5. The burners were allowed to run until visible signs of battery involvement occurred. These visible signs included:
    a. Arcing, visible flames, or projectiles emanating from battery;
    b. 80 °C measured at internal temperature sensors (if applicable);
    c. Individual cell voltages decreasing (if applicable); and
    d. Venting of electrolyte and/or combustion.
6. After turning off the burners, the fire was allowed to independently burn for 1 minute before suppression operations began.
7. The electrical measurements at the VFT chassis and nozzle were monitored while water application was underway to verify no electrical safety hazards occurred during suppression operations.
8. Fire department operations continued until signs of combustion ceased.
9. Still photographs were recorded throughout the test, as necessary.
10. A water runoff sample was collected at the end of the test.

11. All data collection equipment was turned off once visible signs of combustion had ceased and TC / thermal imaging measurements were near ambient temperatures.
12. The battery was continuously monitored with the thermal imager and TCs, as necessary, to verify safe handling temperatures had been reached before overhaul.

6 Test Results

6.1 HRR Testing

The HRR test was performed at the SwRI testing facility located at 6220 Culebra Road, Building #143, San Antonio, Texas 78238 on March 13, 2013, under the supervision of Karen Carpenter from SwRI and R. Thomas Long, Jr., Andrew Blum, and Thomas Bress from Exponent.

6.1.1 Battery B

Due to the limited number of batteries available for this research project, only one of the B batteries was designated for full-scale HRR testing as a standalone battery pack. The following sections summarize the data collected by SwRI (HRR, TCs, HFGs, gas sampling, videos, still photography, and observations) and the data collected by Exponent (internal battery sensors, burner heat output, thermal imaging, videos, still photography, and observations) during the HRR test.

6.1.1.1 Test Observations

Table 6 summarizes the key events observed by Exponent and SwRI during the HRR test. Images at significant test times are provided in Figure 50 through Figure 52. In general, the test demonstrated that an external heat source, such as the propane burners, could induce Battery B into thermal runaway and result in a visible release and ignition of electrolyte material. However, once the external heat source was removed (i.e., the burners were turned OFF) the battery fire quickly subdued to a controlled release of flammable gasses and ultimately burned itself out.

Table 6 Summary of Key Observations from the HRR Test

Time	Event
-0:02:00	Baseline data begins
0:00:00	Propane burners ignited with a flow of 67 l/m (~100 kW)
0:00:46	Plastic coating on battery edge ignites
0:01:36	Propane flow fully increased to 267 l/m (~400 kW)
0:02:30 – 0:02:40	First flash fire observed (small) and a loud pop is heard
0:04:21	Lost CAN bus communication
0:09:50	Flames shooting out of the south battery vent
0:12:00 – 0:12:35	Increase in flame size, loud pop heard, venting and flames shooting out of top fuse
0:13:03	Visible sparks coming from interior of NW end of battery
0:14:50	Large stream of sparks shoot out from the bottom of the NW end of the battery from its interior
0:15:02	Liquid pool fire ignites on the ground south of battery
0:17:42	Visible sparks coming from interior of NW vent hole
0:20:36	Propane burners turned off
0:23:00 – 0:25:00	Fire size noticeably begins to weaken
0:47:10	Flames only observed shooting out of the northwest battery vent, top fuse and CAN bus connection ports
1:03:00	Loud pop heard and the fire at the top fuse goes out
1:20:00	Loud popping heard
1:30:00	Loud popping heard
1:34:00	Last flame goes out, battery continues to smoke

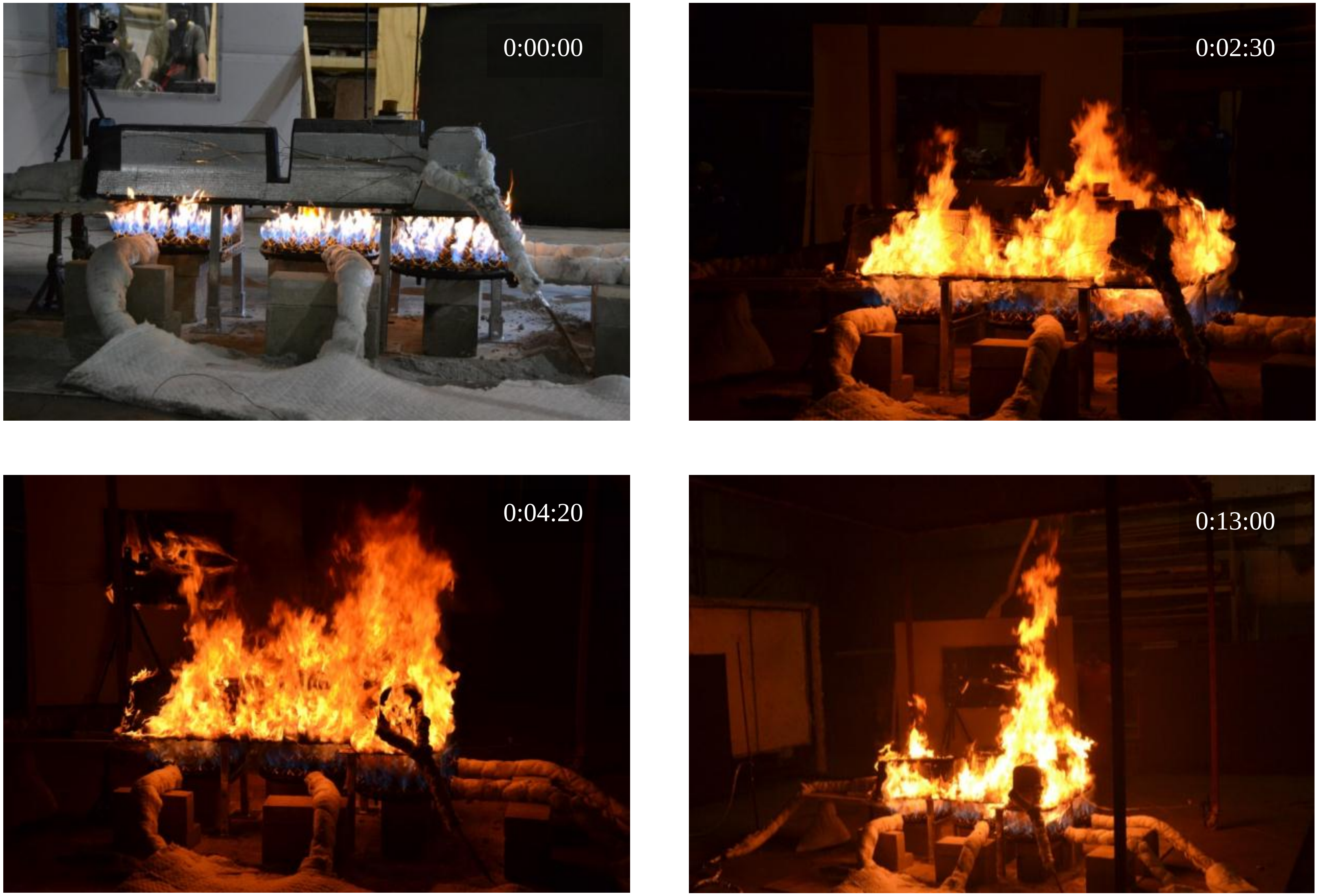

Figure 50 0 minutes (top left), 2:30 minutes (top right), 4:20 minutes (bottom left), 13 minutes (bottom right)

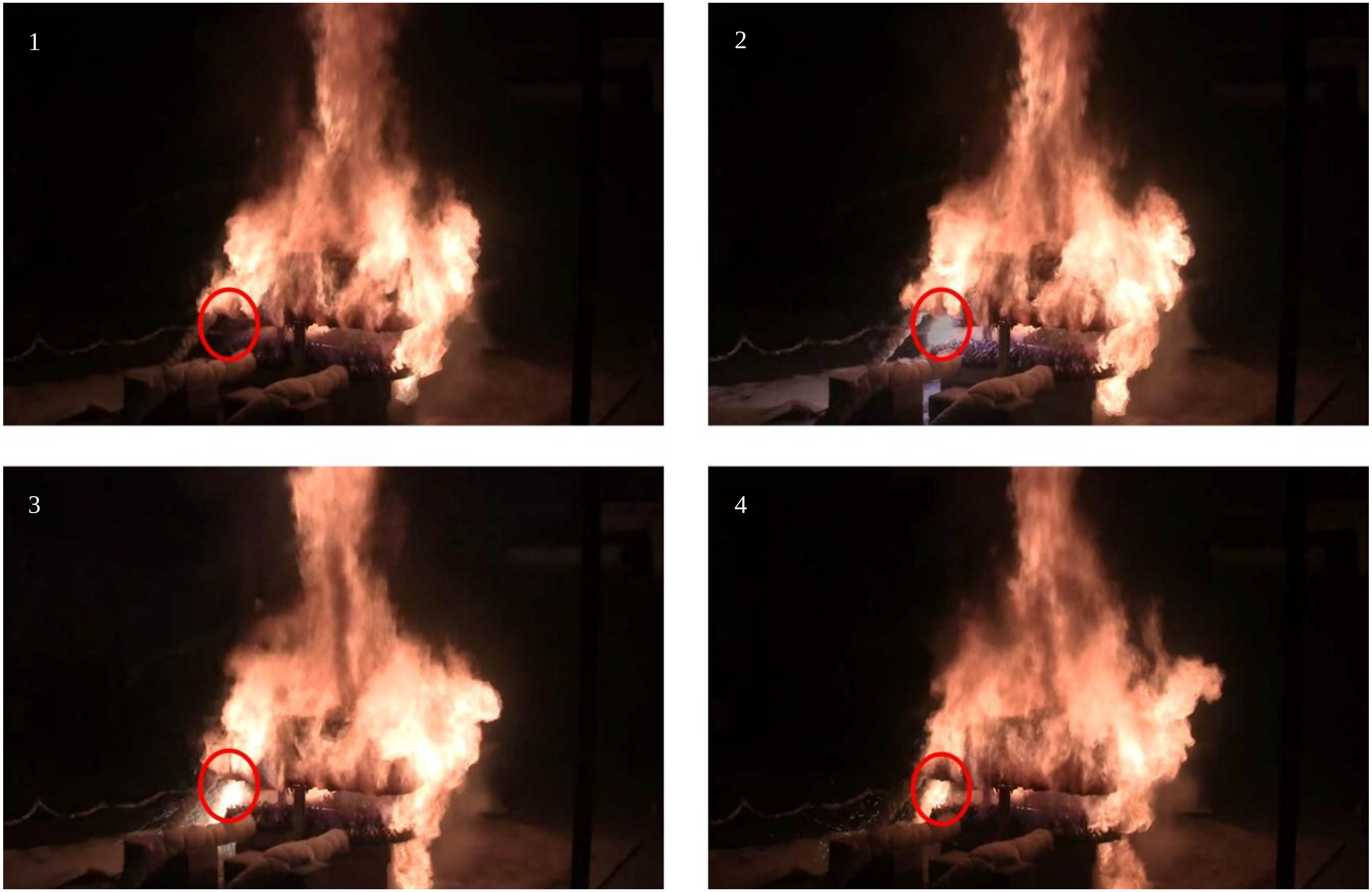

Figure 51 14:50 minutes: A large stream of sparks shoot out from the bottom of the NW end of the battery from its interior

Figure 52 20:40 minutes (top left), 25:00 minutes (top right), 47:10 minutes (bottom left), 01:34:00 minutes (bottom right)

6.1.1.2 HRR Measurements

The HRR measurements were collected by SwRI during testing once every second, as shown in Figure 53. The results mirror the observations from the test. The maximum HRR measured during testing was approximately 700 kW, at test time 17 minutes and 30 seconds (about 3 minutes prior to the burners being turned OFF), as summarized in Table 7. Removing the 400 kW propane burners, the peak heat release the battery attributed to the fire was only approximately 300 kW. The initial increase from zero to approximately 100 kW at test time zero was the turning on of the burners. The second bump seen at time 1 minute 30 seconds was the flow of propane being ramped up to the full flow of 400 kW. Between test time 3 and 4 minutes there is a spike in HRR to approximately 550 kW, which was attributed to the ignition of the limited battery cover materials, many of which were plastic. The HRR decreased and settled into the 400 kW range produced by the burners from test time 5 minutes to 12 minutes 30 seconds; during this time, the battery was not providing much, if any, additional HRR after the initial plastic cover materials were consumed. The HRR then spiked to over 600 kW and remained there from test time 15 minutes to 20 minutes, when the burners were turned OFF. During this period of time, visible flames were observed venting out of the top fuse of the battery, the CAN Bus connection ports, and the three battery vents, which provided the additional HRR. Once the burners were turned OFF around 20 minutes, the HRR slowly decayed from time 20 minutes to 36 minutes, when it essentially reached a reading of zero.

In addition to the maximum HRR reported in Table 7, the average HRR over the entire 90 minute test and the total heat release were calculated to be 128 kW was 720 MJ, respectively.

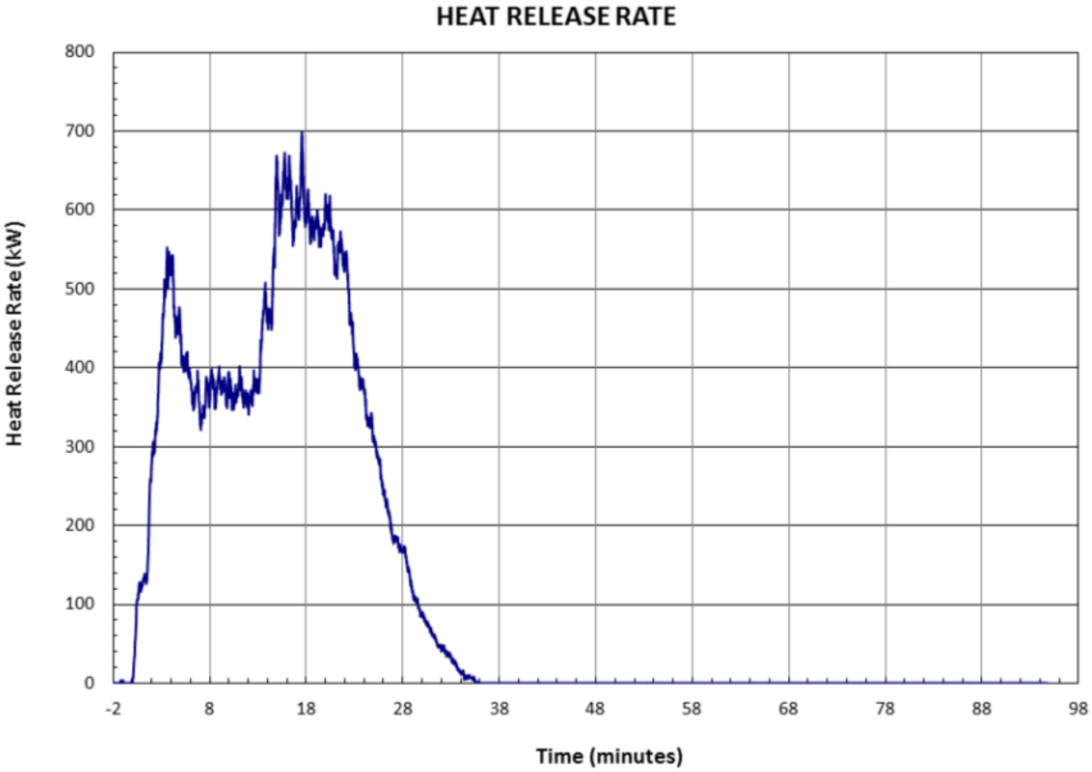

Figure 53 HRR as a function of time

Table 7 Summary of HRR Measurements

HRR	Value	Time
Maximum	698 kW	0:17:33
Average	128 kW	----
Total Heat Released	720 MJ	----

6.1.1.3 Temperatures and Heat Flux Measurements

Temperature and heat flux measurements were collected by SwRI during testing once every second. The maximum temperatures measured during testing and their corresponding times are summarized in Table 8 and Table 9. The majority of the maximum temperatures measured during the test occurred while the propane burners were still ON. TCs 5, 6, and 13 experienced a maximum temperature after the burners were turned OFF; however, those maximums were shortly after (within 30 seconds) the burners were turned OFF. TCs 12, 14, 17, 18, and 20 all experienced maximum temperatures at a time after the burners were turned OFF (between 2 and 27 minutes after the burners were turned OFF), which can be explained by their position in and around the battery. Each of those TCs were in close contact to the flames and hot gases venting either out of the CAN bus connection area, were either inside the three vent holes that continued to produce flames for some time after the burners were turned OFF or were in close proximity to those vent holes.

The maximum temperatures measured on the exterior of the battery (TCs 1 through 12) were between 1264 and 2112 °F. Internal maximum temperatures (TCs 13 through 15) were between 1263 and 2234 °F. Maximum temperatures at a standoff distance of five feet from the battery were between 202 and 230 °F. At a standoff distance of ten feet, the maximum temperatures dropped to between 107 and 127 °F.

The heat flux measurements followed a similar trend as seen in the TC data, where the majority of the maximum values were found prior to the burners being turned OFF. The one exemption was HFG1, which had a peak heat flux approximately three minutes after the burners were turned OFF. This was due to flames and hot gases emanating from the CAN bus connection area at that time. Maximum heat fluxes at a standoff distance of five feet from the battery were between 17.1 and 18 kW/m^2 and at ten feet dropped to between 3.7 and 4.7 kW/m^2.

Table 8 Summary of Maximum Temperature Measurements

TC	Maximum Temperature (°F)	Time	TC	Maximum Temperature (°F)	Time
1	1600.5	0:18:19	11	1490.7	0:17:09
2	1342.4	0:18:19	12	1264.1	0:23:26
3	2111.9	0:18:19	13	2233.8	0:20:54
4	1472	0:17:04	14	1311.4	0:47:04
5	2040.1	0:20:58	15	1262.7	0:18:13
6	1977.4	0:20:54	16	1975.5	0:05:20
7	1533.4	0:19:57	17	201.7	0:24:09
8	1713.9	0:16:57	18	127	0:24:27
9	1609.9	0:06:45	19	230	0:18:14
10	1419.8	0:05:58	20	106.7	0:22:35

Table 9 Summary of Maximum Heat Flux Measurements

Measurement	Value	Time
HFG1 (5 feet)	17.1 kW/m^2	0:23:05
HFG2 (10 feet)	4.7 kW/m^2	0:15:52
HFG3 (5 feet)	18.0 kW/m^2	0:14:54
HFG4 (10 feet)	3.7 kW/m^2	0:14:54

6.1.1.4 Internal Battery Sensor Measurements

Internal cell voltages and internal battery temperature sensor measurements were collected by Exponent during testing at an effective rate of once per second, as shown in Figure 54. As demonstrated in the plot, the DAQ system lost contact with the battery after 6 minutes and 21 seconds (0:04:21 test time). At that time, only one internal temperature sensor (Sensor #7) had changed significantly since the start of the test. As such, this was the only temperature sensor plotted in Figure 54. It recorded a maximum temperature of at 41 °C at the time communication to the battery was lost. At that same time, none of the individual cell voltages had recorded a drop in voltage. As shown previously in Figure 50 and Figure 53, the combustible coverings on the exterior of the battery were fully involved around this time and the HRR had spiked to above 500 kW.

Temperature Sensor #7 was found in the eastern portion of the long span of the battery, as shown in Figure 55. The closest internal thermocouple installed by Exponent (TC13) through the south vent spiked from approximately 200 °F at time 0:02:45 to over 1500 °F by 0:04:21, when communication with the battery ceased. A post-test forensic investigation into the CAN bus and DAQ system communication cables and connections points revealed the failure mode was internal to the battery, possibly a short in the CAN bus power supply. The battery CAN bus operates on an externally provided 12V power supply. The power is provided through pins in the same connector that carries the CAN bus signal pins. During the burn tests, this power was provided by a GPC-3030D power supply. When CAN bus communication failed, the output power of the supply dropped from 12V to approximately 8V and the power supply switched from constant-voltage to constant-current mode, indicating that the power supply terminals had been short-circuited internally. The CAN bus cables spanning from the DAQ to the CAN bus connection area were retrieved after the tests and the continuity of the pins carrying the input voltage was checked. The cables were not short-circuited, further indicating that the communication problem was internal to the battery. The likely failure mode was an internal wire transmitting power to the CAN bus developed a short circuit, terminating the ability of the battery to communicate via the CAN bus.

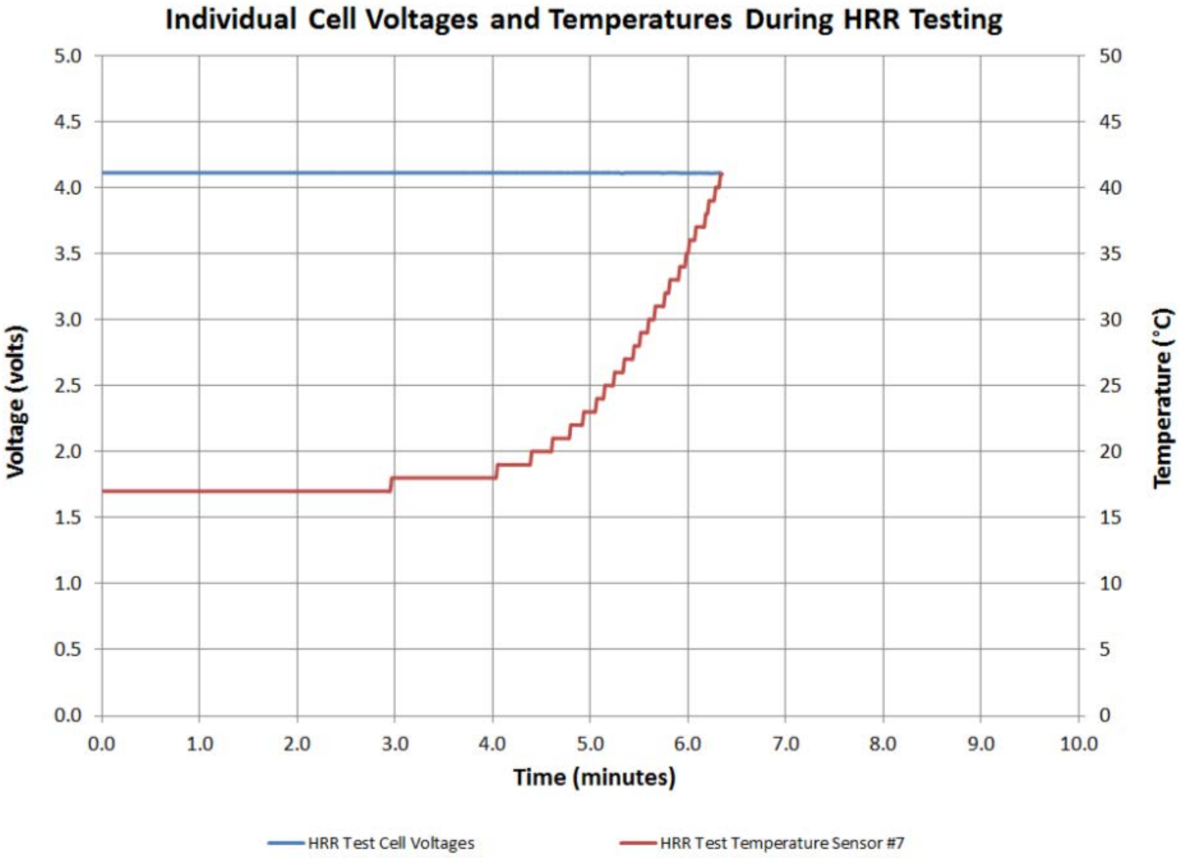

Figure 54 Internal cell voltages and temperatures (Sensor #7) during HRR Testing

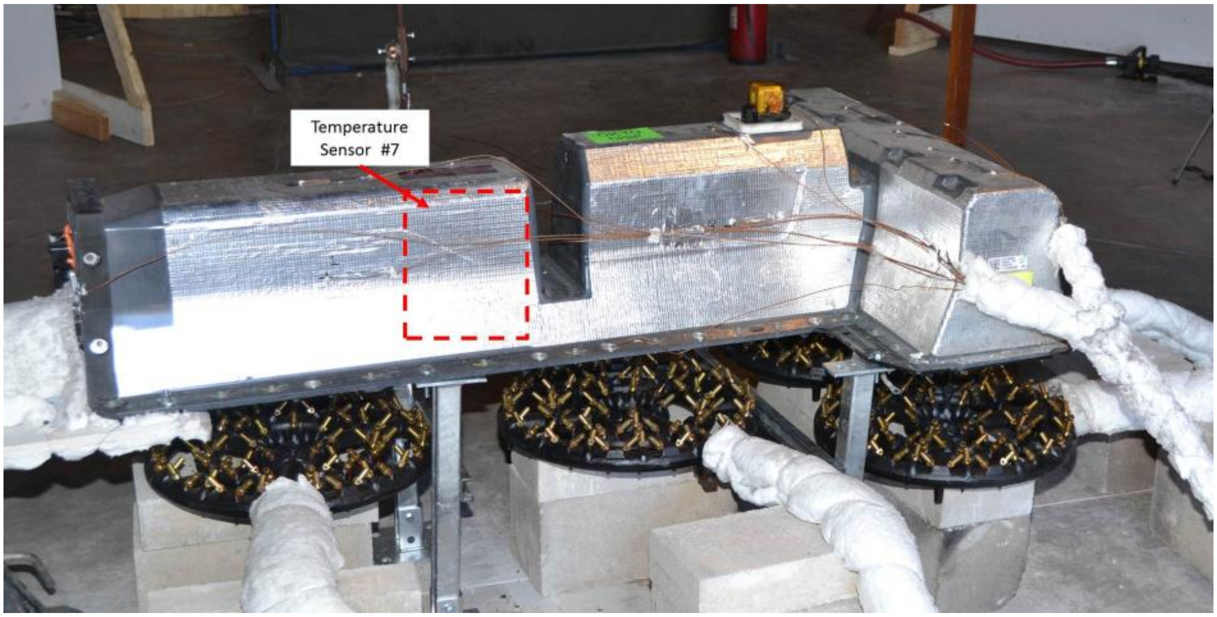

Figure 55 Location of Temperature Sensor #7 within Battery B

6.1.1.5 Gas Sampling Results

A total of fourteen air samples were taken using Tedlar grab bags. Sampling was conducted every 5 minutes, starting 5 minutes into the test. Each sample was pulled over a 1 minute period. The bags were then analyzed for HCl, HF, HBr, HCN, CO_2, CO, NO_x, SO_2, acrolein, and formaldehyde via FTIR. The results showed only CO and CO_2 present. Each spectra was directly examined for the vapor phase signatures for HCN; none were detected. Additionally, each spectra was directly examined for HF. No HF was detected; however, a noisy baseline resulted in some false-positive readings.

