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

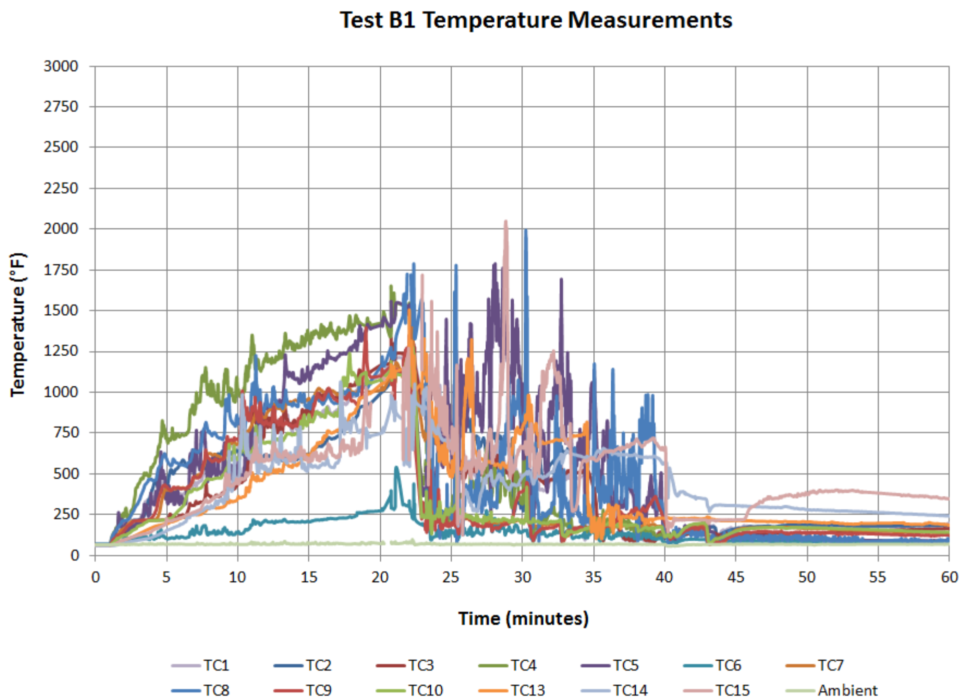

Figure 76 Test B1 TC plot

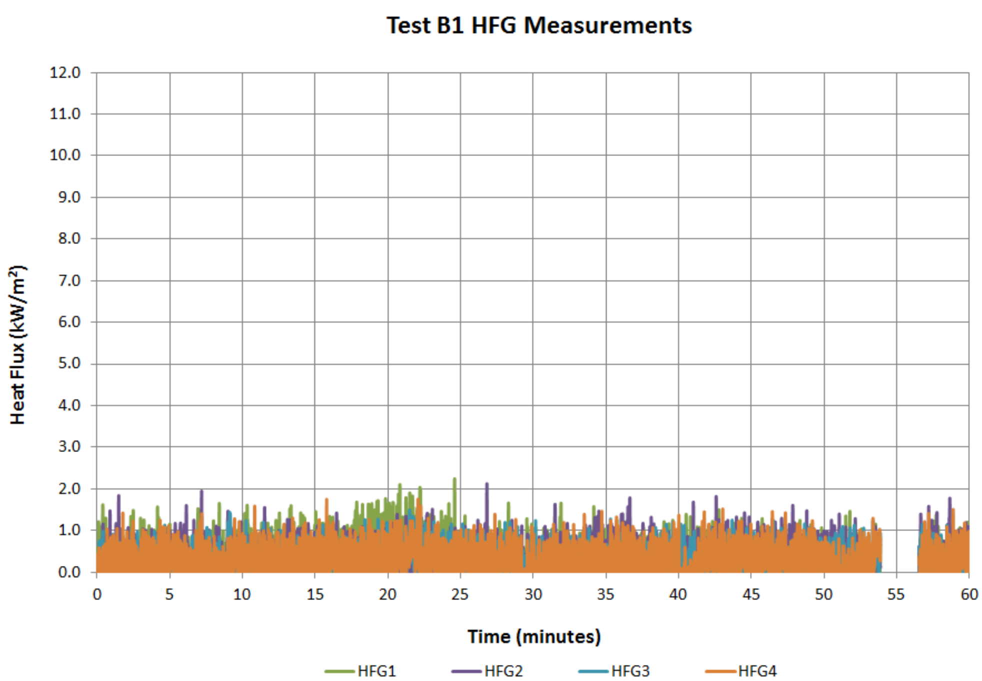

Figure 77 Test B1 HFG plot[64]

[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.

