

# Full-scale Fire Tests of Electric Drive Vehicle Batteries

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## ABSTRACT

Fires involving cars, trucks, and other highway vehicles are a common concern for emergency responders. In 2013 alone, there were approximately 188,000 highway vehicle fires. Fire Service personnel are accustomed to responding to conventional vehicle (i.e., internal combustion engine [ICE]) fires, and generally receive training on the hazards associated with those vehicles and their subsystems. However, in light of the recent proliferation of electric drive vehicles (EDVs), a key question for emergency responders is, "what is different with EDVs and what tactical adjustments are required when responding to EDV fires?"

The overall goal of this research program was to develop the technical basis for best practices for emergency response procedures for EDV battery incidents, with consideration for suppression methods and agents, personal protective equipment (PPE), and clean-up/overhaul operations. A key component of this project goal was to conduct full-scale fire testing of large format Lithium-ion (Li-ion) batteries as used in EDVs.

This paper summarizes the full-scale fire tests performed, reviews the current emergency response tactics, and discusses what, if any, tactical changes relating to emergency response procedures for EDV battery incidents are required.

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## INTRODUCTION

Fires involving cars, trucks, and other highway vehicles are a common concern for emergency responders. In 2013 alone, there were approximately 188,000 highway vehicle fires [1]. Fire Service personnel are accustomed to responding to conventional vehicle (i.e., internal combustion engine [ICE]) fires, and generally receive training on the hazards associated with those vehicles and their subsystems. However, in light of the recent proliferation of electric drive vehicles (EDVs), a key question for emergency responders is, "what is different with EDVs and what tactical adjustments are required when responding to EDV fires?"

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 program to provide safety training to emergency responders to prepare them for their role in safely handling incidents involving electric drive vehicles (EDVs). This program had a lack of data to draw on to address the potential hazards associated with damaged EDV batteries.

In an effort to bolster preliminary guidance issued by NFPA and the Society of Automotive Engineers (SAE) for fire emergencies involving EDVs, full-scale fire suppression tests were conducted to collect data and evaluate differences in EDV fires as compared to traditional internal combustion engine (ICE) vehicle fires [2]. In

particular, members of the emergency response community had questions regarding, (1) personal protective equipment (PPE); (2) firefighting suppression tactics; and (3) the best practices for overhaul and post-fire clean-up.

## CURRENT BEST PRACTICES FOR FIREFIGHTING TACTICS FOR ICE AND EDVs

SAE's J2990, Hybrid and EV First and Second Responder Recommended Practice [3], NFPA's Electric Vehicle Emergency Field Guide [4], and the National Highway Traffic Safety Administration (NHTSA), Interim Guidance for Electric Vehicle and Hybrid-Electric Vehicles Equipped With High Voltage Batteries [5], describe the potential consequences associated with hazards from EDVs and suggest common procedures to protect emergency responders, tow and/or recovery, storage, repair, and salvage personnel after an incident has occurred involving an EDV. Nickel metal hydride (NiMH) and Lithium-ion (Li-ion) batteries used for vehicle propulsion power are the assumed battery systems of these recommended practices and guides.

The recommended practices and guides listed above outline the same basic steps for fire service personnel responding to an EDV fire: identify the vehicle; immobilize the vehicle; disable the vehicle; extrication; extinguishment; and overhaul operations. ICE tactics are

generally consistent with the current recommendations for EDV tactics; however, given the proliferation of EDVs, first responders must now first identify the vehicle (i.e. is it an ICE or EDV) before performing any actions. After identification, first responders can then respond to the fire appropriately given the type of vehicle involved. The key differences between ICE and EDV tactics include, the need for copious amounts of water to extinguish an EDV battery fire, the high voltage electrical hazards associated with EDVs, and the recommendation to store all damaged EDVs 50 feet from other structures or vehicles post-fire during overhaul operations and storage.