6.1.1.6 Overhaul Results

After approximately 1:34 minutes of elapsed time, all visible flaming ceased. Thermal images were recorded as the battery cooled. Thermal images were captured for an additional three hours and 15 minutes. When visible flaming ceased at 1:34, the observed exterior maximum temperatures were approximately 753 °F. Two hours later, maximum observed temperatures were approximately 358 °F. Three hours after all visible flaming ceased, maximum observed temperatures were approximately 312 °F, as shown in Figure 56.

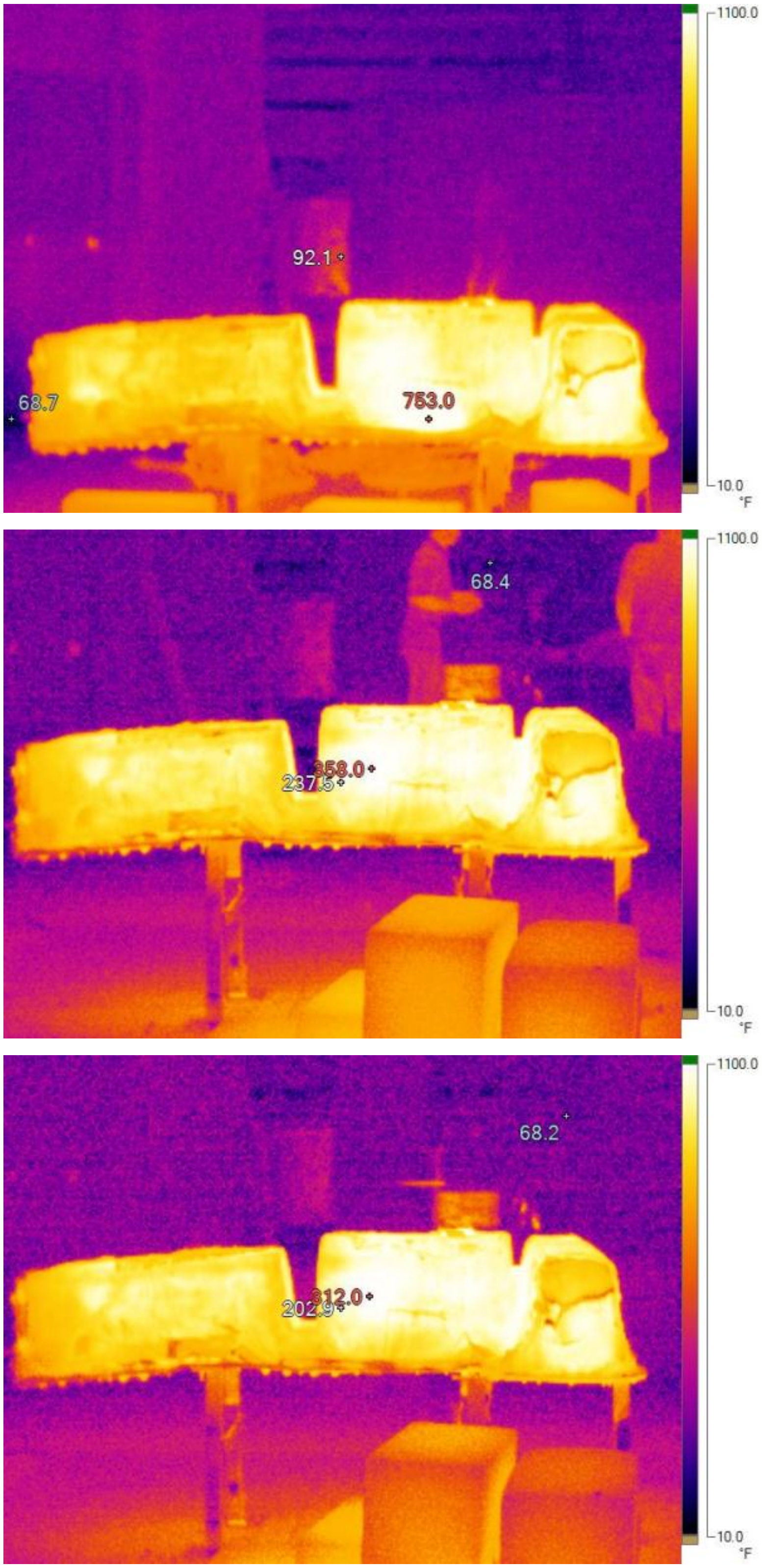

Figure 56 Thermal image 0 hours (top); 2 hours (middle); and 3 hours (bottom) after visible flaming ceased

6.2 Suppression Testing

The suppression tests were performed at the MFRI test facility at 4500 Paint Brach Parkway, College Park, Maryland 20742 between March 27, 2013 and April 3, 2013, under the supervision of Marty Lepore from MFRI and R. Thomas Long, Jr., Andrew Blum, Thomas Bress, and Benjamin Cotts from Exponent. Six tests were conducted; three using Battery A (designated A1, A2, and A3) and three using Battery B (designated B1, B2, and B3). For each battery type, two of the tests were performed with the battery pack alone positioned inside the VFT (A1, A2, B1, and B2) and one test was performed with typical interior finishes/upholstery installed within the VFT in addition to the battery pack (A3 and B3), as described in Section 5.2. The tests were arranged in this manner to evaluate the repeatability of the exposure fire inducing thermal runaway in the battery pack and to collect observations as to the differences between a battery only fire and a fire involving a battery and vehicle interior finishes/upholstery. Feedback from the fire service community indicated that any training recommendations would be most well received if fires looked as realistic as possible.

6.2.1 Battery A1 Test

Battery A is a 4.4 kWh HV battery pack enclosed in a metal case and was rigidly mounted in the lower part of the rear cargo area of the VFT, as described previously in Sections 4.1.1 and 5.2. Test A1 was conducted on March 27, 2013, at approximately 2 p.m. At the start of the test, the weather was overcast, with temperatures of approximately 51 °F and a relative humidity of approximately 40%. The wind was out of the west-northwest with an average wind speed of 15 miles per hour (mph) and gusts up to 24 mph. The following sections summarize the data collected by Exponent during suppression Test A1.

6.2.1.1 Test Observations

Table 10 summarizes the key events observed by Exponent staff during the suppression testing. Images at significant test times are provided in Figure 57 and Figure 58. In general, the test demonstrated that an external heat source, such as the propane burners, could induce Battery A into thermal runaway while it was positioned inside the VFT and result in visible release and ignition of electrolyte material. Loud popping sounds from the interior of the battery were heard and visible sparks were observed on many occasions throughout the test. White smoke and white off gassing were observed on several occasions and were consistent with the release of flammable electrolyte material from individual cells. However, no violent projectiles, explosions, or bursts were observed during the test while the battery was exposed to the burners, while it was in a free burn state, while it was being suppressed, or after suppression efforts ceased.

Once manual suppression started, the initial battery fire was quickly knocked down (within approximately 25 seconds), however the battery continued to smoke and off gas for some time afterwards. On several occasions, the off gases were reignited and required additional water to suppress the rekindled flames. Active suppression efforts ceased approximately six minutes after the first application of water and within an hour, the exterior of the battery had returned to near ambient temperatures. See Sections 6.2.1.2 and 6.2.1.3 for more details on the firefighting efforts and Section 6.2.1.6 for more details on overhaul operations.

Table 10 Test A1 Key Observations

Time	Event
0:00:00	Start DAQ and video cameras
0:01:27	Ignite burners
0:01:30	White smoke produced
0:02:28	Pop sound heard from battery interior (pops)
0:02:40	White smoke production increases
0:02:59 – 0:04:32	Sporadic pops, increasing flame size
0:05:20	Pops increasing; dark smoke produced
0:05:29	Pops
0:06:05	Increase in fire size; steady pops; darker smoke produced
0:07:00 – 0:07:40	Pops steady; heavy smoke
0:08:27	Burners terminated, no noticeable change in fire size
0:09:24	Suppression starts
0:09:49 – 0:10:20	Pops
0:10:54	Battery fire reignited and suppressed

Time	Event
0:11:45	Battery fire reignited and suppressed
0:12:15 – 0:12:23	Electrical sparks observed
0:13:00	Pops
0:14:30	Start water application up into rear ports of battery
0:14:43	Sparks observed
0:18:26 – 0:19:04	Off gassing / white smoke
0:23:18	Pops
0:35:20	Off gassing / white smoke
1:00:00	Data acquisition off

Figure 57 Test A1: ignition (top left); off gassing (top right); fully involved (bottom left); burners off (bottom right)

Figure 58 Test A1: Suppression starts (top left); reignition and suppression (top right, bottom left); post suppression (bottom right)

6.2.1.2 Water Flow Measurements

As reported in Table 11, the initial battery fire was quickly knocked down by MFRI after approximately 23 seconds of water application at a flow rate of 125 gpm. However, the battery continued to smoke, off gas white smoke, and reignite for some time afterwards, which required seven additional water applications for times ranging between four and twenty six seconds. All active suppression efforts ceased approximately six minutes after the first application of water. Exponent estimates a total of approximately 275 gallons of water was used to control the fire in Test A1.

Table 11 Test A1 Water Flow Times

Flow Start	Flow Stop	Δt	Flow (gallons)	Comments
0:09:24	0:09:47	0:00:23	48	
0:10:17	0:10:21	0:00:04	8	
0:11:34	0:12:00	0:00:26	54	
0:12:17	0:12:38	0:00:21	44	
0:13:04	0:13:24	0:00:20	42	
0:13:33	0:13:52	0:00:19	40	
0:14:54	0:15:02	0:00:08	17	
0:15:06	0:15:17	0:00:11	23	
	Total	**0:02:12**	**275**	

6.2.1.3 Firefighter Tactics and Observations

During Test A1, approximately at the fourteen minute mark, the firefighter on the nozzle stated, “We can't get water where it needs to be.” Post-test discussions with the firefighters echoed this statement. The single biggest challenge the firefighters faced was applying water to where the fire was actually occurring, which was inside the metal battery casing and most likely at individual cells. Since the firefighters were unable to get direct access inside the battery, their main tactic was to apply water intermittently to flames that rekindled after initial suppression. While this intermittent application reduced the overall water application volume, a constant flow of water may have cooled the metal casing of the battery, thereby reducing the chance of further cell thermal runaway.

6.2.1.4 Temperature and Heat Flux Measurements

Temperature and heat flux measurements were collected by Exponent during Test A1 once every second. The maximum temperatures and heat fluxes measured during the test and their corresponding times have been summarized in Table 12 and Table 13 and plotted in Figure 59 and Figure 60.[59] The majority of the maximum temperatures and heat fluxes measured during the test occurred prior to the burners being turned OFF. TC4 experienced a maximum temperature after the burners were turned OFF, just prior to the start of suppression.

The maximum temperatures measured on the exterior of the battery (TCs 1, 4, 5, 7, 10, and 11) were between 766 and 2547 °F. Once suppression efforts began, the temperatures quickly dropped to near ambient with a few spikes between 10 and 15 minutes as the battery reignited.

The heat flux measurements followed a similar trend to the TC data, where all of the maximum values were found prior to the burners being turned OFF. The maximum heat flux at a standoff distance of five feet from the VFT was 3.5 kW/m^2 and at further distances, 15, 20 and 25 feet, the maximum heat fluxes were between 1.6 and 2.6 kW/m^2.

Table 12 Summary of Test A1 Maximum Temperature Measurements

TC	Maximum Temperature (°F)	Time	TC	Maximum Temperature (°F)	Time
1	1760	0:08:11	7	1408	0:03:26
4	1156	0:09:11	10	2547	0:06:51
5	766	0:08:24	11	1827	0:06:45

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[59] Several of the TCs failed during testing or provided erroneous values likely during shorting/suppression events. As such, to provide clearer plots and summary tables , one TC was plotted/reported for each side of the exterior of the battery (TCs 1, 7, 10, and 11) and two TCs from the top of the battery (TCs 4 and 5) were plotted/reported.

Table 13 Summary of Test A1 Maximum Heat Flux Measurements

Measurement	Heat Flux (kW/m^2)	Time
HFG1 (5 feet)	3.5	0:01:37
HFG2 (15 feet)	2.6	0:03:57
HFG3 (20 feet)	2.0	0:04:17
HFG4 (25 feet)	1.6	0:02:40

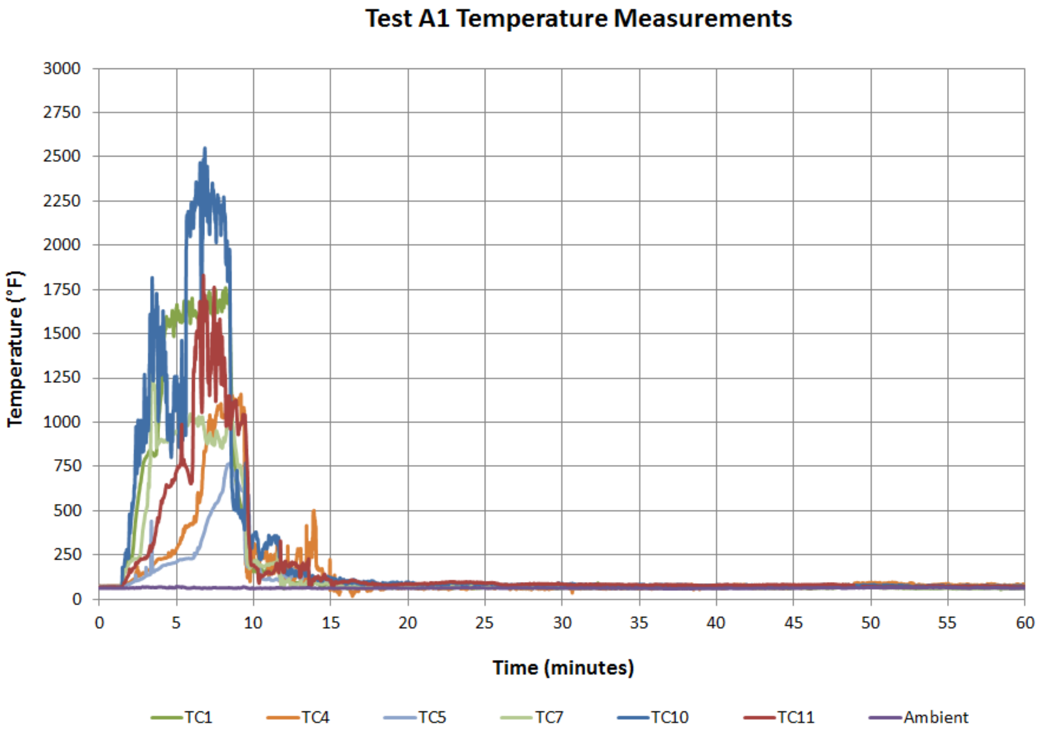

Figure 59 Test A1 TC plot

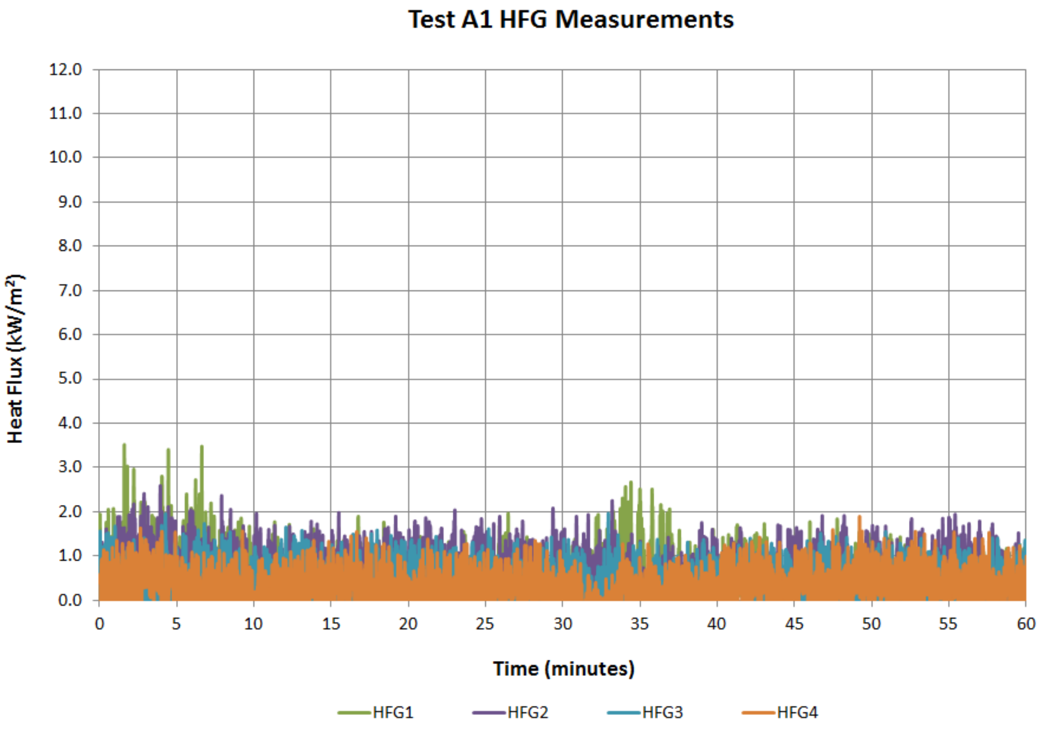

Figure 60 Test A1 HFG plot

6.2.1.5 Electrical Measurements

Current and voltage measurements for Test A1 were performed using the configuration and methodology described previously. The measurements were recorded during an initial startup period of the test prior to ignition or fire suppression in order to determine a baseline measurement of background noise sources. Measurements continued throughout the entire test and a summary of results during fire suppression activities are provided in Table 14 below, showing the maximum, minimum, and three quartile values for all four recorded measurements. Full measurements are provided in Appendix E.

Table 14 Summary of Test A1 Current (mA) and Voltage (V) Measurements

	Maximum	**Q3**	**Median**	**Q1**	**Minimum**
Nozzle Current	1.5	0.2	0.0	-0.2	-1.8
Nozzle Voltage	0.37	0.01	0.00	-0.01	-0.05
Chassis Current	≤5	--	--	--	≥-5
Chassis Voltage	1.09	0.48	0.00	-0.48	-0.99

A detailed analysis of the full resolution 2 kHz recorded signal for nozzle current and voltage measurements was performed. Current measurements during fire suppression activities remained within the same noise levels as were observed during initial background recording and the results above are summarized for 50 ms median filtering of the data in order to reduce the apparent effect of noise on the results. Likewise, voltage measurements during fire suppression activities generally remained within the same noise levels as observed during initial background recording. Brief departures from the background level were occasionally observed when firefighters inserted the nozzle inside the chassis, possibly contacting an exposed portion of the battery, however, these changes in voltage were brief and no voltage levels were recorded in excess of ±0.4 V.

The resolution of the chassis current was set at ±5 mA in this test. No measurements exceeded this value at any time during fire suppression activities. Finally, chassis voltage measurements indicate a small DC voltage was intermittently present on the body of the chassis (consistent with post-measurement tests), with brief deviations as high as ±1.1 V.

6.2.1.6 Overhaul Results

Thermal images of the battery commenced at 25 minutes, approximately 10 minutes after active suppression activities had ceased, to monitor, along with the battery TCs, the battery after the fire. As shown in Figure 61, thermal imaging demonstrated the exterior of the battery was below 100 °F on all sides 10 minutes after suppression efforts ended. The battery was left within the VFT for another 35 minutes and monitored with thermal images and TCs for any additional activity. After 60 minutes, the exterior TCs installed on the battery had decreased further to near ambient levels, as reported in Table 15, and the test was stopped. At this time, all other signs of combustion, including off gassing and smoke had ceased as well.

The battery remained within the VFT for the remainder of the day and was removed the following morning after an elapsed time of 18 hours. Prior to removal, thermal image results indicated the exterior case temperatures were approximately ambient. It was moved to a battery storage area with no issues.

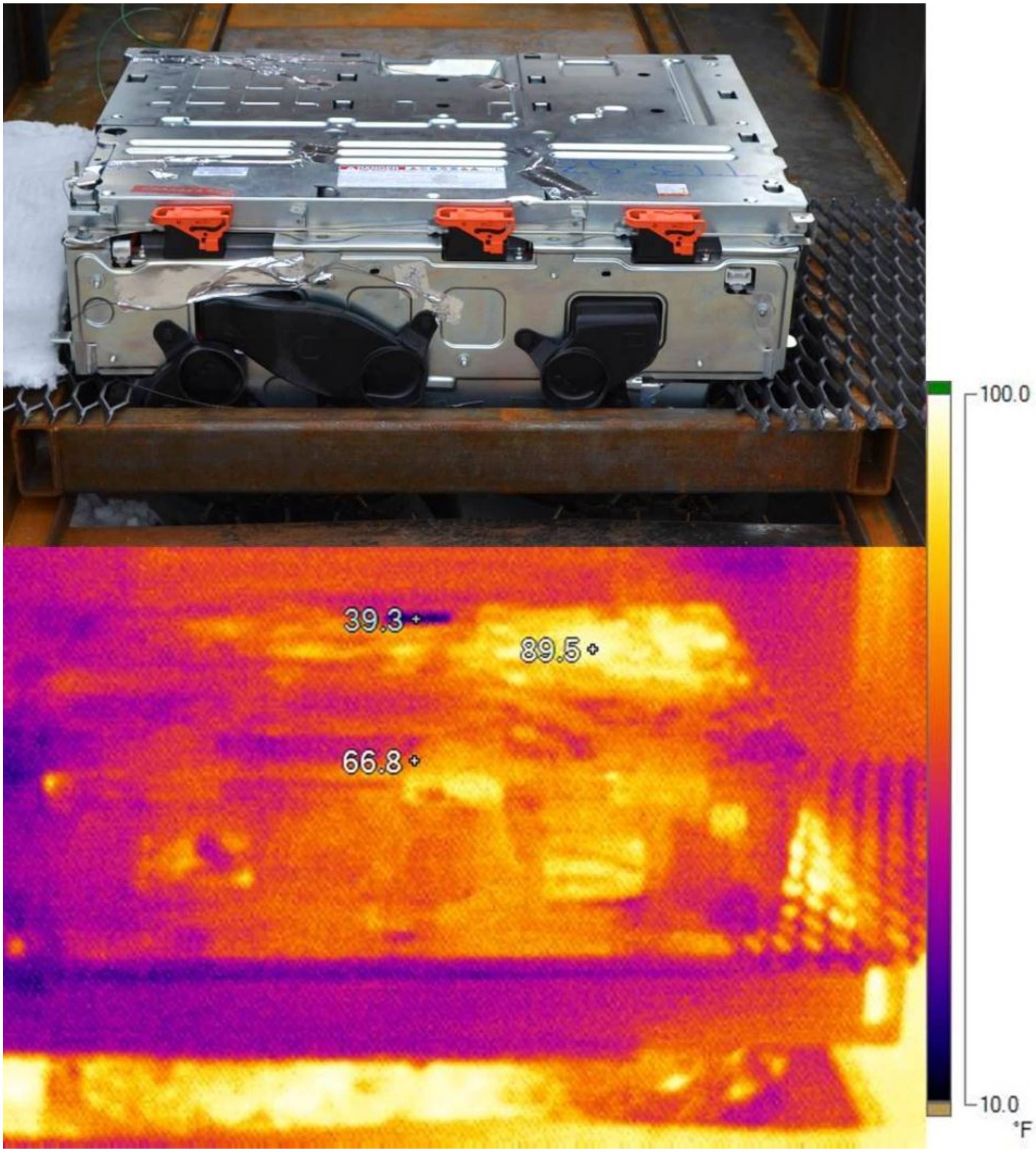

Figure 61 Battery A1 from rear of VFT (top); thermal image (same view) of Battery A1 at 25 minutes (bottom)

Table 15 Summary of Test A1 Temperature Measurements after 60 Minutes

TC	Temperature after 60 Minutes (°F)	TC	Temperature after 60 Minutes (°F)
1	62	7	65
4	79	10	68
5	63	11	66

6.2.1.7 Water Sampling Results

Detailed water sampling was not performed for Test A1. Water samples for each battery type were analyzed for the expected worst case fire suppression test, which included interior finishes (Tests A3 and B3). See Section 6.2.3.7 for water sampling results for Battery A.

6.2.2 Battery A2 Test

Battery A is a 4.4 kWh HV battery pack enclosed in a metal case and was rigidly mounted in the lower part of the rear cargo area of the VFT, as described previously in Sections 4.1.1 and 5.2. Test A2 was conducted on March 28, 2013, at approximately 10:30 a.m. At the start of the test, the weather was overcast, with temperatures of approximately 47 °F and a relative humidity of approximately 56%. The wind was out of the west-northwest with an average wind speed of 13 miles per hour (mph) and gusts up to 17 mph. The following sections summarize the data collected by Exponent during suppression Test A2.