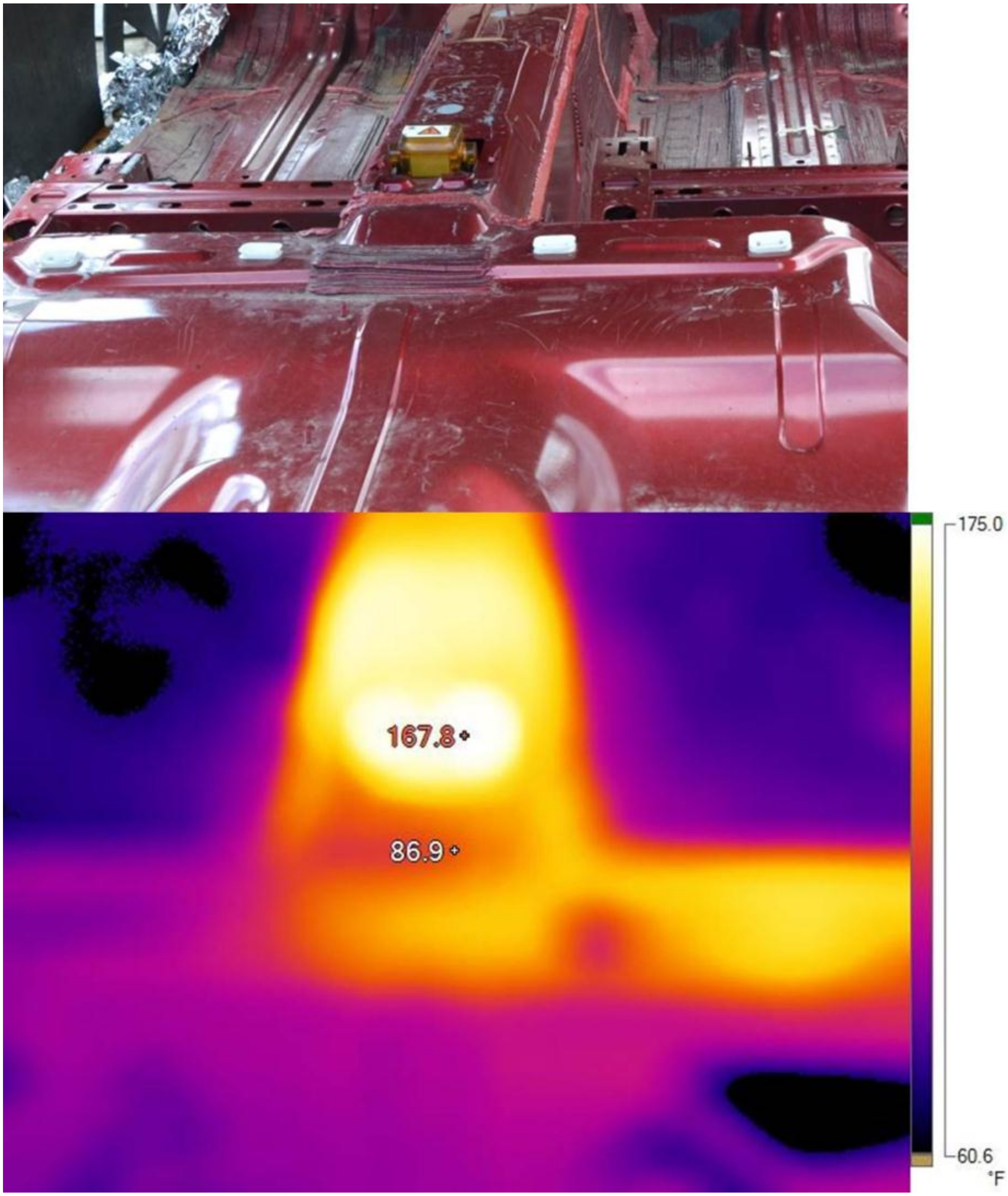

Figure 78 Floor pan assembly from rear of VFT (top); thermal image (same view) of Battery B1 at 60 minutes (bottom)

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

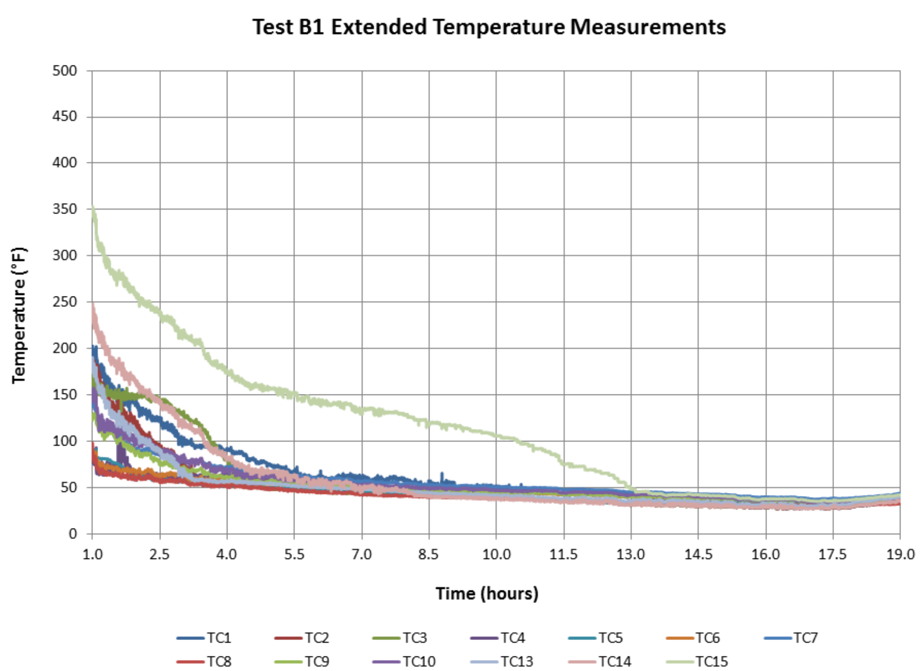

Figure 79 Extended temperature measurements for Test B1

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.

