Test Report

Full Circle Lithium Evaluating Extinguishing Agents on Secondary Lithium-Ion Batteries Undergoing Thermal Runaway

Location of Test: 5901 Elwin Buchanan Dr. Sanford, NC 27330

Date of Tests: September 5, 2023
November 7-8, 2023

NORTH CAROLINA PROFESSIONAL SEAL 039022 ENGINEER RICHARD W. ALARCON

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AUTHORED BY: Richard W. Alarcon, P.E. Date

SAFE Laboratories and Engineering Corp
5901 Elwin Buchanan Drive, Sanford, NC 27330
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I. SUMMARY OF TEST AND RESULTS

1. The purpose of the testing was to compare and understand the effects of different extinguishing agents on secondary lithium-ion batteries undergoing thermal runaway.
2. On September 5, 2023, Stage 2 testing for Full Circle Lithium occurred at the SAFE Laboratories and Engineering Corp. (SAFE Labs) facility in Sanford, NC.
3. The testing protocol was developed to replicate current industry standards for lithium-ion propagation testing as well as fire suppression certification testing outlined in *UL 9540A 4th edition* and *UL 711 8th edition*.
4. A combination of video recording (RGB and Thermal), Thermocouples, and Continuous Emissions Monitoring were used to collect data to evaluate the extinguishing agents.
5. Real-time gas monitoring using FTIR revealed the presence of methane, ethylene, CO, CO2, and HCl during thermal runaway events, with levels remaining relatively consistent across all extinguishing agents.
6. HCl levels were insignificant and require further and larger scale testing for definitive conclusions.
7. Hydrogen, while detected, remained at background levels throughout the tests.
8. All three agents effectively mitigated the initial fire, with F500 and FCL FSS demonstrating quicker cool-down times.
9. Beyond surface cooling, F500 and FCL FSS appear to involve additional mechanisms speeding up cool down times that require further investigation.
10. Uncontrolled thermal runaway remains a critical risk, highlighting the need for optimized application strategies and further research.
11. On November 7-8, 2023, Stage 3 testing occurred at the SAFE Laboratories and Engineering Corp. (SAFE Labs) facility in Sanford, NC.
12. Commercially available Electric Bike batteries (960 Wh) were pushed into thermal runaway. Water, F500, and FCL FSS were used as extinguishing agents for comparability.
13. Testing methodology was adjusted from Stage 2 to better focus on firefighter-centric variables, Stage 3 aimed to bridge the gap between laboratory testing and practical application.

14. Real-time gas monitoring during Stage 3 confirmed the presence of methane, ethylene, CO, CO_2, and HCL while hydrogen remained negligible compared to background atmosphere.
15. Firefighter observations offer valuable insights into real-world fire control dynamics by reflecting natural decision-making and endpoint determination.
16. FCL FSS (2 seconds) demonstrated an order of magnitude faster cool-down time compared to F500 (46 seconds), highlighting its potential for rapid fire control in real-world settings.
17. Both F500 and water experienced prolonged smoke, when compared to FCL FSS, even though they both extinguished the E-bike fire.
18. Introducing a firefighter into Stage 3 added uncontrollable variables that could potentially influence dose and coverage but also provided valuable insights by mimicking real-world decision making.
19. Extensive larger scale testing is crucial to comprehensively evaluating the efficacy and nuanced differences between each agent. Future investigations should explore various deployment techniques to refine and optimize practical application scenarios.

II. INTRODUCTION

The purpose of the testing was to compare and understand the effects of different extinguishing agents on secondary lithium-ion batteries undergoing thermal runaway. The testing procedure was developed to replicate current industry standards for thermal runaway propagation testing and fire suppressant agent certification testing. Three different extinguishing agents were applied for each stage: water, F500, and Full Circle Lithium Fire Suppressant Solution (FCL FSS). On September 5, 2023, Stage 2 testing for Full Circle Lithium occurred at the SAFE Laboratories and Engineering Corp. (SAFE Labs) facility in Sanford, NC. Stage 2 was a small cluster of 18650 cells placed near each other. On November 7-8, 2023, Stage 3 testing occurred. Stage 3 was forcing commercially available Electric Bike (E-Bike) batteries into thermal runaway and testing the same extinguishing agents for comparability.

III. PRODUCT DESCRIPTION

FCL FSS is a proprietary solution designed to be readily deployable by first responders for A Class, B Class, or lithium-ion fires. The solution was developed by Full Circle Lithium. It can be mixed into any number of portable firefighting equipment.

IV. STAGE 2 TEST CONFIGURATION

The test was conducted in accordance with the "**Suggested Test Method for Evaluating Extinguishing Agents on Secondary Lithium-Ion Batteries Undergoing Thermal Runaway" protocol.** This protocol was developed to replicate current industry standards for lithium-ion propagation testing as well as fire suppression certification testing outlined in *UL 9540A 4th edition* and *UL 711 8th edition*.

A. Equipment

The lithium-ion batteries used for the test were 18650 NMC 2800 mAh (milliampere hour) 35A (ampere) cells as manufactured by Molicel. The 18650 cells were brand new from the distributor and were fully charged to ~4.2V (volt) each. The 18650 cells were arranged in a circular cluster of 19 cells with a center cell and an adjacent cell designated as the initiating cells with PLM-203/10-P flexible Kapton film heater wrapping.

Type K thermocouples (24 gauge) were attached to all 19 cells to monitor temperatures and control heater ramp rates through a proportional-integral-derivative (PID) controller. Lastly, a 2.5-gallon stainless steel fire extinguisher was used for each of the three extinguishing agents. Each extinguishing agent had its own canister to prevent any cross contamination between agents.

B. Installation

The fully charged and instrumented 18650 cells were arranged in a cluster as represented in Figure 1 through **Figure 6** and placed on a table in the middle of the test site. The 2.5-gallon extinguisher was attached to an extended nozzle so that the handle could be operated by a firefighter at a safe distance. The tip of the nozzle was secured at a fixed angle 24 inches from the top center of the cell cluster. This installation ensured repeatability between tests. The extinguishers were charged to 100 pounds per square inch (PSI) **Figure 7**.

