

Fire Testing of Electric Vehicle Battery Packs and Vehicles as Compared to ICE Vehicles

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Summary

Electric vehicles (Plug-in Hybrid Electric Vehicles (PHEV) and Battery Electric Vehicles (BEV)) store large amounts of electrical energy within their battery packs and the components of the individual cells have significant stored chemical energy. In an abuse situation, this energy will be liberated leading to a potential safety issue. The National Research Council of Canada (NRC) is currently working alongside Transport Canada with respect to potential safety issues within electric vehicles. In this presentation, we will present recent results from fire exposure tests on EV battery packs and vehicles in comparison to traditional gasoline, gasoline tanks and Internal Combustion Engine (ICE) vehicles.

Keywords: safety; RCS (Regulations Codes and Standards); thermal management; Battery; Energy Storage

1. Introduction

An increase in the number of electric vehicles on the roads is directly related to the development of high energy and long range battery packs with a proven safety record. Recent safety events in the field (Tesla and Volt fires [1,2]) as well as issues with lithium-ion batteries used in other transportation industries (Boeing [3]) have highlighted the potential dangers and the requirement for research activities on the safety of high energy battery packs in relation to mechanical [4], physical [5] and electrical abuse [6] scenarios. In an abuse situation, the energy (electrical and chemical) stored in the battery can be liberated, leading to a potential safety issue, the magnitude of which is dependent on the choice of battery materials, cell/battery pack design, internal safety features, etc.. The National Research Council of Canada (NRC) is currently working with Transport Canada to look at some of these issues. The goal is to perform research on potential safety issues with respect to EVs to inform policy makers of the potential hazards of EVs in comparison to ICE vehicles. The policy makers can then use this research to make informed decisions regarding the implementation of national, regional, or global automotive technical regulations.

2. Experimental

Using the UL 2580 [7] standard as a guideline, EV battery packs and vehicles (at different states of charge), as well as gasoline, filled gasoline tanks and ICE vehicles, were each exposed to a controlled fire. A fire exposure test is currently being considered by regulators in the context of a Global Technical Regulation (GTR) on EVs [5]. The objective of these tests was to evaluate electric vehicles/packs (EV) and/or hybrid electric vehicles/packs (HEV) under exposure to an external fire simulating a fuel spill fire, in comparison to internal combustion engine (ICE) vehicles/gasoline tanks exposed to the same conditions. Commercial vehicles and the battery packs of commercial vehicles were provided to NRC by Transport Canada. No modifications to the vehicles or battery packs were performed, except for the installations of feed through that were required for various instrumentation sensors.

The testing was performed indoors at an NRC facility, in an unheated environment, under a 6 m by 6 m exhaust hood connected through a duct system to an exhaust fan system, which was used to collect the smoke and gases produced by the fire. The vehicles/packs were suspended on a platform around a large propane sand burner centred underneath the hood. A photo of the burner, without the 9.5 mm (3/8") diameter round rocks placed above the steel piping, is shown in Figure 1. The burner was used to mimic the flame geometry of a gasoline pool or spill fire, while permitting control of the fire size, heat release and duration. The rock bed permitted an even distribution of propane over the surface of the burner, so that a fuel spill is properly simulated. The ground clearance for the vehicles was kept at ~200mm above the sand burner using cinder blocks, while the battery packs/gas tank were suspended ~300mm above the burner using a metal support frame. Tests were conducted on four lithium-ion battery packs from two different commercial EVs, 25-45L of regular winter grade gasoline (burned in a separate pan of the same size as the sand burner), a plastic gas tank filled with 45L of gasoline, five commercial EVs and two commercial ICE vehicles. Before the initiation of the tests, the battery packs were charged to either 100 or 0%, while the vehicles were charged to 100 or 85% based on the driver readout from the vehicles. The ICE vehicles contained a full tank of gasoline (Canadian regular winter grade).