[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

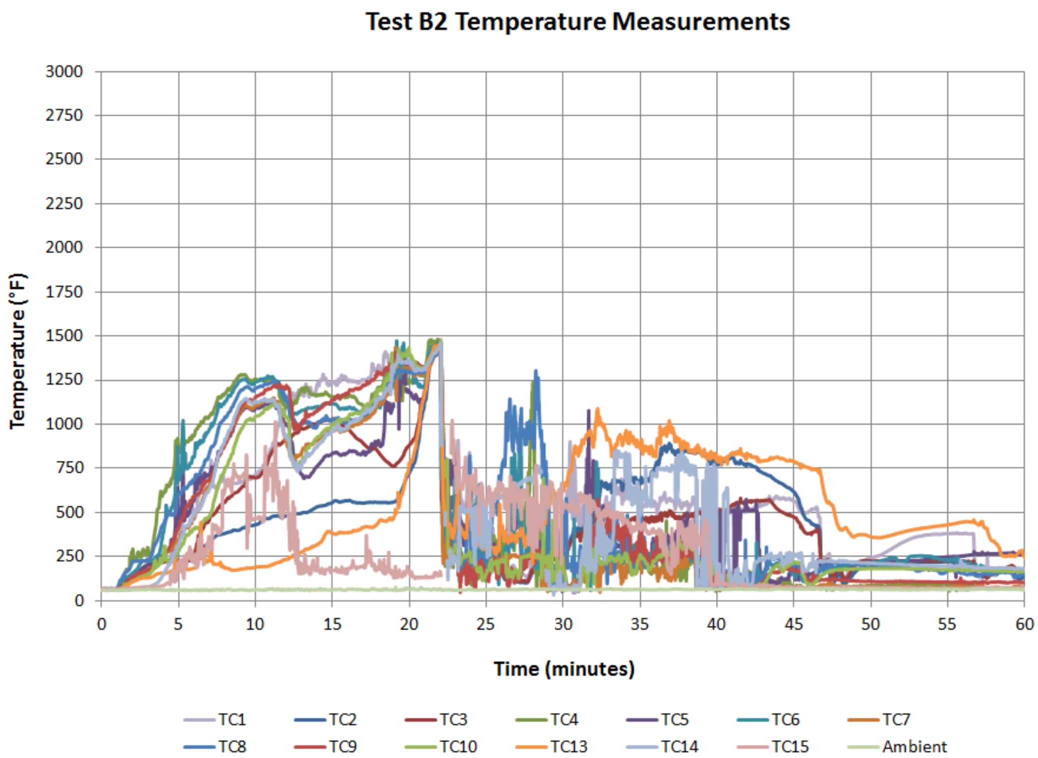

Figure 82 Test B2 TC plot

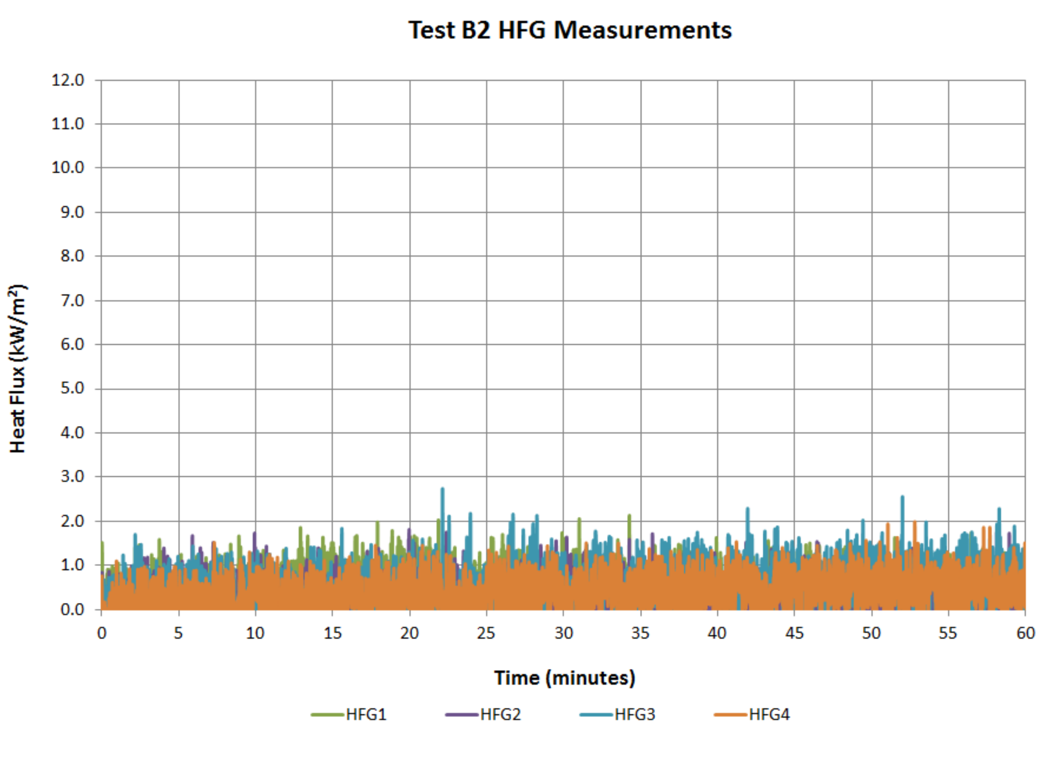

Figure 83 Test B2 HFG plot

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.