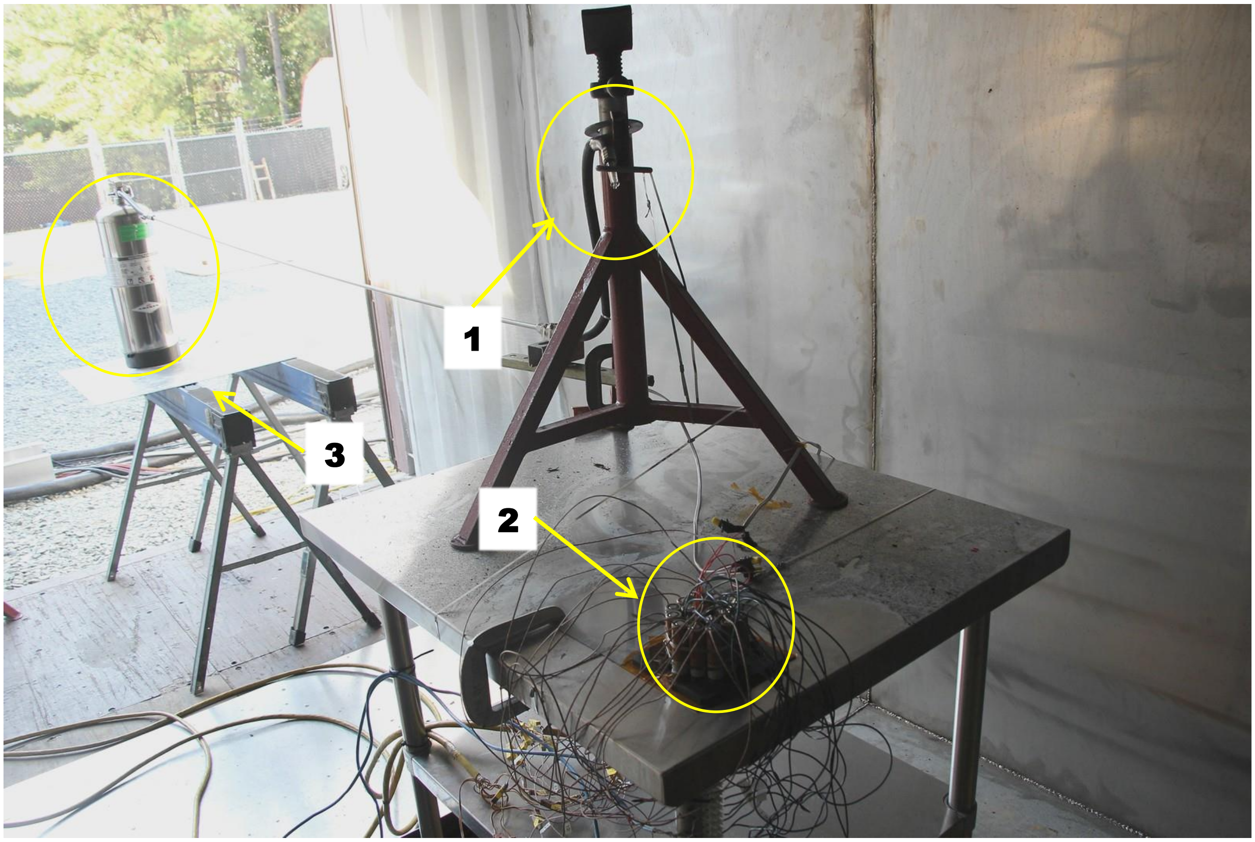

Figure 1. Test setup overview, looking outward.

Notes:

1. Nozzle where extinguishing agent was released
2. Cluster of target cells
3. Extinguishing agent canister

Figure 2. Test setup overview, looking inward.

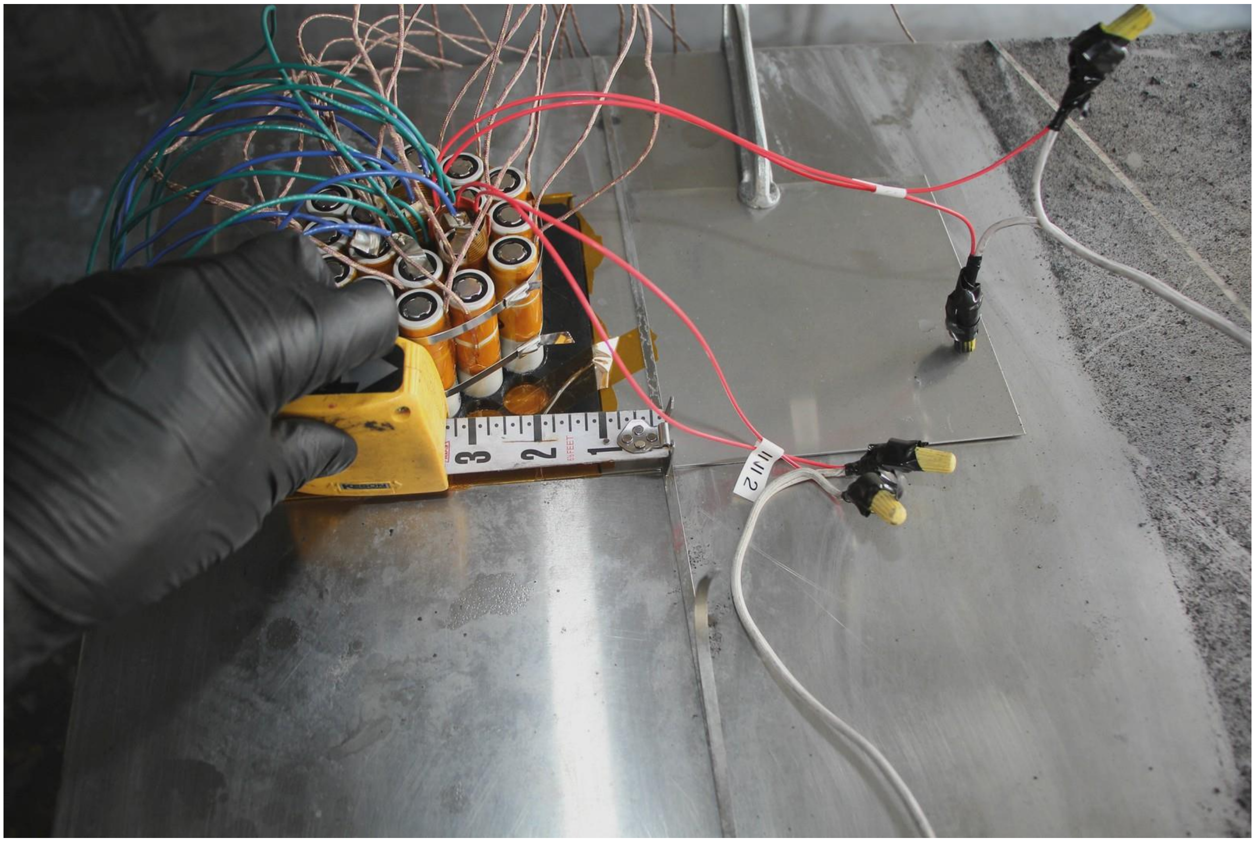

Figure 3. Front measurement of target cells.