## KEY REQUIRED ELEMENTS OF EDV EMERGENCY RESPONSE PPE

Typical first responder PPE consists of a polybenzimidazole (PBI) coat, PBI pants, polycarbonate helmet, kangaroo skin or leather gloves, PBI or lanzing hood, leather boots, and a self-contained breathing apparatus (SCBA). Additional hazards of EDV fires that may require some form of PPE can be grouped into three distinct categories: chemical (corrosive or toxic compounds), electrical (high voltage systems), and thermal (burns).

Currently, recommendations regarding first responder PPE are lacking in scientific data to support the necessity of additional PPE. One of the objectives of this research program was to take scientific data from actual EDV battery fires to provide a basis for what first responders could encounter in an EDV fire and how best to protect themselves and their equipment.

## IDENTIFY BATTERY TYPES FOR FULL-SCALE TESTING

Li-ion battery cells arranged in large format Li-ion battery packs are being used to power many EDVs currently in the U.S. marketplace. This chemistry is different from previously popular rechargeable battery chemistries (e.g., NiMH, nickel cadmium, and lead acid) [6, 7]. Most notably, Li-ion batteries contain a high energy density coupled with a flammable organic electrolyte, rather than an aqueous solution typically employed in previous battery chemistries. This has created a number of new challenges with regard to fire suppression for first responders.

Given the current direction of the automotive industry, Li-ion batteries were chosen for full-scale testing. Batteries were procured from two car manufacturers, designated Battery A and Battery B. Both of the batteries procured were based on a Li-ion technology currently being used in production vehicles in the United States. Battery A is a 4.4 kWh battery utilized in a plug-in hybrid electric vehicle (PHEV) that is installed under the rear cargo compartment of the vehicle. The 4.4 kWh battery pack is enclosed in a metal case and is rigidly mounted in the lower portion of the rear cargo area behind the rear seat. The electrolyte used in the Li-ion battery cells is a flammable organic electrolyte.

Battery B is a 16 kWh battery that is utilized in an extended range electric vehicle (EREV). 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. 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.

## DEVELOPMENT OF A FULL-SCALE FIRE TESTING PROGRAM FOR EDV BATTERIES

The testing program developed included one full-scale heat release rate (HRR) test of a standalone EDV battery (HRR test) and six suppressed tests of EDV batteries installed within a generic vehicle fire trainer (VFT) prop (fire suppression tests). The fire suppression tests were conducted with and without vehicle interior finishes to demonstrate the impact of the burning battery on the overall vehicle fire, if any. All tests subjected the batteries to simulated exposure fires originating underneath the battery/vehicle chassis and all fire suppression activities were conducted by qualified, active duty firefighters. The simulated exposure fires were produced using an external propane gas burner system that provided a steady and repeatable 400 kW exposure to the batteries, which is equivalent to a moderate size gasoline pool fire. Gas samples and fire suppression water samples were collected for analysis of potential contaminants (chemical hazards). Voltage and current measurements were recorded at the battery, VFT chassis, and the suppression nozzle (electrical hazards). Instrumentation also monitored fire growth and development, including, but not limited to, HRR, temperature, and heat flux (thermal hazards).

## FULL-SCALE FIRE TESTS

Full-scale HRR testing was performed at Southwest Research Institute (SwRI) in San Antonio, Texas. The primary objective of the HRR testing was to determine the amount of energy released from the battery alone when ignited by an external ignition source.

Full-scale suppression testing was performed at Maryland Fire Research Institute (MFRI) in College Park, Maryland. The primary objectives of the suppression testing were to evaluate 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.

### HRR Testing

Due to the limited number of EDV batteries provided, only one battery was subjected to HRR testing. Battery B was centered under a 20-foot by 20-foot hood supported by five stainless steel legs. The leg supports held the battery in place, 20 inches above the ground to provide a viewing angle to the bottom of the battery during testing. Four propane fueled burners were placed six inches underneath the battery and provided an approximately 400 kW exposure fire to the bottom of the battery for 20 minutes (see Figure 1).



Figure 1. Battery B configuration and burner locations for HRR testing.

Temperature and heat flux measurements were recorded on the exterior battery casing, interior battery, and at standoff distances of 5 and 10 feet from the battery (see Figure 2). Gas samples were collected for analysis for toxic or corrosive compounds. This was performed by positioning a smaller, 10-foot by 10-foot hood directly above the battery to funnel products of combustion into a gas sampling line. HD video and thermal imaging cameras were also positioned around the battery to record the tests. The battery was allowed to burn until completion (i.e., no suppression).