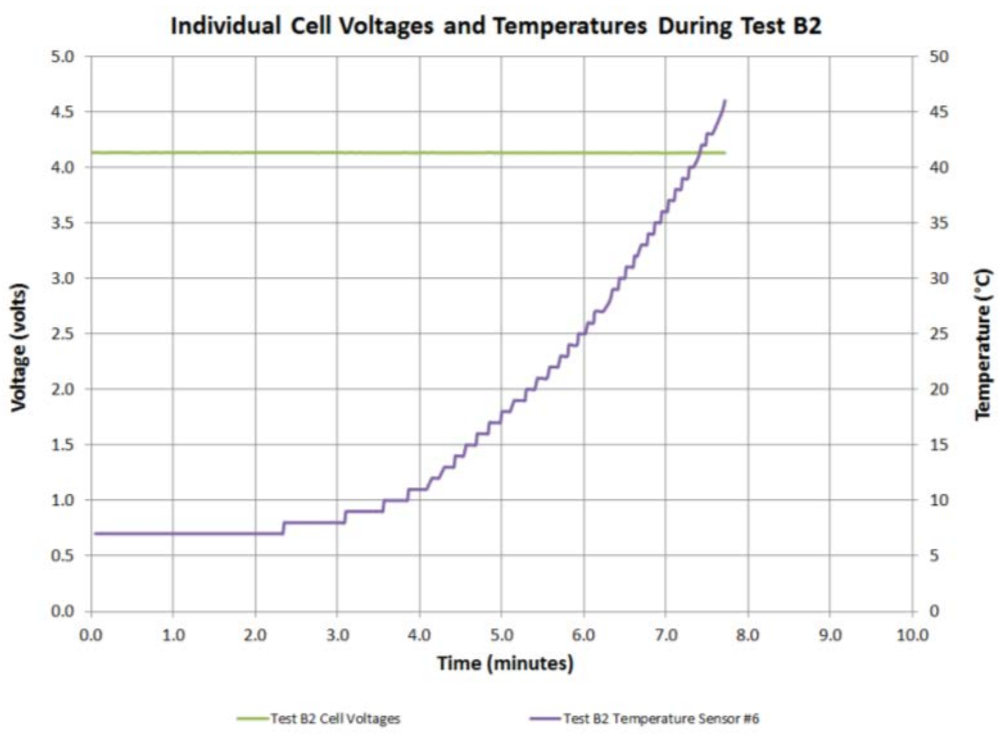

Figure 84 Internal cell voltages and temperatures during Test B2

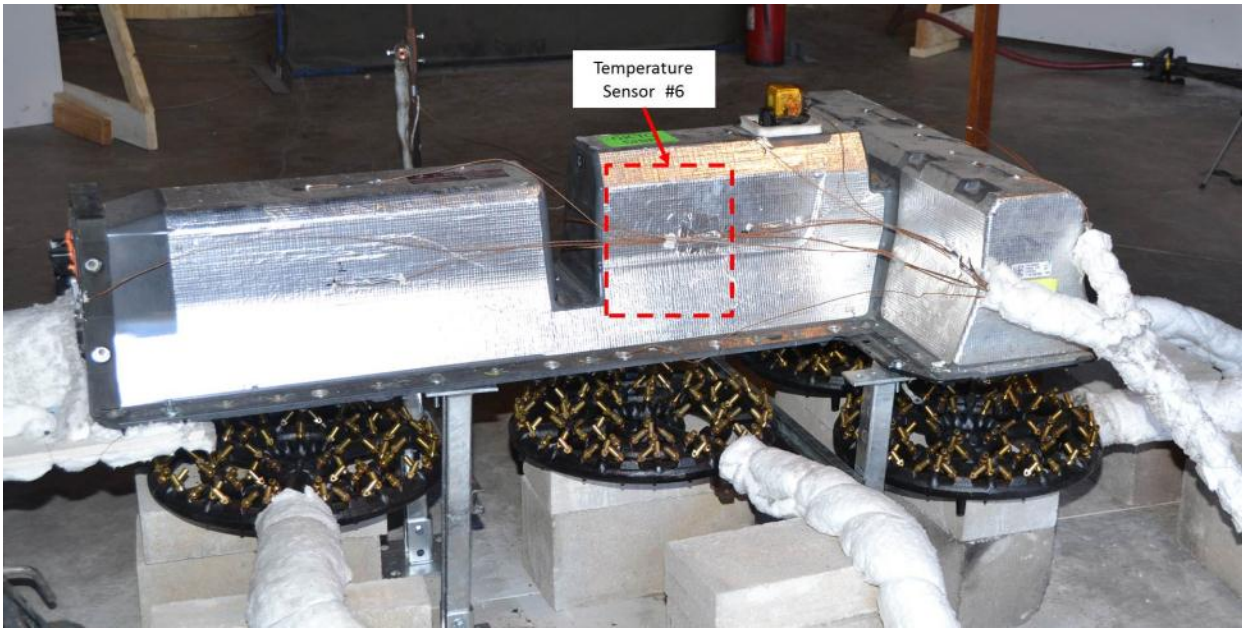

Figure 85 Location of temperature Sensor #6 within Battery B2

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.