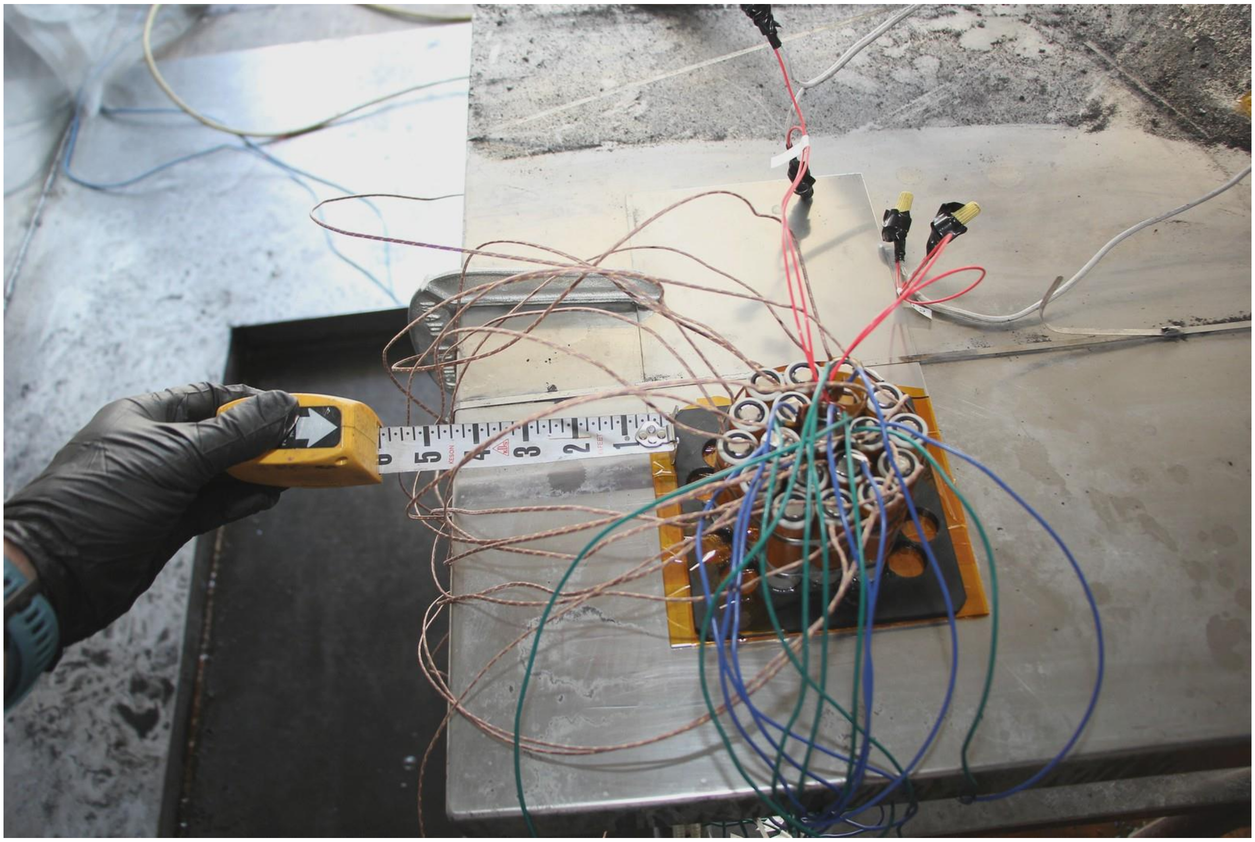

Figure 4. Side measurement of target cells.

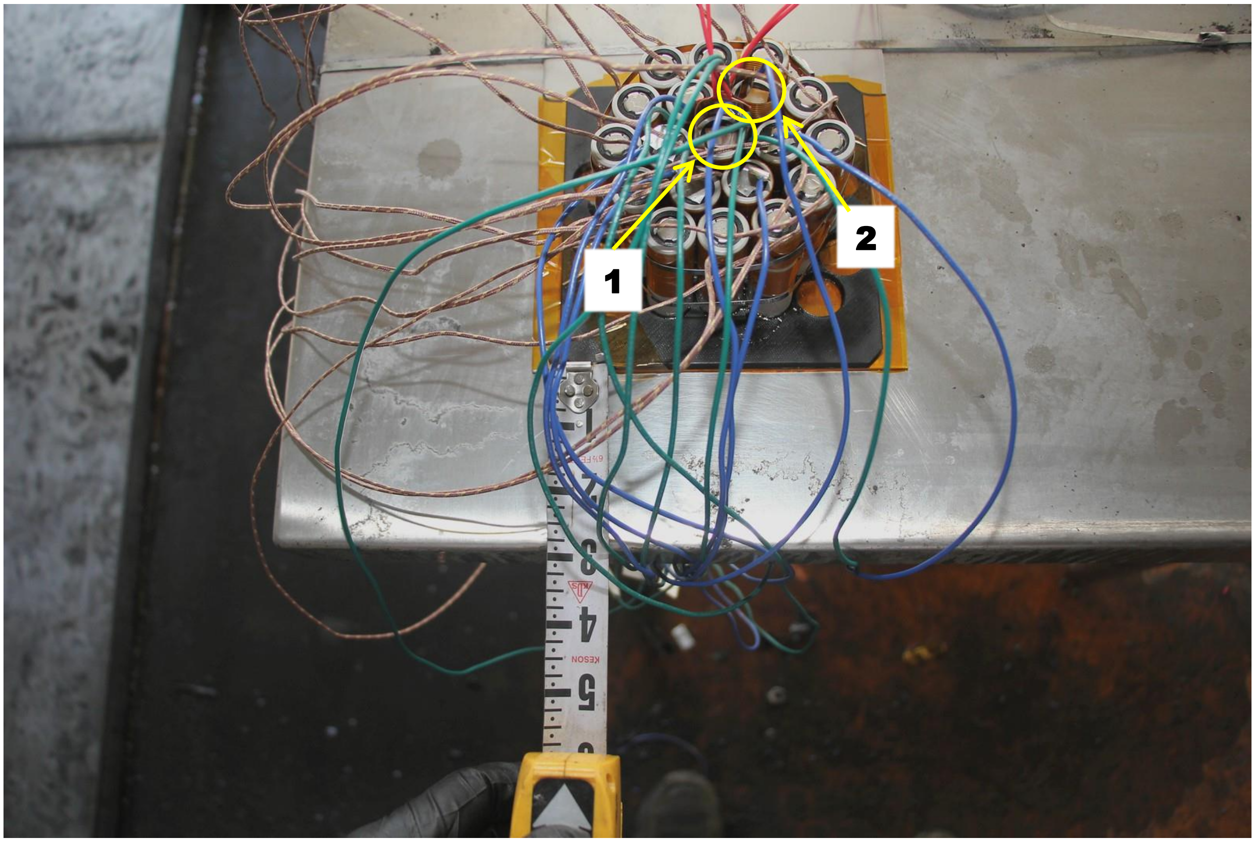

Figure 5. Rear measurement of target cells.

Notes:

1. Initiating cell
2. Back-up initiating cell

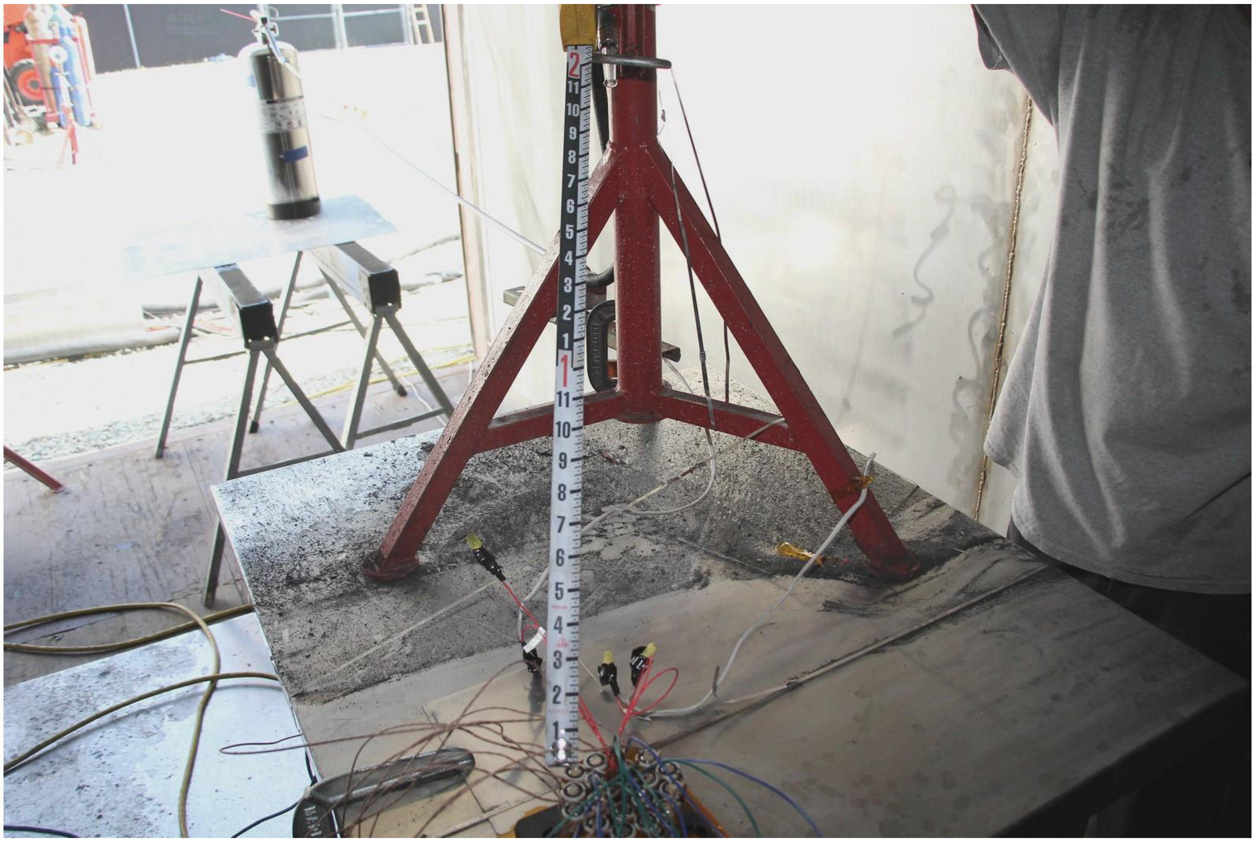

Figure 6. Distance from nozzle to target cells.

