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

5.3 Full-scale Fire Protocols

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

5.3.1 HRR Testing

The test protocol for the HRR test was as follows:

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

    d. Internal battery sensor measurements.

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

5.3.2 Suppression Testing

The test protocol for the suppression tests was as follows:

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

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

6 Test Results

6.1 HRR Testing

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

6.1.1 Battery B

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

6.1.1.1 Test Observations

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

Table 6 Summary of Key Observations from the HRR Test

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

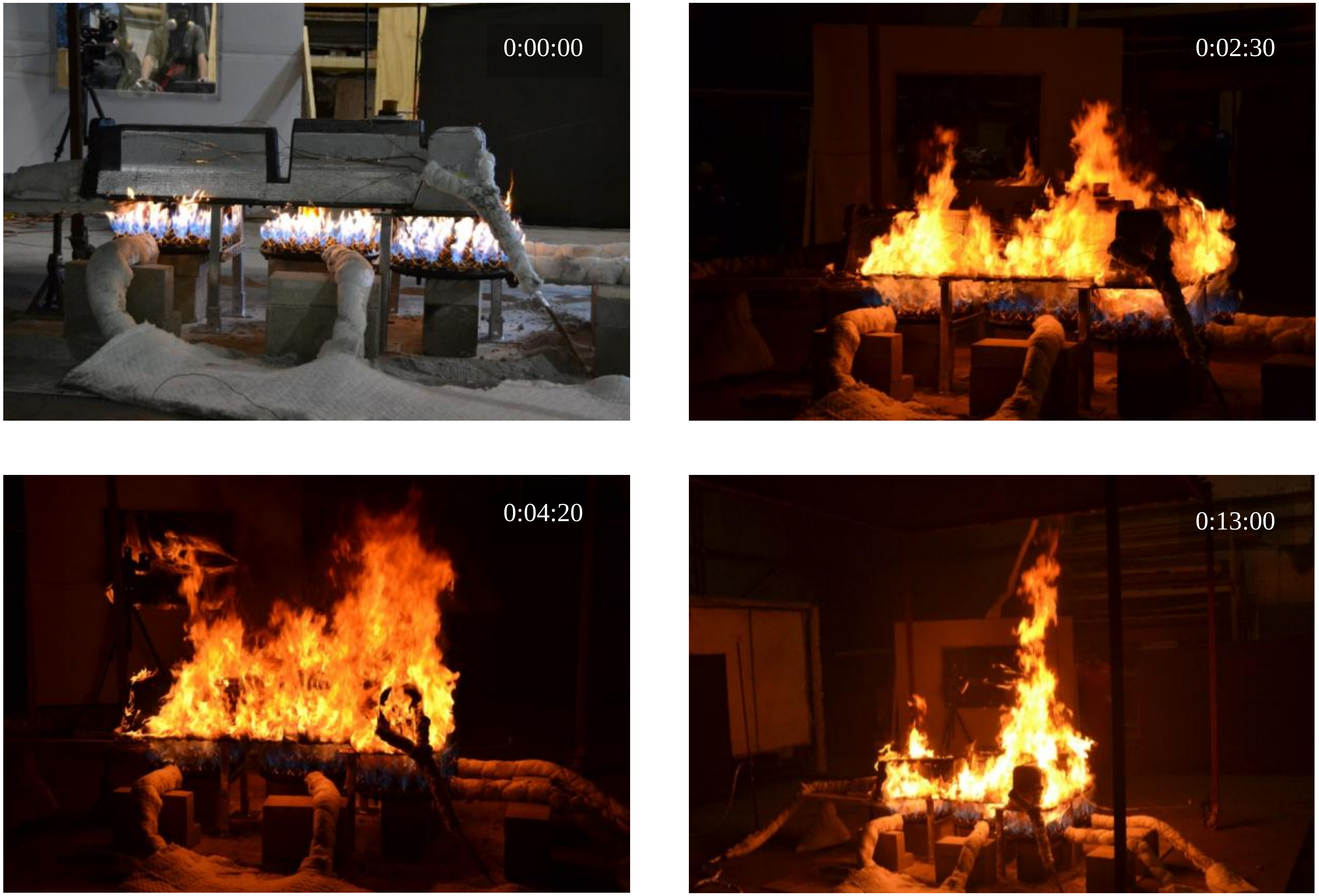

Figure 50 0 minutes (top left), 2:30 minutes (top right), 4:20 minutes (bottom left), 13 minutes (bottom right)