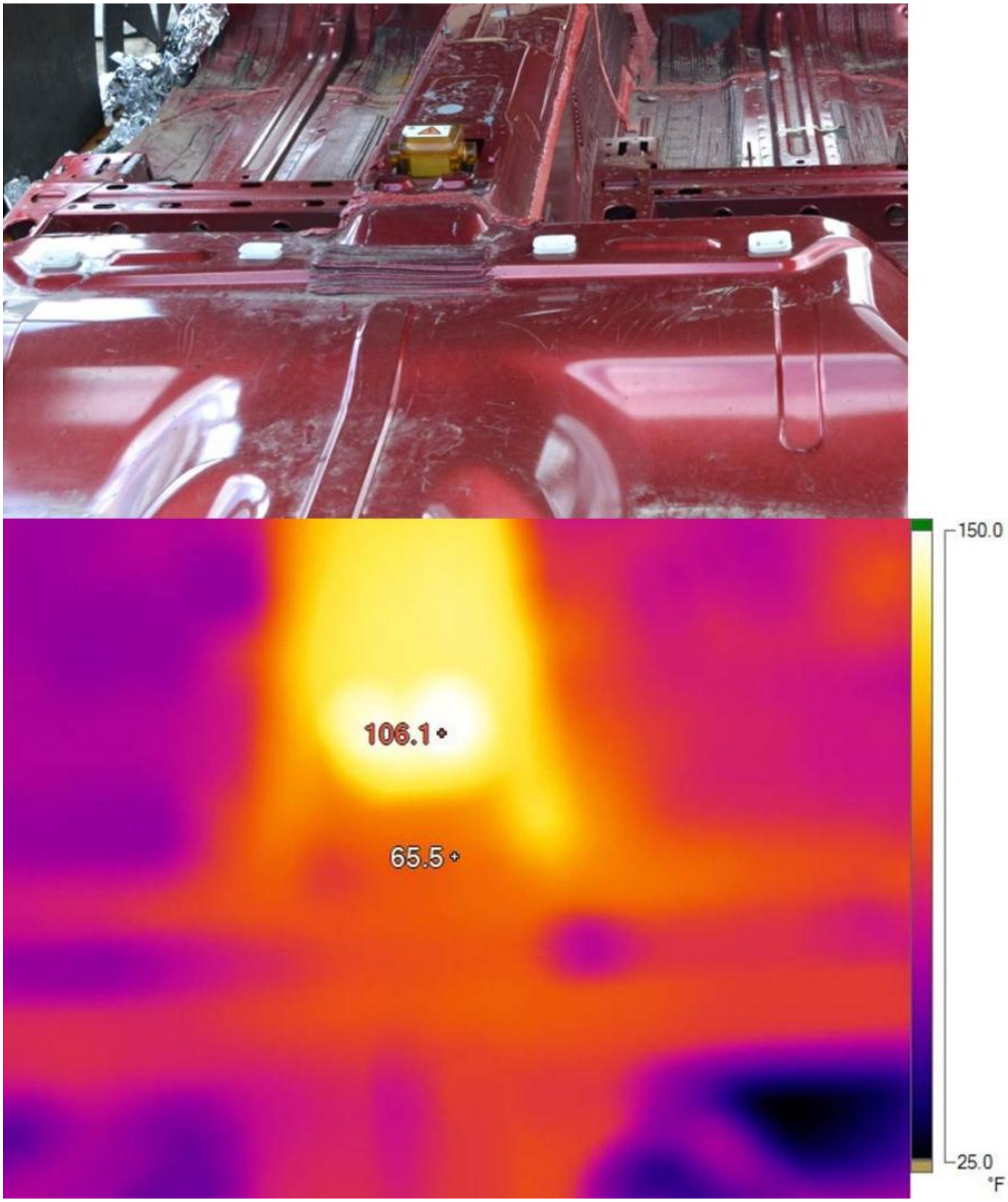

Figure 86 Floor pan assembly from rear of VFT (top); thermal image (same view) of Battery B2 at 75 minutes (bottom)