2.1 Instrumentation

2.1.1 Temperature

All temperature measurements were made using Type K, 24-gauge, bare-bead thermocouples. In accordance with UL 2580 [7], six of these thermocouples were shielded inside a stainless steel tube centered approximately 25 mm below the battery/vehicle's underside and aligned with the longitudinal mid-plane of the burner. The tube was 2 m long, and had an outer diameter of 13 mm and wall thickness of 1.6 mm. The thermocouples were spaced 0.25 m apart inside the tube. For the vehicle tests, two additional tubes, each also containing six thermocouples, were placed on either side of the first tube, separated by a centreline-to-centreline distance of 0.3 m (one-quarter width of the sand burner). For the battery pack tests, a thermocouple tree was located above the battery at the centre of the propane sand burner. The thermocouple tree consisted of seven Type K, 24-gauge, bare-bead thermocouples, spaced vertically at 0.25 m intervals starting at the top of the battery. The thermocouples were used to measure the temperatures in the flame. For the vehicle based tests, a thermocouple tree, consisting of five thermocouples spaced 0.25 m apart, was located inside the vehicle near the centre of the passenger cabin with the highest thermocouple within 0.2 m of the ceiling. Additional thermocouples were attached to key areas within the vehicle, as well as within the battery pack where possible.

2.1.2 Heat Flux

In the vehicle based tests, up to two Directional Flame Thermometers (DFTs) [8] were used to measure heat flux to help quantify the intensity of exposure from the propane fire to the vehicle. Areas of interest included the underside of the battery pack/gas tank, and the centre of the underside of the vehicle. In all tests, up to two Gardon gauges [9] were used to measure radiative heat flux from the burning pack/vehicle to the exterior surroundings.

2.1.3 Heat Release Rate

Smoke and gases produced by the fire were collected using an exhaust hood system located above the pack/vehicle. The system was connected through a duct to an exhaust fan system. A measuring station in the duct system contained a thermocouple to measure the gas temperature and a bi-directional probe (pitot tube) to measure the pressure difference produced by the flow in the duct. These measurements were used to estimate the equivalent volumetric flow rate at standard atmospheric conditions. Gas samples were taken from the centre of the duct and analyzed to determine the concentrations of O₂, CO and CO₂. These concentrations, along with the estimated volumetric flow rate of the exhaust gases, were used to determine the heat release rate using the oxygen depletion method [10] in all tests.

2.1.4 Smoke Analysis

For the vehicle based tests, a sampling smoke meter (consisting of a light source and photodetector) was used to measure the optical density of the smoke in gas samples extracted from inside the passenger cabin. The sampling region was at head height near the driver's seat (~0.25 m below the vehicle ceiling).

2.1.5 Video

Up to five video cameras were used to record the fire during testing. Viewing points included the front, back and both sides of the pack/vehicle. An infrared (IR) camera was also set up to record the pack/vehicle during testing.

2.1.6 Mass Loss

The weight of the pack/vehicle was measured before and after testing using load cells.

3. Results and Discussion

Figure 2 shows the initial calibration of the test setup, whereby the propane sand burner was calibrated to reach flame temperatures near those from burning 25L of gasoline. The temperatures at the various heights within the propane fire stabilized near 800°C, which was very similar to the flame temperatures measured when burning gasoline in the same setup. The key differences between the gasoline and propane fires were in the heat release rate and burn time. Gasoline provided a significantly larger heat release rate than propane, but the propane fire provided a constant 2 MW output that could be maintained as long as the pressure of propane in the setup (fed through an external source) could be maintained. This meant the propane setup could produce a much more controllable and reproducible test result that could be used during the experiments. It is important to note the burn time for gasoline is dependent on the volume of gasoline used (25L here) and thus any true field event would be dependent on the source and volume of the available gasoline. The long exposure time used here with the propane setup (30 min) ensures that the pack/vehicle is completely consumed during the test and aligns with previous UL standards on battery pack level testing.