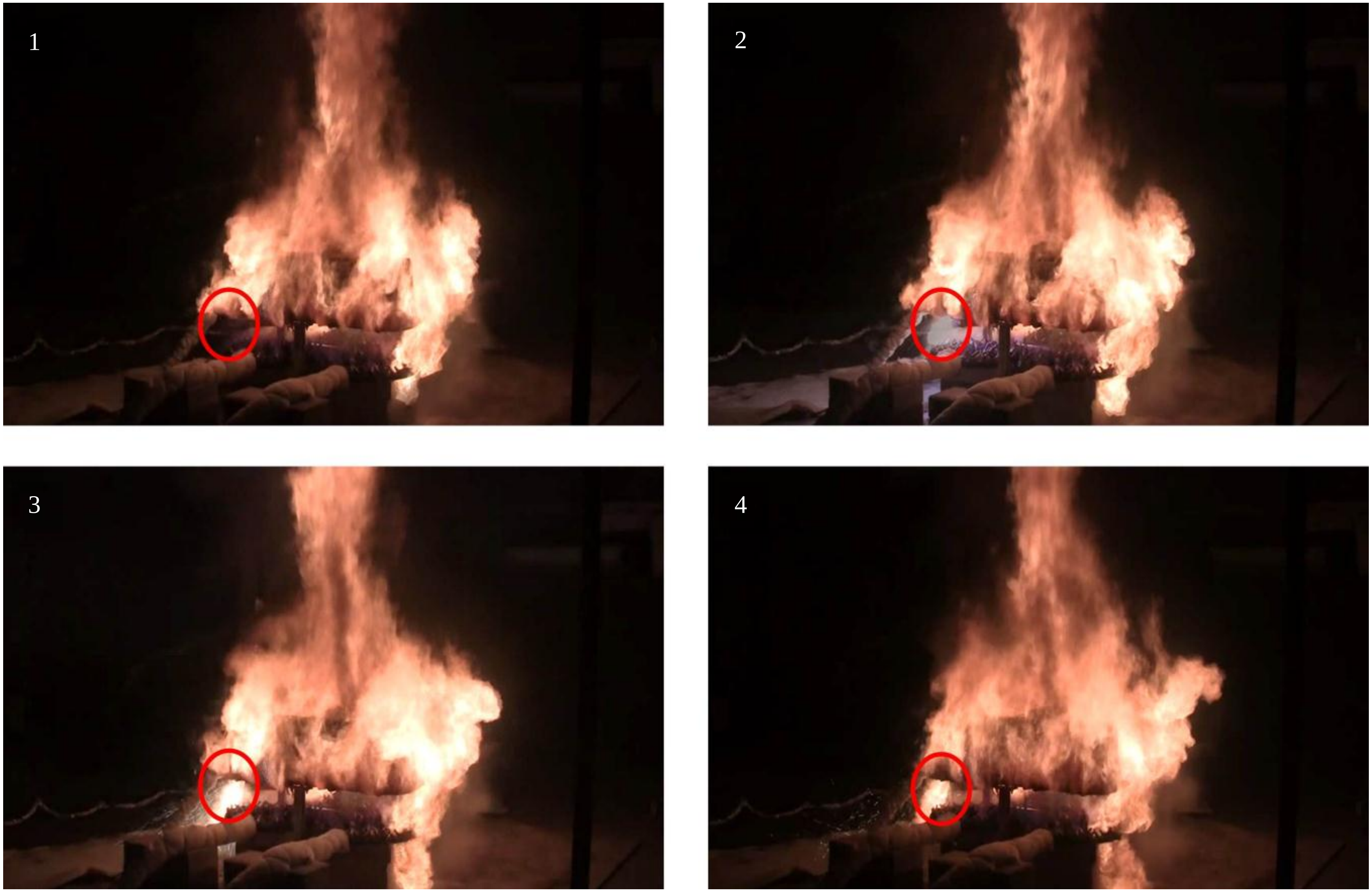

Figure 51 14:50 minutes: A large stream of sparks shoot out from the bottom of the NW end of the battery from its interior