6.2.2.1 Test Observations

Table 16 summarizes the key events observed by Exponent staff during Test A2. Images at significant test times are provided in Figure 62 and Figure 63. In general, the test performed similarly to Test A1, where the battery was induced into thermal runaway by the burners and did not noticeably decrease in fire size once the burners were turned OFF. Visible release and ignition of electrolyte material was observed and loud popping from the interior of the battery was heard coinciding with the observation of visible arcing/sparks on many occasions. The white smoke and white off gassing observed on several occasions were consistent with the release of electrolyte material. Of interest during Test A2, was the ability to predict the release of electrolyte. As noted in Table 16, there were many instances where you could hear a "whoosh", observe arcing, and then heavy white smoke off gassing from the battery interior. This occurred on several occasions and was also observed and noted by the firefighters, as discussed in Section 6.2.2.3. However, no violent projectiles, explosions, or bursts were observed during the test while the battery was exposed to the burners, while it was in a free burn state, while it was being suppressed, or after suppression efforts ceased.

Once suppression started, the initial battery fire was quickly knocked down (within approximately 20 seconds), however the battery continued to smoke and off gas for some time afterwards. On several occasions, the off gases were reignited and required additional water to suppress the rekindled flames. Active suppression efforts ceased approximately thirty-six minutes after the first application of water and within an hour, the exterior of the battery had returned to near ambient temperatures. See Sections 6.2.2.2 and 6.2.2.3 for more details on the firefighting efforts and Section 6.2.2.6 for more details on overhaul operations.

Table 16 Test A2 Key Observations

Time	Event
0:00:00	Start DAQ and video cameras
0:01:11	Ignite burners
0:02:00	White smoke produced
0:02:15	Pop sound heard from battery interior (pops)
0:02:29	Pops
0:02:37	Flames observed on battery
0:03:09 – 0:05:00	Sporadic pops, increasing flame size
0:05:08	Black smoke produced
0:05:22 – 0:05:31	Louder pops heard
0:05:38 – 0:07:01	Pops increase, black smoke increasing
0:07:15	Flames extend out rear and top of vehicle
0:08:14	Burners terminated, no noticeable change in fire size
0:08:28 –	Steady pops and black smoke

Time	Event
0:08:52	
0:09:11	Suppression starts from rear of the vehicle
0:09:48	Battery fire reignited
0:10:21 – 0:12:57	Sporadic pops with heavy white smoke off gassing
0:13:29 0 0:15:07	Would hear a “whoosh”, then observe arcing and heavy white smoke off gassing
0:15:21	Battery fire reignited
0:15:33	Firefighters attack fire from passenger side window
0:16:02 – 0:21:48	Sporadic pops with heavy white smoke off gassing
0:23:06	Battery fire reignited
0:24:26	Battery fire reignited
0:26:31	Small pop
0:26:48	Firefighters attack fire from rear of vehicle
0:27:36 – 0:37:20	Occasional small pops
0:44:00	Battery fire reignited
0:44:49	Firefighters insert nozzle directly into right vent hole on metal battery case
0:47:55	Pop
1:00:00	DAQ system off

Figure 62 Test A2: ignition (top left); off gassing (top right); fully involved (bottom left); burners off (bottom right)

Figure 63 Test A2: suppression starts (top left); reignition and suppression (top right, bottom left); post-suppression (bottom right)

6.2.2.2 Water Flow Measurements

As reported in Table 17, the initial battery fire was quickly knocked down by MFRI after approximately 18 seconds of water application at a flow rate of 125 gpm. However, the battery continued to smoke, off gas white smoke, and reignite for some time afterwards, which required ten additional water applications for times ranging between eleven and thirty four seconds. All active suppression efforts ceased approximately thirty six minutes after the first application of water. Exponent estimates a total of approximately 442 gallons of water was used to control the fire in Test A2.

Table 17 Test A2 Water Flow Times

Flow Start	Flow Stop	Δt	Flow (gallons)	Comments
0:09:11	0:09:29	0:00:18	37	
0:09:57	0:10:10	0:00:13	27	
0:17:06	0:17:28	0:00:22	46	
0:19:08	0:19:23	0:00:15	31	
0:20:57	0:21:09	0:00:12	25	
0:23:15	0:23:34	0:00:19	40	
0:23:38	0:24:03	0:00:25	52	
0:24:37	0:25:01	0:00:24	50	
0:25:15	0:25:26	0:00:11	23	
0:44:49	0:45:08	0:00:19	40	
0:45:13	0:45:47	0:00:34	71	
	Total	**0:03:32**	**442**	

6.2.2.3 Firefighter Tactics and Observations

After test discussions with the firefighters echoed their statements from Test A1. The firefighters indicated that the single biggest challenge was applying water to where the fire was actually occurring, which was inside the metal battery casing. Since they were unable to get direct access inside the battery, their tactic was to only apply water to flames that rekindled after initial suppression.

Interestingly, the firefighter indicated that they could hear a release of “pressure” followed by white smoke and then flames, essentially they were able to predict when the fire was going to reignite. These observations were also consistent with Exponent’s, see Section 6.2.2.1. In addition, a localized hot spot on the battery, located on the passenger side of the vehicle, was observed by the firefighters and resulted in a change in positioning for them. The firefighters moved from the rear of the vehicle to the passenger side to gain better access to that portion of the battery to cool it down.

6.2.2.4 Temperature and Heat Flux Measurements

Temperature and heat flux measurements were collected by Exponent during Test A2 once every second. The maximum temperatures and heat fluxes measured during the test and their corresponding times have been summarized in Table 18 and Table 19 and plotted in Figure 64 and Figure 65.[60] The majority of the maximum temperatures measured during the test occurred prior to the burners being turned OFF. TC5 experienced a maximum temperature after the burners were turned OFF, prior to the start of suppression.

The maximum temperatures measured on the exterior of the battery (TCs 1, 4, 5, 7, 10, and 11) were between 510 and 1196 °F. Once suppression efforts began, the temperatures quickly dropped to near ambient with a few spikes between 10 and 25 minutes as the battery reignited.

The heat flux measurements differed from the TC data, as the majority of the maximum values were found after the burners were turned OFF and after initial suppression efforts. The maximum heat flux at a standoff distance of five feet from the VFT was 3.7 kW/m^2 and at further distances, 15, 20 and 25 feet, the maximum heat fluxes were between 1.6 and 2.2 kW/m^2.

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[60] For consistency the same TCs reported and plotted for Test A1 (TCs 1, 4, 5, 7, 10, 11) have been summarized and plotted for Test A2 for direct comparison.

Table 18 Summary of Test A2 Maximum Temperature Measurements

TC	Maximum Temperature (°F)	Time	TC	Maximum Temperature (°F)	Time
1	1107	0:05:25	7	1001	0:05:44
4	987	0:07:58	10	1196	0:07:48
5	510	0:08:26	11	1138	0:06:39

Table 19 Summary of Test A2 Maximum Heat Flux Measurements

Measurement	Heat Flux (kW/m^2)	Time
HFG1 (5 feet)	3.7	0:04:55
HFG2 (15 feet)	2.2	0:43:00
HFG3 (20 feet)	1.6	0:13:51
HFG4 (25 feet)	1.8	0:09:15

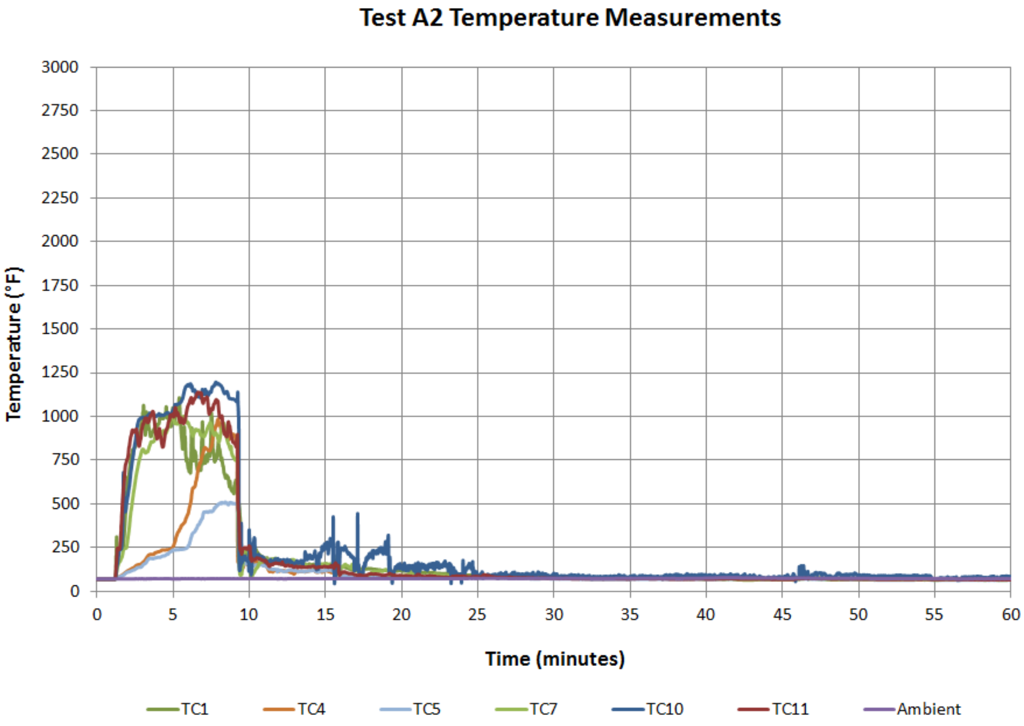

Figure 64 Test A2 TC plot

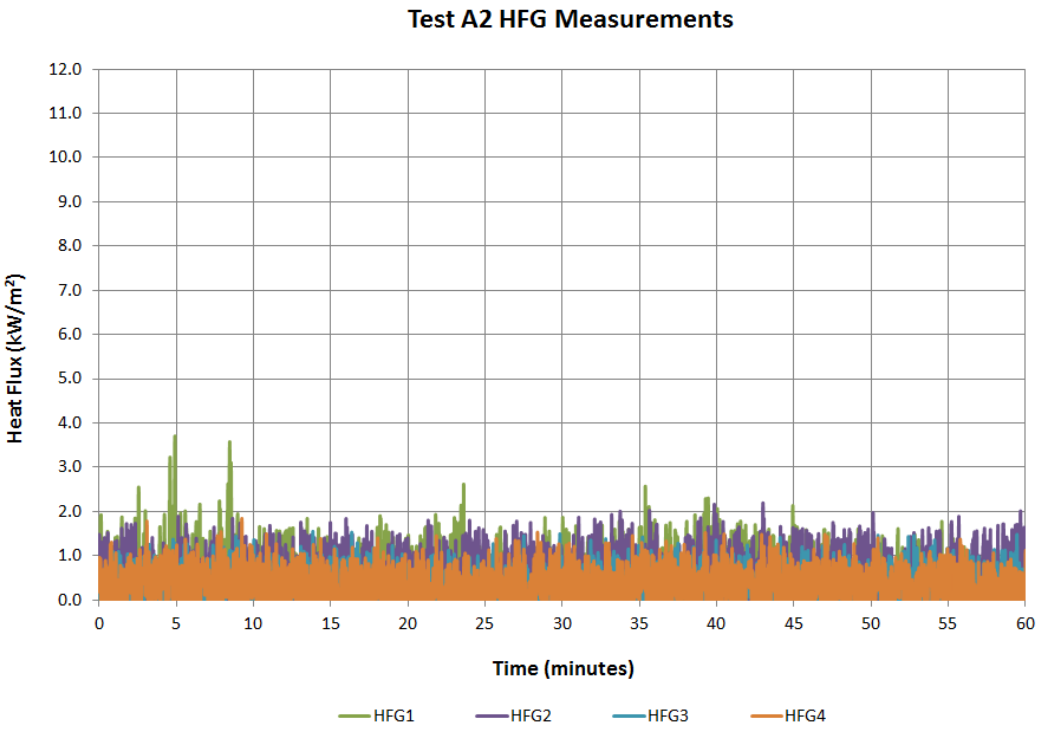

Figure 65 Test A2 HFG plot

6.2.2.5 Electrical Measurements

Current and voltage measurements for Test A2 were performed using the configuration and methodology described previously. The measurements were recorded during an initial startup period prior to ignition or fire suppression in order to determine a baseline measurement of background noise sources. Measurements continued throughout the entire test and a summary of results during fire suppression activities are provided in Table 20 below, showing the maximum, minimum, and three quartile values for all four recorded measurements. Full measurements are provided in Appendix E.

Table 20 Summary of Test A2 Current (mA) and Voltage (V) Measurements

	Maximum	**Q3**	**Median**	**Q1**	**Minimum**
Nozzle Current	1.3	0.2	0.0	-0.2	-1.9
Nozzle Voltage	0.02	0.00	0.00	0.00	-0.28
Chassis Current	≤5	--	--	--	≥-5
Chassis Voltage	1.23	0.86	0.28	-0.33	-0.67

A detailed analysis of the full resolution 2 kHz recorded signal for nozzle current and voltage measurements was performed. Current measurements during fire suppression activities remained within the same noise levels as were observed during initial background recording and the results above are summarized for 50 ms median filtering of the data in order to reduce the apparent effect of noise on the results. Likewise, voltage measurements during fire suppression activities generally remained within the same noise levels as observed during initial background recording. Brief departures from the background level were occasionally observed when firefighters inserted the nozzle inside the chassis, possibly contacting an exposed portion of the battery, however, these changes in voltage were brief and no voltage levels were recorded in excess of ±0.3 V.

The resolution of the chassis current was set at ±5 mA in this test. No measurements exceeded this value at any time during fire suppression activities. Finally, chassis voltage measurements indicated a small DC voltage of approximately 0.3 V was intermittently present on the body of the chassis (consistent with post-measurement tests) with brief deviations as high as ±1.23 V.

6.2.2.6 Overhaul Results

Thermal images of the battery commenced at approximately 40 minutes, approximately 5 minutes prior to the last suppression activities and the last time flames were observed around the battery. The thermal images along with the battery TCs, where recorded to monitor the battery after the fire to determine when it could be safely overhauled. As shown in Figure 66, thermal imaging demonstrated the exterior of the battery was still significantly hot in the front passenger side of the battery with a maximum temperature of 543 °F. It is of note that this “hot spot” was not identified by the discreet, localized external battery TCs. Approximately four minutes after this thermal image the fire rekindled in this location and was suppressed by the firefighters.

After the last suppression activities around 45 minutes, the battery was left within the VFT for another 15 minutes and monitored with thermal images and TCs for any additional activity. After 60 minutes, the exterior TCs installed on the battery had decreased to near ambient levels, as reported in Table 21, and the test was stopped. At this time, all other signs of combustion, including off gassing and smoke had ceased as well.

The battery remained within the VFT for approximately another hour and was then removed. It was moved to a battery storage area with no issues.

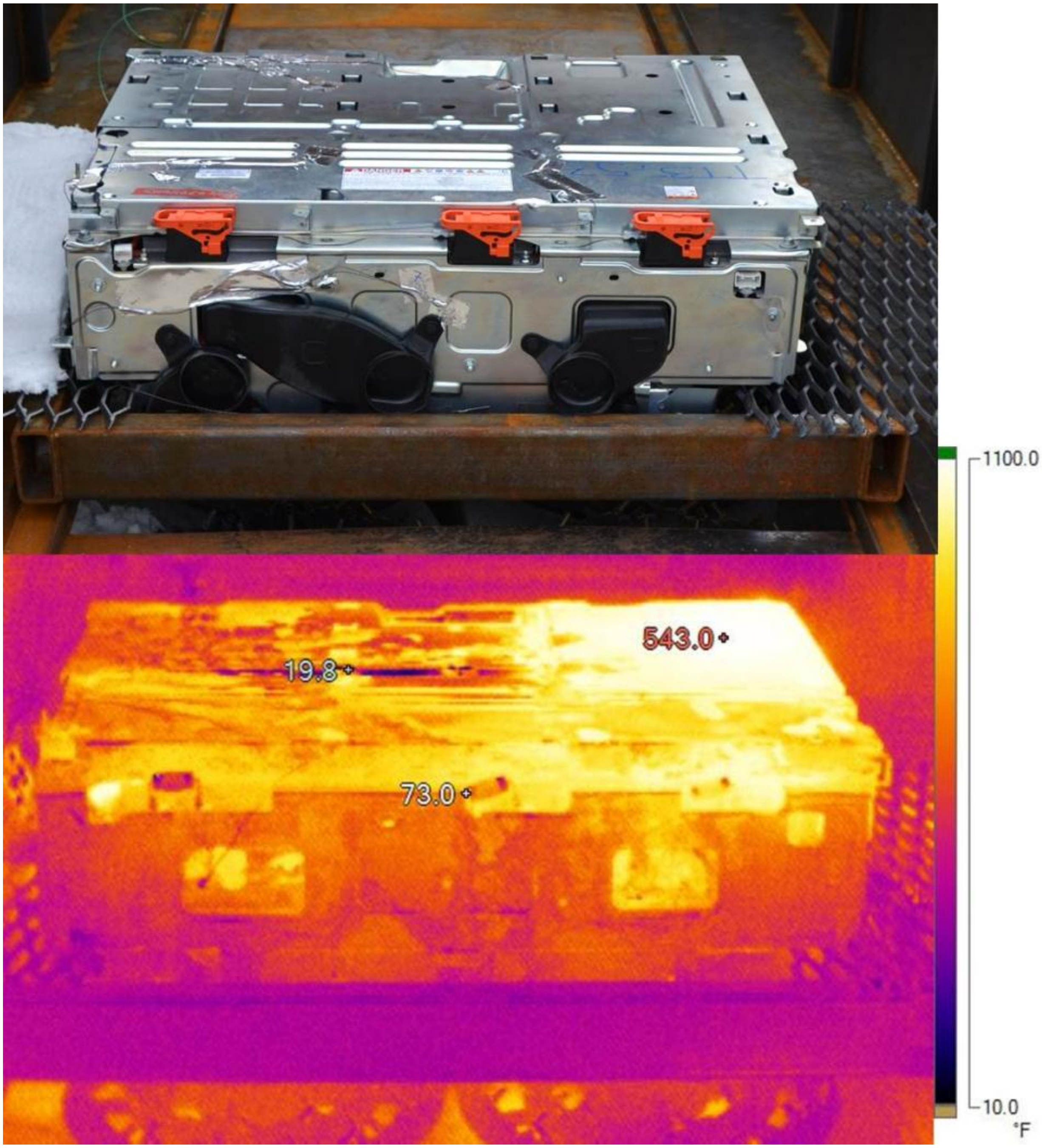

Figure 66 Battery A2 from rear of VFT (top); thermal image (same view) of Battery A2 at 40 minutes depicting the "hot spot" (bottom)

Table 21 Summary of Test A2 Temperature Measurements after 60 Minutes

TC	Temperature after 60 Minutes (°F)	TC	Temperature after 60 Minutes (°F)
1	68	7	67
4	N/A[61]	10	83
5	63	11	65

6.2.2.7 Water Sampling Results

Detailed water sampling was not performed for Test A2. Water samples for each battery type were analyzed for the expected worst case fire suppression test, which included interior finishes (Tests A3 and B3). See Section 6.2.3.7 for water sampling results for Battery A.

6.2.3 Battery A3 Test

Battery A is a 4.4 kWh HV battery pack enclosed in a metal case and was rigidly mounted in the lower part of the rear cargo area of the VFT along with other interior finishes, as described previously in Sections 4.1.1 and 5.2. Test A3 was conducted on March 28, 2013, at approximately 2 p.m. At the start of the test, the weather was overcast, with temperatures of approximately 50 °F and a relative humidity of approximately 42%. The wind was out of the northwest with an average wind speed of 13 mph and gusts up to 24 mph. The following sections summarize the data collected by Exponent during suppression Test A3.

6.2.3.1 Test Observations

Table 22 summarizes the key events observed by Exponent staff during Test A3. Images at significant test times are provided in Figure 67 and Figure 68. In general, the test performed more closely to Test A2 than A1, where significant additional time for suppression operations was required to control the fire. The burners induced the battery into thermal runaway and the fire size did not noticeably decrease once the burners were turned OFF, in fact visual observations of the fire size indicated it may have increased in intensity after the burners were OFF. Similar to Tests A1 and A2, the visible release and ignition of flammable electrolyte

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[61] TC4 was consumed during Test A2 around the 20 minute mark, as such no data was recorded after this point

material was observed and loud popping from the interior of the battery was heard coinciding with the observation of visible arcing/sparks and off gassing on many occasions. The white smoke and off gassing observed on several occasions were consistent with the release of flammable electrolyte material. Often times, a distinct “whoosh” was heard, followed by white smoke off gassing and a reignition, as described in Section 6.2.2.1 for Test A2. However, no violent projectiles, explosions, or bursts were observed during the test while the battery was exposed to the burners, while it was in a free burn state, while it was being suppressed, or after suppression efforts ceased. Of interest during Test A3, was the inclusion of additional interior finishes, which greatly increased the visual appearance of the fire intensity and flame heights prior to suppression operations by the firefighters when compared to a standalone battery pack that was used in Test A1 and A2.

Once suppression started, the initial battery fire required significantly more time to knock down (over 1 minute) than Tests A1 and A2. Afterwards, the battery continued to smoke, off gas and reignite. Active suppression efforts ceased approximately forty-nine minutes after the first application of water and within an hour, the exterior of the battery had returned to near ambient temperatures, as verified through TCs and thermal images. See Sections 6.2.3.2 and 6.2.3.3 for more details on the firefighting efforts and Section 6.2.3.6 for more details on overhaul operations.

Table 22 Test A3 Key Observations

Time	**Event**
0:00:00	Start DAQ and video cameras
0:00:58	Ignite burners
0:01:27	Rear seats ignite
0:02:30	Pop sound heard from battery interior (pops), rear carpet fully involved
0:03:10	Rear half of vehicle fully involved
0:03:33 – 0:03:41	Pops
0:04:10	Front seat involved

Time	Event
0:05:00 – 0:05:46	Steady pops
0:06:16	Smoke increasing
0:06:35	Large boom
0:06:48	Series of rapid pops
0:06:59 – 0:07:43	Steady pops
0:08:00	Burners terminated, no noticeable change in fire size
0:08:03 – 0:08:49	Large pops and arcs, followed by an increase in flame size
0:09:00	Suppression starts from rear of the vehicle
0:09:29 – 0:10:20	Steady pops
0:13:12 – 0:14:51	Arcing and white smoke off gassing
0:15:33 – 0:16:41	Sporadic pops and white smoke off gassing
0:17:39	White smoke off gassing, battery fire reignited
0:18:05 – 0:19:25	Sporadic pops and heavy white smoke off gassing
0:19:57	Firefighters insert nozzle directly into right rear vent hole on metal battery case, results in continuous arcs and pops
0:21:00 – 0:21:58	Sporadic pops and white smoke off gassing
0:22:10	Battery fire reignited
0:22:51 – 0:24:12	Sporadic pops, arcs and white smoke off gassing
0:24:25	“Whoosh” heard, white smoke off gassing observed, battery fire reignited
0:25:26 – 0:27:08	Sporadic pops and white smoke off gassing
0:27:15	Battery fire reignited
0:27:52 – 0:28:31	Sporadic pops and white smoke off gassing
0:29:30	Heavy white smoke, battery fire reignited, self-extinguished

Time	Event
0:30:30	Smoke diminishing
0:30:48 – 0:39:05	Sporadic pops and white smoke off gassing
0:39:14	“Whoosh” heard, white smoke off gassing observed, battery fire reignited
0:42:51	Loud pop
0:44:30	Pops, white smoke off gassing, battery fire reignited
0:47:43	White smoke off gassing, battery fire reignited
0:50:27	Sporadic pops and white smoke off gassing
0:50:33	Battery fire reignited
0:51:21	Pops
0:51:28	Battery fire reignited
0:51:40	Pops, battery fire reignited
0:52:33	Arcing, battery fire reignited
0:53:07	Battery fire reignited
0:53:25	Battery fire reignited
0:54:32 – 0:55:37	Firefighters drizzle water over battery
0:57:04	Pops
1:00:00	DAQ system off

Figure 67 Test A3: ignition (top left); rear involved (top right); fully involved (bottom left); burners off (bottom right)

Figure 68 Test A3: Suppression starts (top left); reignition and suppression (top right, bottom left); post suppression (bottom right)

6.2.3.2 Water Flow Measurements

As reported in Table 23, the initial battery fire was knocked down by MFRI after approximately 1 minute and 12 seconds of water application at a flow rate of 125 gpm. However, even after this duration of water application, the battery continued to smoke, off gas, and reignite for some time afterwards, which required fourteen additional water applications for times ranging between five and ninety seconds. In addition, near the end of the test, the nozzle was placed over the battery at a reduced flow (estimated to be one-half the normal flow rate) to drown the exterior of the battery on three separate occasions with a continuous flow of water in an attempt to cool the battery. All active suppression efforts ceased approximately forty nine minutes after the first application of water. Exponent estimates a total of approximately1060 gallons of water was used to control the fire in Test A3.