After calibration of the setup, testing of the battery packs in comparison to gasoline was initiated. The results will be described in detail during the presentation. Figure 3 presents some still photographs of one battery pack at various times during the fire exposure test. It took roughly 400 seconds after ignition of the fire for this battery pack to liberate more heat than the burner (as measured by an increase in heat release rate above that of the propane fire). A second battery pack (from a different vehicle) was tested and this pack took over 700 seconds after ignition of the fire to liberate more heat than the burner. The difference in reaction time for the various battery packs is due to the different pack construction and thermal management systems causing a large difference in the thermal mass of both packs. In addition, the state of charge of the battery has shown a small difference in onset temperature. The first pack uses a passive thermal management design, while the second pack uses an active liquid thermal management design that requires significant time to heat up due to the higher thermal mass. It is important to note that in this setup, 25L of gasoline takes only ~200 seconds to completely burn (~300 seconds for 45L). During the course of the battery pack tests, a number of flares could be seen being ejected from the battery pack signifying that individual battery cells or modules were compromised, but there were no catastrophic explosions from the pack. Further testing has shown that the present test method shows good reproducibility and that the total heat released by a battery pack is relatively independent of its charged state; only the onset and peak heat release rates are affected by the state of charge. A detailed comparison of both battery packs will be provided during the conference.

Subsequent to the fire tests on EV battery packs, a series of comparative fire tests were conducted on both EV and ICE vehicles. The objective was to perform a comparative study on the effects of a rechargeable electrical energy storage system and EV vehicle architecture with respect to a gasoline fuel tank and ICE vehicle architecture. An additional goal was to identify what, if any, are the potential safety issues with respect to the EV system in comparison to traditional ICE vehicles. Two gasoline and five electric vehicles were tested and the vehicles/battery packs under test were equipped with multiple thermocouples, voltage sensors, heat flux meters, smoke detectors and gas sampling lines as described in the experimental section. The vehicles under test included two baseline ICE vehicles containing between 40 and 50 liters of gasoline, a small PHEV (SOC-100%), a large PHEV (SOC-100%) and three BEV. Two of the BEVs were identical (EV #1 and #2), except that one was tested at a SOC of 100% (EV#1) and the other at a SOC of 85% (EV#2). The third BEV (EV#3) was tested at a SOC of 100%. The BEVs under test are the same make and model as the vehicles to which the battery packs of the previous study belong; thus some direct comparisons can be made between the fire tests on the battery packs and those on the corresponding vehicles.

Figure 4 presents the results of the battery voltage measurements for both the 12V and high voltage systems of the EVs under test. All vehicles were tested in the “On” position; thus the 12V system was energized and all vehicles show roughly 14.5V for the 12V system at the start of the test. Within 100 seconds most of the vehicles have detected an issue and have turned “Off” the 12V system as the voltage falls rapidly to roughly 12V. The voltage holds at roughly 12V for another 200-300 seconds and all vehicles show a complete loss of voltage on the 12V battery by 400 seconds. It is estimated that by 400 seconds there is significant heat entering the location of the 12V battery such that the 12V battery is compromised and no voltage reading is possible. The measurements from the high voltage system of the five EVs under test (two PHEV + three BEV) are shown in the lower panel of Figure 4. It is important to note that there was a premature loss of data collection on the high voltage line of EV #1 (black curve), resulting in a premature loss of high

voltage data. Among the remaining vehicles, except for the small PHEV, high voltage data collection (measured at the main high voltage relays) was maintained up to 400 seconds or later. The point where high voltage data is lost is an indication of a compromised high voltage system due to the fire burning underneath the vehicle. However, it does not guarantee that the high voltage battery pack is compromised as these measurements were not performed directly on the cells in the interior of the battery pack and a loss of voltage may just signify a compromised high voltage relay. More critical to the identification of a compromised battery pack are the temperature measurements made within the battery pack as well as the heat release data from the test. This data will be presented in detail during the presentation and it provides an indication as to when gasoline is released (for PHEV vehicles) as well as to the timing of the compromised battery pack, when internal reactivity within the electrochemical cells and the burning of the organic electrolyte cause a rapid rise in the temperatures within and the heat released from the battery pack.