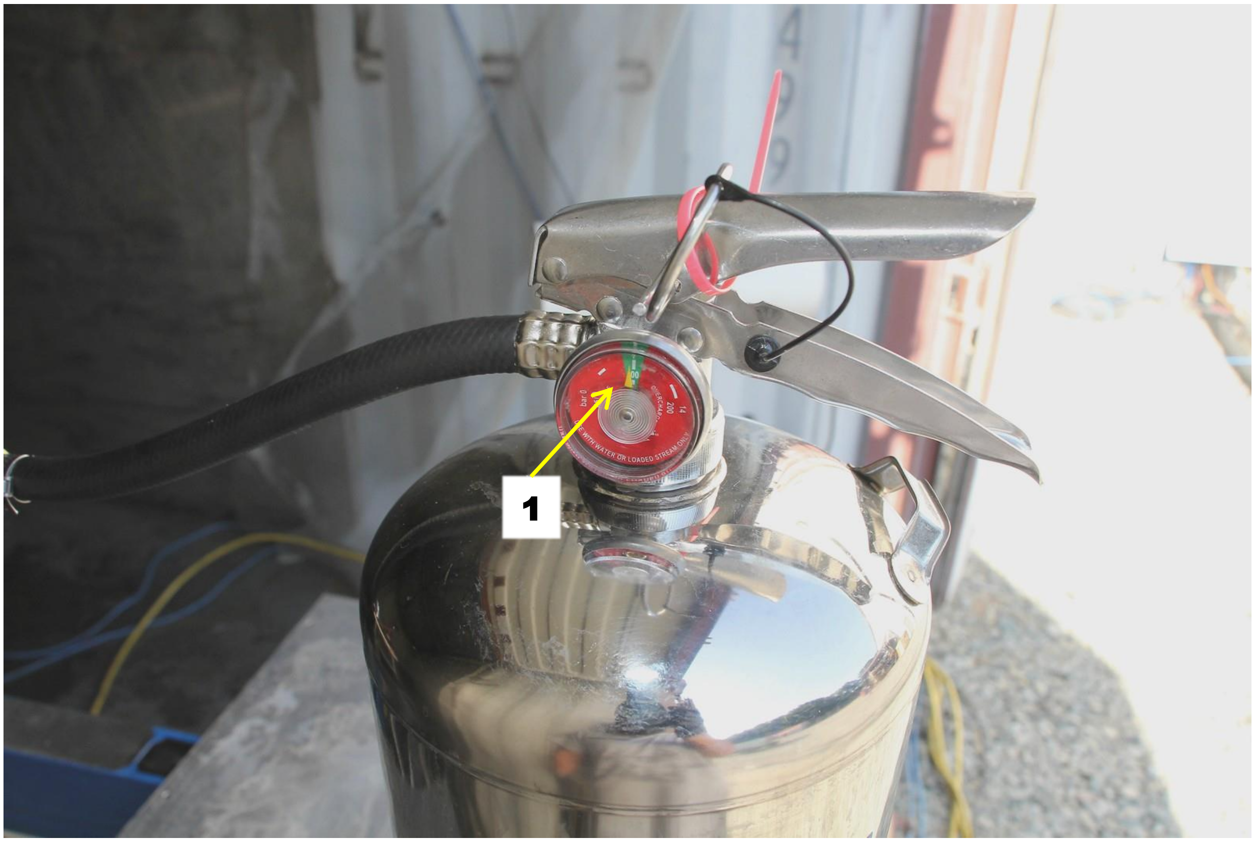

Figure 7. Charged fire suppression canister.

Notes:

1. Charged to 100 PSI

C. Instrumentation

Except for the Nitecore Intellicharger New i4 battery cell charger, the instrumentation used for this test was calibrated and used in accordance with SAFE Labs' ISO 17025 accreditation. The instrumentation for this test consisted of the equipment listed below.

1. Nitecore Intellicharger New i4 to charge battery cells
2. Weather station for monitoring environmental conditions
3. Electrically isolated K-type thermocouples for measuring temperature
4. Red Green Blue (RGB) cameras for video recording
5. Thermal imaging cameras for video recording and monitoring external temperatures
6. Optima OP-900 AMS Scale for weighing extinguishers before and after tests
7. Continuous Emissions Monitoring Systems (CEMS)

a. Fourier-Transform Infrared Spectrometer
b. High Temperature Flame Ionization Detector
c. Oxygen Detector
d. Gas Chromatograph with Thermal Conductivity Detector

1. Charger

Prior to the test, each cell was charged to 4.2V using the Nitecore Intellicharger New i4 charger.

2. Weather Station

A local onsite weather station is used to monitor the environmental condition before, during, and after the test. The weather station acquires the following data at 1 sample / minute:

1. Temperature
2. Humidity
3. Dew Point
4. Wind Speed
5. Wind direction
6. Wind Chill
7. Heat Index
8. Pressure
9. Rainfall
10. Rainfall rate

The weather station is located on the roof of the SAFE Labs facility, approximately 50 feet from the test area.

3. Thermocouples

A total of 18 K-type thermocouples were used to monitor temperature for the duration of each test. The thermocouple data was logged every second (60 times per minute). Thermocouples were placed on the side of each cell and underneath each heater.

The location of each thermocouple and its designation as assigned by SAFE Labs is shown in Figure 8.

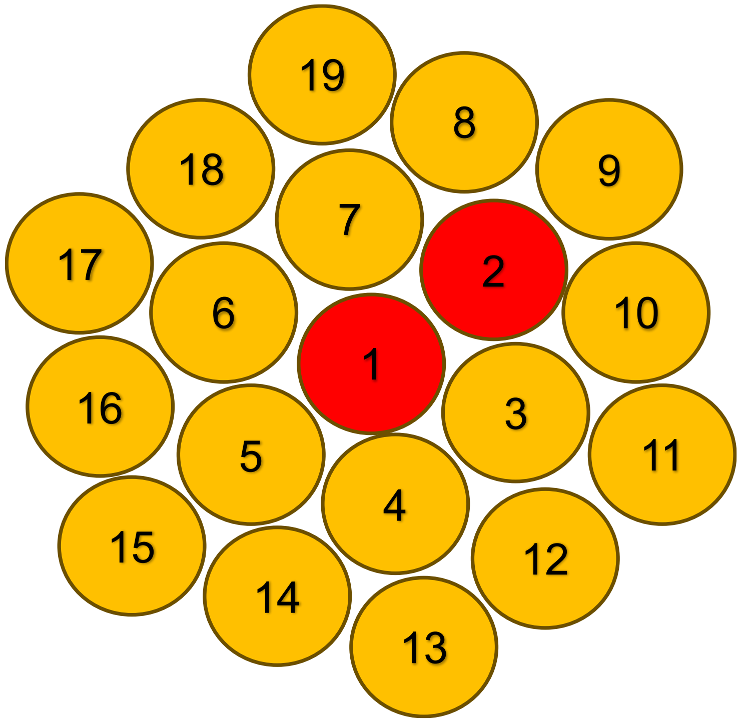

Figure 8. Top-down view of cells with numbers indicating thermocouple labels.

Notes: Both red cells are initiating cells

4. Video Cameras

A total of 5 video cameras were used during the test. Four RGB cameras were placed around the test area, directed towards the initiating cells.