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

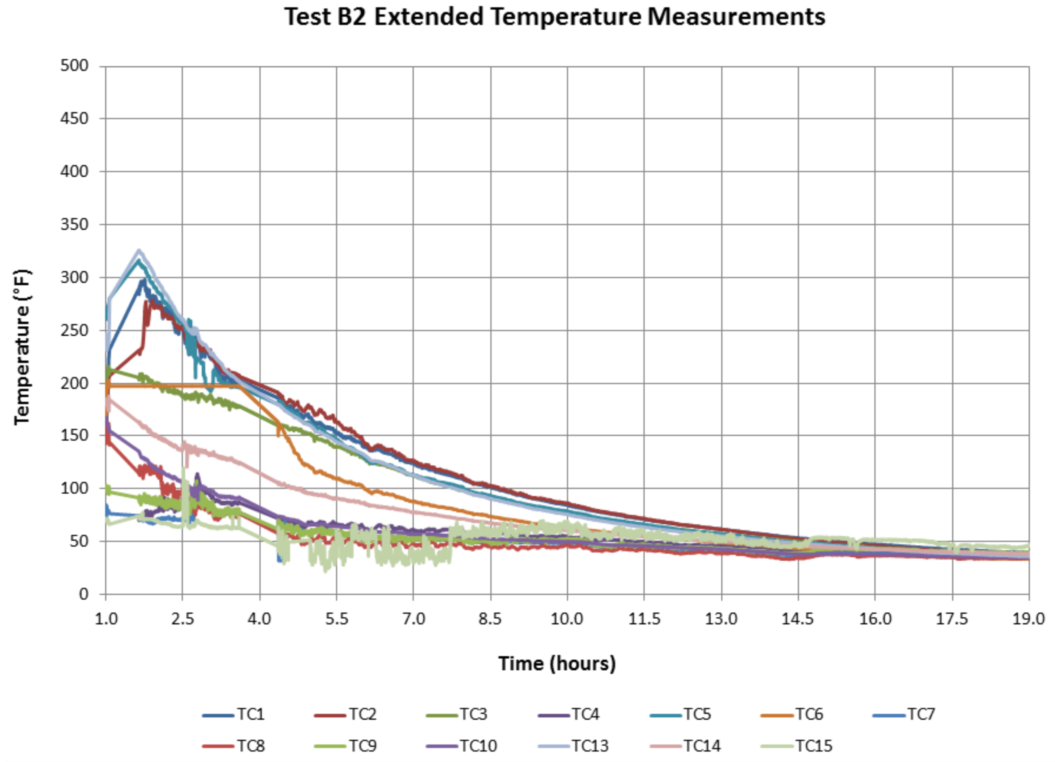

Figure 87 Extended temperature measurements for Test B2

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)