Table 23 Test A3 Water Flow Times

Flow Start	Flow Stop	Δt	Flow (gallons)	Comments
0:09:00	0:10:12	0:01:12	150	
0:10:17	0:10:41	0:00:24	50	
0:17:40	0:17:55	0:00:15	31	
0:19:59	0:20:24	0:00:25	52	
0:22:07	0:22:42	0:00:35	73	
0:24:33	0:24:48	0:00:15	31	
0:24:58	0:25:16	0:00:18	38	
0:25:26	0:25:34	0:00:08	17	
0:27:23	0:28:00	0:00:37	77	
0:32:26	0:32:32	0:00:06	13	
0:33:00	0:33:05	0:00:05	10	
0:52:02	0:53:32	0:01:30	188	
0:53:35	0:53:48	0:00:13	27	
0:53:56	0:54:28	0:00:32	67	
0:54:28	0:54:53	0:00:25	26	Flow reduced; estimated to be 62.5 gpm
0:54:53	0:55:30	0:00:37	77	

Flow Start	Flow Stop	Δt	Flow (gallons)	Comments
0:55:30	0:56:06	0:00:36	38	Flow reduced; estimated to be 62.5 gpm
0:56:37	0:58:10	0:01:33	97	Flow reduced; estimated to be 62.5 gpm
	Total	**0:09:46**	**1060**	

6.2.3.3 Firefighter Tactics and Observations

After test discussions with the firefighters echoed their statements from Test A1 and A2, with a few additional insights. Firefighters indicated that the single biggest challenge was applying water to where the fire was actually occurring, which was inside the metal battery casing. Since they were unable to get direct access inside the battery, their tactic was to only apply water to flames that rekindled after initial suppression. This tactic was changed slightly at the end of the test though when they decided to try to cool the battery by simply flowing water from the nozzle, at about one-half the flow rate, over the top of the battery to essentially drown the battery with a continuous application of water. The firefighters could predict when the fire was going to reignite based upon hearing a release of "pressure" followed by a release of white smoke. The firefighters expanded on this previous observation even further after Test A3. The firefighters felt that when the white smoke came out of the battery slowly it did not ignite readily, however, when the white smoke came out fast it was more prone to ignite. The firefighters reported finding localized hot spots on the battery that required moving positions (from rear to the passenger side of the VFT) several times to gain better access to that portion of the battery to cool it down.

6.2.3.4 Temperature and Heat Flux Measurements

Temperature and heat flux measurements were collected by Exponent during Test A3 once every second. The maximum temperatures and heat fluxes measured during the test and their corresponding times have been summarized in Table 24 and Table 25 plotted in Figure 69 and Figure 70.[62] The majority of the maximum temperatures measured during the test occurred prior to the burners being turned OFF. TC4 experienced a maximum temperature after the burners were turned OFF, prior to the start of suppression.

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[62] For consistency the same TCs reported and plotted for Tests A1 and A2 (TCs 1, 4, 5, 7, 10, 11) have been summarized and plotted for Test A3 for direct comparison.

The maximum temperatures measured on the exterior of the battery (TCs 1, 4, 5, 7, 10, and 11) were between 1247 and 1539 °F. Once suppression efforts began, the temperatures quickly dropped to near ambient with very few spikes afterwards, even as the battery reignited.

The heat flux measurements followed the same trend as the TC data, as all of the maximum values were found before the burners were turned OFF. The maximum heat flux from the VFT was 11.9 kW/m^2 at a standoff distance of 5 feet and at further distances, 15, 20, and 25 feet, the maximum heat fluxes were between 1.6 and 2.2 kW/m^2.

Table 24 Summary of Test A3 Maximum Temperature Measurements

TC	Maximum Temperature (°F)	Time	TC	Maximum Temperature (°F)	Time
1	1494	0:04:41	7	1482	0:06:02
4	1247	0:08:12	10	1311	0:05:58
5	1409	0:06:44	11	1539	0:04:53

Table 25 Summary of Test A3 Maximum Heat Flux Measurements

Measurement	Heat Flux (kW/m^2)	Time
HFG1 (5 feet)	11.9	0:06:02
HFG2 (15 feet)	2.4	0:06:13
HFG3 (20 feet)	2.0	0:06:53
HFG4 (25 feet)	2.2	0:05:04

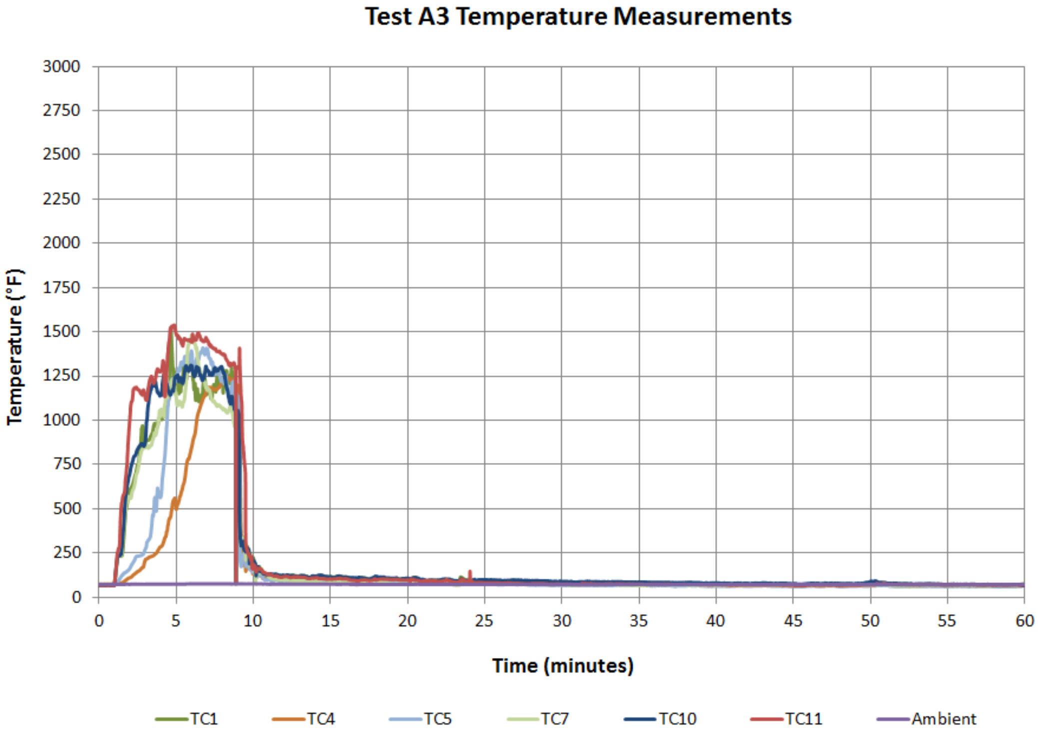

Figure 69 Test A3 TC plot

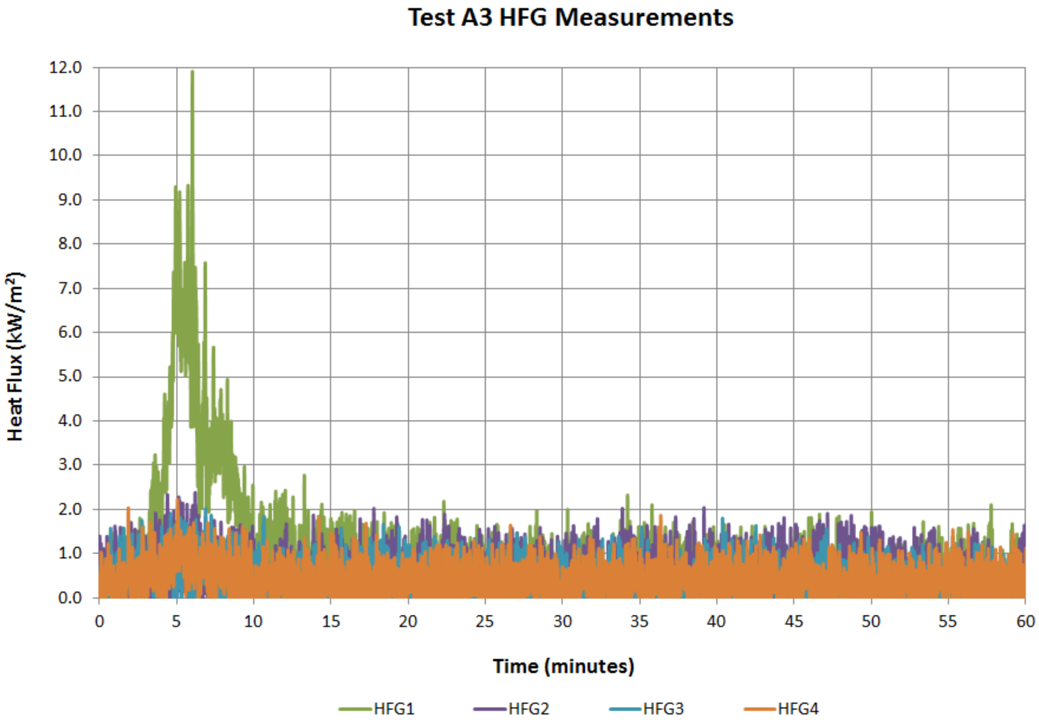

Figure 70 Test A3 HFG plot

6.2.3.5 Electrical Measurements

Current and voltage measurements for Test A3 were performed using the configuration and methodology described previously. The measurements were recorded during an initial startup period prior to ignition or fire suppression in order to determine a baseline measurement of background noise sources. Measurements continued throughout the entire test and a summary of results during fire suppression activities are provided in Table 26 below, showing the maximum, minimum, and three quartile values for all four recorded measurements. Full measurements are provided in Appendix E.

Table 26 Summary of Test A3 Current (mA) and Voltage (V) Measurements

	Maximum	Q3	Median	Q1	Minimum
Nozzle Current	1.4	0.2	0.0	-0.2	-2.0
Nozzle Voltage	0.02	0.00	0.00	0.00	-0.35
Chassis Current	≤5	--	--	--	≥-5
Chassis Voltage	1.17	0.73	0.16	-0.28	-0.62

A detailed analysis of the full resolution 2 kHz recorded signal for nozzle current and voltage measurements was performed. Current measurements during fire suppression activities remained within the same noise levels as were observed during initial background recording and the results above are summarized for 50 ms median filtering of the data in order to reduce the apparent effect of noise on the results. Likewise, voltage measurements during fire suppression activities generally remained within the same noise levels as observed during initial background recording. Brief departures from the background level were occasionally observed when firefighters inserted the nozzle inside the chassis, possibly contacting an exposed portion of the battery, however, these changes in voltage were brief and no voltage levels were recorded in excess of ±0.4 V.

The resolution of the chassis current was set at ±5 mA in this test. No measurements exceeded this value at any time during fire suppression activities. Finally, chassis voltage measurements indicate that a small DC voltage of approximately 0.2 V was intermittently present on the body of the chassis (consistent with post-measurement tests) with brief deviations as high as ±1.2 V.

6.2.3.6 Overhaul Results

Thermal images of the battery commenced at approximately 37 minutes, in between a number of battery reignitions and while suppression activities were still underway. As shown in Figure 71, thermal imaging demonstrated the exterior of the battery was still significantly hot in the front passenger side of the battery with a maximum temperature of 408 °F. Approximately three minutes after this thermal image the fire rekindled in this location and was suppressed by the firefighters.

After the last suppression activities around 58 minutes, the battery was left within the VFT and monitored with thermal images and TCs for any additional activity. As described previously in Section 6.2.3.3, a different tactic was utilized by the firefighters on this test where they flowed water over the top of the battery for several minutes to thoroughly cool the battery down. As such, at 60 minutes, the exterior TCs installed on the battery had decreased to near ambient levels, as reported in Table 21, and thermal imaging also demonstrated near ambient temperatures. At this time, all other signs of combustion, including off gassing and smoke had ceased as well and the test was stopped.

The battery remained within the VFT for the remainder of the day and was removed the following morning, approximately 18 hours after the test had concluded. At the time thermal imaging indicated the exterior of the battery was at ambient temperature levels. During removal the battery from the VFT a few pops were heard, however no activity consistent with combustion, such as off gassing, smoke, or elevated temperatures were noted. The battery was then moved to the battery storage area.

At approximately 1:02 p.m., 22 hours since the conclusion of the test and 4 hours since its removal from the VFT, Battery A3 began to lightly off gas, as shown in Figure 72. Shortly thereafter at 1:07 p.m. (5 minutes after off gassing was first observed) flames were visible on the interior of the battery, as shown in Figure 73 and pops were heard. MFRI staff quickly connected a hose line and extinguished the flames and cooled the exterior of the battery. It was estimated that an additional 2 minutes of water was applied to the battery at a flow rate of 125 gpm. By 1:40 p.m. (38 minutes after off gassing was first observed), the battery had stopped smoking and was not showing signs of any combustion. The battery was monitored for the remainder of the day and did not exhibit any additional reignitions.

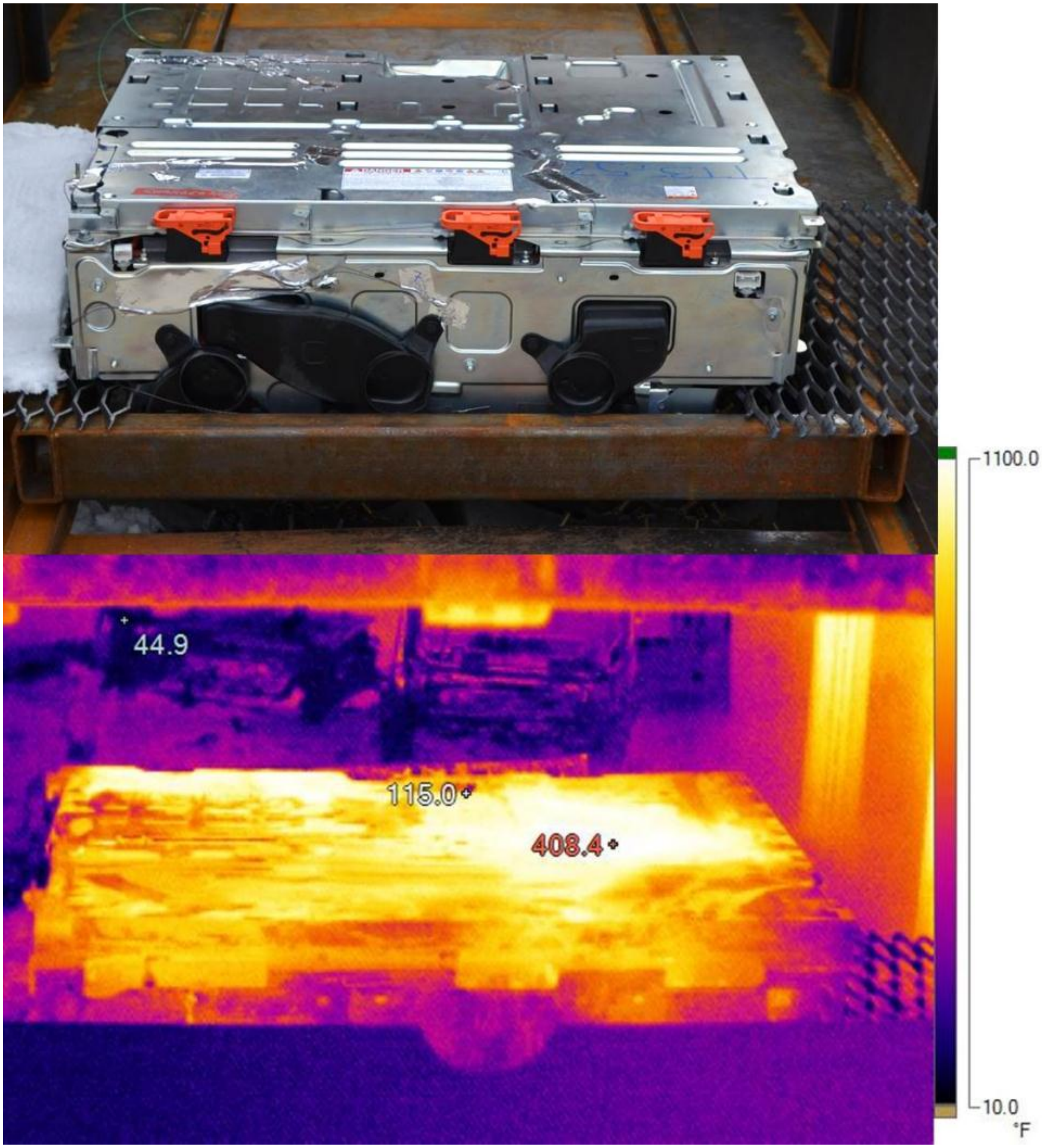

Figure 71 Battery A3 from rear of VFT (top); thermal image (same view) of Battery A3 at 41 minutes depicting the “hot spot” (bottom)

Table 27 Summary of Test A3 Temperature Measurements after 60 Minutes

TC	Temperature after 60 Minutes (°F)	TC	Temperature after 60 Minutes (°F)
1	74	7	67
4	66	10	65
5	63	11	69

Figure 72 Off gassing of Battery A3 approximately 22 hours after the conclusion of the test

Figure 73 Reignition of Battery A3 approximately 22 hours after the conclusion of the test (flame circled red)

6.2.3.7 Water Sampling Results

The water sample from Test A3 was collected and sent to an independent third-party laboratory, Analyze, Inc., for chemical analysis, as described in Section 5.2.4, along with a control sample collected from the suppression water source. A summary of the water sampling results is provided in Table 28. The water sample from Test A3 exhibited a slightly acidic (6.18) pH value. In addition, low levels of chloride (143 ppm) and fluoride (27 ppm) anions were detected. When HF and / or hydrogen chloride (HCl) is present in an aqueous solution, it dissociates into a cation and an anion. Additionally, the presence of hydrogen cations increases the acidity of the solution, causing the pH to drop. Based on the presence of chloride and fluoride anions and the lower pH of the Test A3 sample as compared to the control sample, HF and HCl were likely present (in a small amount) during suppression.

Table 28 Water Sample Analysis Summary for Test A3

Element / Assay	**Concentration (ppm)**	
	Control	**Test A3**
pH	7.82	6.18
Total Organic C	1.3	150
Total Inorganic C	7.3	7.7
Chloride	34	143
Fluoride	0.7	27
Li	< 0.005	0.25
P	< 1.0	7.5
Ca	23	72
Na	13	19
Mg	4.8	6.9
K	2.4	6.0
Sr	0.08	4.5
Al	0.01	3.0
Fe	0.09	0.72
Ba	0.02	0.61
B	0.01	0.05
Zn	< 0.005	29.0

Element / Assay	Concentration (ppm)	
	Control	Test A3
Mn	< 0.005	0.27
Sb	< 0.002	0.70
Ni	< 0.010	0.05
Co	< 0.005	0.02
Cu	< 0.005	0.15
As	< 0.010	< 0.010
V	< 0.002	0.002

6.2.4 Battery B1 Test

Battery B is a 16.0 kWh EDV battery pack enclosed in a T-shaped fiberglass case and was rigidly mounted in the central portion of the VFT, as described previously in Sections 4.1.2 and 5.2. Test B1 was conducted on April 1, 2013, at approximately 1:30 p.m. At the start of the test, the weather was mostly cloudy, with a temperature of approximately 66 °F and a relative humidity of approximately 36%. The wind was out of the west with an average wind speed of 13 mph and gusts up to 24 mph. The following sections summarize the data collected by Exponent during suppression Test B1.

6.2.4.1 Test Observations

Table 29 summarizes the key events observed by Exponent staff during Test B1. Images at significant test times are provided in Figure 74 and Figure 75. In general, the test demonstrated that an external heat source could induce Battery B into thermal runaway while it was positioned inside a VFT and result in the visible release and ignition of electrolyte material. Loud popping sounds from the interior of the battery were heard and visible sparks were observed on many occasions. White smoke and off gassing were observed steadily throughout the test and were consistent with the release of flammable electrolyte material. However, no projectiles, explosions, or bursts were observed during the test while the battery was exposed to the burners, while it was in a free burn state, while it was being suppressed, or after suppression efforts ceased.

Once suppression started, the firefighters were constantly applying water to the battery fire attempting to control the flames. The initial battery fire was not immediately knocked down, as the firefighters were more or less consistently applying water to the battery with only short breaks (10 to 20 seconds) between each water application to reposition themselves or while waiting for the battery to reignite. Active suppression efforts ceased approximately 26 minutes after the first application of water. Once the battery fire was under control, it continued to smoke and off gas for several hours afterwards, although no reignition was observed. External temperatures on the battery casing did not decrease to near ambient levels until nearly four hours after the test started and internal battery temperatures did not reach ambient temperatures until nearly 12 hours after the test started. See Sections 6.2.4.2 and 6.2.4.3 for more details on the firefighting efforts and Section 6.2.4.7 for more details on overhaul operations.

Table 29 Test B1 Key Observations

Time	Event
0:00:00	Start DAQ and video cameras
0:01:02	Ignite burners
0:01:29	Smoke produced
0:01:51	Smoke production increasing, grey color
0:02:30	Grey smoke production increasing
0:03:05 – 0:03:44	White smoke produced
0:03:51	Flames observed on battery, “whoosh” sound heard
0:04:13	Arcing in rear of battery, molten drips observed
0:04:56	Pop sound heard from battery interior (pops)
0:05:18 – 0:06:02	Flames increase at battery rear
0:07:10	White smoke produced
0:07:52	Flames at front of battery
0:08:24	“Boom” sound heard followed by black smoke
0:12:18	Smoke turns white
0:12:35 – 0:17:05	Sporadic pops
0:17:15	“Whoosh” heard

Time	Event
0:17:27 – 0:19:07	Pops increasing and getting louder
0:21:00	Burners terminated, no noticeable change in fire size
0:21:38	Arcing observed
0:22:00	Suppression starts at rear of VFT
0:23:07 – 0:25:50	Fire reignited at rear of battery, firefighters working at front
0:25:02	White smoke produced
0:25:18 – 0:25:40	Fire reignited at front of battery, firefighters working at rear
0:26:17	Large off gas of white smoke, battery fire reignited
0:26:43	White smoke produced
0:27:08	Fire reignited at front of battery
0:28:12	Fire reignited at front of battery
0:29:09	Fire reignited at front of battery
0:30:07	Steady production of white smoke
0:30:14	Fire reignited at front of battery
0:30:50	Fire reignited at front of battery
0:31:39	Fire reignited at rear of battery
0:34:23	Start suppression operations with hood up
0:34:56	Fire reignited at rear of battery
0:35:36	Increased flames at rear of battery
0:36:35	Fire reignited at front of battery
0:36:48	Fire reignited at rear of battery
0:38:25	Fire reignited at rear of battery, firefighters at front of battery
0:48:34	Active suppression ends
19:00:00	DAQ system off

Figure 74 Test B1: ignition (top left); off gassing (top right); fully involved (bottom left); burners off (bottom right)

Figure 75 Test B1: suppression starts (top left); reignition and suppression (top right, bottom left); post suppression (bottom right)

6.2.4.2 Water Flow Measurements

As reported in Table 30, the battery fire was not quickly knocked down and required a fairly consistent application of water occurred 22 and 48 minutes to control the fire. An estimated 14 minutes of water at a flow rate of 125 gpm was applied to the battery during those 26 minutes of active fire suppression. In total, 29 water applications were applied to the battery ranging between 4 and 87 seconds for each application. Exponent estimates a total of approximately 1754 gallons of water was used during Test B1.

Table 30 Test B1 Water Flow Times

Flow Start	Flow Stop	Δt	Flow (gallons)	Comments
0:22:03	0:22:19	0:00:16	33	
0:22:22	0:22:43	0:00:21	44	
0:22:49	0:23:40	0:00:51	106	
0:24:00	0:24:24	0:00:24	50	
0:24:35	0:24:47	0:00:12	25	
0:25:22	0:25:33	0:00:11	23	
0:25:49	0:25:54	0:00:05	10	
0:25:59	0:26:05	0:00:06	12	
0:26:24	0:26:36	0:00:12	25	
0:26:45	0:26:59	0:00:14	29	
0:27:11	0:27:38	0:00:27	56	
0:27:47	0:28:11	0:00:24	50	
0:28:22	0:29:44	0:01:22	171	
0:30:13	0:30:48	0:00:35	73	
0:30:59	0:32:13	0:01:14	154	
0:32:40	0:32:53	0:00:13	27	
0:33:08	0:33:18	0:00:10	21	
0:33:20	0:33:32	0:00:12	25	
0:34:20	0:34:24	0:00:04	8	
0:34:30	0:34:43	0:00:13	27	
0:34:46	0:35:43	0:00:57	119	

Flow Start	Flow Stop	Δt	Flow (gallons)	Comments
0:35:59	0:36:24	0:00:25	52	
0:36:45	0:38:10	0:01:25	177	
0:38:24	0:39:15	0:00:51	106	
0:39:40	0:41:07	0:01:27	181	
0:42:52	0:43:09	0:00:17	35	
0:43:26	0:43:53	0:00:27	56	
0:47:09	0:47:13	0:00:04	8	
0:48:11	0:48:34	0:00:23	48	
	Total	**0:14:02**	**1754**	

6.2.4.3 Firefighter Tactics and Observations

After test discussions with the two firefighter suppression team revealed the following statements regarding their observations of the fire and their tactics to suppress it during Test B1:

- This test was more difficult than the previous tests (Battery A tests).
- There was a “floorboard” in place (the steel floor pan placed on top of the battery pack). This made “all the difference,” as it was harder to fight the fire and gain access to the battery.
- This test had significantly less arcing and popping compared to the previous tests (Battery A tests).
- However, there was “tremendous heat” coming off the battery and floor pan assembly.
- The fire size felt like it was the same as the prior tests (Battery A tests); however, the “floorboard” (floor pan) made this one harder to extinguish.
- This fire was worse than a regular vehicle fire, because it was harder to extinguish.
- In a real vehicle fire scenario, firefighters would have two hoses present, one at the front and one at the back. This would have made it easier, as the firefighters would not have had to keep repositioning as the flames moved back and forth.
- Unable to extinguish the fire, the firefighters concentrated their efforts on cooling down the metal floor pan.