One thermal imaging camera was placed in the entrance of the test chamber facing the cell cluster. This provided real-time thermal imaging of the cells undertest.

5. Scale

The weight of each fire extinguisher was recorded before and after each test to identify how much EA was expelled during the test.

6. CEMS

A Continuous Emission Monitoring System (CEMS) was used to measure the various gases evolved during burn testing. The CEMS is a movable rack with multiple analyzers and detectors that quantify and data log various gases.

a. Fourier-Transform Infrared Spectrometer (FTIR):

FTIR uses infrared light to identify and quantify various gas constituents. The hot wet sample is carried through a small heated sample line to the FTIR's gas cell. Inside the gas cell, the instrument's infrared beam interacts with the gas and is partially absorbed. Different gas molecules have atomic bonds with different bond strengths and, in generic terms, the infrared light that is at the same frequency as a molecule's vibration will be absorbed; therefore, some infrared light is absorbed, and some is transmitted to the detector. The absorbed frequencies are unique for each gas constituent. The intensity of absorption is indicative of the concentration of the gas. An FTIR can simultaneously measure multiple gases and the list that SAFE Lab's FTIR can detect is shown in Table 1. The other analyzers in the CEM are single-gas analyzers.

Table 1: FTIR Elements Measured

<table>
<tr><td colspan="2">FTIR – Elements Measured</td></tr>
<tr><td colspan="2">Butadiene</td></tr>
<tr><td colspan="2">Acetylene</td></tr>
<tr><td colspan="2">Methane</td></tr>
<tr><td colspan="2">Carbon Monoxide</td></tr>
<tr><td colspan="2">Carbon Dioxide</td></tr>
<tr><td colspan="2">Carbonyl Sulfide</td></tr>
<tr><td colspan="2">Alkyl Carbonates</td></tr>
<tr><td colspan="2">Ethane</td></tr>
<tr><td colspan="2">Ethylene</td></tr>
<tr><td colspan="2">Ethylene Oxide</td></tr>
<tr><td colspan="2">Formaldehyde</td></tr>
<tr><td colspan="2">Water</td></tr>
<tr><td colspan="2">Isobutylene</td></tr>
<tr><td colspan="2">MeOH</td></tr>
<tr><td colspan="2">N2O</td></tr>
<tr><td colspan="2">NH3</td></tr>
<tr><td colspan="2">NO</td></tr>
<tr><td colspan="2">NO2</td></tr>
<tr><td colspan="2">Oil as Octane</td></tr>
<tr><td colspan="2">POF3</td></tr>
<tr><td colspan="2">Propane</td></tr>
<tr><td colspan="2">Propylene</td></tr>
<tr><td rowspan="5">Acid Gases</td><td>H2SO4</td></tr>
<tr><td>HBr</td></tr>
<tr><td>HCl</td></tr>
<tr><td>HCN</td></tr>
<tr><td>HF</td></tr>
</table>

b. High Temperature Flame Ionization Detector (HFID):

The FTIR analyzer does not permanently alter the gas so when the gas leaves the FTIR it is carried through a separate heated line to the HFID. The HFID is used to measure total hydrocarbons (THC). It contains a burner situated inside a heated oven. Hydrocarbons in the gas are ionized in the flame. The HFID also houses a split-ring detector with two electrodes, one of which is positively charged and one negatively charged. The ions migrate to their respective electrodes and this migration creates a current between the electrodes. The strength of the current is proportional to the concentration of total hydrocarbons.

c. Oxygen Detector:

Oxygen is paramagnetic, which means it is attracted to a magnetic field. Most other gases are not. SAFE Lab's oxygen sensor capitalizes on this fact and was chosen because it can measure zero oxygen, whereas most oxygen detectors do not. The instrument contains a non-homogeneous magnetic field that attracts oxygen. Two glass spheres connected by a platinum wire form a dumbbell that is balanced in the non-homogeneous magnetic field but moves with the flow of oxygen. A mirror mounted on the dumbbell communicates movement and an opposing current is applied to return the dumbbell to its neutral position. The amount of compensating current required is directly proportional to the amount of oxygen. The analyzer purchased by SAFE Labs accomplishes this with minimum dead space so that the response time is fast, and oxygen can be continuously monitored.

d. Gas Chromatograph with Thermal Conductivity Detector (GC-TCD):

The gas sample is unchanged by the oxygen analyzer and when it exits, it is carried to a GC-TCD for hydrogen analysis. A GC separates gas into its individual constituents by carrying the gas through a column packed with what is referred to as a stationary phase. The various constituents of the gas interact with this stationary phase and constituents with strong interactions stay in the column longer. As the components exit the column, or 'elute', they do so at unique times and thus individual components of gas sample are separated into their various components. From there, the sample is carried to a TCD. The TCD detector uses a bridge circuit to compare the variation in resistance between a constituent plus inert carrier gas to that of inert carrier gas alone. The change in resistance is a function of the amount of constituent present. In this way, the presence of hydrogen is determined by the GC and the amount of hydrogen is determined by the TCD. This standalone GC-TCD is set up to detect only hydrogen, followed by a purge, followed by a repeat detection of hydrogen. This, along with the fact that hydrogen elutes first and elutes quickly, allows this standalone GC-TCD to provide continuous monitoring of hydrogen.

e. Grab Samples:

To research and detect other potential gas constituents, specifically fluoride and lithium, there are two grab sample stations on the CEM. One grab sample port is for obtaining hot wet gas samples and the other is for obtaining cool, dry, scrubbed gas samples. This uses pumps to pull the gas through the adsorbent material for further analysis. The effluents were pulled through a solution of calcium hydroxide and set aside for sampling at another laboratory to analyze the levels of fluoride and lithium.

D. Procedure

The two initiating film heaters were set to a ramp rate of 5 degrees Celsius per minute until thermal runaway was achieved. Extinguishing agents (EA) were only applied after five cells were observed to be going through thermal runaway. Great care was taken to try and deploy the EA at the midpoint of a thermal runaway event to represent a worst-case scenario and consistent results between experiments. A firefighter deployed the EA by squeezing the handle of the canister until all visible flames were extinguished (approximately 1-2 seconds). Cells were monitored for reignition and if reignition was observed, the EA was deployed again for approximately 1-2 seconds.

The thermocouples on cells 1 and 2 were used to control the ramp rate in the PID loop and are not included in the below temperature graphs.

V. STAGE 2 RESULTS

The first observations of thermal runaway for each test are referred to as t=00:00 (mm:ss), throughout this report.

At the start of the test, the outdoor temperature was 89 degrees Fahrenheit with approximately 63% relative humidity and a 3-mph wind speed.

None of the graphs in Figure 17, Figure 25, Figure 31, or Figure 34 show initiating cells 1 and 2 since their thermocouples were used for PID control of the heaters.