1205174.000 F0F0 0613 RTL3

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

[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

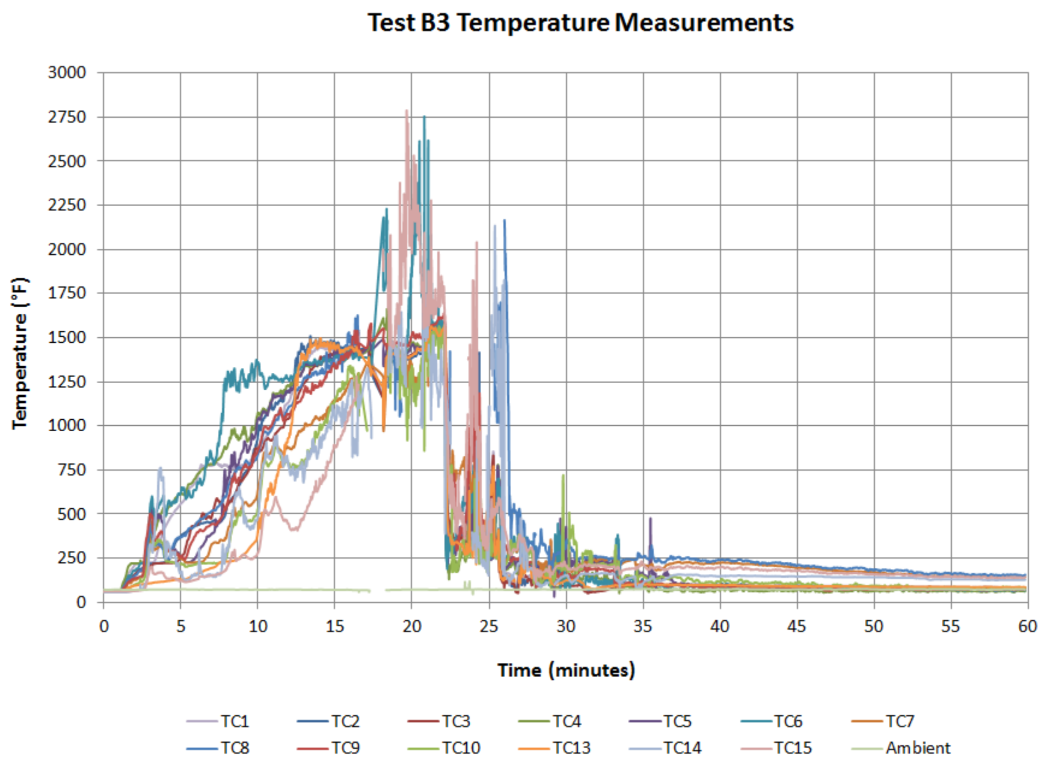

Figure 90 Test B3 TC plot

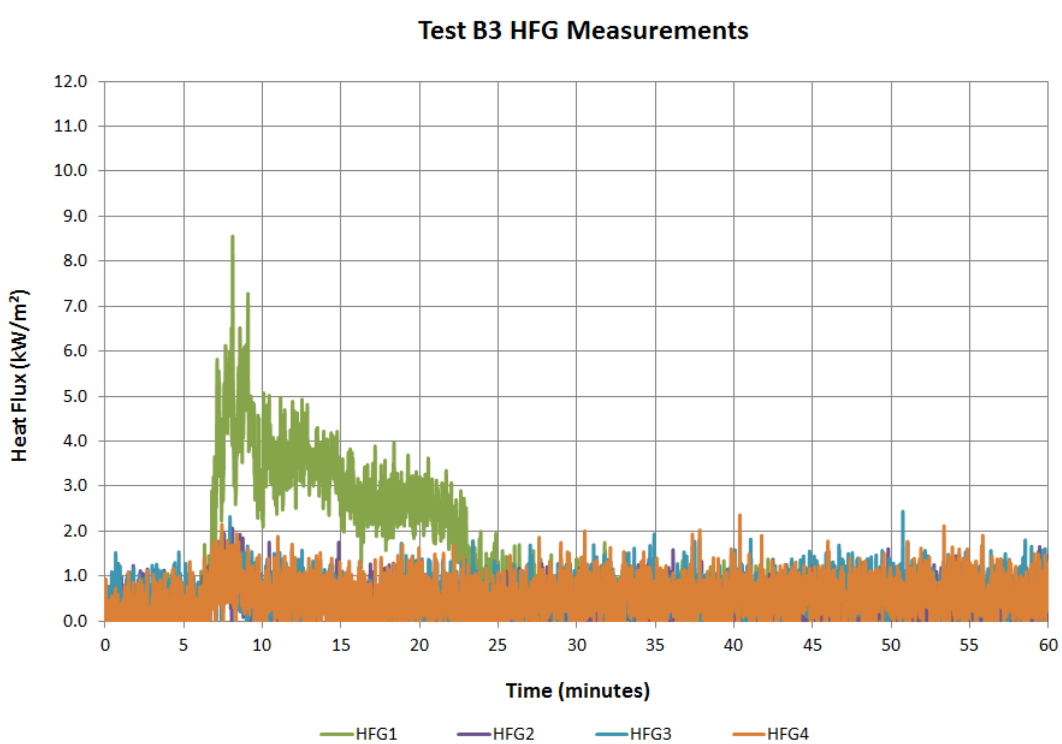

Figure 91 Test B3 HFG plot

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.

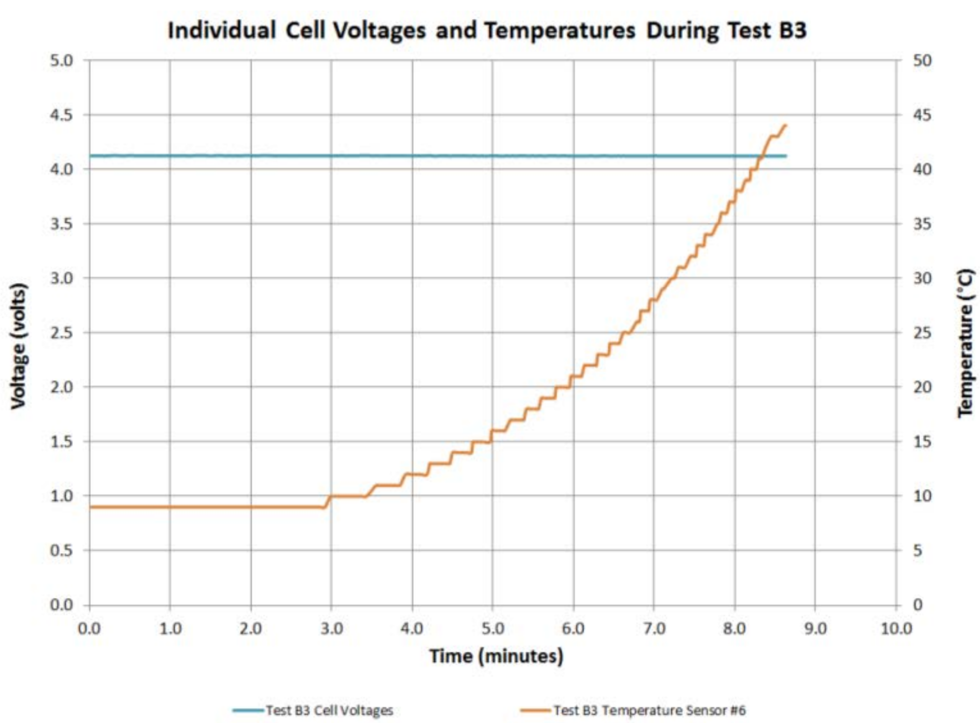

Figure 92 Internal cell voltages and temperatures during Test B3

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.