Figure 5 presents a comparison of the temperatures within the passenger cabin at roughly the driver's head height for all vehicles under test. All vehicles experienced a sudden high rate of temperature rise around 200 seconds or later. It is interesting to note that the times of this temperature rise for all EV powertrain vehicles lie in between those for the two ICE vehicles under test. This indicates that the vehicle construction and the choice of material within the cabin play a much more important role in terms of cabin temperatures than the chosen propulsion technology. In addition, the times of sudden temperature rise seen in Figure 5 occur immediately after one of the windows of the vehicle is compromised. A compromised vehicle window permits more combustion air to enter the cabin and accelerates burning, thereby causing significant increase in the rate of temperature rise as shown in Figure 5. Further data comparisons and videos will be presented during the talk to enhance understanding of the risks, if any, that electric vehicles pose in terms of exposure to fire, compared to ICE vehicles. It is important to note that no electric vehicle showed any catastrophic explosion, although numerous pops, flares and fire jets were expelled during the test indicating a reactive fire due to not only the battery pack but also tires, shocks and air bags (common to all vehicles, not just EVs).

Acknowledgments

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Figures



Figure 1. Propane sand burner during construction.

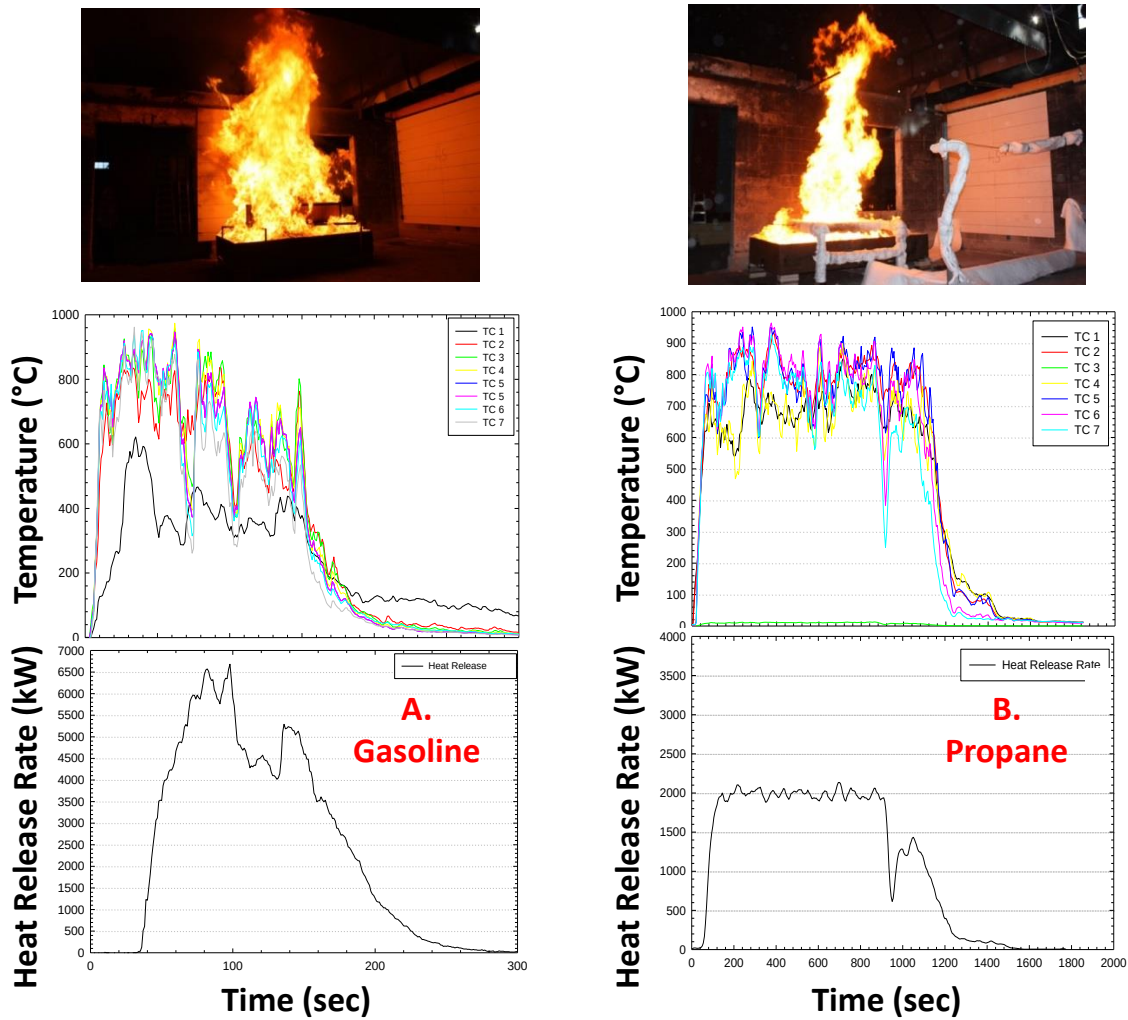


Figure 2: Calibration of the fire exposure set-up. Heat release rate and temperature versus time of either 25L of gasoline (A) or propane (B) in the setup as shown above.

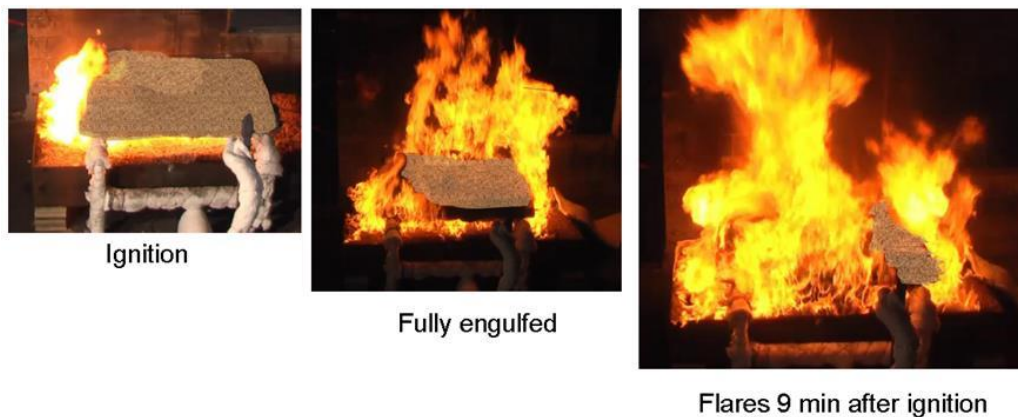


Figure 3: Visual photographs of one commercial EV battery pack under fire exposure test at indicated times after ignition, showing flares being released from the battery pack.