A. Water

It took until t=04:58 for the first five cells to enter thermal runaway upon which water was deployed on the cells. At t=08:05 reignition was observed on 2 cells. After the second cell went into thermal runaway on reignition water was sprayed again. Ultimately 2.6 lbs of water were used for this test. At t=19:00 all thermocouples were consistently trending downward and below 120 degrees Celsius. Seven cells appeared to have entered thermal runaway: 5 before application of EA and 2 between EA applications. Cell 3 was the third cell to enter thermal runaway after the two initiating cells. The arrows point to the locations on the graph when water was applied **(Figures 9 through 16).**

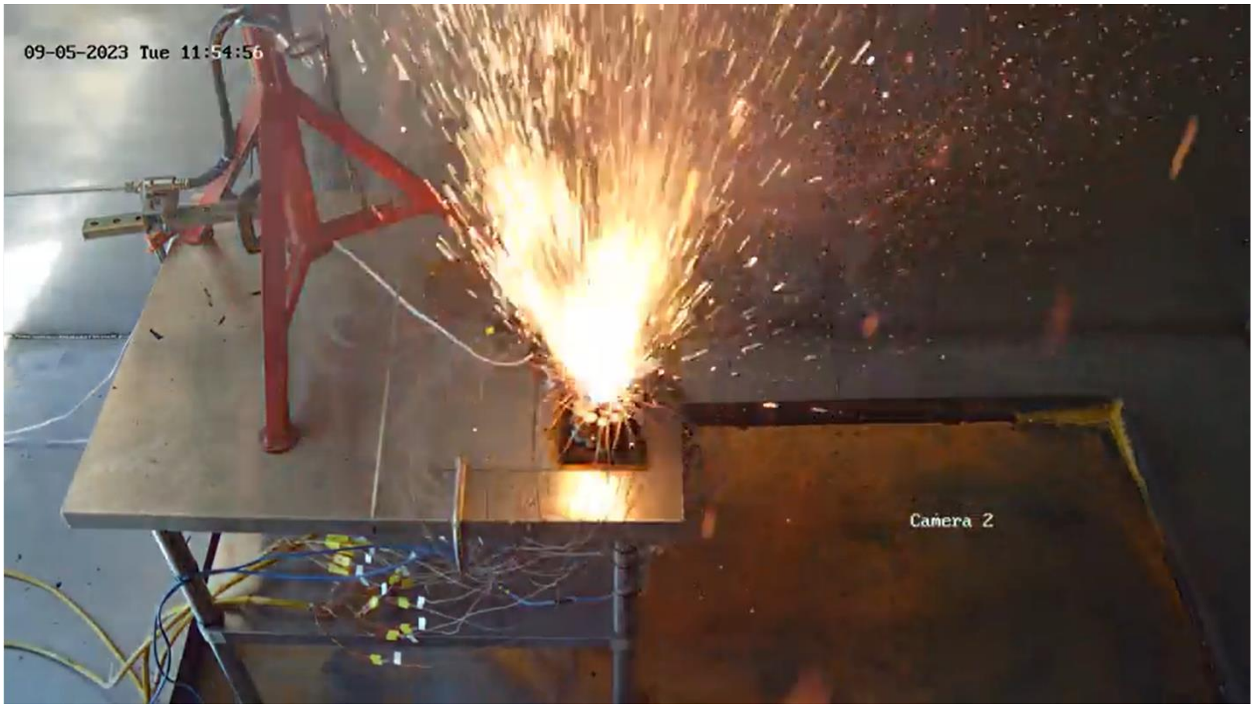

Figure 9. First cell undergoing thermal runaway, t=00:00.

Figure 10. Small flame that heated up adjacent cells.

Figure 11. Fifth cell undergoing thermal runaway.

Figure 12. Water is sprayed on the cell cluster.

Figure 13. A picture immediately after the water was sprayed.

Figure 14. Reignition of cells.

Figure 15. The second time water was sprayed on the cell cluster.

Figure 16. Cells smoking after the second application of water.

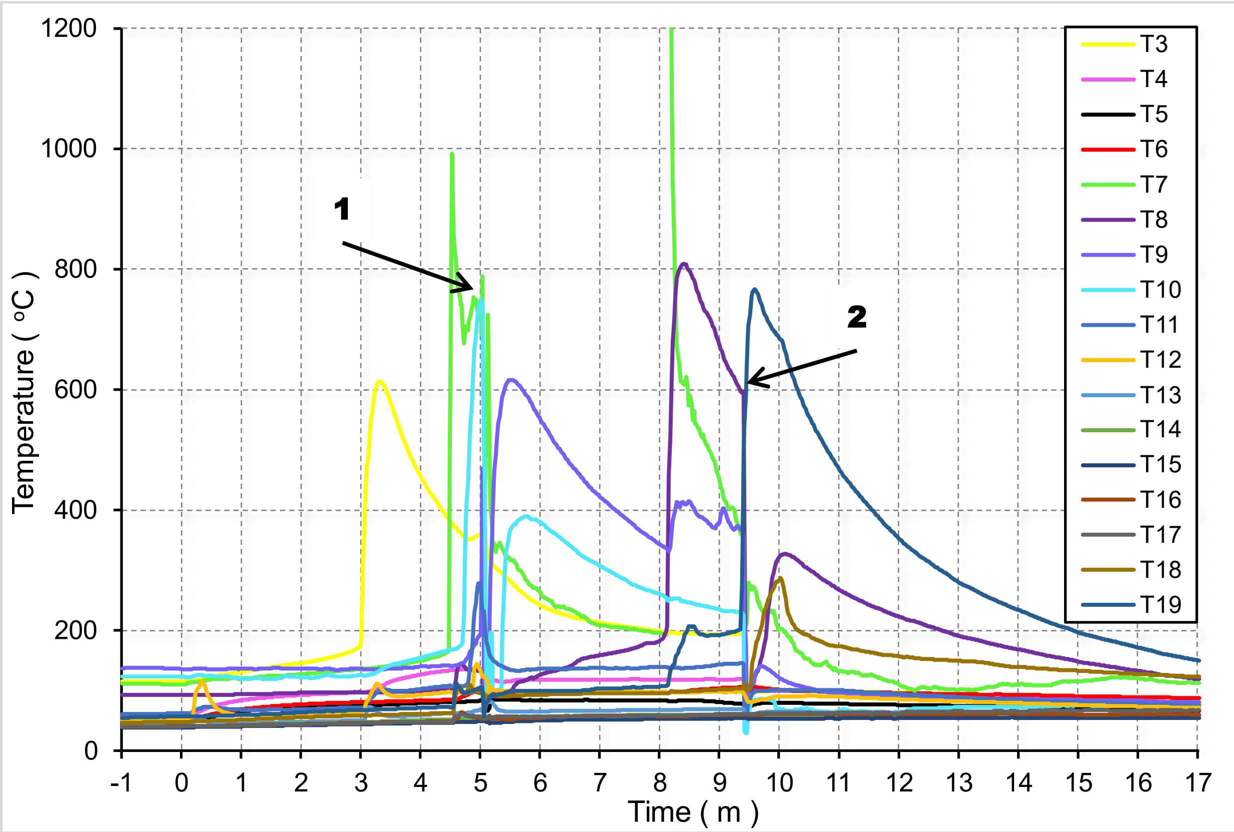

Figure 17. Graph of cell temperatures with water as an extinguishing agent.

Notes:

1. First time water was applied
2. Second time water was applied

B. F500

F500 was mixed in a 3% solution with water as per manufacturer recommendations. Between t=00:00 and t=01:15 the first five cells entered thermal runaway at which time F500 was deployed on the cells. At t=03:43 reignition was observed, 2 cells entered thermal runaway with a slight delay between them. F500 was applied on the second reignited cells. Ultimately 2.3 lbs of F500 was used overall for this test. Around t=12:00 all thermocouples were consistently trending downward and below 120 degrees Celsius. Seven cells appeared to enter thermal runaway: 5 before application of EA and 2 between EA applications (**Figures 18 through 24)**.