1205174.000 F0F0 0613 RTL3

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

6.1.1.2 HRR Measurements

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

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

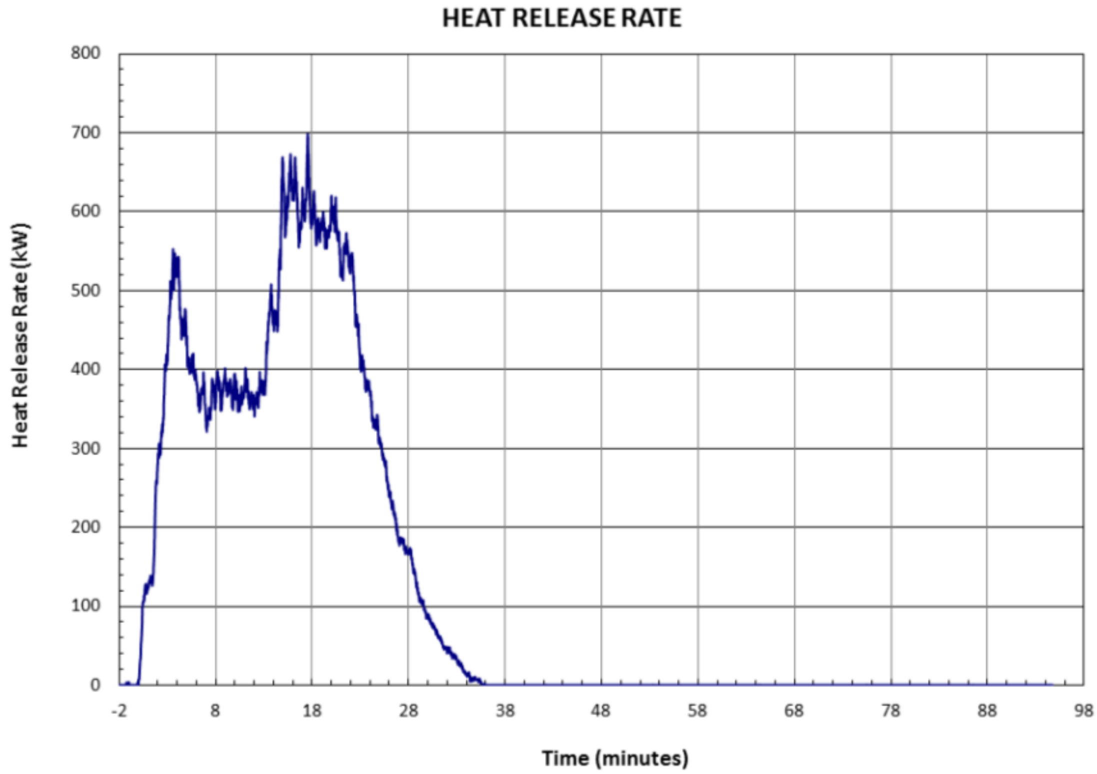

Figure 53 HRR as a function of time

Table 7 Summary of HRR Measurements

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

6.1.1.3 Temperatures and Heat Flux Measurements

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

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

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

Table 8 Summary of Maximum Temperature Measurements

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

Table 9 Summary of Maximum Heat Flux Measurements

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

6.1.1.4 Internal Battery Sensor Measurements

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

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

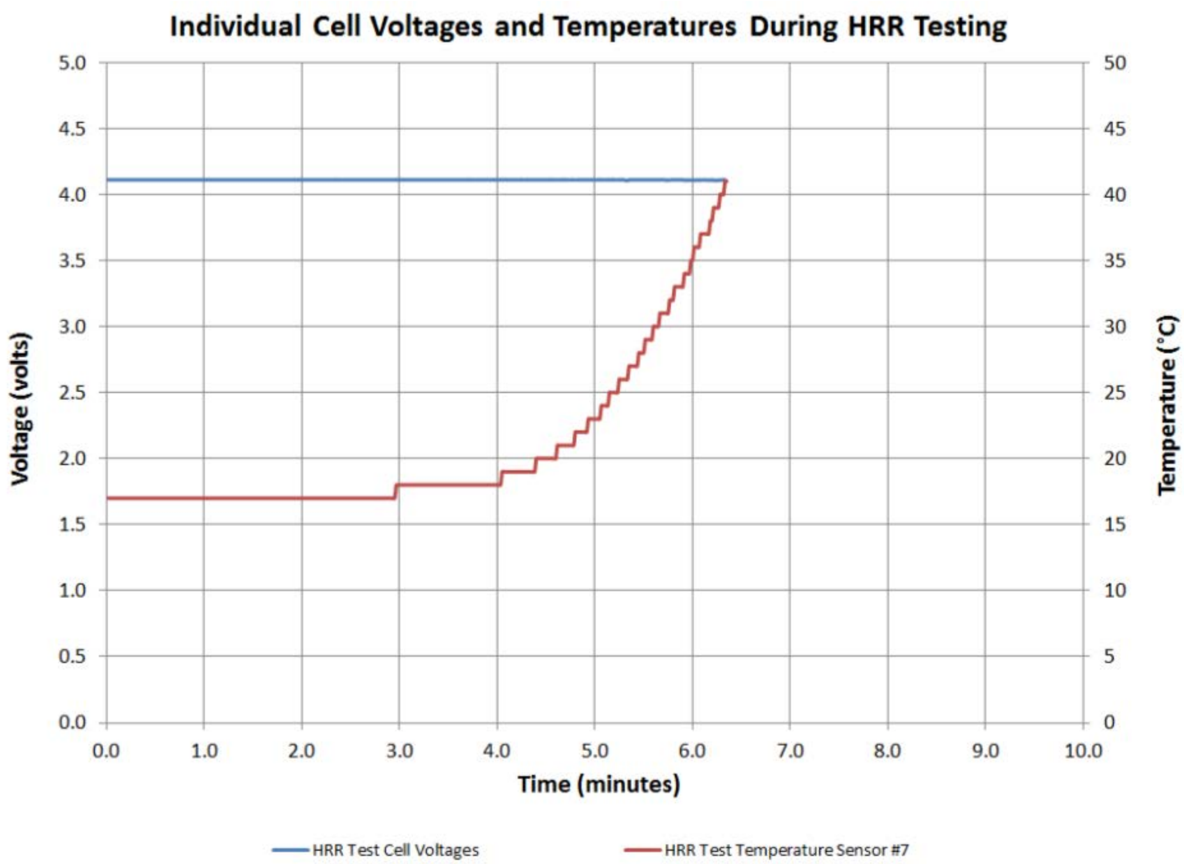

Figure 54 Internal cell voltages and temperatures (Sensor #7) during HRR Testing

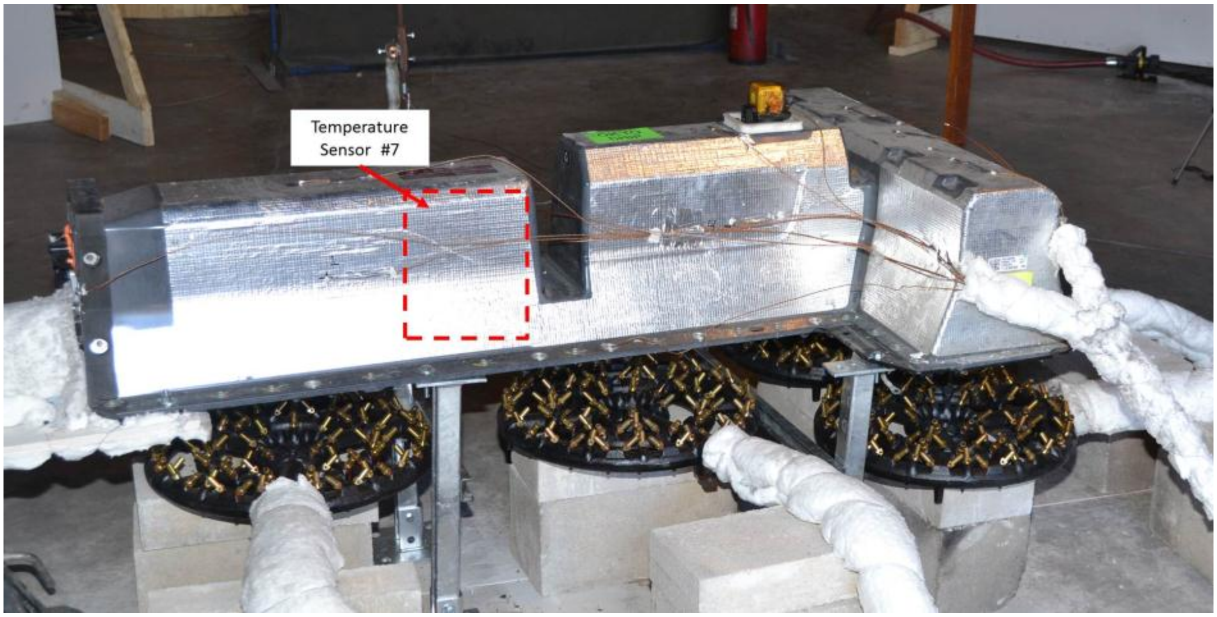

Figure 55 Location of Temperature Sensor #7 within Battery B

6.1.1.5 Gas Sampling Results

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

6.1.1.6 Overhaul Results

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

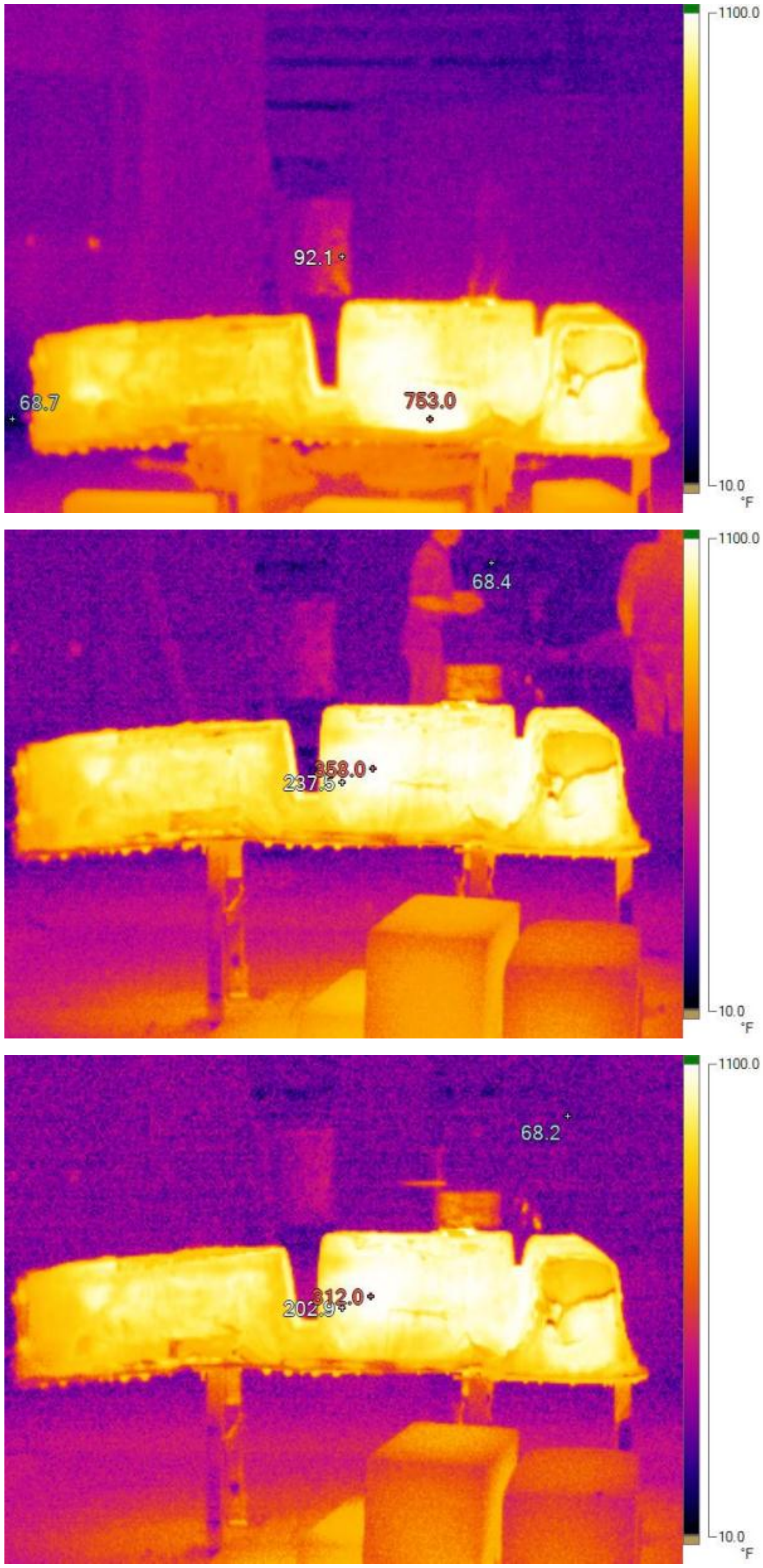

Figure 56 Thermal image 0 hours (top); 2 hours (middle); and 3 hours (bottom) after visible flaming ceased

6.2 Suppression Testing

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

6.2.1 Battery A1 Test

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

6.2.1.1 Test Observations

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

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

Table 10 Test A1 Key Observations

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

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

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

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

6.2.1.2 Water Flow Measurements

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

Table 11 Test A1 Water Flow Times

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

6.2.1.3 Firefighter Tactics and Observations

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

6.2.1.4 Temperature and Heat Flux Measurements

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

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

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

Table 12 Summary of Test A1 Maximum Temperature Measurements

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

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

Table 13 Summary of Test A1 Maximum Heat Flux Measurements

Measurement	Heat Flux (kW/m²)	Time
HFG1 (5 feet)	3.5	0:01:37
HFG2 (15 feet)	2.6	0:03:57
HFG3 (20 feet)	2.0	0:04:17
HFG4 (25 feet)	1.6	0:02:40

