Presentation 1. INL Experience With Vehicle Thermal Events

Presentation 2. Intentional R&D: Evaluating Suppression Technologies

Jim Francfort

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Idaho National Laboratory

Presentation 1. INL Experience With Vehicle Thermal Events

INL Experience with "Thermal Anomalies"

- **AVTA test vehicles have included preproduction vehicles from OEMs, conversion company modified vehicles, and OEM production vehicles**
- **The AVTA has never experienced a thermal event with a production vehicle from an OEM**
- **AVTA's direct experience with vehicle thermal events includes**
  - **Passenger battery electric buses**
  - **Conversion company conversion of a HEV sedan to a PHEV**
  - **Conversion company conversion of a HEV SUV to a PHEV**
  - **Original equipment manufacturer (OEM) preproduction PHEV**

Grand Canyon National Park - Passenger Battery Electric Bus

- INL provided assistance investigating bus battery melting events at the Grand Canyon
- 3 packs per bus, 108 total NiCad modules per bus
- Approximately 60 modules melted during 4 events
  - Minor module damage from battery arcing as a result of an inadequately tightened terminal
  - A battery module was installed incorrectly by the bus manufacturer, which was undertaken to repair event 1
  - Melting resulting from electrolyte tracking in the watering system
  - Melting due to defective construction resulting from arcing under load. Pack design issue
- Buses had “smoke” event each time with passengers onboard

Third Party Conversion of a HEV Sedan to a PHEV

- Conversion company used a Prius as the base vehicle and converted it into a PHEV-15 with a lithium ion mule battery

- Smoke filled the vehicle cabin while the vehicle was being driven
- Driver pulled over and noted fire in the right side of the rear cargo compartment. The vehicle was consumed (see pictures)
- Event occurred in a rural area and there was no fire suppression

- The conversion company did not follow the battery manufacturer's guidelines when designing and building their packs
- Likely cause was a loose high voltage connection within the battery enclosure, not a battery cell specific caused event
- At autopsy, high voltage was still present in the damaged battery
- Next pages show that the battery survived the event fairly well
- Note sandals and lack of personal protection equipment on conversation company staff

Third Party Conversion of a HEV Sedan to a PHEV

Third Party Conversion of a HEV Sedan to a PHEV

Third Party Conversion of a HEV SUV to a PHEV

- INL was benchmarking a conversion HEV SUV to a PHEV in Phoenix
- Conversion company used a HEV SUV as the base vehicle and added their own 12 KWh lithium ion mule battery
- Vehicle was parked overnight in a fenced area. A security guard called the fire department when smoke was observed at approximately 2 a.m.
- Vehicle did not catch “fire” (insert offline comment here) but suffered extensive heat and smoke damage
- It is believed high voltage was still present in the damaged battery when the Phoenix fire department forcibly removed part of the pack and applied water to the pack and vehicle
- Cause was over-charge events, caused by onboard battery charger or BMS failure – per review of data logger data indicating a 15 kWh charge occurred pre event. Cells significantly overheated
- Partial pack removal stopped overcharging and internal shorting, while water cooled the pack
- Bottom right (next page) is the same converter’s PHEV at a student competition

Third Party Conversion of a HEV SUV to a PHEV

Third Party Conversion of a HEV SUV to a PHEV

OEM Preproduction PHEV @ INL

- **The AVTA was benchmarking the performance, use and charging profiles of 110 OEM preproduction PHEV that used a 12 KWh lithium ion battery**
- **This included one PHEV physically at INL**
- **During the INL event, it should be noted that a conscience decision was made to preserve the battery pack for autopsy if staff safety was not jeopardized**
- **Immediately stopping the thermal event by disassembling the pack across the parking lot was <u>NOT</u> the preferred course of action**
- **A total of three events occurred with this prototype PHEV, with the first event occurring at INL**

OEM Preproduction PHEV @ INL

- **The 12 KWh lithium ion traction battery was installed under the back seat of the crew cab pickup**

Preproduction PHEV @ INL: Day One

- During a short drive, the PHEV shutdown twice
- After 30 seconds of key cycling, the vehicle restarted. Returned to outside INL parking lot and connected to EVSE
  - Manufacturer called and directed INL to disconnect from the EVSE
  - While discounting the vehicle from the EVSE, smoke was observed coming from the closed cabin
  - Smoke source was the PHEV pack
  - The Idaho Falls fire department disconnected the 12 Volt battery, removed the PHEV battery lid, and 1,250 gallons of water was applied over two hours
  - When water was interrupted, smoke would reappear
  - After the two hours, the fire department left and a garden hose was used to continue the water stream into the PHEV battery with the lid off
  - Three times over six hours, the water was turned off and smoke resumed. It was decided to leave the water running into the pack all night (at sub-freezing temperatures)