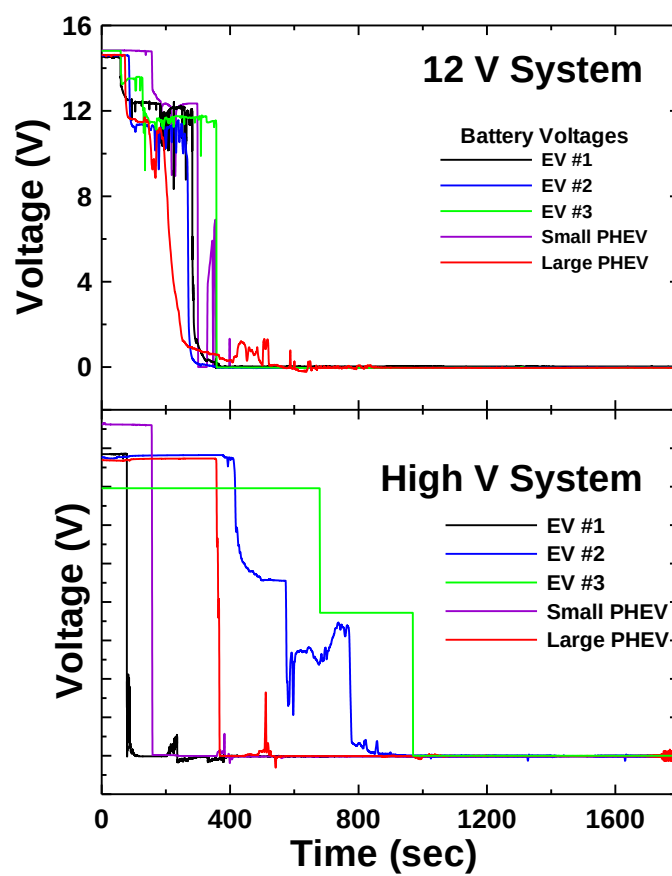


Figure 4: Voltage versus Time during the 30 min fire exposure test for the various vehicles under study for both the 12V (top panel) and high voltage (lower panel) systems.

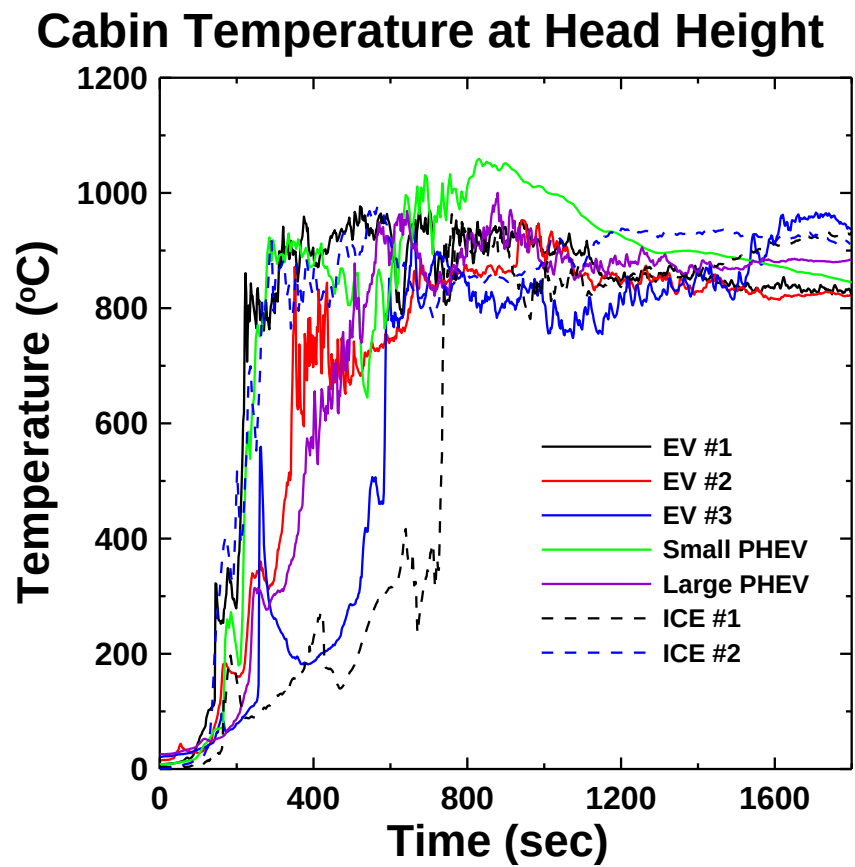


Figure 5: The temperatures recorded inside the vehicle cabin for all vehicles under test during the 30 min fire exposure test. The temperature was recorded in each vehicle at roughly the head height for the driver.