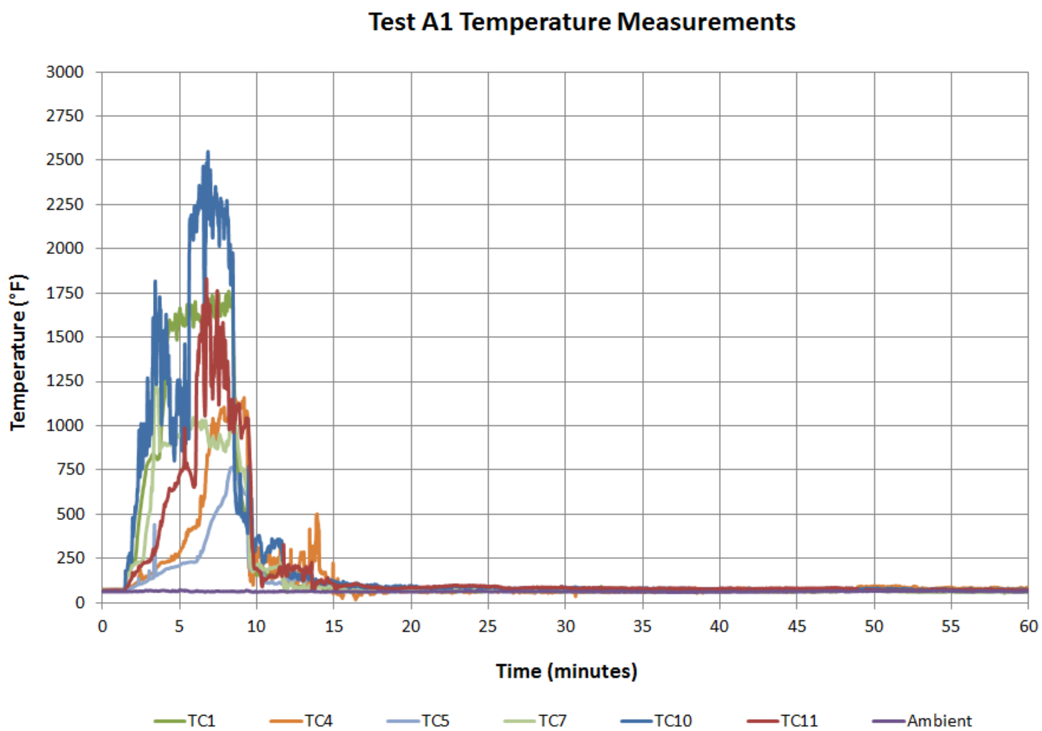

Figure 59 Test A1 TC plot

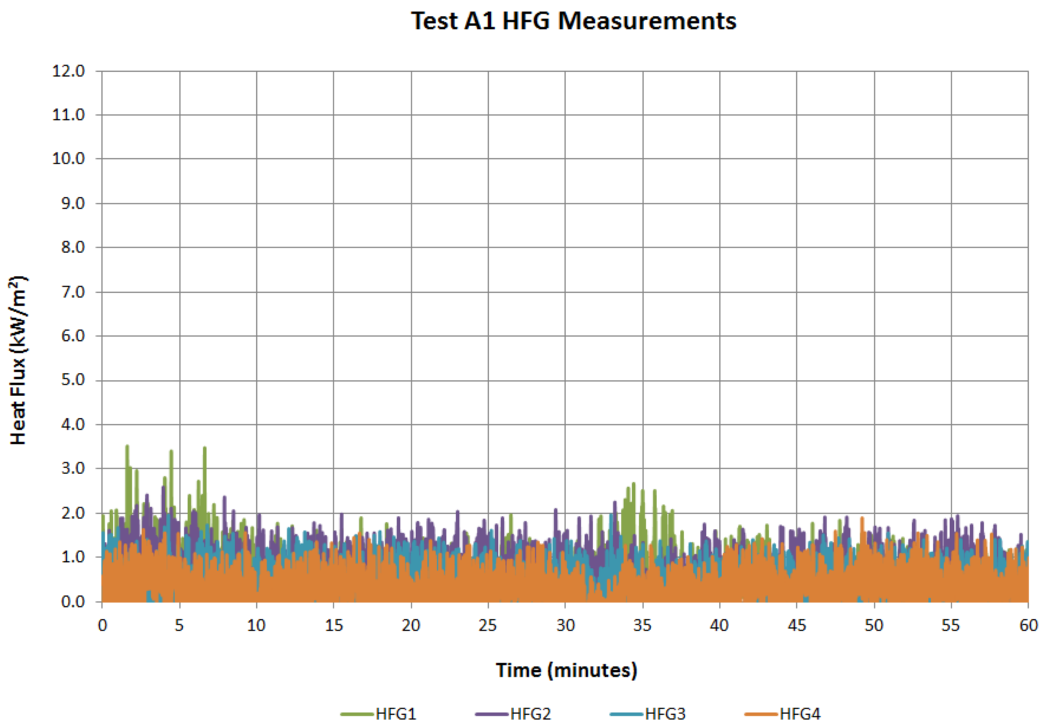

Figure 60 Test A1 HFG plot

6.2.1.5 Electrical Measurements

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

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

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

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

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

6.2.1.6 Overhaul Results

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

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

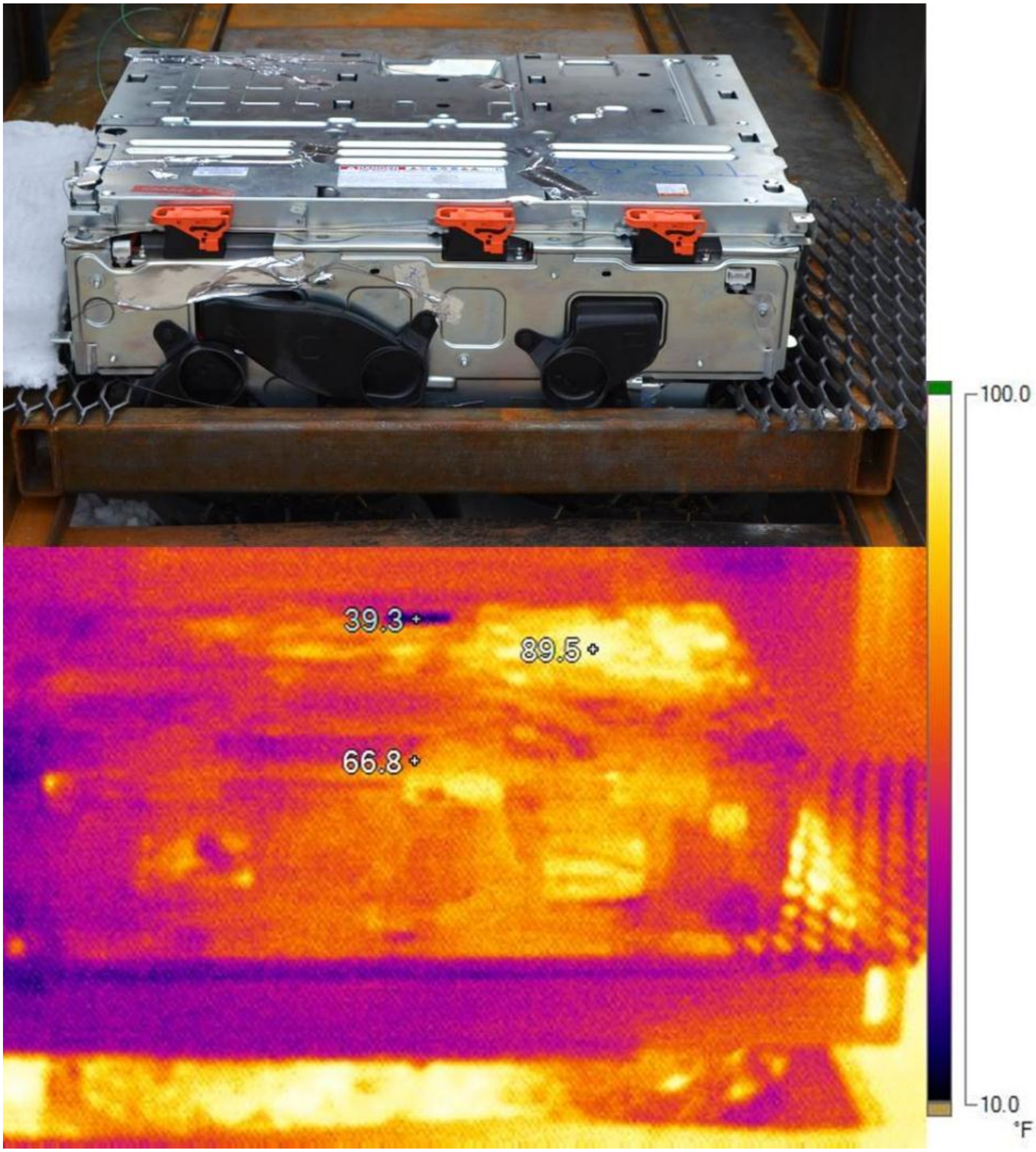

Figure 61 Battery A1 from rear of VFT (top); thermal image (same view) of Battery A1 at 25 minutes (bottom)