Preproduction PHEV @ INL: Day Two

- **During the second day, a series of water removal, pack warming, and smoke coming from the pack**
  - **In the afternoon, the vehicle and battery manufacturers arrived**
  - **Water was removed and again the pack heated and smoke reappeared**
  - **Using a thermal imager, with the water removed, pack temperatures were:**
    - **8 a.m. -1C**
    - **8:15 a.m. 15C**
    - **10 a.m. 40C**
  - **With a daytime high temperature below freezing, with full electrical safety gear, highly trained INL battery technicians measured the voltage across each of the four damaged modules: 0.9, 87.5, 3.1 and 14.3 V**
  - **It was agreed that the 87.5 V module had to be safely discharged before the vehicle could be safely shipped offsite**

Preproduction PHEV @ INL: Day Three

- Again with full electrical safety gear, a power resistor bank was used to discharge the 87.5 V module for about 2.5 hours
  - The modules voltages were then 0.0, 9.0, 0.8 and 8.99 V
  - While the pack was believed to be stable, running water was placed on the back overnight
- After removing the water the morning of the fourth day, the pack was stable, no temperature rise, and no smoke present
  - Vehicle was shipped off site for autopsy with vermiculite on top of the pack as a further safety step
- INL's and two additional events with same PHEV model were likely caused by pack design and wiring decisions, not actual cell problems
  - INL event: Not properly insulating wires used for diagnostics after the wires where cut before installing the packs into the vehicles
  - Second event: High and low voltage wires rubbing together in same wiring bundle during vehicle operations induced vibration. High voltage flowed into low voltage pack diagnostics and cells
  - Third event: cause not identified

PEV Thermal Events Lessons Learned

- Battery thermal events have been suppressed or “finished” by:
  - Disassembling the pack and applying water to the cool the pack to avoid in-pack and in-vehicle combustible materials from burning
  - Allowing the event to continue unsuppressed and ensuring personnel and facility safety. Will ultimately result in all combustible materials burned and PEV likely destroyed
  - Stop active event with water and move vehicle to secure area away from structures and other vehicles
    - Using trained electrical safety worker to discharge the pack while applying cooling water to stop combustible materials from burning
      - However, this should only be undertaken by electric safety trained workers with large battery pack safety and equipment experience
      - May take hours or days when the vehicle may or may not be in an unsafe location

Presentation 2. Intentional R&D: Evaluating Suppression Technologies

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

- **The need for first responder training was recognized based on field experiences**
- **Partners:**
  - **Alliance of Automobile Manufactures**
  - **U.S. Department of Energy**
  - **U.S. Department of Transportation (National Highway Traffic Safety Administration)**
  - **National Fire Protection Association**
  - **National Fire Protection Research Foundation**
  - **Idaho National Laboratory**
  - **Maryland Fire Research Institute**
  - **Exponent, Inc.**
  - **Emergency Responder Advisory Panel and Battery Technology Advisory Panel**
  - **Southwest Research Institute**

NFPA Project - Goal

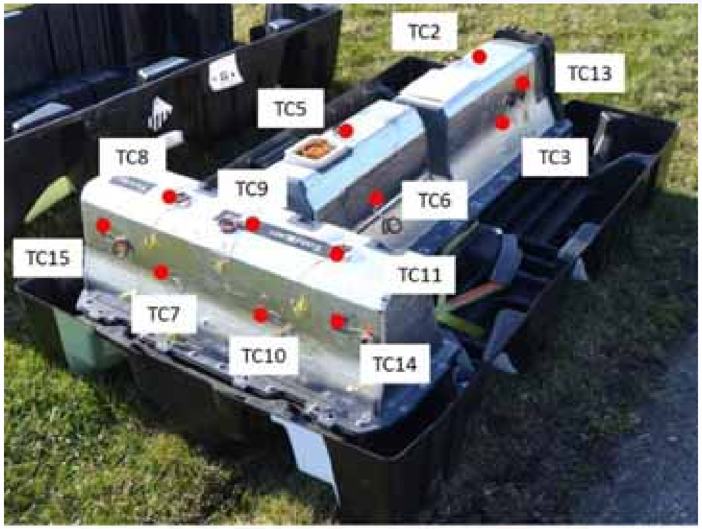
- Identify full-scale heat release rate (HRR) and fire suppression testing of PEV large format Li-ion batteries
- In particular, members of the emergency response community had questions regarding
  - Appropriate PPE (personal protection equipment) to be used for responding to fires involving PEV batteries
  - Tactics for suppression of fires involving PEV batteries
  - Best practices for tactics and PPE to be used during overhaul and post-fire clean-up operations