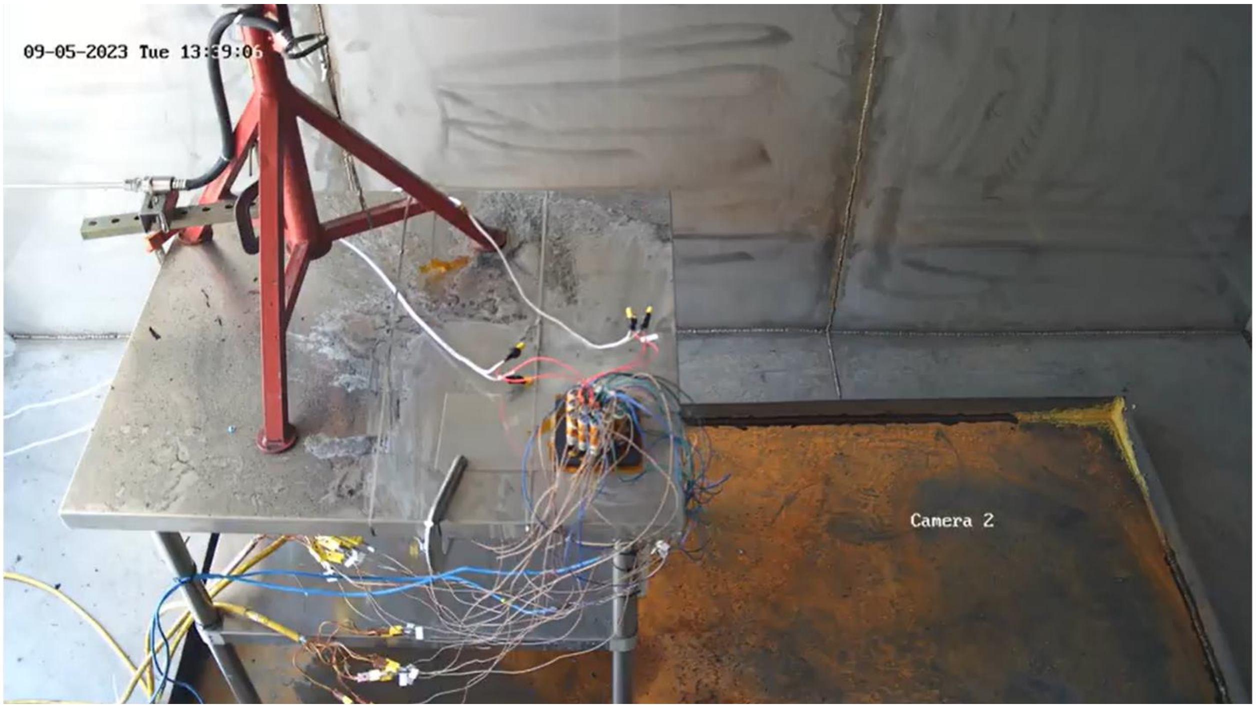

Figure 18. Immediately before the first cell experienced thermal runaway.

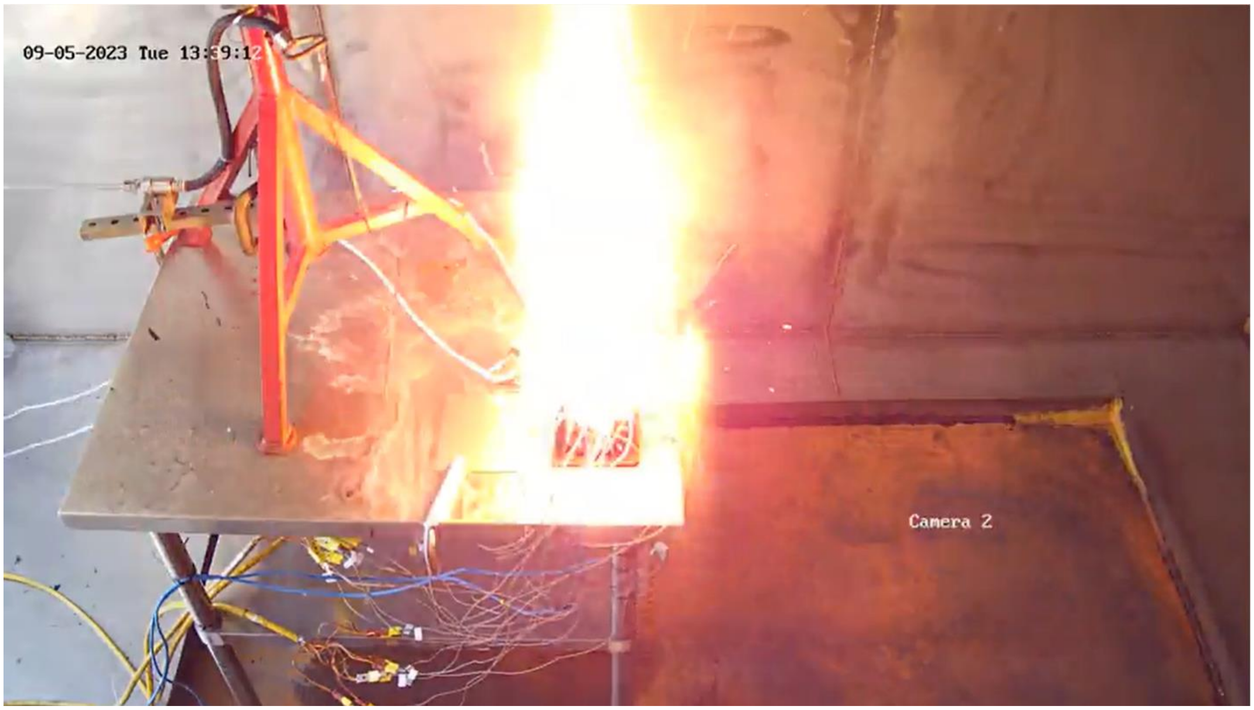

Figure 19. The first cell experiences thermal runaway.

Figure 20. Small flame and off gassing.

Figure 21. F500 is sprayed on the cell cluster.

Figure 22. After F500 is sprayed.

Figure 23. Second time F500 is sprayed on the cluster during propagation.

Figure 24. End of the test for F500.

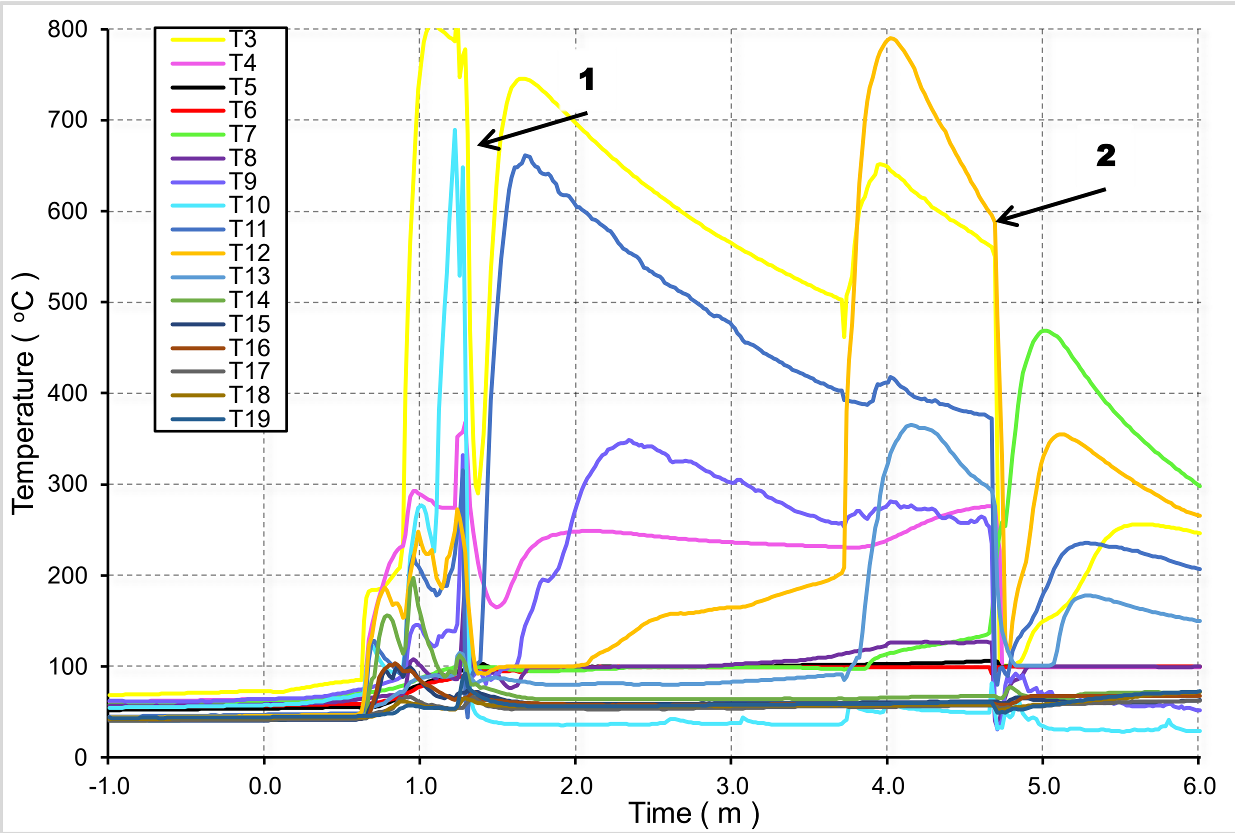

Figure 25. Graph of cell temperatures with F500 as an extinguishing agent.