Table 15 Summary of Test A1 Temperature Measurements after 60 Minutes

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

6.2.1.7 Water Sampling Results

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

6.2.2 Battery A2 Test

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

6.2.2.1 Test Observations

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

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

Table 16 Test A2 Key Observations

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

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

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

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

6.2.2.2 Water Flow Measurements

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

Table 17 Test A2 Water Flow Times

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

6.2.2.3 Firefighter Tactics and Observations

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

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

6.2.2.4 Temperature and Heat Flux Measurements

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

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

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

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

Table 18 Summary of Test A2 Maximum Temperature Measurements

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

Table 19 Summary of Test A2 Maximum Heat Flux Measurements

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

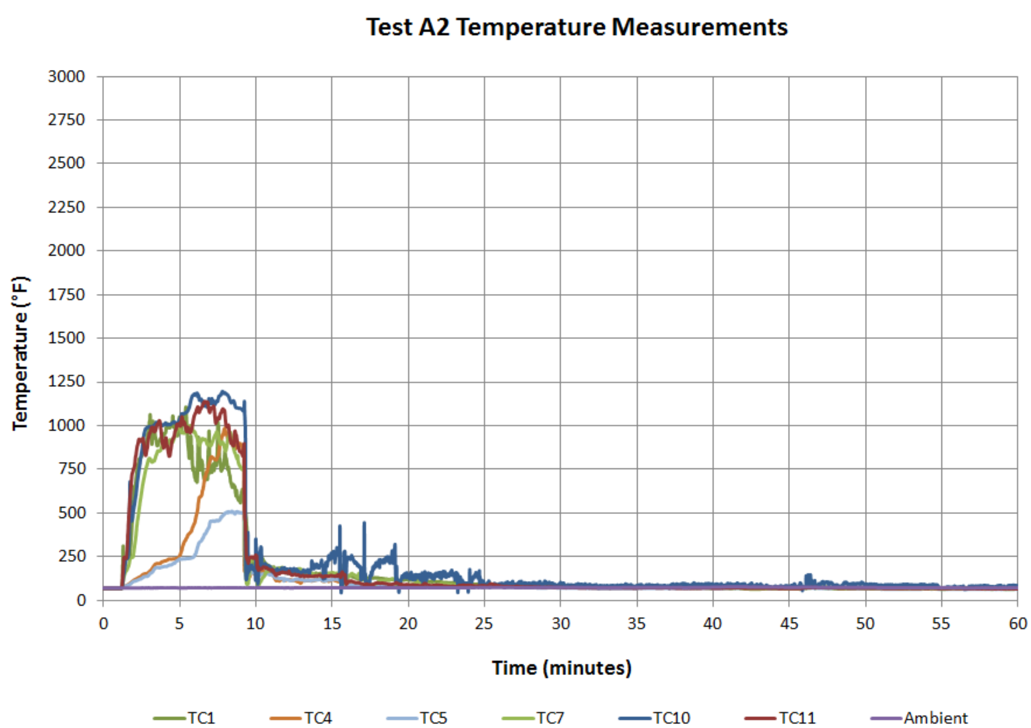

Figure 64 Test A2 TC plot

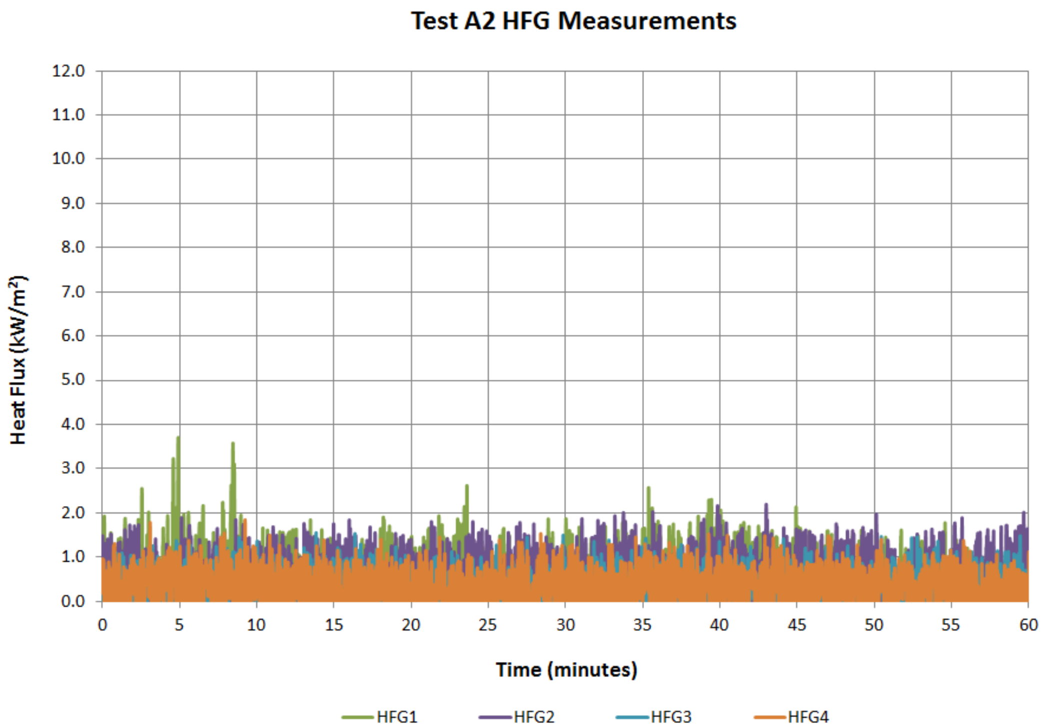

Figure 65 Test A2 HFG plot

6.2.2.5 Electrical Measurements

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

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

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

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

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

6.2.2.6 Overhaul Results

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

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

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

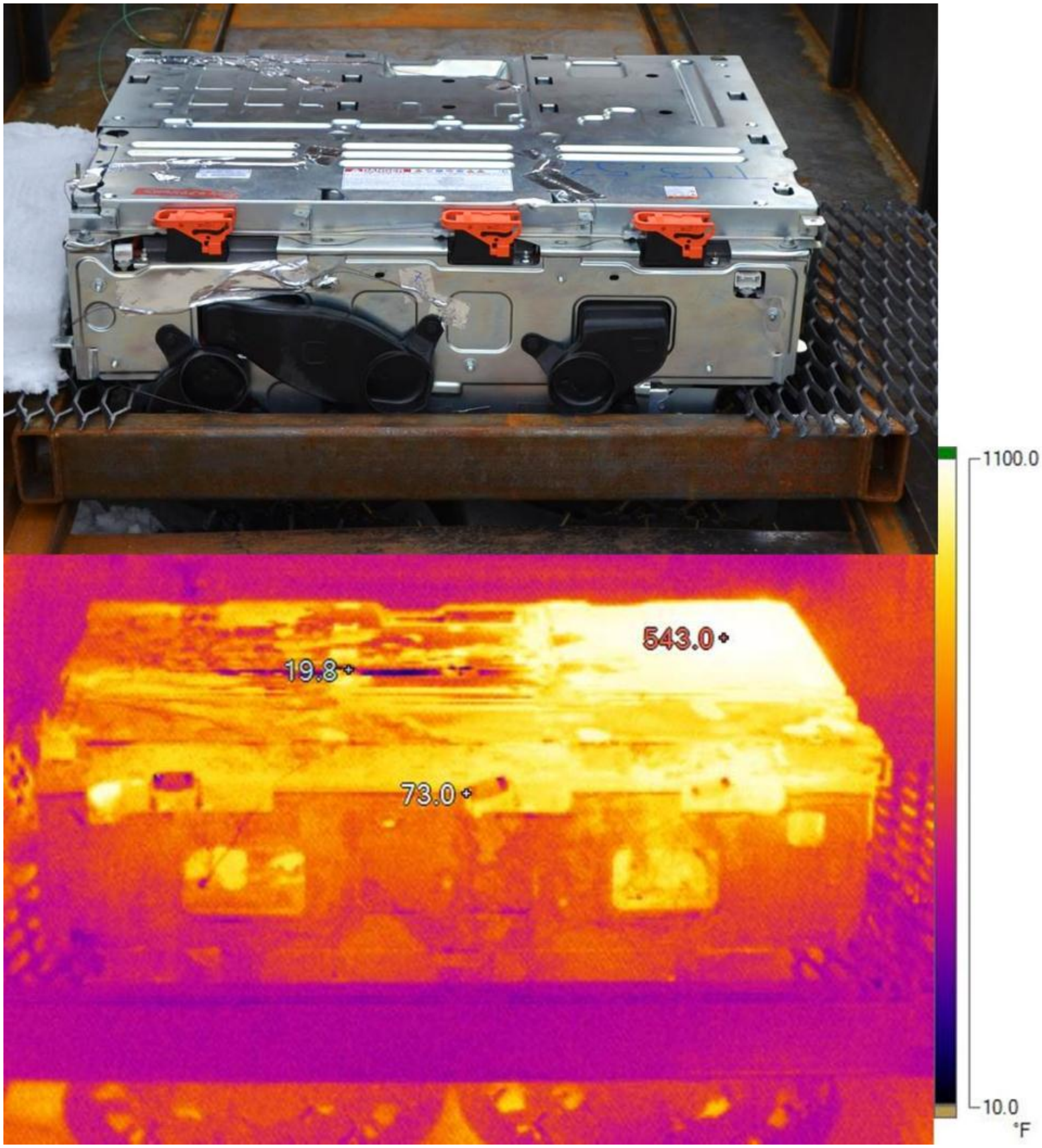

Figure 66 Battery A2 from rear of VFT (top); thermal image (same view) of Battery A2 at 40 minutes depicting the “hot spot” (bottom)