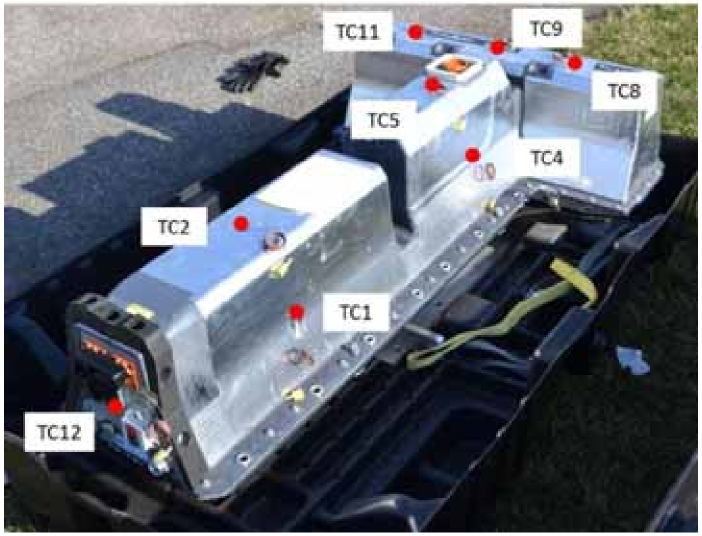
- One, laboratory test was conducted to determine HRR
- Six, full-scale fire suppression tests were conducted to collect data and evaluate any differences associated with PEV fires as compared to traditional internal combustion engine (ICE) vehicle fires
  - Battery “A”, 4.4 kWh lithium ion battery pack
  - Battery “B”, 16 kWh lithium ion battery pack

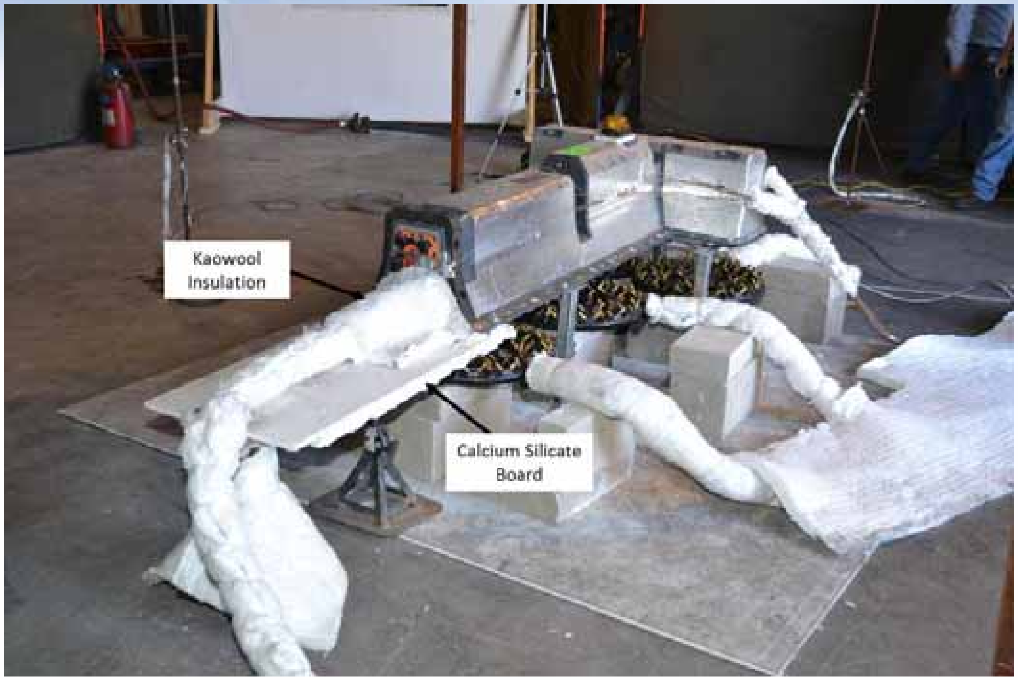
NFPA Laboratory HRR Test

- Objective: determine the amount of energy released from the battery alone when it was ignited by an external ignition source
- 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
- Based on a review of NFPA data on vehicle fire risk
  - 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
  - Pool fire scenario under the PEV was selected as the likely ignition scenario where the batteries become near fully involved and "burning on their own"