- The nozzle has both fog and straight patterns. The firefighters used the straight stream for the initial attack and the fog setting for cooling the metal floor pan.

Similar to previous tests (Battery A series tests), the firefighters indicated that the single biggest challenge they faced was trying to apply water to where the fire was actually occurring, inside the battery. This was further complicated during Test B1 by the steel floor pan positioned above the battery. In addition, due to the size and geometry of Battery B, the firefighters were chasing the fire back and forth from front to back, as only one hose line was being utilized for the test. Since the firefighters were unable to directly access the inside of the battery, they changed their tactics to cool the floor pan with the nozzle set on fog.

6.2.4.4 Temperature and Heat Flux Measurements

Temperature and heat flux measurements were collected by Exponent during Test B1 once every second. The maximum temperatures and heat fluxes measured during the test and their corresponding times have been summarized in Table 31 and Table 32 and plotted in Figure 76 and Figure 77.[63] The majority of the maximum temperatures and heat fluxes measured during the test occurred after to the burners were turned OFF, signifying the battery fire remained hot even after the removal of the burners.

The maximum temperatures measured on the exterior of the battery (TCs 1 through 10) were between 541 and 1993 °F. The maximum temperatures measured on the interior of the battery (TCs 13 through 15) were between 1061 and 2049 °F. Once suppression efforts began, the temperatures dropped; however, significant spikes continued to occur between 22 and 39 minutes, as the battery reignited multiple times.

The heat flux measurements followed a similar trend to the TC data, where half of the maximum values were observed after the burners were turned OFF. The maximum heat flux at a standoff distance of five feet from the VFT was 2.2 kW/m^2 and at further distances, 15, 20, and 25 feet, the maximum heat fluxes were between 1.5 and 2.1 kW/m^2.

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[63] TCs 11 and 12 failed during testing and were not included in the tables or plots.

Table 31 Summary of Test B1 Maximum Temperature Measurements

TC	Maximum Temperature (°F)	Time	TC	Maximum Temperature (°F)	Time
1	1275	0:22:03	8	1993	0:30:14
2	1204	0:22:18	9	1389	0:19:00
3	1405	0:22:18	10	1273	0:22:19
4	1650	0:20:46	13	1506	0:22:03
5	1780	0:28:05	14	1061	0:17:13
6	541	0:21:08	15	2049	0:28:50
7	1403	0:22:18			

Table 32 Summary of Test B1 Maximum Heat Flux Measurements

Measurement	Heat Flux (kW/m^2)	Time
HFG1 (5 feet)	2.2	0:24:36
HFG2 (15 feet)	2.1	0:26:49
HFG3 (20 feet)	1.5	0:21:30
HFG4 (25 feet)	1.7	0:15:48

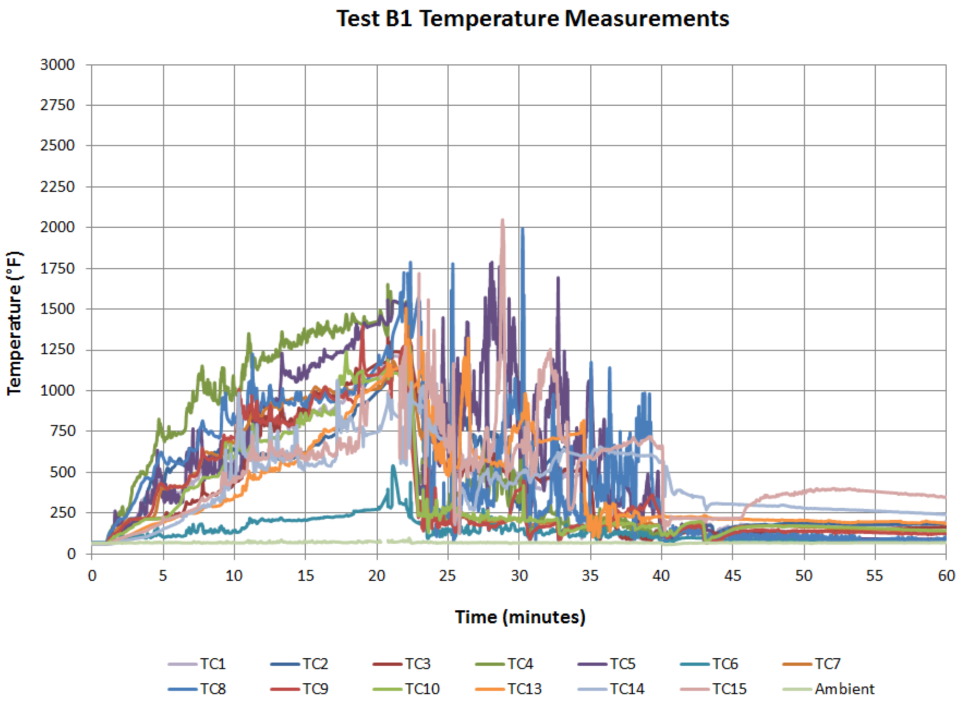

Figure 76 Test B1 TC plot

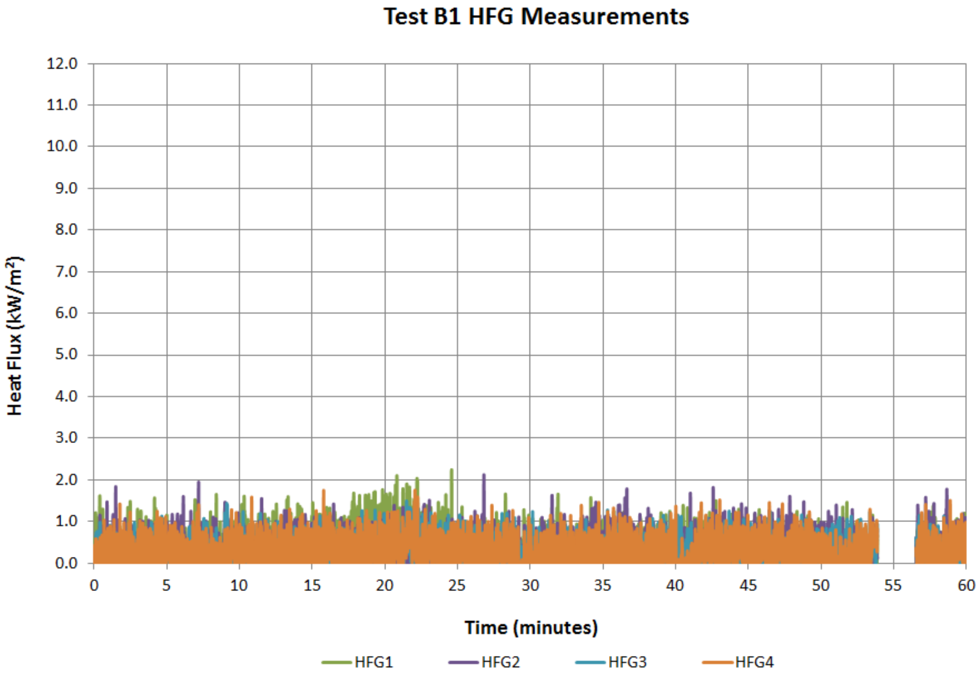

Figure 77 Test B1 HFG plot[64]

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[64] The connection between the HFGs and the DAQ system was lost between 53 and 56 minutes, resulting in the depicted data gap.

6.2.4.5 Internal Battery Sensor Measurements

No internal battery sensor measurements were recorded during Test B1 due to a communication error between the battery and the DAQ system. See Sections 6.2.5.5 and 6.2.6.5 for internal battery sensor measurements for Tests B2 and B3.

6.2.4.6 Electrical Measurements

Current and voltage measurements for Test B1 were performed using the configuration and methodology described previously. The measurements were recorded during an initial startup period prior to ignition or fire suppression in order to determine a baseline measurement of background noise sources. Measurements continued throughout the entire test and a summary of results during fire suppression activities are provided in Table 33 below, showing the maximum, minimum, and three quartile values for all four recorded measurements. However, the wire connecting the chassis to the grounding rod was found post-test to be disconnected. As such, the chassis voltage and current measurements for this test are excluded from the analysis and Table 33. Full measurements are provided in Appendix E.

Table 33 Summary of Test B1 Current (mA) and Voltage (V) Measurements

	Maximum	**Q3**	**Median**	**Q1**	**Minimum**
Nozzle Current	1.7	0.2	0.0	-0.2	-1.3
Nozzle Voltage	0.44	0.05	-0.01	-0.08	-0.93
Chassis Current	--	--	--	--	--
Chassis Voltage	--	--	--	--	--

A detailed analysis of the full resolution 2 kHz recorded signal for nozzle current and voltage measurements was performed. Current measurements during fire suppression activities remained within the same noise levels as were observed during initial background recording and the results above are summarized for 50 ms median filtering of the data in order to reduce the apparent effect of noise on the results. Likewise, voltage measurements during fire suppression activities generally remained within the same noise levels as observed during initial background recording. Brief departures from the background level were occasionally observed when firefighters inserted the nozzle inside the chassis, possibly contacting an exposed portion of the battery, however, these changes in voltage were brief and no voltage levels were recorded in excess of ±1 V.

6.2.4.7 Overhaul Results

Thermal images of the battery commenced at 48 minutes, just after active suppression activities had ceased, to monitor, along with the battery TCs, the battery after the fire. As shown in Figure 78, thermal imaging demonstrated the exterior of the battery was still above 100 °F in certain locations, specifically at the fuse (shown in Figure 78) and at the CAN bus connection area. The battery was left within the VFT for the remainder of the day and was monitored with thermal images and TCs for any additional activity. After 60 minutes, the exterior and interior TCs installed on and in the battery still measured elevated temperatures, as high as 197 °F on the exterior and 348 °F on the interior. As such, Exponent continued to collect temperature measurements for an additional 18 hours to record the temperature profile of the battery as it cooled. As reported in Table 34 and plotted in Figure 79, all TCs on the exterior of the battery did not reach ambient temperatures until approximately 4 hours after testing. All internal TCs of the battery did not reach ambient temperatures until approximately 12 hours after testing.

The battery remained within the VFT for the remainder of the day and was removed the following morning, approximately 19 hours after testing was concluded. It was moved to a battery storage area with no issues.

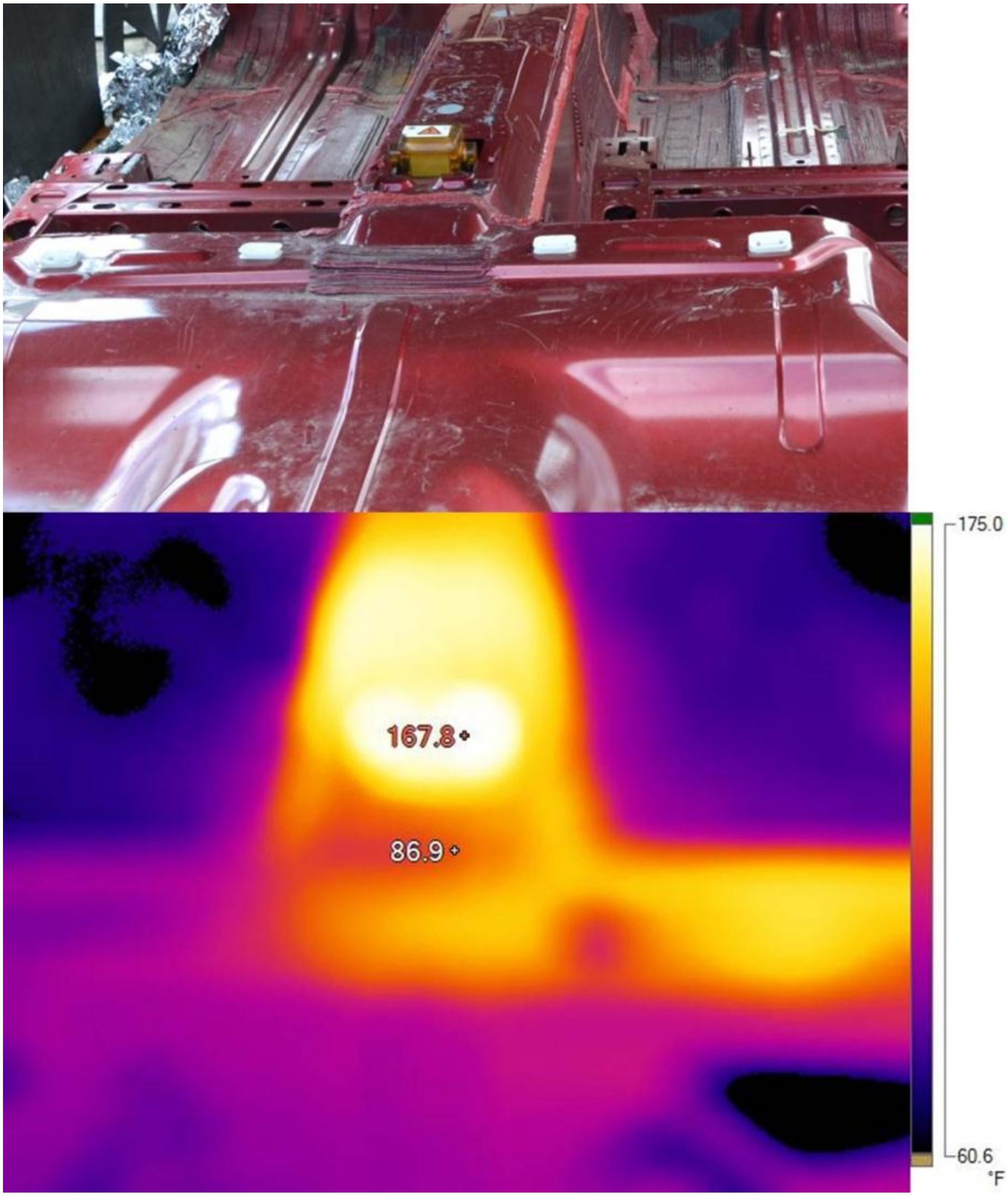

Figure 78 Floor pan assembly from rear of VFT (top); thermal image (same view) of Battery B1 at 60 minutes (bottom)

Table 34 Summary of Test B1 Temperature Measurements after 1, 2, 3, 6, 12, and 18 hours

TC	**Temperature (°F) After:**					
	1 hour	**2 hours**	**3 hours**	**6 hours**	**12 hours**	**18 hours**
1	197	140	98	60	43	30
2	183	121	70	46	37	30
3	163	146	130	46	37	30
4	84	59	62	54	43	34
5	93	62	56	47	34	33
6	85	67	65	52	42	37
7	139	91	78	60	47	39
8	88	61	56	44	36	32
9	123	89	70	51	42	34
10	142	100	79	56	45	35
13	186	109	64	50	39	34
14	242	164	117	57	36	30
15	348	256	213	143	69	38

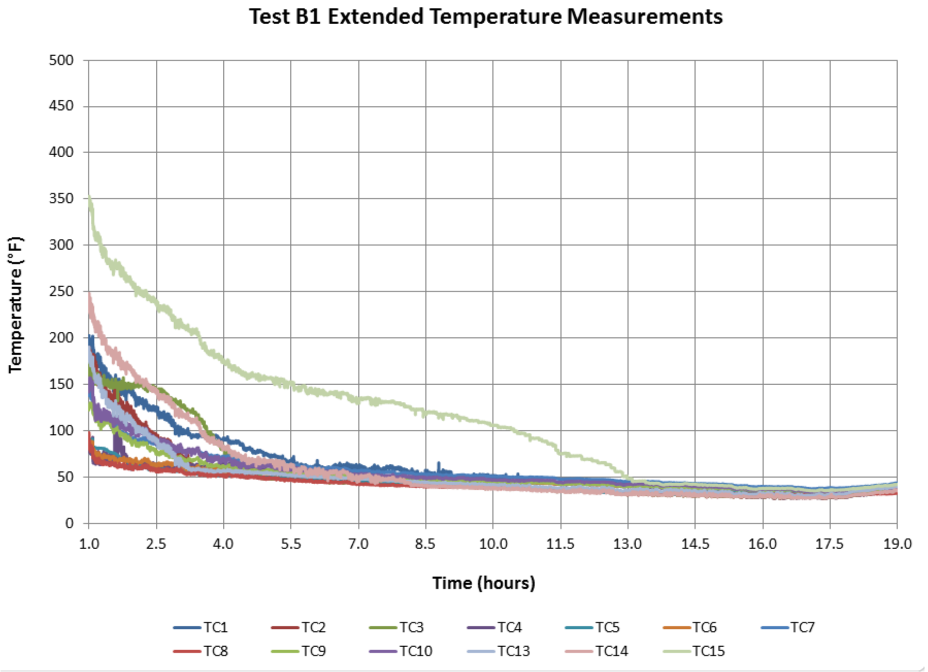

Figure 79 Extended temperature measurements for Test B1

6.2.4.8 Water Sampling Results

Detailed water sampling was not performed for Test B1. Water samples for each battery type were analyzed for the expected worst case fire suppression test, which included interior finishes (Tests A3 and B3). See Section 6.2.6.8 for water sampling results for Battery B.

6.2.5 Battery B2 Test

Battery B is a 16.0 kWh EDV battery pack enclosed in a T-shaped fiberglass case and was rigidly mounted in the central portion of the VFT, as described previously in Sections 4.1.2 and 5.2. Test B2 was conducted on April 2, 2013, at approximately 1:30 p.m. At the start of the test, the weather was clear, with a temperature of approximately 49 °F and a relative humidity of approximately 25%. The wind was out of the west-northwest with an average wind speed of 16.1 mph and gusts up to 23 mph. The following sections summarize the data collected by Exponent during suppression Test B2.

6.2.5.1 Test Observations

Table 35 summarizes the key events observed by Exponent staff during Test B2. Images at significant test times are provided in Figure 80 and Figure 81. In general, the test demonstrated a similar fire scenario seen in Test B1. Loud popping sounds from the interior of the battery were heard and visible sparks were observed on multiple occasions. White smoke and off gassing were observed steadily throughout the test consistent with the release of electrolyte material. However, no projectiles, explosions, or bursts were observed during the test while the battery was exposed to the burners, while it was in a free burn state, while it was being suppressed, or after suppression efforts ceased.

Once suppression started, the firefighters were constantly applying water to the battery fire attempting to control the flames. The initial battery fire was not immediately knocked down, as the firefighters consistently applied water to the battery with short breaks (10 to 20 seconds) between each water application to reposition themselves or while waiting for the battery to reignite. Active suppression efforts ceased approximately 37 minutes after the first application of water. Once the battery was under control, it continued to smoke and off gas for several hours afterwards, although no reignition was observed during this period. External temperatures on the battery casing and internal battery temperatures did not decrease to near ambient levels until nearly 13 hours after the test started. See Sections 6.2.4.2 and 6.2.4.3 for more details on the firefighting efforts and Section 6.2.4.7 for more details on overhaul operations.

Table 35 Test B2 Key Observations

Time	Event
0:00:00	Start DAQ and video cameras
0:01:00	Ignite burners
0:01:42 – 0:02:21	White smoke produced
0:02:52	Pop sound heard from battery interior (pops)
0:04:35	Gust of wind affects fire
0:06:10 – 0:07:24	White smoke production increasing
0:07:39	Flames at rear of battery
0:08:29	White smoke production increasing
0:12:23	Flames out of fuse on top of battery
0:13:21	White smoke production increasing
0:14:09	Flames increasing at rear of battery
0:14:41	Flames at front of battery
0:18:51	Arcing observed, “whoosh” sound heard
0:19:33	Pops, flames increasing around battery
0:21:00	Burners terminated, no noticeable change in fire size
0:22:00	Suppression starts at rear of VFT
0:22:50	Flames at bottom of battery
0:23:14	Firefighters attack fire from rear of VFT
0:23:52	Firefighters attack fire from passenger side of VFT
0:25:23	Firefighters open hood to VFT and attack fire from opened hood of VFT
0:25:55	Fire reignited
0:26:11	Fire reignited
0:26:35	Fire reignited at rear of battery
0:28:38	Firefighters attack fire from rear of VFT
0:29:51	Fire reignited at rear of battery
0:30:21	Fire reignited at front of battery

Time	Event
0:38:10	Fire reignited below battery
0:38:13	Fire reignited
0:39:52	Firefighters swap out SCBA tank
0:40:41	Firefighters attack fire from rear of VFT
0:42:35	Firefighters attack fire from passenger side of VFT
0:43:35	Fire reignited below battery
0:46:33	Firefighters attack fire from front of VFT
0:55:06	Firefighters use hook to remove protective box from around the CAN bus connection area
0:56:40	Firefighters attack fire from passenger side of VFT
0:58:11	Active suppression ends
19:00:00	DAQ system off

Figure 80 Test B2: ignition (top left); off gassing (top right); flames from fuse (bottom left); burners off (bottom right)

Figure 81 Test B2: suppression starts (top left); reignition and suppression (top right, bottom left); post suppression (bottom right)

6.2.5.2 Water Flow Measurements

As reported in Table 36, the battery fire was not quickly knocked down and required a fairly consistent application of water between 22 and 48 minutes to control the fire. Water applications continued sporadically until time 59 minutes. An estimated 21 minutes of water at a flow rate of 125 gpm was applied to the battery during those 37 minutes of active fire suppression. In total, 32 water applications were applied to the battery ranging between 5 and 105 seconds for each application. Exponent estimates a total of approximately 2639 gallons of water was used during Test B2.

Table 36 Test B2 Water Flow Times

Flow Start	Flow Stop	Δt	Flow (gallons)	Comments
0:22:05	0:23:03	0:00:58	121	
0:23:13	0:23:25	0:00:12	25	
0:23:51	0:24:08	0:00:17	35	
0:24:16	0:24:48	0:00:32	67	
0:25:27	0:25:55	0:00:28	58	
0:25:58	0:26:29	0:00:31	65	
0:26:41	0:28:26	0:01:45	219	
0:28:38	0:29:39	0:01:01	127	
0:29:54	0:31:03	0:01:09	144	
0:31:10	0:31:53	0:00:43	90	
0:32:00	0:32:05	0:00:05	10	
0:32:11	0:33:45	0:01:34	196	
0:34:02	0:34:41	0:00:39	81	
0:34:48	0:35:33	0:00:45	94	
0:35:59	0:37:10	0:01:11	148	
0:37:16	0:38:12	0:00:56	117	
0:38:38	0:39:10	0:00:32	67	
0:39:20	0:39:45	0:00:25	52	
0:39:57	0:40:28	0:00:31	65	
0:40:43	0:41:34	0:00:51	106	

Flow Start	Flow Stop	Δt	Flow (gallons)	Comments
0:41:52	0:42:09	0:00:17	35	
0:42:35	0:42:56	0:00:21	44	
0:43:24	0:43:34	0:00:10	21	
0:44:05	0:44:15	0:00:10	21	
0:44:40	0:46:07	0:01:27	181	
0:46:32	0:46:50	0:00:18	37	
0:46:59	0:47:14	0:00:15	31	
0:47:19	0:47:40	0:00:21	44	
0:47:55	0:48:20	0:00:25	52	
0:56:40	0:58:11	0:01:31	190	
0:58:11	0:58:42	0:00:31	32	Flow reduced; estimated to be 62.5 gpm
0:59:10	0:59:41	0:00:31	65	
	Total	**0:21:22**	**2639**	

6.2.5.3 Firefighter Tactics and Observations

After test discussions with the two firefighter suppression team revealed the following statements regarding their observations of the fire and their tactics to suppress it during Test B2:

- Test B2 was similar to Test B1; however, the fire did not seem to burn as vigorously and the flames did not seem to have the same intensity as Test B1.
- Access to the front of the battery was limited because the CAN bus connection ports were protected with a modified calcium silicate board structure, which was not in place during Test B1.
- The modified calcium silicate board structure made access to the battery more difficult in that area; however, the scenario was more realistic in that during an actual vehicle fire, firefighters would not have direct access to that portion of the battery.
- Ultimately, the firefighters used a hook at the front of the battery to pull the protective structure out of the way to gain the required access.
- Unique to this test, a fire developed in the rear wheel well of the VFT and the firefighters were unable to reach it with the hose line.

- The firefighters used the same tactics as used in Test B1 regarding nozzle flow patterns; straight for initial attack and fog for cooling of the floor pan.
- The firefighters recommended that at least two hose lines and a backup hose line be utilized for an EDV battery fire such as this one (an ICE vehicle fire typically only requires one hose line in addition to a backup hose line), one for the front of the vehicle and one for the rear of the vehicle, otherwise the fire is chased back and forth as the battery reignites.

Similar to Test B1, the firefighters indicated that the single biggest challenge they faced was trying to apply water to where the fire was actually occurring, inside the battery. This was further complicated during Test B2 by the protective structure over the CAN bus connection port area limiting access to the front of the battery.[65] The firefighters chased the fire back and forth from the front of the vehicle to the rear of the vehicle, as only one hose line was utilized. In addition, since they were unable to gain direct access to the inside of the battery, the firefighters utilized the same tactics as in Test B1 and cooled the floor pan with the nozzle set on fog to help bring the fire under control.

6.2.5.4 Temperature and Heat Flux Measurements

Temperature and heat flux measurements were collected by Exponent during Test B2 once every second. The maximum temperatures and heat fluxes measured during the test and their corresponding times have been summarized in Table 37 and Table 38 and plotted in Figure 82 and Figure 83.[66] The majority of the maximum temperatures and heat fluxes measured during the test occurred after the burners were turned OFF, signifying the battery fire remained hot even after the removal of the burners.