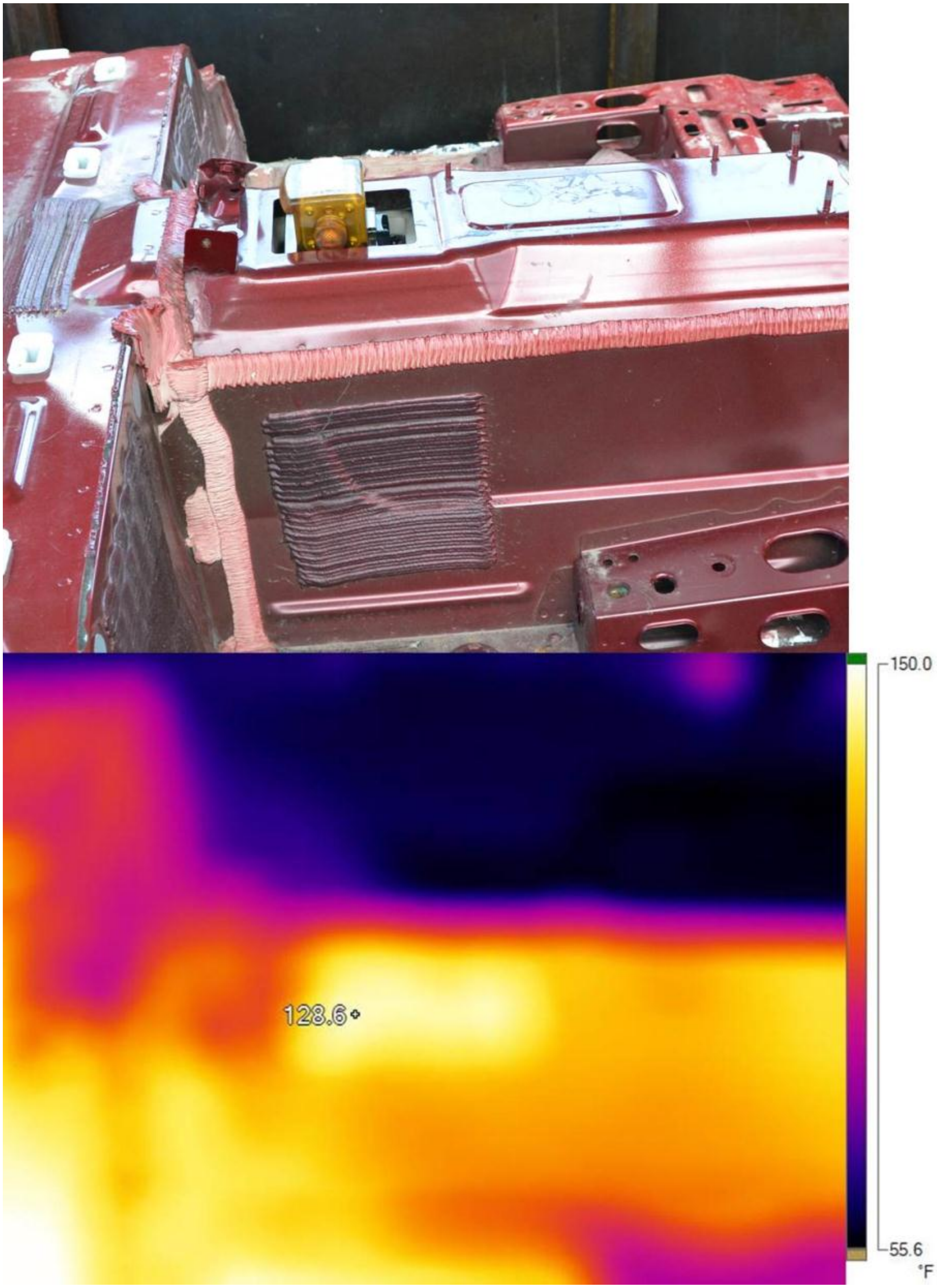

Figure 93 Floor pan assembly from side of VFT (top); thermal image (same view) of Battery B3 at 60 minutes (bottom)

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

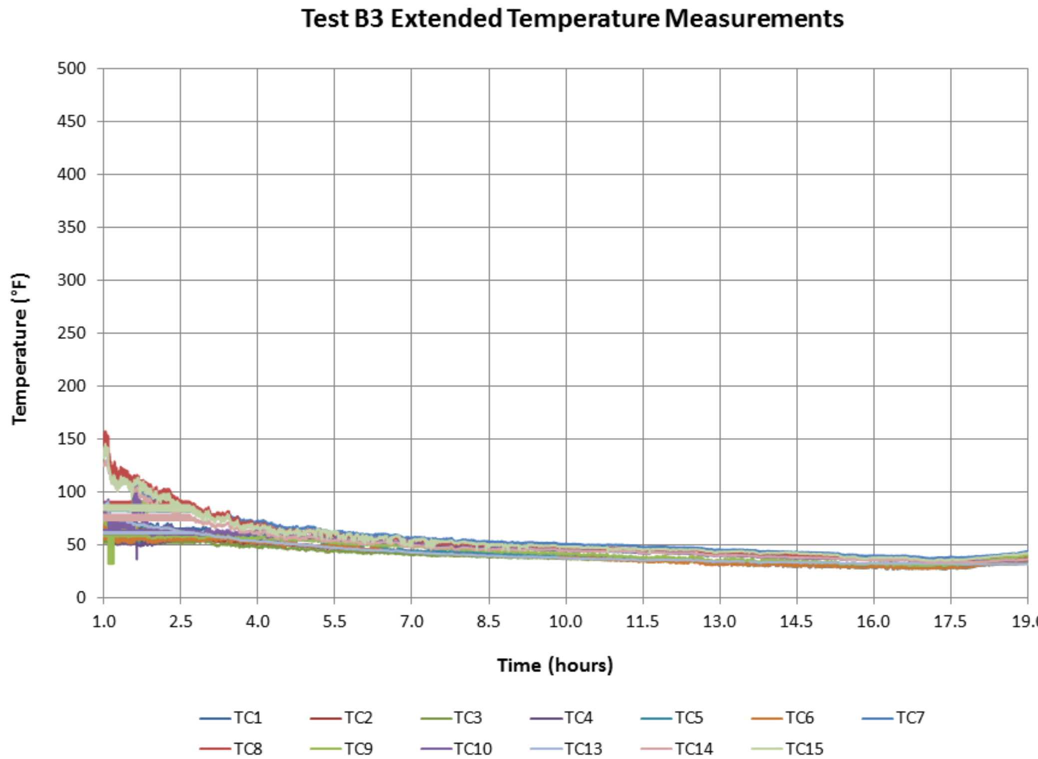

Figure 94 Extended temperature measurements for Test B3

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.

[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.

[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

[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