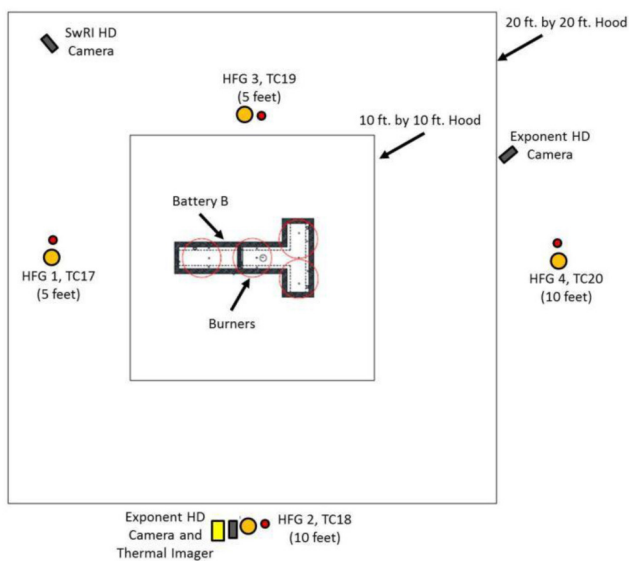


Figure 2. HRR testing setup.

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). Removing the 400 kW propane burners, the peak heat release the battery attributed to the fire was approximately 300 kW. Once the burners were turned off, around the 20 minute mark, the HRR plateaued as the battery underwent self-sustaining combustion and then slowly decayed (see Figure 3). As seen in the HRR data and shown in Figure 4, after the 36 minute mark, flaming had subsided significantly on the battery to a point where the HRR was essentially zero. Small, localized flames on the battery continued for approximately another hour, at which time all visible flaming ceased. Thermal images were recorded as the battery

cooled for an additional three hours and 15 minutes. When visible flaming ceased, the observed exterior maximum temperatures were approximately 750°F (400°C). Three hours after all visible flaming ceased, maximum observed exterior temperatures on the battery were still elevated, at approximately 310°F (155°C).

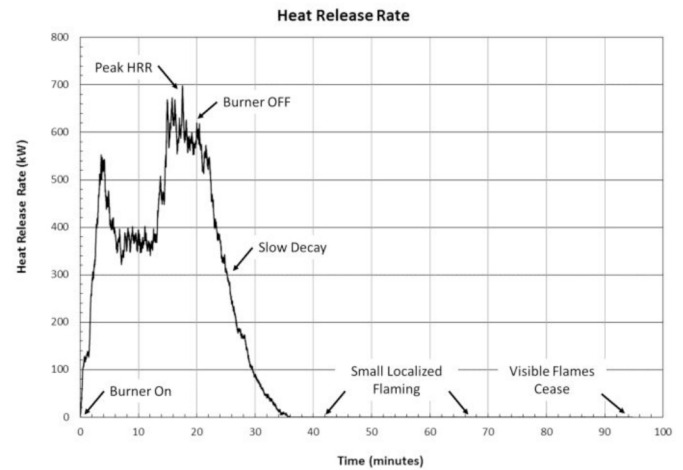


Figure 3. HRR test results.



Figure 4. HRR test images: initial burner startup (top left); initial peak HRR (~550 kW) around 4:00 (top right); peak HRR (~700 kW) around 17:30 (center left); burners off around 20:00 (center right); small flames from battery vents around 47:00 (bottom left); and visible flames extinguished around 1:34:00 (bottom right).

Maximum air temperatures and heat fluxes measured during testing at a standoff distance of five feet from the battery were between 201.7 and 230.0 °F (94.3 and 110°C) and 17.1 and 18 kW/m<sup>2</sup>, respectively. At ten feet those values dropped to between 106.7 and 127.0 °F (41.5 and 52.8°C) and 3.7 and 4.7 kW/m<sup>2</sup>, respectively (see Table 1).