The maximum temperatures measured on the exterior of the battery (TCs 1 through 10) were between 1439 and 1628 °F. The maximum temperatures measured on the interior of the battery (TCs 13 through 15) were between 1022 and 1459 °F. Once suppression efforts began, the temperatures dropped; however, significant spikes continued to occur between 22 and 47 minutes, as the battery reignited multiple times.

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[65] The CAN bus connection was bolstered for this test to attempt to create a longer period of data collection.

[66] TCs 11 and 12 failed during testing and were not included in the tables or plots.

The heat flux measurements followed a similar trend to the TC data, where the majority of the maximum values were found after the burners were turned OFF. The maximum heat flux at a standoff distance of five feet from the VFT was 2.1 kW/m^2 and at further distances, 15, 20 and 25 feet, the maximum heat fluxes were between 1.8 and 2.7 kW/m^2.

Table 37 Summary of Test B2 Maximum Temperature Measurements

TC	Maximum Temperature (°F)	Time	TC	Maximum Temperature (°F)	Time
1	1481	0:22:03	8	1436	0:22:02
2	1453	0:21:52	9	1457	0:22:02
3	1439	0:21:37	10	1466	0:22:02
4	1482	0:21:51	13	1450	0:21:53
5	1437	0:22:02	14	1459	0:22:02
6	1628	0:19:07	15	1022	0:22:48
7	1440	0:22:00			

Table 38 Summary of Test B2 Maximum Heat Flux Measurements

Measurement	Heat Flux (kW/m^2)	Time
HFG1 (5 feet)	2.1	0:34:16
HFG2 (15 feet)	1.8	0:19:58
HFG3 (20 feet)	2.7	0:22:08
HFG4 (25 feet)	2.0	0:52:48

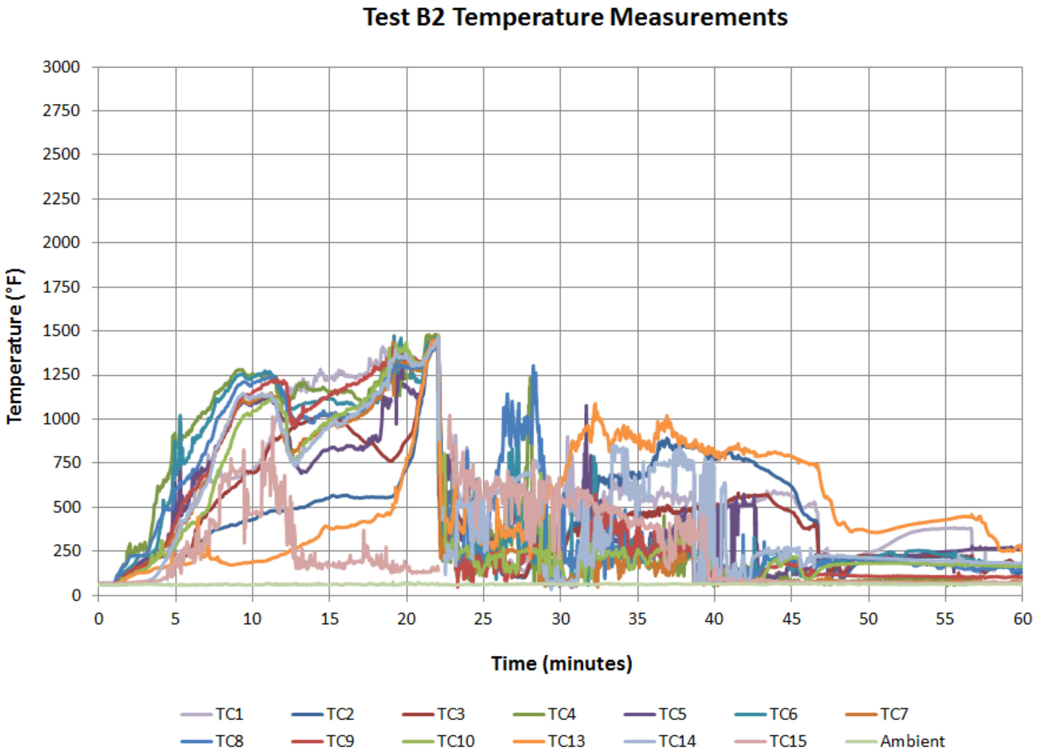

Figure 82 Test B2 TC plot

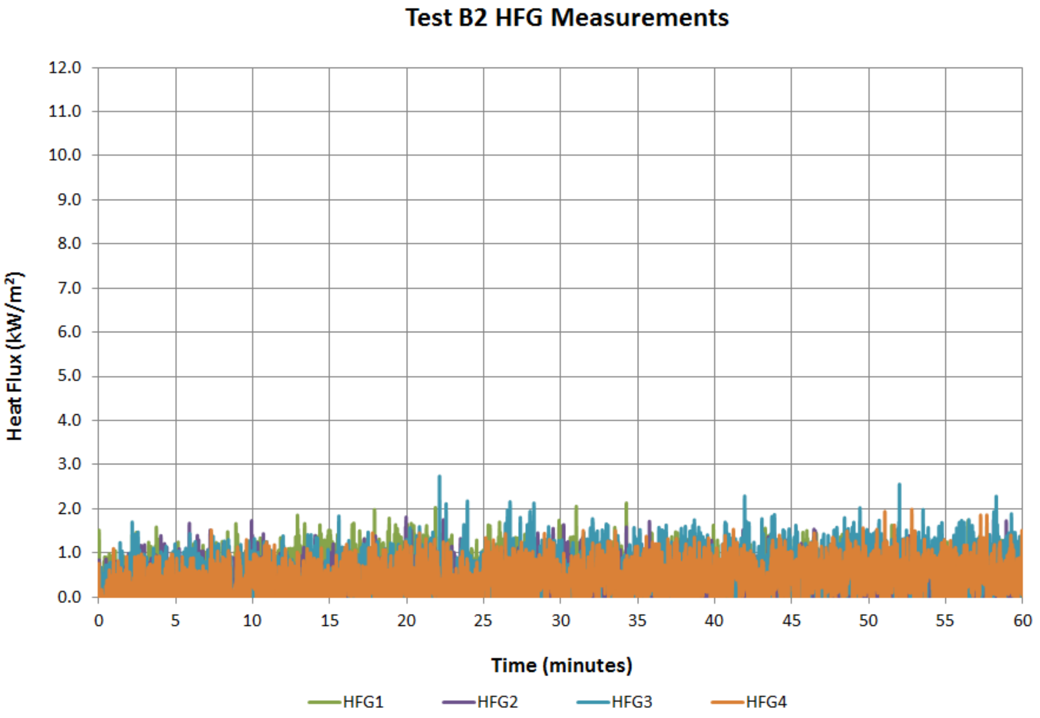

Figure 83 Test B2 HFG plot

6.2.5.5 Internal Battery Sensor Measurements

Internal cell voltages and internal battery temperature sensor measurements were collected by Exponent during testing at an effective rate of once per second, as shown in Figure 84. As demonstrated in the plot, the DAQ system lost contact with the battery after 7 minutes and 43 seconds (0:07:43 in test time). At the time, only one internal temperature sensor (Sensor #6) had changed significantly since the start of the test. As such, this was the only temperature sensor plotted in Figure 84, which had recorded a maximum temperature of at 46 °C. At that same time, none of the individual cell voltages had recorded a drop in voltage.

Temperature Sensor #6 was found in the center portion of the long span of the battery by the fuse, as shown in Figure 85. None of internal TCs installed by Exponent (TCs 13-15) were in the same area as this sensor to provide any additional insight into the thermal assault the battery was under at the time. The three internal TCs remote from Sensor #6 at the time of CAN bus failure measured temperatures between 208 and 757 °F. A post-test forensic investigation revealed the failure mode was the same as was described for the HRR test (see Section 6.1.1.4), where the failure was likely an internal short in the CAN bus power supply.

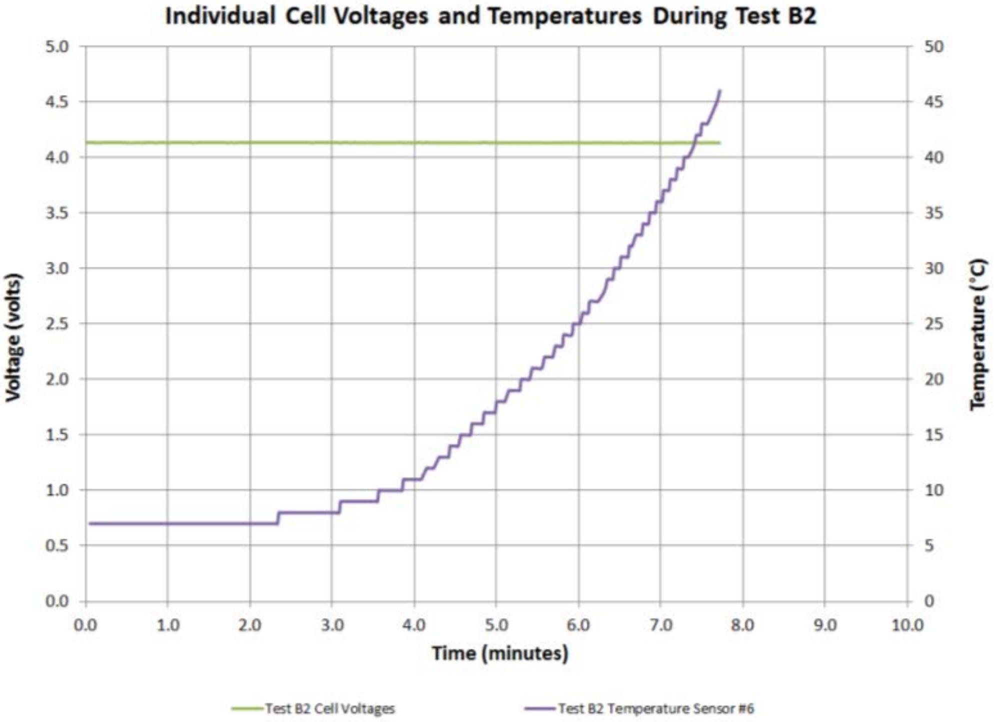

Figure 84 Internal cell voltages and temperatures during Test B2

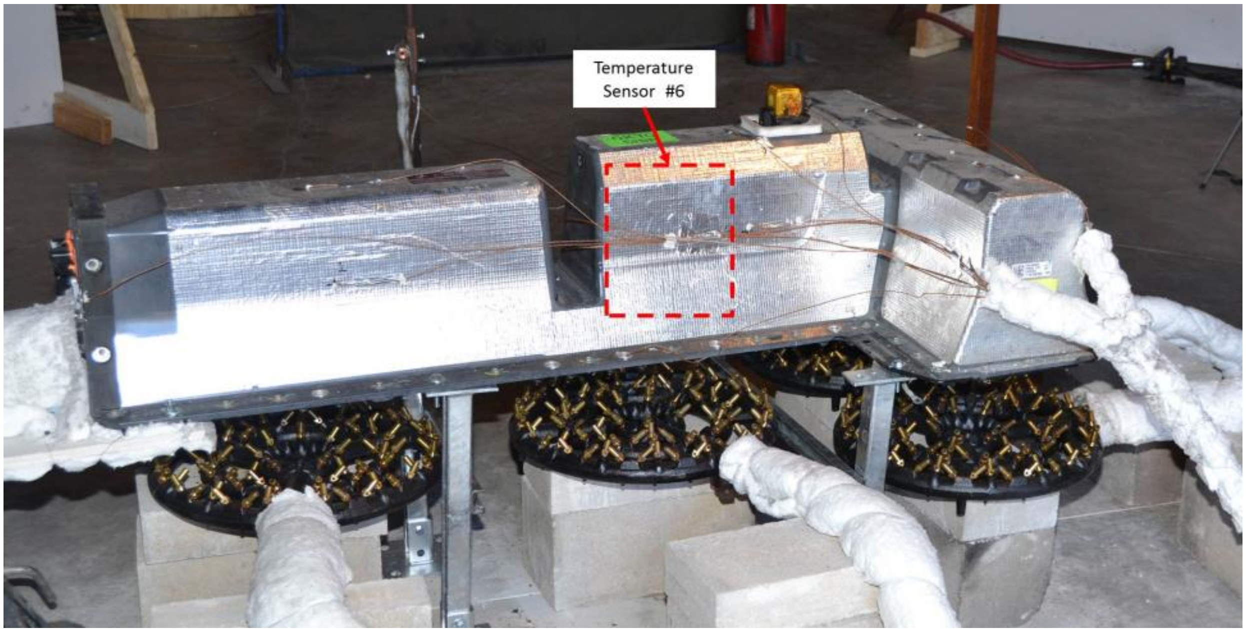

Figure 85 Location of temperature Sensor #6 within Battery B2

6.2.5.6 Electrical Measurements

Current and voltage measurements for Test B2 were performed using the configuration and methodology described previously. The measurements were recorded during an initial startup period prior to ignition or fire suppression in order to determine a baseline measurement of background noise sources. Measurements continued throughout the entire test and a summary of results during fire suppression activities are provided in Table 39 below, showing the maximum, minimum, and three quartile values for all four recorded measurements. Full measurements are provided in Appendix E.

Table 39 Summary of Test B2 Current (mA) and Voltage (V) Measurements

	Maximum	**Q3**	**Median**	**Q1**	**Minimum**
Nozzle Current	2.6	0.4	0.0	-0.4	-2.6
Nozzle Voltage	0.45	0.04	0.02	-0.09	-0.10
Chassis Current	4.1	1.4	0.5	-0.6	-3.6
Chassis Voltage	0.75	0.52	0.43	0.35	0.20

A detailed analysis of the full resolution 2 kHz recorded signal for nozzle current and voltage measurements was performed. Current measurements during fire suppression activities remained within the same noise levels as were observed during initial background recording and the results above are summarized for 50 ms median filtering of the data in order to reduce the apparent effect of noise on the results. Likewise, voltage measurements during fire suppression activities generally remained within the same noise levels as observed during initial background recording. Brief departures from the background level were occasionally observed when firefighters inserted the nozzle inside the chassis, possibly contacting an exposed portion of the battery, however, these changes in voltage were brief and no voltage levels were recorded in excess of ±0.5 V.

No chassis current measurement exceeded 4.1 mA at any time during fire suppression activities. Chassis voltage measurements indicate that a small DC voltage of approximately 0.4 V was intermittently present on the body of the chassis (consistent with post-measurement tests) with brief deviations as high as ±0.75 V.

6.2.5.7 Overhaul Results

Thermal images of the battery commenced at an elapsed time of 60 minutes, just after active suppression activities had ceased, to monitor, along with the battery TCs, the battery after the fire. As shown in Figure 86, thermal imaging demonstrated that the exterior of the battery was still above 100 °F in certain locations, specifically at the fuse (shown in Figure 86) and at the CAN bus connection area. The battery was left within the VFT for the remainder of the day and was monitored with thermal images and TCs for any additional activity. After 60 minutes, the exterior and interior TCs installed on and in the battery still measured elevated temperatures, as high as 260 °F on the exterior and 247 °F on the interior. As such, Exponent continued to collect temperature measurements for an additional 18 hours to record the temperature profile of the battery as it cooled. As reported in Table 40 and plotted in Figure 87, all exterior and interior battery TCs did not reach ambient temperatures until almost 13 hours after testing.

The battery remained within the VFT for the remainder of the day and was removed the following morning approximately 19 hours after testing was concluded. It was moved to a battery storage area with no issues.

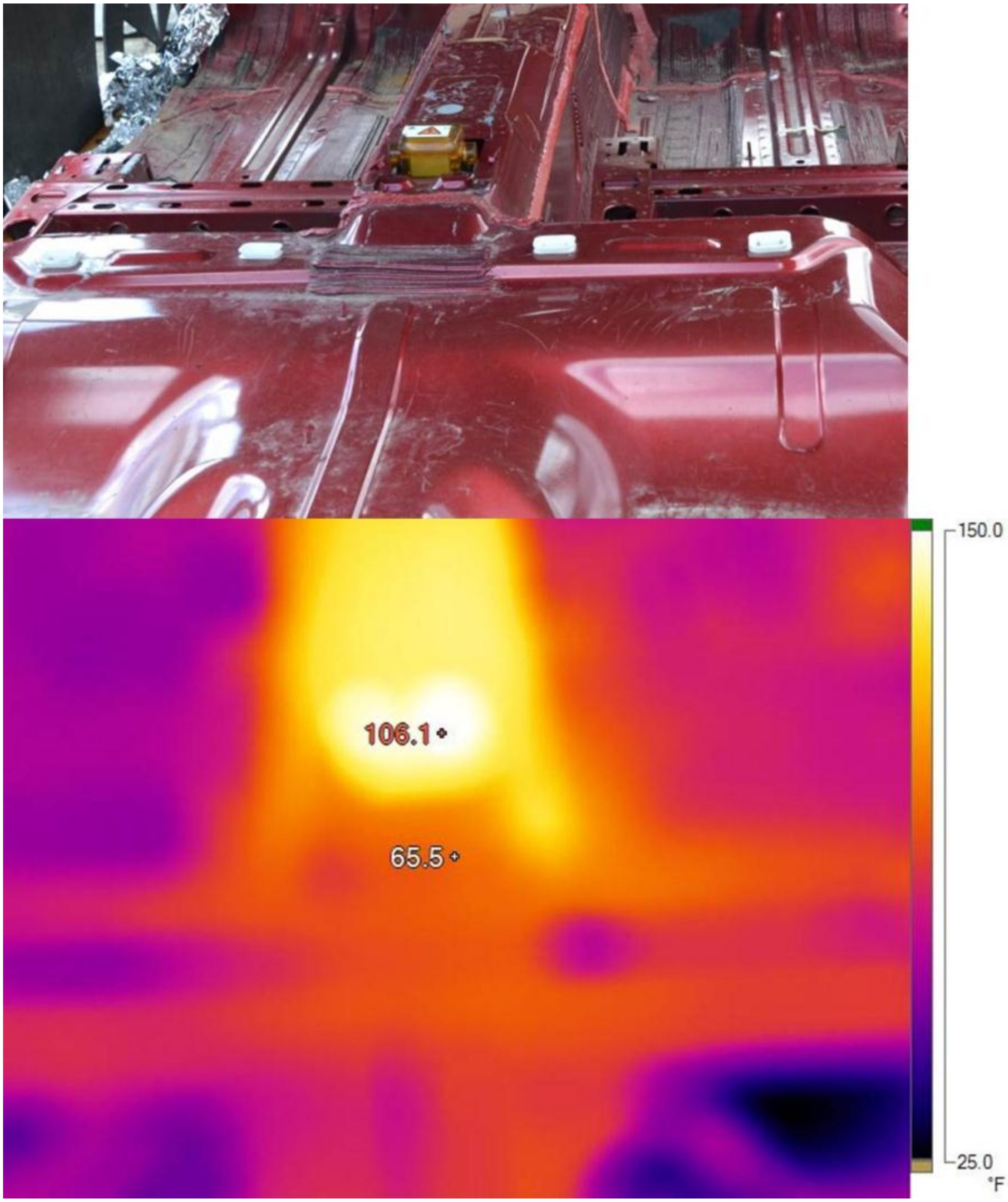

Figure 86 Floor pan assembly from rear of VFT (top); thermal image (same view) of Battery B2 at 75 minutes (bottom)

Table 40 Summary of Test B2 Temperature Measurements after 1, 2, 3, 6, 12, and 18 hours

TC	Temperature (°F) After:					
	1 hour	2 hours	3 hours	6 hours	12 hours	18 hours
1	149	274	229	140	68	42
2	143	272	231	147	68	40
3	168	200	187	131	63	39
4	75	79	96	65	48	36
5	260	287	196	132	63	38
6	170	197	197	102	53	35
7	74	71	82	56	43	37
8	147	116	79	47	40	34
9	103	87	84	53	45	40
10	165	118	99	62	45	36
13	247	297	232	133	60	38
14	182	150	133	86	53	40
15	72	70	65	58	54	46

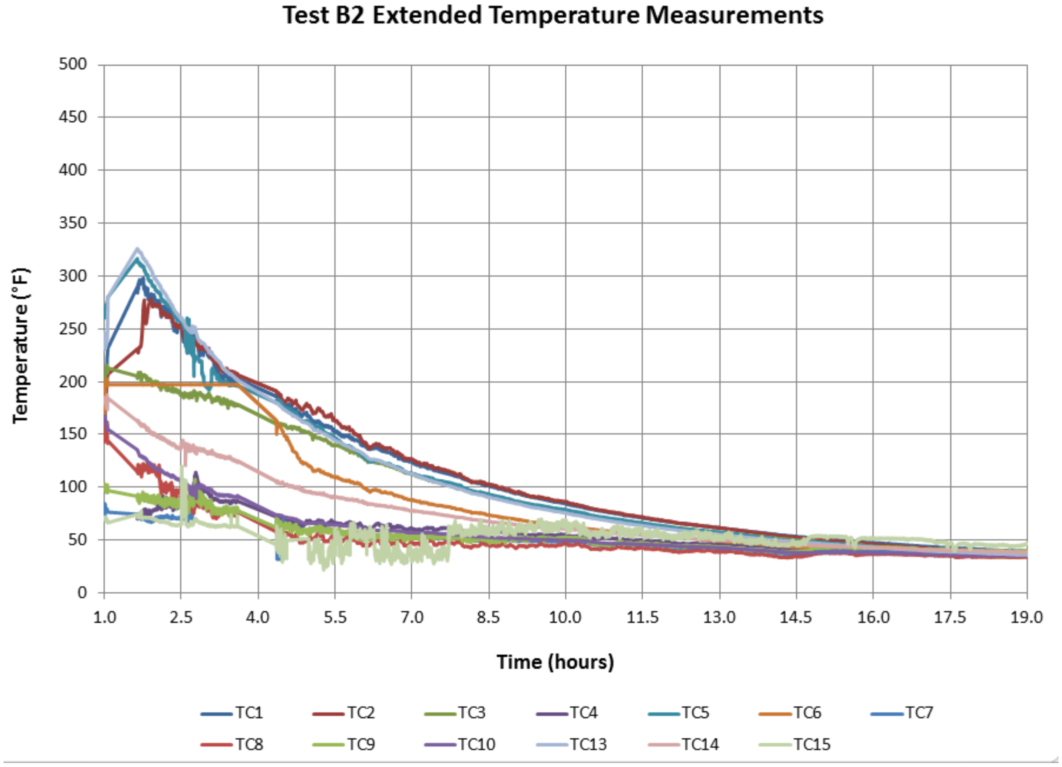

Figure 87 Extended temperature measurements for Test B2

6.2.5.8 Water Sampling Results

Detailed water sampling was not performed for Test B2. Water samples for each battery type were analyzed for the expected worst case fire suppression test, which included interior finishes (Tests A3 and B3). See Section 6.2.6.8 for water sampling results for Battery B.

6.2.6 Battery B3 Test

Battery B is a 16.0 kWh EDV battery pack enclosed in a T-shaped fiberglass case and was rigidly mounted in the central portion of the VFT, as described previously in Sections 4.1.2 and 5.2. Test B3 was conducted on April 3, 2013, at approximately 1:30 p.m. At the start of the test, there were scattered clouds, with a temperature of approximately 51 °F and a relative humidity of approximately 29%. The wind was out of the west-northwest with an average wind speed of 12 mph and gusts up to 18 mph. The following sections summarize the data collected by Exponent during suppression Test B3.

6.2.6.1 Test Observations

Table 41 summarizes the key events observed by Exponent staff during Test B3. Images at significant test times are provided in Figure 88 and Figure 89. In general, the test demonstrated a more severe fire scenario than seen in Tests B1 and B2 due to the additional interior finishes. Observations relating to battery involvement included loud popping sounds from the interior of the battery and visible arcing. White smoke and off gassing were observed steadily throughout the test and were consistent with the release of electrolyte material. However, no projectiles, explosions, or bursts were observed during the test while the battery was exposed to the burners, while it was in a free burn state, while it was being suppressed, or after suppression efforts ceased.

Once suppression started, the firefighters applied a constant flow of water to the battery fire attempting to control the flames. Unlike in Tests B1 and B2, the firefighters were more focused on applying a significant amount of water to the battery at several different angles (rear, front, side, through the wheels) early on to get water onto the battery anyway possible. This tactic was successful, as active suppression efforts ceased approximately fourteen minutes after the first application of water. Once the fire was under control, it continued to smoke and off gas for several hours afterwards, although no reignition was observed. External temperatures on the battery casing and battery internal temperatures did not decrease to near ambient levels until nearly three hours after the test started. See Sections 6.2.6.2 and 6.2.6.3 for more details on the firefighting efforts and Section 6.2.6.7 for more details on overhaul operations.