Table 21 Summary of Test A2 Temperature Measurements after 60 Minutes

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

6.2.2.7 Water Sampling Results

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

6.2.3 Battery A3 Test

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

6.2.3.1 Test Observations

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

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

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

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

Table 22 Test A3 Key Observations

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

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

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

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

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

6.2.3.2 Water Flow Measurements

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

Table 23 Test A3 Water Flow Times

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

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

6.2.3.3 Firefighter Tactics and Observations

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

6.2.3.4 Temperature and Heat Flux Measurements

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

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

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

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

Table 24 Summary of Test A3 Maximum Temperature Measurements

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

Table 25 Summary of Test A3 Maximum Heat Flux Measurements

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

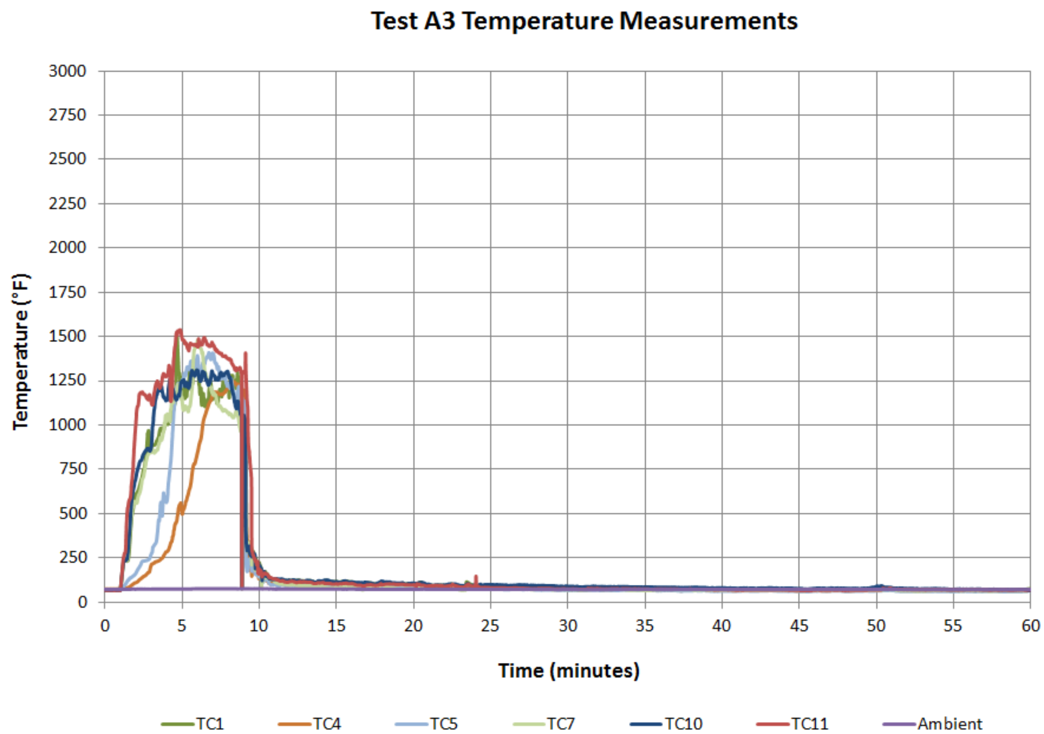

Figure 69 Test A3 TC plot

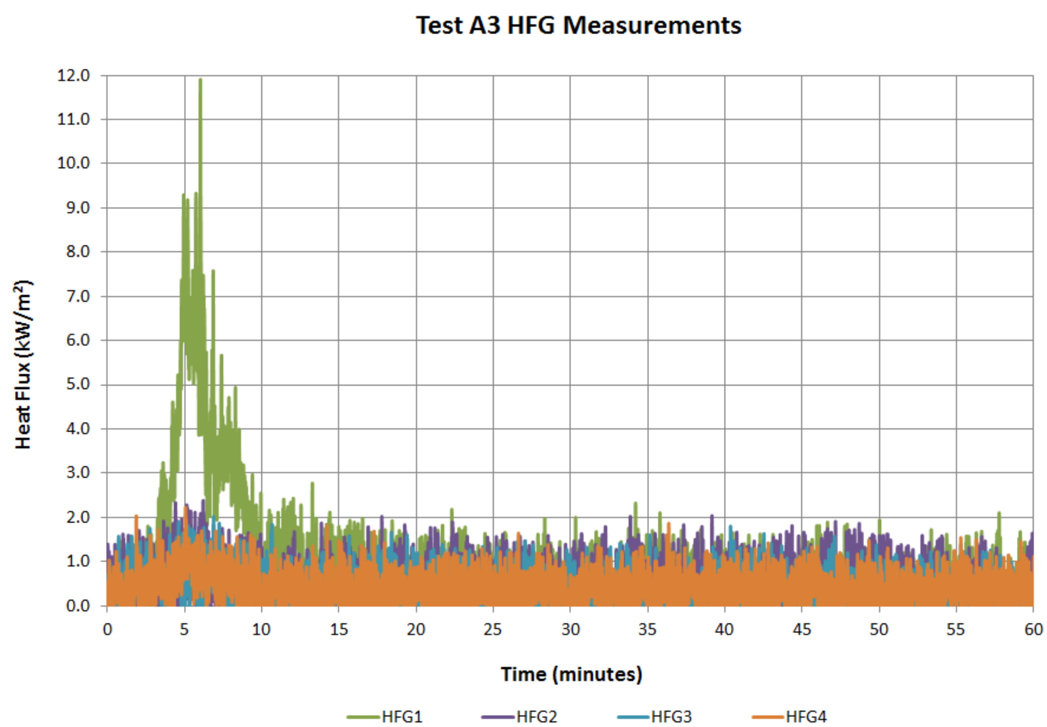

Figure 70 Test A3 HFG plot

6.2.3.5 Electrical Measurements

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

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

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

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

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

6.2.3.6 Overhaul Results

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

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

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

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

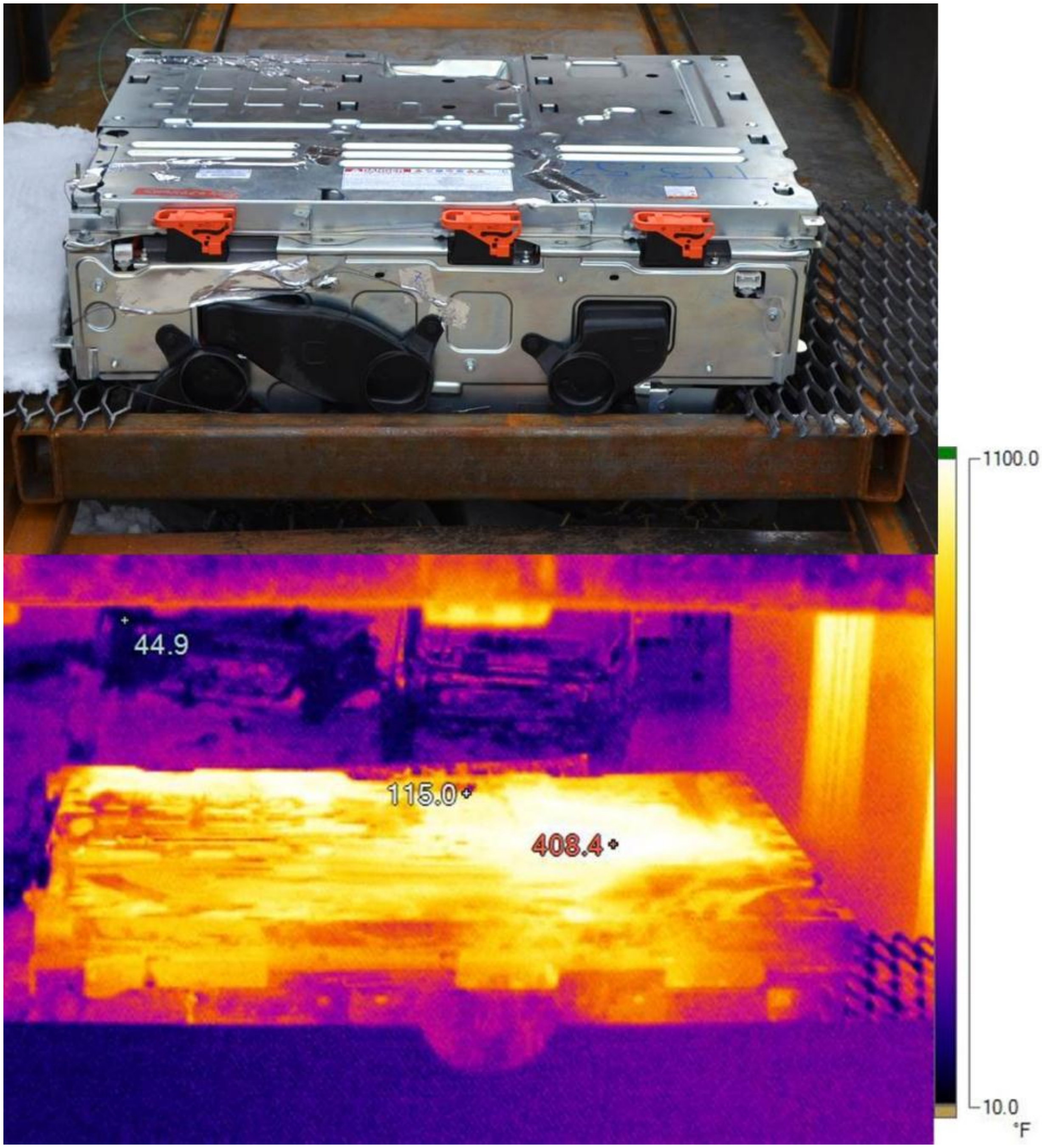

Figure 71 Battery A3 from rear of VFT (top); thermal image (same view) of Battery A3 at 41 minutes depicting the “hot spot” (bottom)

Table 27 Summary of Test A3 Temperature Measurements after 60 Minutes

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

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

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

6.2.3.7 Water Sampling Results

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

Table 28 Water Sample Analysis Summary for Test A3

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