NFPA HRR Test







NFPA HRR Test

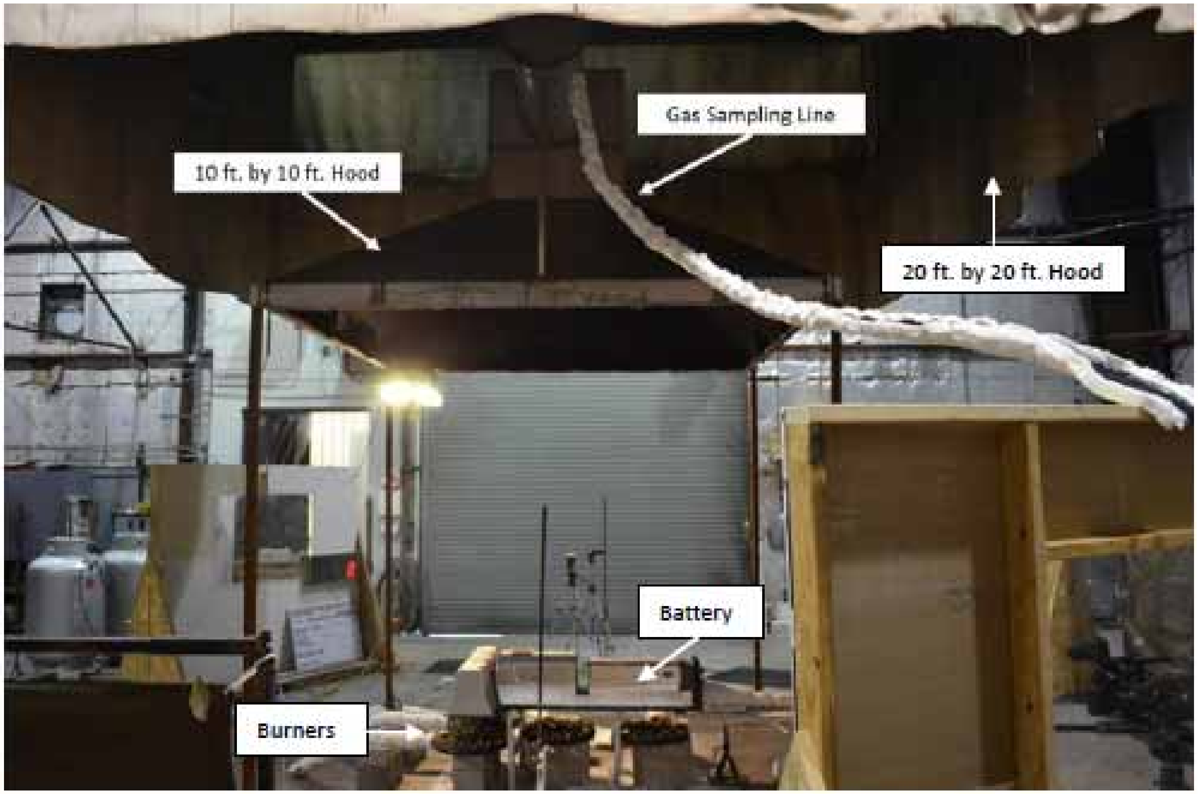


Figure 17 SwRI hood and test arrangement

NFPA HRR Test

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

NFPA HRR Test

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

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

HRR Test Summary

Idaho National Laboratory

HRR	Value	Time
Maximum	698 kW	0:17:33
Average	128 kW	---
Total Heat Released	729 MJ	---

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

NFPA Fire-Mule Suppression

- **Three tests Battery A and three tests Battery B**
- **Two tests each battery with just battery in fire mule vehicle**
- **One test each battery with typical interior finishes/upholstery**

NFPA Suppression "A" With Typical Interior Finishes/Upholstery/Airbags

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

NFPA Suppression "A"

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

NFPA Suppression "A"

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

NFPA Suppression “A”

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 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

NFPA Suppression

NFPA Suppression

NFPA Suppression

NFPA Suppression – Off Gassing 22 Hours Later

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

- **At the conclusion of testing, an OEM's procedures for soaking PEV batteries in a salt bath were followed before shipping the six damaged battery packs. This method requires a minimum of 24 hours of submission**

NFPA Suppression Summary

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

NFPA - Best Practices

- An example of key findings includes questions and answers such as below
- 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

NFPA - Best Practices cont'd

- A small sample of additional findings are listed below
  - Use standard vehicle firefighting equipment and tactics in accordance with department SOPs/SOGs
  - All personnel should wear and utilize full PPE and SCBA as required at all vehicle fires
  - Use water or other standard agents for vehicle fires
  - The use of water does not present an electrical hazard to firefighting personnel
  - If a PEV battery catches fire, it will require a large, sustained volume of water
    - Battery A required 275 to 1,060 gallons
    - Battery B required 1,165 to 2,639 gallons
  - If a Lithium Ion (Li-Ion) HV battery is involved in a fire, there is a high 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

Report

- **NFPA Final Report and Appendices**
  - **http://avt.inel.gov/energystoragetesting.shtml**

- **NFPA Final Report**
  - **http://avt.inel.gov/pdf/energystorage/FinalReportNFPA.pdf**
- **NFPA Appendix A**
  - **http://avt.inel.gov/pdf/energystorage/AppendixBthruE1NFPA.pdf**
- **NFPA Appendix B**
  - **http://avt.inel.gov/pdf/energystorage/AppendixBthruE1NFPA.pdf**