Table 41 Test B3 Key Observations

Time	Event
0:00:00	Start DAQ and video cameras
0:01:06	Ignite burners
0:01:37	White smoke produced
0:01:49	Dark grey smoke produced
0:02:51	Pop sound heard from battery interior (pops)
0:04:18	White smoke production increasing
0:04:33	Flames at rear of battery

Time	Event
0:04:53	Steady white smoke production
0:05:30	Flames at front seat
0:06:18	Rattle sound heard
0:06:29	Black smoke produced
0:07:01	Passenger compartment fully involved
0:07:22	Peak flame height
0:08:01	Fire size plateauing
0:08:26	Loud pop
0:09:31	Flame height decreasing
0:09:49 – 0:10:51	Pops
0:12:00	Burning at front battery increases
0:12:33	White smoke produced at front of battery
0:14:43	Sustained flame at fuse
0:17:14 - 0:17:28	Pops
0:18:19	Significant increase in fire size, “whoosh” sound heard
0:18:35	Rumbling sound heard, flames increase, white smoke production increasing
0:18:53	Fire out at front of battery
0:19:10 - 0:20:53	Pops
0:21:00	Burners terminated, no noticeable change in fire size
0:21:05 - 0:21:07	Pops
0:22:05	Suppression starts from rear of VFT
0:22:43	Firefighters attack fire from passenger side of VFT
0:24:25	Firefighters attack fire from rear wheel
0:24:45	Pops, arcing
0:25:16 – 0:25:33	Fire reignited at front of battery
0:25:55	Firefighters open hood to VFT and attack fire from opened hood of VFT
0:27:45	Firefighters open rear hatch to VFT and attack fire from rear of the VFT
0:28:53	Firefighters attack fire from rear wheel

Time	Event
0:29:36	Firefighters attack fire from passenger side of VFT
0:30:42	Firefighters attack fire from the front of VFT
0:33:04	Firefighters attack fire from the rear of VFT
0:34:28	Firefighters attack fire from rear wheel
0:35:24	Firefighters attack fire from passenger side of VFT
0:35:58	Active suppression ends
0:38:20	Firefighters swap out SCBA tank
19:00:00	DAQ system off

Figure 88 Test B3: ignition (top left); off gassing (top right); fully involved (bottom left); burners off (bottom right)

Figure 89 Test B3: suppression starts (top left); reignition and suppression (top right, bottom left); post suppression (bottom right)

6.2.6.2 Water Flow Measurements

As reported in Table 42, the fire was not quickly knocked down and required a fairly consistent application of water between 22 and 36 minutes to control the fire. An estimated 9.5 minutes of water flow at 125 gpm was applied to the battery during those 14 minutes of active fire suppression. In total, 11 water applications were applied to the battery ranging between 3 and 174 seconds for each application. Exponent estimates a total of approximately 1165 gallons of water was used during Test B3.

Table 42 Test B3 Water Flow Times

Flow Start	Flow Stop	Δt	Flow (gallons)	Comments
0:22:05	0:24:59	0:02:54	363	
0:25:05	0:25:08	0:00:03	6	
0:25:17	0:25:26	0:00:09	19	
0:25:36	0:27:32	0:01:56	242	
0:27:53	0:28:23	0:00:30	62	
0:28:52	0:29:15	0:00:23	48	
0:29:37	0:30:19	0:00:42	88	
0:30:38	0:31:52	0:01:14	154	
0:33:05	0:33:31	0:00:26	54	
0:34:28	0:34:55	0:00:27	56	
0:35:23	0:35:58	0:00:35	73	
	Total	**0:09:32**	**1165**	

6.2.6.3 Firefighter Tactics and Observations

After test discussions with the two firefighter suppression team revealed the following statements regarding their observations of the fire and their tactics to suppress it during Test B3:

- Test B3 was easier to extinguish, because the firefighter on the nozzle had fought the fire during Test B2 and knew how best to attack the battery fire.
- Due to the time provided to involve the battery (20 minutes), the upholstery was consumed by the fire by the time suppression began; just the seat frames remained.
- Test B3 produced more heat and flames than Tests B1 and B2.

- There were not as many issues in regards to getting to the fire during Test B3, as the firefighter on the nozzle had prior experience.
- Test B3 had more popping than Test B2.
- The firefighters felt the upholstery made the battery burn faster.
- According to the firefighters, EDV fires require additional work and water to get under control.
- The firefighters used the same tactics as in Tests B1 and B2 regarding nozzle flow patterns; straight for initial attack and fog for cooling of the floor pan.

Unlike in Test B1 and B2, the firefighter working the nozzle during Test B3 had prior knowledge (Test B2) on how best to attack the fire. The suppression tactics utilized were different for Test B3, as they were more focused on applying a significant amount of water early on to the battery (their initial water application was for 2 minutes and 54 seconds) at several different angles (rear, front, side, through the wheels) instead of chasing the fire as it reignited. This tactic was successful, as active suppression efforts ceased approximately fourteen minutes after the first application of water.

6.2.6.4 Temperature and Heat Flux Measurements

Temperature and heat flux measurements were collected by Exponent during Test B3 once every second. The maximum temperatures and heat fluxes measured during the test and their corresponding times have been summarized in Table 43 and Table 44 and plotted in Figure 90 and Figure 91.[67] Approximately half of the maximum temperatures and heat fluxes measured during the test occurred after the burners were turned OFF, signifying the addition of the interior finishes inside the VFT increased the temperatures and heat fluxes measured prior to the burners being shut OFF.

The maximum temperatures measured on the exterior of the battery (TCs 1 through 10) were between 1465 and 2754 °F. The maximum temperatures measured on the interior of the battery (TCs 13 through 15) were between 1568 and 2782 °F. Once suppression efforts began, the

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[67] TCs 11 and 12 failed during testing and were not included in the tables or plots.

temperatures dropped; however, significant spikes continued to occur between 22 and 30 minutes, as the battery reignited multiple times.

The heat flux measurements followed a similar trend to the TC data, where half of the maximum values were found after the burners were turned OFF. The maximum heat flux at a standoff distance of five feet from the VFT was 8.1 kW/m^2 and at further distances, 15, 20 and 25 feet, the maximum heat fluxes were between 2.1 and 2.4 kW/m^2.

Table 43 Summary of Test B3 Maximum Temperature Measurements

TC	Maximum Temperature (°F)	Time	TC	Maximum Temperature (°F)	Time
1	1585	0:22:06	8	2166	0:26:00
2	1535	0:22:06	9	1639	0:22:05
3	1589	0:22:06	10	1571	0:22:05
4	1663	0:18:23	13	1568	0:22:06
5	1543	0:21:43	14	2133	0:25:23
6	2754	0:20:48	15	2782	0:19:39
7	1465	0:18:27			

Table 44 Summary of Test B3 Maximum Heat Flux Measurements

Measurement	Heat Flux (kW/m^2)	Time
HFG1 (5 feet)	8.1	0:08:07
HFG2 (15 feet)	2.1	0:07:59
HFG3 (20 feet)	2.4	0:50:45
HFG4 (25 feet)	2.4	0:40:23

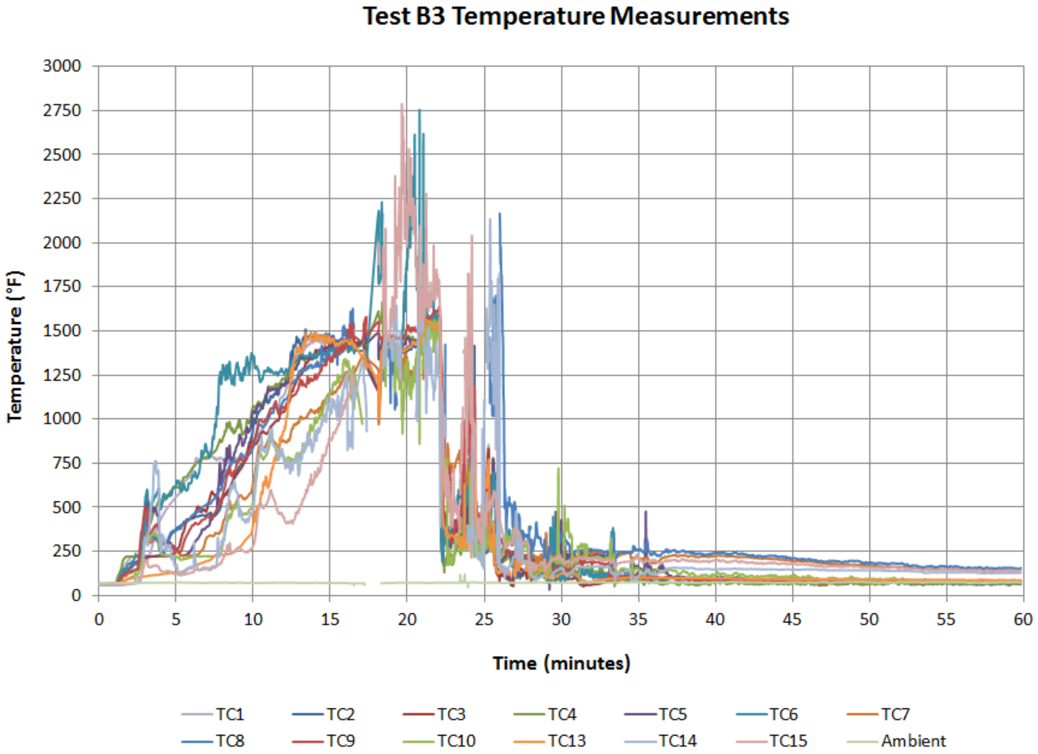

Figure 90 Test B3 TC plot

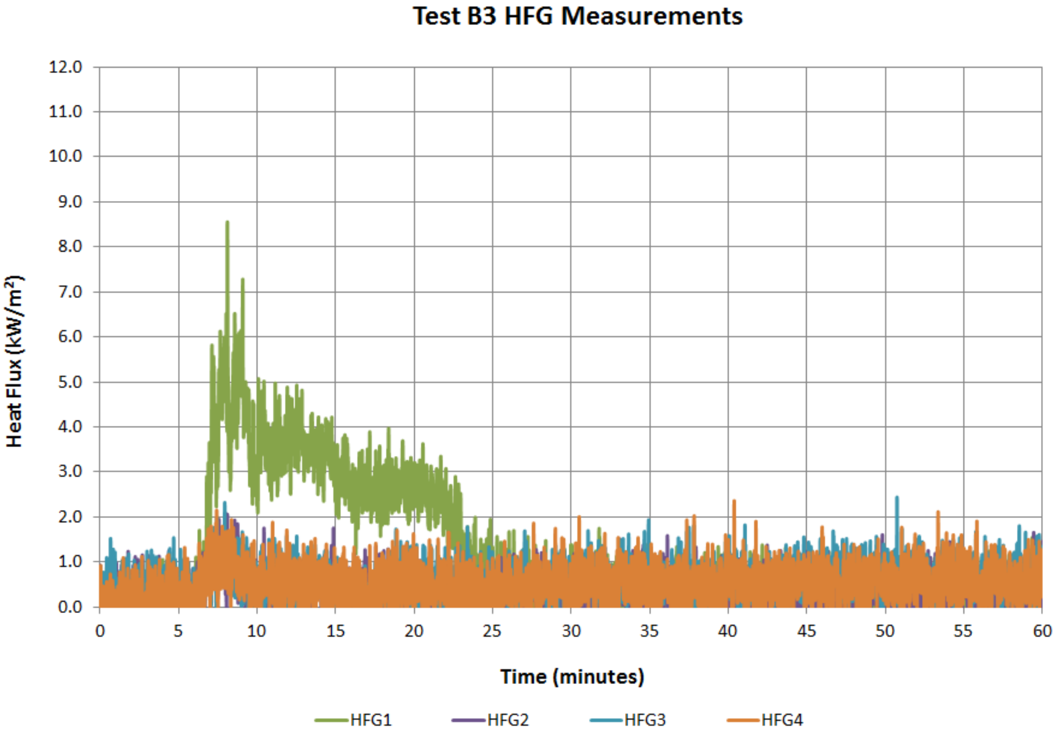

Figure 91 Test B3 HFG plot

6.2.6.5 Internal Battery Sensor Measurements

Internal cell voltages and internal battery temperature sensor measurements were collected by Exponent during testing at an effective rate of once per second, as shown in Figure 92. As demonstrated in the plot, the DAQ system lost contact with the battery after 8 minutes and 38 seconds (0:08:38 in test time). At that time, only one internal temperature sensor (Sensor #6) had changed significantly since the start of the test. As such, this was the only temperature sensor plotted in Figure 92, which had recorded a maximum temperature of at 44 °C. At that same time, none of the individual cell voltages had recorded a drop in voltage.

Temperature Sensor #6 was found in the center portion of the long span of the battery by the fuse, as shown previously in Figure 85. None of the internal TCs installed by Exponent (TCs 13-15) were in the same area as this sensor to provide any additional insight into the thermal assault the battery was under at the time. The three internal TCs remote from Sensor #6 at the time of CAN bus failure measured temperatures between 232 and 405 °F. A post-test forensic investigation revealed the failure mode was the same as was described for the HRR test (see Section 6.1.1.4), where the failure was likely an internal short in the CAN bus power supply.

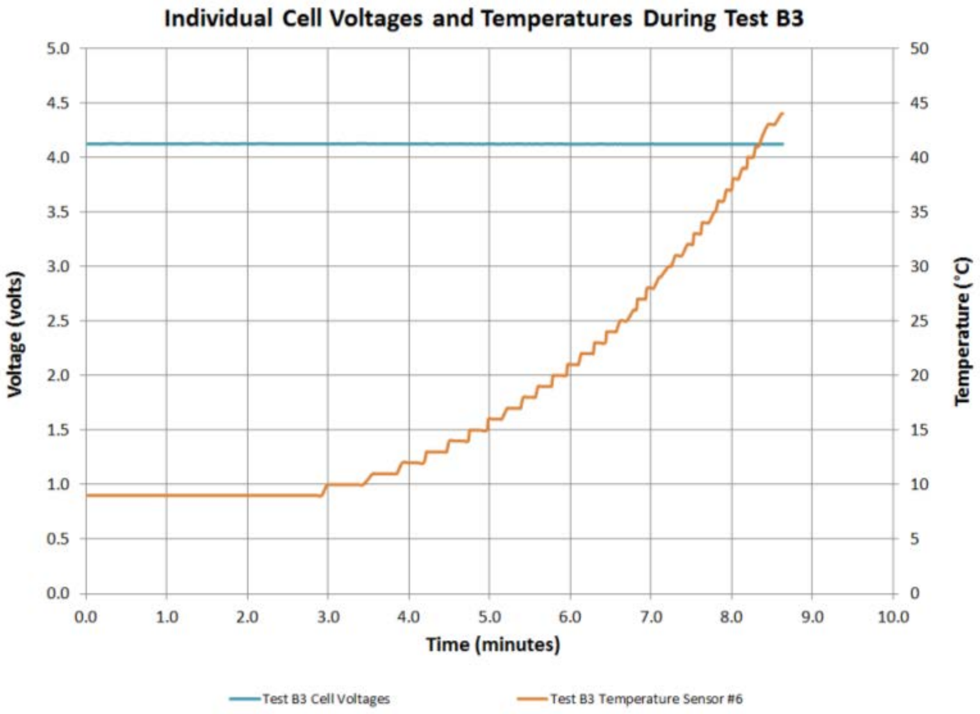

Figure 92 Internal cell voltages and temperatures during Test B3

6.2.6.6 Electrical Measurements

Current and voltage measurements for Test B3 were performed using the configuration and methodology described previously. The measurements were recorded during an initial startup period prior to ignition or fire suppression in order to determine a baseline measurement of background noise sources. Measurements continued throughout the entire test and a summary of results during fire suppression activities are provided in Table 45 below, showing the maximum, minimum, and three quartile values for all four recorded measurements. Full measurements are provided in Appendix E.

Table 45 Summary of Test B3 Current (mA) and Voltage (V) Measurements

	Maximum	Q3	Median	Q1	Minimum
Nozzle Current	1.5	0.2	0.0	-0.2	-1.5
Nozzle Voltage	0.31	0.00	0.00	-0.01	-0.02
Chassis Current	3.2	1.0	0.4	-0.1	-2.6
Chassis Voltage	0.58	0.46	0.40	0.35	0.23

A detailed analysis of the full resolution 2 kHz recorded signal for nozzle current and voltage measurements was performed. Current measurements during fire suppression activities remained within the same noise levels as were observed during initial background recording and the results above are summarized for 50 ms median filtering of the data in order to reduce the apparent effect of noise on the results. Likewise, voltage measurements during fire suppression activities generally remained within the same noise levels as observed during initial background recording. Brief departures from the background level were occasionally observed when firefighters inserted the nozzle inside the chassis, possibly contacting an exposed portion of the battery, however, these changes in voltage were brief and no voltage levels were recorded in excess of ±0.3 V.

No chassis current measurement exceeded 3.2 mA at any time during fire suppression activities. Finally, chassis voltage measurements indicate that a small DC voltage of approximately 0.4 V was intermittently present on the body of the chassis (consistent with post-measurement tests), with brief deviations as high as ±0.6 V.

6.2.6.7 Overhaul Results

Thermal images of the battery commenced at 60 minutes, after active suppression activities had ceased, to monitor, along with the battery TCs, the battery after the fire. As shown in Figure 93, thermal imaging demonstrated that the exterior temperature of the battery was still above 100 °F in certain locations, specifically at the fuse (shown in Figure 93) and at the CAN bus connection area. The battery was left within the VFT for the remainder of the day and was monitored with thermal images and TCs for any additional activity. After 60 minutes, the exterior and interior TCs installed on and in the battery still measured elevated temperatures, as high as 150 °F on the exterior and 136 °F on the interior of the battery. As such, Exponent continued to collect temperature measurements for an additional 18 hours to record the temperature profile of the battery as it cooled. As reported in Table 46 and plotted in Figure 94, all exterior and interior battery TCs did not reach ambient temperatures until 3 hours after testing.

The battery remained within the VFT for the remainder of the day and was removed the following morning approximately 19 hours after testing was concluded. It was moved to a battery storage area with no issues.

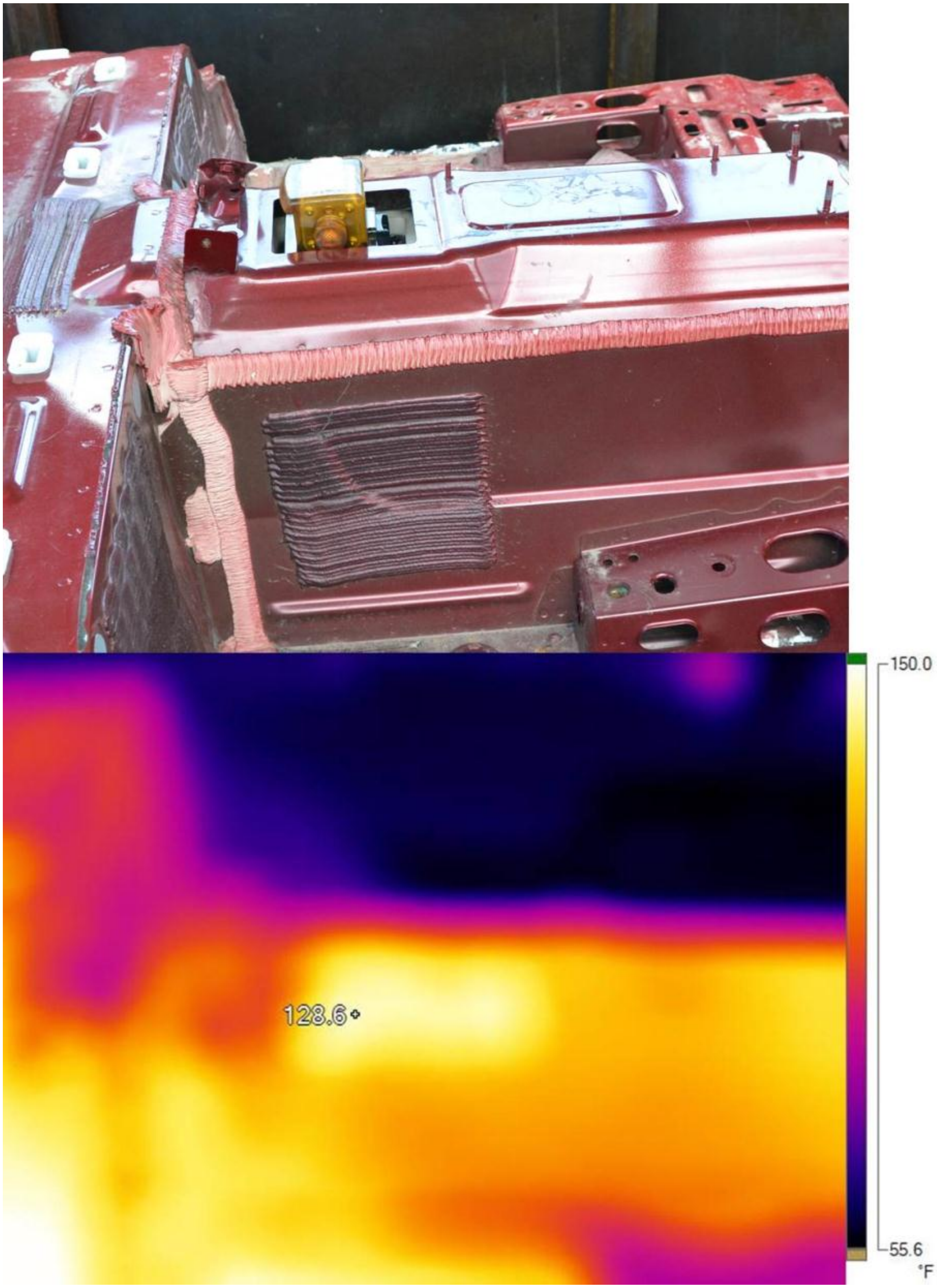

Figure 93 Floor pan assembly from side of VFT (top); thermal image (same view) of Battery B3 at 60 minutes (bottom)

Table 46 Summary of Test B3 Temperature Measurements after 1, 2, 3, 6, 12, and 18 hours

TC	Temperature (°F) After:					
	1 hour	**2 hours**	**3 hours**	**6 hours**	**12 hours**	**18 hours**
1	86	67	65	52	42	37
2	78	61	56	44	36	32
3	73	55	53	43	34	32
4	67	50	57	46	37	30
5	74	55	60	46	37	30
6	72	52	56	45	36	30
7	139	91	78	60	47	39
8	150	100	79	56	45	35
9	76	57	58	50	39	34
10	85	59	62	54	43	34
13	86	67	60	45	36	32
14	125	89	70	51	42	34
15	136	98	75	57	45	38

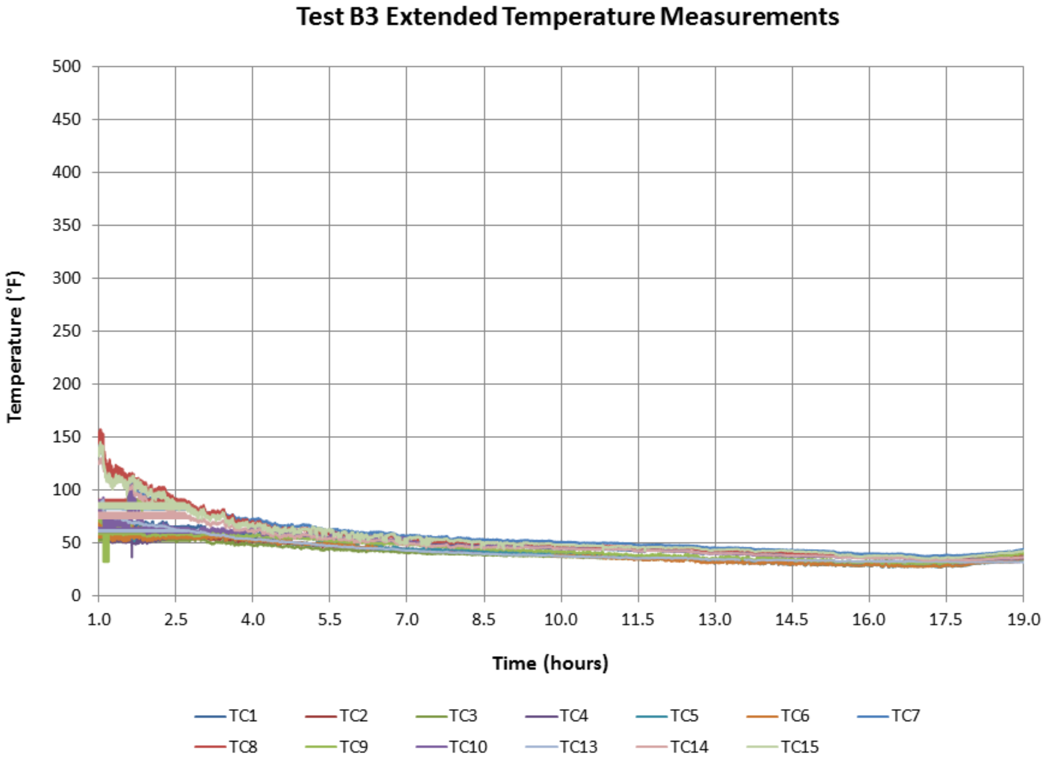

Figure 94 Extended temperature measurements for Test B3

6.2.6.8 Water Sampling Results

The water sample from Test B3 was collected and sent to an independent third-party laboratory, Analyze, Inc., for chemical analysis, as described in Section 5.2.4, along with a control sample collected from the suppression water source. A summary of the water sampling results is provided in Table 47. The water sample from Test B3 exhibited a slightly more acidic (7.3) pH value. In addition, low levels of chloride (60 ppm) and fluoride (33 ppm) anions were detected. When HF and / or HCl is present in an aqueous solution, it dissociates into a cation and an anion. Additionally, the presence of hydrogen cations increases the acidity of the solution, causing the pH to drop. Based on the presence of chloride and fluoride anions and the lower pH of the Test B3 sample as compared to the control sample, HF and HCl were likely present (in a small amount) during suppression.

Table 47 Water Sample Analysis Summary for Test B3

Element / Assay	Concentration (ppm)	
	Control	Test A3
pH	7.82	7.31
Total Organic C	1.3	360
Total Inorganic C	7.3	21
Chloride	34	60
Fluoride	0.7	33
Li	< 0.005	3.60
P	< 1.0	11
Ca	23	42
Na	13	17
Mg	4.8	7.0
K	2.4	4.8
Sr	0.08	0.44
Al	0.01	1.0
Fe	0.09	0.17
Ba	0.02	0.27
B	0.01	1.8
Zn	< 0.005	2.7
Mn	< 0.005	4.6
Sb	< 0.002	0.70
Ni	< 0.010	0.69
Co	< 0.005	0.76
Cu	< 0.005	0.14
As	< 0.010	< 0.010
V	< 0.002	0.003

7 Discussion

The following section is a discussion of the data and observations collected during the full-scale HRR and fire suppression tests and serves to supplement the presentation of the data in Section 6.

7.1 Overall Test Observations

The following is a summary of the overall test observations.

- Fire tests involving vehicle interior finishes produced significantly more intense fires with overall greater flame heights than battery only fires.
- At a standoff distance of five feet from the VFT, maximum heat flux measurements for tests without interior finishes (A1, A2, B1, B2) were between 2.1 and 3.7 kW/m^2. In comparison, maximum heat flux measurements for tests with interior finishes (A3 and B3) were between 8.1 and 11.9 kW/m^2.
- No projectiles were observed from the battery pack in any of the tests. None of the batteries tested "burst" or "exploded" in anyway, however, violent sparking was observed during the HRR test.
- In all tests, "popping" and "arcing" sounds and off gassing of white smoke consistent with internal battery cells from the battery pack undergoing thermal runaway were recorded. A further description of the thermal runaway events is provided in Section 7.2.
- Water was used to successfully extinguish all fires during the suppression tests; however, the amount of time required applying water and the total volume of water necessary for extinguishment was significantly larger than what is typically required for extinguishing a traditional ICE vehicle fire. A further description of the time and amount of water is provided in Section 7.8.
- In one test, the battery reignited 22 hours after the battery was extinguished (i.e., no signs of visible flaming, no signs of significant off gassing or smoking, and surface temperature readings on the battery were approximately ambient).

7.2 Firefighting Tactics

The following is a summary of observations and firefighter feedback regarding firefighting tactics.

- After initial size up and knock down of the visible flames, suppression activities were halted. In all tests, reignitions occurred. These events likely coincided with thermal runaway at the individual cell level internal to the battery packs. While visible flames from the batteries were clearly extinguished, it was evident that temperatures within the batteries were still high enough that thermal runaway of internal cells was occurring.
- Firefighters reported and the test data supports the following observations regarding these delayed reignition events. After knockdown of the visible flames, and as the cells likely underwent thermal runaway, the subsequent reignitions were characterized by “whooshing” or “popping” sounds, followed by off gassing of white smoke and/or electrical arcs/sparks that reignited with visible flames/fire. Typically this would result in visible flames that could be quickly knocked down by the firefighters with a single hose line. This reignition process would repeat until enough water had flowed to sufficiently reduce the internal battery temperatures to the point where thermal runaway would not proceed.
- The continuous application of water on a localized area of the battery for a prolonged period of time before moving onto another area of the battery can provide faster total extinguishment, as was seen in Test B3. In addition, once the main battery fire has been controlled, continuous application of water to the battery with the nozzle set on fog, as was performed during several of the tests, could further cool the exterior of the battery, thereby helping to reduce the temperatures of the internal cells. This could reduce the likelihood of additional off gassing of electrolyte and reignition of internal battery cells.
- In two tests (B2 and B3) the total time for extinguishment exceeded the available air supply for one of the firefighters. Given the long durations expected to cool burning batteries to the point where thermal runaway ceases, firefighter protocols should account for the potential for the need for multiple SCBA tanks. A support team will be necessary to bolster and possibly relieve the two firefighter suppression team, as needed.

- Water application times were longer for the Battery B test series. This may have been influenced by the overall larger size and rating of Battery B, however, the presence of the vehicle floor pan on top of the battery also posed a significant barrier to the application of water to the burning battery. See Section 7.8 for a further discussion of total water volumes necessary for extinguishment.
- Firefighters unanimously reported that access to the "hot spots" or "heat" was a significant barrier to extinguishing efforts. In the case of Battery A, located in the rear cargo compartment, all but the bottom side of the battery was readily exposed during firefighting activities. In the case of Battery B, the vehicle floor pan positioned on top of the battery significantly impeded the ability of the firefighters to directly apply water to the burning battery. However, in both tests, access to the batteries was much more than what firefighters will experience in real world vehicle fire scenarios.
- It can be assumed that access issues experienced by firefighters during this test program will be magnified during real world vehicle fire scenarios.

7.3 First Responder PPE

In all full-scale fire suppression tests, firefighters utilized NFPA compliant PPE that consisted of boots, turn out gear, standard structural firefighting gloves, helmets, hoods, and full SCBA. No adverse conditions were observed that supported changing any of the utilized PPE. However, while firefighters were instructed to utilize offensive operations, firefighters performing suppression tasks were specifically instructed not to interact with the VFT or battery packs beyond opening or closing compartment access doors in the front or rear of the VFT. No forcible entry tools or other handheld equipment was permitted. Evaluation of forcible tactics is beyond the scope of this study.

7.4 Electrical Hazards

The test data shows that the chassis and nozzle current was negligible, and the voltage levels at the chassis made it up to the approximately 0.3 or 0.4 V range, which was consistent with post-measurement tests. In addition, voltage levels at the nozzle were negligible. No adverse electrical conditions were noted.

7.5 Respiratory Hazards

Significant plumes of smoke were generated during all tests. White plumes of smoke consistent with off gassing from venting cells internal to the batteries were observed in all tests and often when visible flames were not present. Generally, off gassing of white smoke was followed by delayed reignition events with visible flames/fire coming from the battery pack. Given these observations, respiratory hazards do exist. Recent work that involved the burning of complete (i.e., full) ICE vehicles and EDVs identified similar levels of toxic compounds in the smoke, including CO_2, nitrogen oxides (NO_x), hydrogen cyanide (HCN), HCl, CO, and HF.[68] Gas sampling conducted during the HRR test showed only CO and CO_2 present. No HF or HCN was detected. The test data indicates that consistent with other recent work, respiratory hazards associated with EDV fires are similar to traditional ICE fires. Any and all firefighters involved in the extinguishment, handling, and overhaul of EDV fires should wear full NFPA compliant PPE, including SCBA, whenever performing suppression, handling, or overhaul tactics.

7.6 Water Hazards

The water sample from Test A3 was slightly more acidic and contained higher (although still low as compared to the control sample) levels of chloride and fluoride than the water sample from Test B3. Therefore, it is likely that HF and HCl were present during suppression activities for both batteries, but in a larger amount for the Battery A tests. In addition, the concentration of chloride likely from HCl in the solution was only 2 to 3 times greater than normal detected levels, while the concentration of fluoride likely from HF in the solution was more than 100 times greater than normal detected levels. Thermal degradation of polymers contained in both batteries is known to generate HF. In addition, although proprietary, it is likely that the electrolyte for both batteries would produce HF and HCl in some amount during thermal decomposition.

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

7.7 Extinguishing Agent (Water)

Water without additives was chosen as the suppressant agent for all tests conducted. Water was supplied from a nearby hydrant connected to a public water system providing fresh water (i.e., not salt water). In all tests, water was successfully used to extinguish the burning batteries. However, in one of the six full-scale suppression tests, the battery reignited after 22 hours.

Given the large quantities of water necessary to sufficiently cool the batteries and the long duration to achieve reduced temperatures, water supplies may be an issue. Long term suppression operations will likely require a sufficiently large water supply. In remote areas or where no hydrant is available, offensive suppression strategies will likely require a water shuttle, drafting arrangement, water rotation, or additional fire department companies equipped with additional water supplies.

7.8 Water Flow Calculations

A summary of elapsed suppression time, water flow time, and the total water volumes applied in each full-scale fire suppression test is provided in Table 48 below. Several observations and trends are apparent:

- Overall, EDV battery fires require significantly longer active suppression operations to battle reignitions and significantly larger total volumes of water than traditional ICE vehicle fires. This increase is attributed to the need for water to not only extinguish the visible flames, but to cool the battery component to the point where thermal runaway will not continue.
- Battery A generally required less water to achieve extinguishment than the larger Battery B. This is likely influenced by the overall size of the battery, but was more likely influenced by the position of the batteries within the VFT. Battery A was located in the rear cargo compartment and was readily accessible on five sides (all but the bottom), whereas Battery B was located beneath the vehicle floor pan and was significantly shielded.

- In the A test series, the full-scale test involving interior finish components required approximately three times the average water volume required for the extinguishment of the battery only fires.
- In the B test series, the full-scale test involving interior finish components required approximately half the average water volume required for the extinguishment of the battery only fires. This number was influenced by the previous experience of one of the firefighters, who extinguished the Test B2 battery the previous day. This firefighter acknowledged that he had gained knowledge on the best and most appropriate way to access the battery below the floor pan during the previous test.

Table 48 Summary of Water Flow Calculations for all Tests

Test	Elapsed Suppression Operation Time (min)	Water Flow Time (min)	Total Water Flow (gal)	Comments
A1	5.88	2.20	275	Battery Only
A2	36.60	3.53	442	Battery Only
A3	49.67	9.77	1060	Battery + Interior Components
B1	26.52	14.03	1754	Battery Only
B2	37.60	21.37	2639	Battery Only
B3	13.88	9.32	1165	Battery + Interior Components

7.9 Overhaul and Cleanup

Following extinguishment of the batteries, temperatures were monitored after the tests. In one test (A3), the battery reignited 22 hours later. During active and post suppression activities, the position of the battery in the vehicle will dictate whether or not thermal imaging techniques can be relied upon to determine when the battery is “cool.” In some cases, the position (e.g., shielding and location in the vehicle) of the battery will be such that thermal imaging is of no use. As demonstrated in the tests, point source TC measurements on the exterior of the battery casing should not be relied upon either.

8 Key Findings

8.1 Emergency Responder Questions and Answers

A summary of questions previously posed by the emergency response community are presented below in black text. Based on the test results and data collected, Exponent offers the following comments, observations, clarifications, and findings in **red text** below.

All information presented below is based upon the tests conducted and data collected as presented in this report. Given that there can be considerable variation in EDV fire scenarios, the users of this information are cautioned to assess any and all risks and exercise the best possible judgment, as well as all available resources to safely respond to and as appropriate, suppress each EDV fire encountered.

1. Appropriate PPE to be used for responding to fires involving EDV batteries:
    a. Is current PPE appropriate with regard to respiratory and dermal exposure to vent gases and combustion products?

       All tests were conducted using NFPA compliant turnout gear, helmet, boots, hoods, structural firefighting gloves, and full SCBA. No adverse conditions related to gear were observed by any of the firefighters who suppressed the fires. In addition, water and gas samples collected during testing did not include any compounds or gases that differed significantly from what is typically found in a conventional ICE vehicle fire. No projectiles or other explosion anomalies were observed. In two cases, due to an increase in the total volume of water to control the fire, the associated time was greater than what was available from a single SCBA cylinder. First responders should be prepared to either rotate suppression staff or have provisions to quickly change cylinders.

    b. Is current PPE appropriate with regard to potential electric shock hazards?

       An analysis of current and voltage measurements recorded at the discharge of the nozzle indicated no significant current or voltage readings in any of

the tests. Based on the test data, full NFPA compliant PPE is appropriate during noninvasive suppression operations. However, tests were conducted with batteries placed in a VFT prop. Full-scale tests involving complete vehicle electrical distribution systems were not conducted and evaluated, nor were offensive firefighter tactics involving cutting, piercing, manipulating the vehicle for extraction purposes or to gain better access for suppression purposes.

   c. What is the size of the hazard zone where full PPE, including respiratory protection, must be worn?

   Based on the data collected, the hazard zone where full PPE, including respiratory protection must be worn was comparable to that of traditional ICE vehicle fires. The fire observed for tests that included the EDV battery as well as interior finishes/upholstery was more intense than the fire observed in the battery alone. Heat flux and temperature measurements recorded around the VFT indicate no data to support changing the 50-foot perimeter standard provided in the NHTSA *Interim Guidance for Electric and Hybrid-Electric Vehicles Equipped with High Voltage Batteries.*[69]

2. Tactics for suppression of fires involving EDV batteries:

   a. How effective is water as a suppressant for large battery fires?

   All suppression tests were conducted with water without any additional additives. This water was able to suppress the battery fires each time. No other suppressant agents were examined as a part of this study. Total water volumes necessary for extinguishment varied widely throughout the tests. A clear trend in the water volume data indicated that as the total battery size increased and/or when the battery was less accessible due to vehicle configurations, there was a significant increase in the total volume of water necessary to extinguish the fire.

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[69] NHTSA *Interim Guidance for Electric and Hybrid-Electric Vehicles Equipped With High Voltage Batteries*, DOT HS 811 574, January 2012.

b. Are there projectile hazards?

No projectiles from the EDV batteries were observed during any of the tests conducted. All tests were conducted on batteries that involved Li-ion polymer/prismatic style battery configurations. No batteries were tested that involved cylindrical style cells.

c. How long must suppression efforts be conducted to place the fire under control and then fully extinguish it?

Total times for extinguishment (elapsed time spent actively suppressing the battery fires) ranged from 6 to 49 minutes; however, this does not include reignition, which occurred in one case, 22 hours later. First responders should be prepared to conduct suppression efforts for one hour or more.

d. What level of resources will be needed to support these fire suppression efforts?

All tests were conducted with a defacto incident commander and assistant and two active firefighters; one on the nozzle and one on the hose. This is equivalent to one company, as defined by NFPA 1710, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments*, 2010 edition. Given that EDV battery fires may require suppression efforts lasting one hour or more, appropriate staffing should be provided if rotating out nozzle or hose personnel is required and/or if suppression times necessitate the need for changing SCBA cylinders.

e. Is there a need for extended suppression efforts? (As compared to ICE vehicles.)

Yes. Factors, including the size, position within the vehicle, and access to the battery will significantly influence the total time necessary for suppression efforts. First responders should be prepared for extended periods of suppression operations and monitoring during overhaul operations due to battery reignition.

f. What are the indicators for instances where the fire service should allow a large battery pack to burn rather than attempt suppression?

Total water volumes were significantly greater in some tests than traditional ICE vehicle fires. In areas where a suitable water source is not present and there are no threats to life safety or to nearby structures, vehicles, or other combustibles, allowing the battery pack to burn to self-extinguishment may be a viable alternative to suppression. However, this may require extended periods of monitoring and observation for any reignitions. In the free burn test, the battery continued to visibly flame for approximately 90 minutes. Once it self-extinguished, it never reignited, although it did continue to off gas and was at elevated temperatures for hours afterwards.

3. Best practices for tactics and PPE to be used during overhaul and post-fire clean-up operations.

   See Section 8.2 below.

8.2 Suggested Best Practices for Tactics and PPE

NFPA Interim Guidance is presented below in black text. Based on the test results and data collected, Exponent offers the following comments, observations, additional clarifications, and findings in **red text** to supplement and bolster, where possible, the interim guidance provided by the NFPA *Electric Vehicle Emergency Field Guide*, 2012 edition.

All information presented below is based upon the tests conducted and data collected as presented in this report. Given that there can be considerable variation in EDV fire scenarios, the users of this information are cautioned to assess any and all risks and exercise the best possible judgment, as well as all available resources to safely suppress each EDV fire encountered.

8.2.1 General Procedures for Hybrid and EDV Fire Suppression[70]

- Use standard vehicle firefighting equipment and tactics in accordance with department SOPs/SOGs.

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[70] All text in black extracted from the National Fire Protection Association (NFPA) *Electric Vehicle Emergency Field Guide* 2012 Edition Chapter *General Procedures* Sub-Chapter *Fire*.

No data was collected to alter this recommendation. All data and observations indicated that in general, standard vehicle firefighting equipment and tactics utilized were applicable to suppressing EDV fires.

- Hybrid and EV fires do not require special equipment for fire suppression / extinguishment.

  No data was collected to alter this recommendation. No special equipment for fire suppression / extinguishment was evaluated as a part of this test series. Traditional hose lines and nozzles utilizing water as the suppression agent were utilized to extinguish all EDV battery fires. In all suppression tests, extinguishment was achieved and the batteries were safely extracted from the vehicles and stored. In one test series, a battery reignited after being extracted and stored 22 hours after "extinguishment". See further details below in Section 8.2.6. In some tests total water applications were an order of magnitude higher than traditional ICE vehicles. See further details below in Section 8.2.3.

8.2.2 Personal Protective Equipment

- All personnel should wear and utilize full PPE and SCBA as required at all vehicle fires.

  No data was collected to alter this recommendation. In addition to wearing and utilizing full NFPA compliant PPE and SCBA, all personnel should don full PPE and SCBA prior to advancing to suppress or overhaul an EDV fire or when operating within 50 feet of a burning EDV. Whenever possible, NFPA compliant PPE and SCBA should be donned and placed into service upwind of the fire. Fire equipment should also be located upwind of the fire. Full PPE and SCBA should be maintained throughout fire suppression and overhaul operations.

8.2.3 Extinguishing Agents

- Use water or other standard agents for vehicle fires.

  No data was collected to alter this recommendation. All suppression tests were sufficiently suppressed with water applied with standard hose lines and nozzles. No

other suppression agents were evaluated as part of this test program. Only fresh water was evaluated.

- The use of water does not present an electrical hazard to firefighting personnel.

  No data was collected to alter this recommendation. An analysis of current and voltage measurements recorded at the discharge of the nozzle and at the VFT chassis indicated no significant current or voltage readings in any of the tests.

- If an HV battery catches fire, it will require a large, sustained volume of water.

  No data was collected to alter this recommendation. Approximations for total water flows necessary for extinguishment of Battery A ranged from 275 gallons to 1060 gallons; Battery B ranged from 1165 to 2639 gallons. Overall, water flow rates were substantially higher than expected flows necessary for extinguishing traditional ICE vehicle fires. In most tests, intermittent water application was used. Continuous flows of water directly on the battery can provide additional cooling and shorten times to full extinguishment, however, total water flows could increase.

8.2.3.1 Warnings and Notes

- If using water to extinguish/suppress a high voltage battery, use a large volume of water. Using only a small amount could allow dangerous toxic gases to be released.

  See discussions on total water flow rates above. Whether or not a small amount of water applied to the battery could allow dangerous toxic gases to be released was not evaluated in this test program.

- If a Lithium Ion (Li-Ion) HV battery is involved in a fire, there is a possibility that it could reignite after extinguishment. If available, use thermal imaging to monitor the battery. Do not store a vehicle containing a damaged or burned Li-Ion HV battery in or within 50 feet of a structure or other vehicle until the battery can be discharged.

  In Test A3, the battery was extinguished and safely removed from the VFT and stored in a remote holding area. Approximately 22 hours after extinguishment, the battery reignited. Where possible, thermal imaging techniques were used to monitor battery temperatures, however, vehicle components and structures limited

direct line of sight measurements in some test configurations. In addition, the outer shell of the battery may prevent reliable measurements or provide false security that there is no additional risk posed once the initial battery fire is extinguished. NFPA should consider expanding the storage requirements to not storing a damaged or burned Li-ion HV battery in or within 50 feet of a structure, another vehicle, or combustible materials until the battery can be safely discharged, if possible, in accordance with vehicle manufacturer procedures by trained and qualified staff. In addition, consider adopting SAE J2990, Section 7.2.2, *Damaged xEV*[71] *Storage Isolation Recommendations*[72], as follows:

> ***xEVs that have sustained (or suspected) damage to the high voltage system should not be stored inside a structure until inspected per 7.4. During isolation, vehicle windows and/or doors should be opened sufficiently to allow ventilation in the vehicle and prevent build-up of potentially flammable gasses from a damaged battery system. For xEV's where the battery system is ruptured, vehicle exposure to elements such as rain should be avoided. The following methods are allowed for isolating a damaged xEV:***
>
> 1. ***Open Perimeter Isolation: An area where the vehicle is separated from all combustibles and structures by a distance of not less than 50 feet (15.2 meters) from all sides of the vehicle/battery system. Per the recommendation provided by NHTSA (reference DOT HS 811 574, 'Interim Guidance for Electric and Hybrid Electric Vehicles Equipped with High Voltage Batteries').***
> 2. ***Barrier Isolation: An area where the vehicle is separated from all combustibles and structures by a barrier constructed of earth, steel, concrete, or solid masonry designed to contain a fire from a stored vehicle from extending to adjacent vehicles. Barriers should be of sufficient height to direct any flame or heat away from the adjacent vehicles. If the barrier is provided only on 3 of the 4 sides of the vehicle, then the open side must***

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[71] Defined by SAE J2990 Section 3.34 as, "Any electrified propulsion vehicle with a high voltage system, including but not limited to HEV, PHEV, PEV, BEV, FCEV, and EV."

[72] SAE International, Surface Vehicle Recommended Practice J2990 NOV2012, 11-2012, Hybrid and EV First and Second Responder Recommended Practice.

maintain the separation distance as referenced above for the open perimeter isolation. It is not recommended to fully enclose the vehicle in a structure due to the risk of a post-incident fire extending to the structure and the possibility of trapped explosive or harmful gasses, therefore a roof is not recommended for the barrier construction.

- Because high voltage batteries are in protective cases, it is very difficult to get any extinguishing agent directly onto the burning cells. The application of large volumes of water may cool the high voltage battery sufficiently to prevent the propagation of fire to adjacent cells.

  Both the protective cases surrounding the battery and/or the vehicle structure and/or components may prevent direct application of the extinguishing agent to internal cells that are burning or in thermal runaway. While the application of large volumes of water may help to cool the battery, utilizing any and all nondestructive means to apply water directly to or into the battery will provide the most efficient means to prevent the propagation of fire through adjacent cells.

8.2.4 Tactics

- DO NOT blindly pierce through the hood with tools such as a Halligan bar to gain access. This tactic could penetrate high voltage components in the engine compartment, creating a severe shock hazard.

  Although this was not evaluated in this test program, NFPA should consider expanding this guidance to not blindly pierce ANY portions of the vehicle that could penetrate high voltage components in any areas (not just the hood) of the vehicle that could contain high voltage components or severe shock hazards.[73]

- **Offensive Attack:** Recommended where exposures are present or the high voltage battery is not involved.

  All tests were conducted with offensive attacks when the high voltage battery was involved. In all tests, extinguishment of the burning batteries was achieved and the

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[73] No specialty nozzles, such as a piercing nozzle, were evaluated during this study.

batteries were safely removed from the VFT. In one test, however, the battery reignited 22 hours after "extinguishment".

- **Defensive Attack:** Recommended if the high voltage battery is involved and no exposures are present. Due to the difficulty in reaching the burning cells inside the battery with the extinguishing agent, the Incident Commander may choose to allow it to burn itself out. Any individuals without SCBA should remain upwind of the fire an avoid inhalation, due to toxic compounds in the smoke.

  Total water application rates were higher than what would be expected for extinguishing traditional ICE vehicle fires. In all tests, difficulties in applying water to the burning cells inside the battery were noted. Offensive attacks were used successfully in all suppression tests where the high voltage battery was involved. Any individuals without full NFPA compliant PPE and full SCBA should remain outside of a 50-foot radius from the fire as outlined in the NHTSA Interim Guidance. The proximity of nearby structures, vehicles, or other combustibles, as well as life safety, should be accounted for in decisions related to defensive attacks.

8.2.5 Fires Involving Charging Stations

- Locate the power source for the charging station and shut it down.

  Not evaluated in this test program.

- Until power to the charging station is cut, treat the fire as you would an energized electrical fire.

  Not evaluated in this test program.

- If a vehicle is plugged in to the charging station, it should be unplugged as soon as it is safe to do so. If possible, shut down the charging station first.

  Not evaluated in this test program.

8.2.6 Overhaul and Recovery

- Immobilize and disable the vehicle if it has not already been done.

  Not evaluated in this test program.

- Never disconnect or contact any exposed high voltage components or wiring.

  Not evaluated in this test program.

- Attempt to contact a dealer or manufacturer representative as soon as possible for help with post-incident vehicle disposition and de-energizing the high voltage battery if necessary.

  Not evaluated in this test program.

- Never breach or remove the high voltage battery. Doing so may result in severe electrical burns, shock, and/or electrocution.

  Not evaluated in this test program.

- Do not store a vehicle with a damaged or burned Li-Ion battery in or within 50 feet (15 meters) of a structure or another vehicle until the battery can be discharged.

  NFPA should consider expanding the storage requirements to not storing a damaged or burned Li-ion EDV battery in or within 50 feet of a structure, another vehicle, or combustible materials until the battery can be safely discharged in accordance with vehicle manufacturer procedures and by trained and qualified staff.

9 Recommendations and Future Work

The following possible future work is suggested (Phase II) to further identify and understand firefighter tactics and suppression strategies for EDVs:

- Full-scale fire suppression testing of actual consumer EDVs to evaluate access issues in water application strategies in specific vehicle fire scenarios.
- Full-scale fire suppression testing of actual consumer EDVs to evaluate access issues in water application strategies in collision scenarios.
- Full-scale fire suppression testing of actual consumer EDVs to evaluate shock hazards when the entire vehicle electrical distribution system is present and possibly energized.
- Full-scale fire suppression testing of EDVs using cell formats different from those tested in this test series, such as 18650s.
- Free burn full-scale EDV fires to compare and contrast the advantages and disadvantages of letting EV fires burn out rather than suppressing.
- Evaluation of novel or alternate nozzle designs that may allow direct application of water to EDV batteries located below the vehicle underbody assembly.
- Determine the effectiveness of various water additives that may accelerate the cooling/extinguishment process.
- Conduct additional full-scale tests to evaluate the total water flow rates necessary to achieve extinguishment using new firefighter tactics, such as constant water application or a two hose line suppression team.

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Appendix A SwRI Test Report

Appendix B VFT Design Drawings

Appendix C Microbac Laboratories Report

Appendix D Analyze, Inc. Report

Appendix E Electrical Measurements