Notes:

1. First time F500 was applied
2. Second time F500 was applied

C. FCL FSS

Between t=00:00 and t=02:17 the first five cells entered thermal runaway upon which FSS was deployed on the cells. At t= 08:47 reignition was observed by 1 cell upon which FSS was applied. Ultimately 2.25 lbs of FSS was used overall for this test. Around t=12:00 all thermocouples were consistently trending downward and below 120 degrees Celsius. Six cells appeared to enter thermal runaway: 5 before application of EA and 1 between EA applications. Only one cell appeared to be heating up after the first EA application compared to the other EAs where multiple cells appeared to still be gaining heat **(Figures 26 through 30)**.

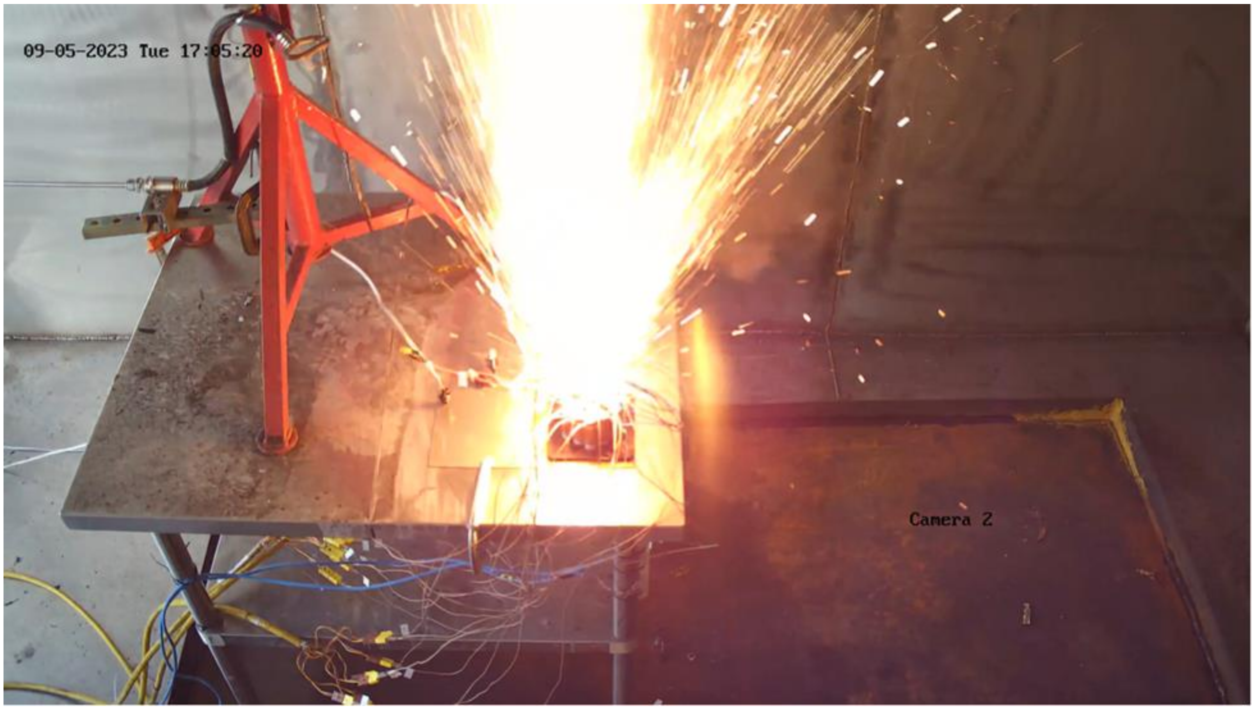

Figure 26. First cell experiencing thermal runaway.

Figure 27. FCL FSS was applied after five cells were experiencing thermal runaway.

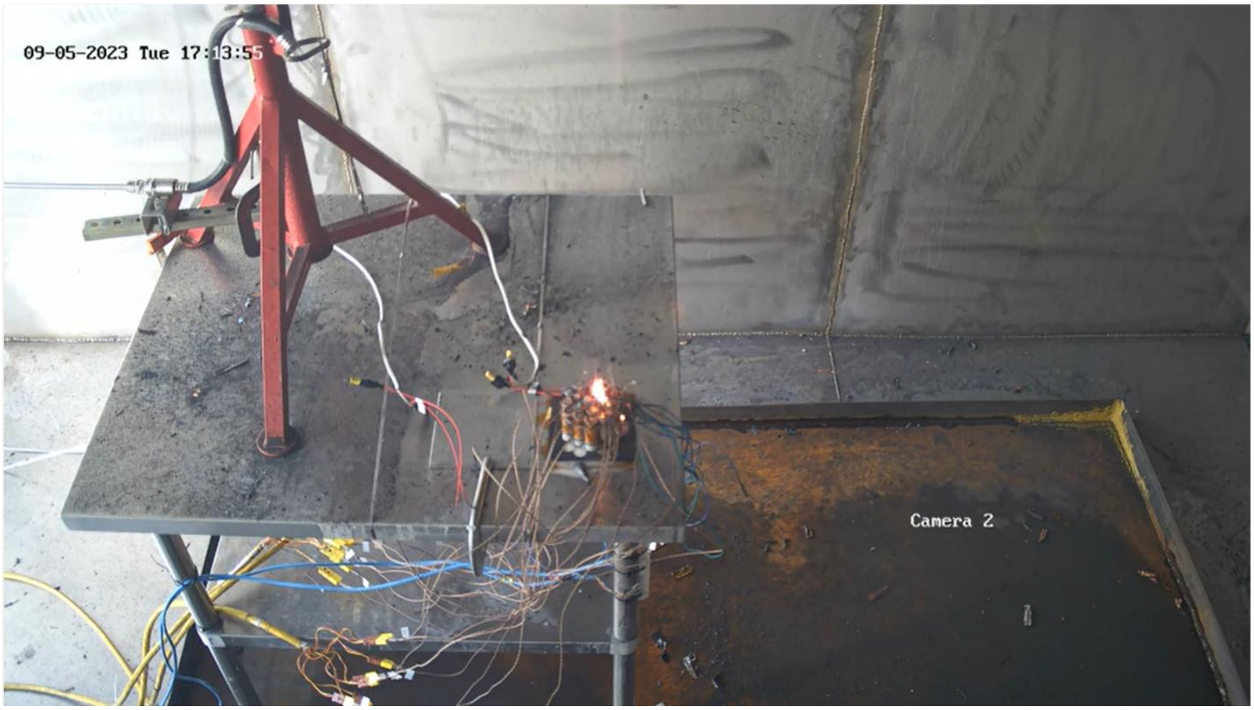

Figure 28. Several minutes after FSS was applied, a small flame appeared.

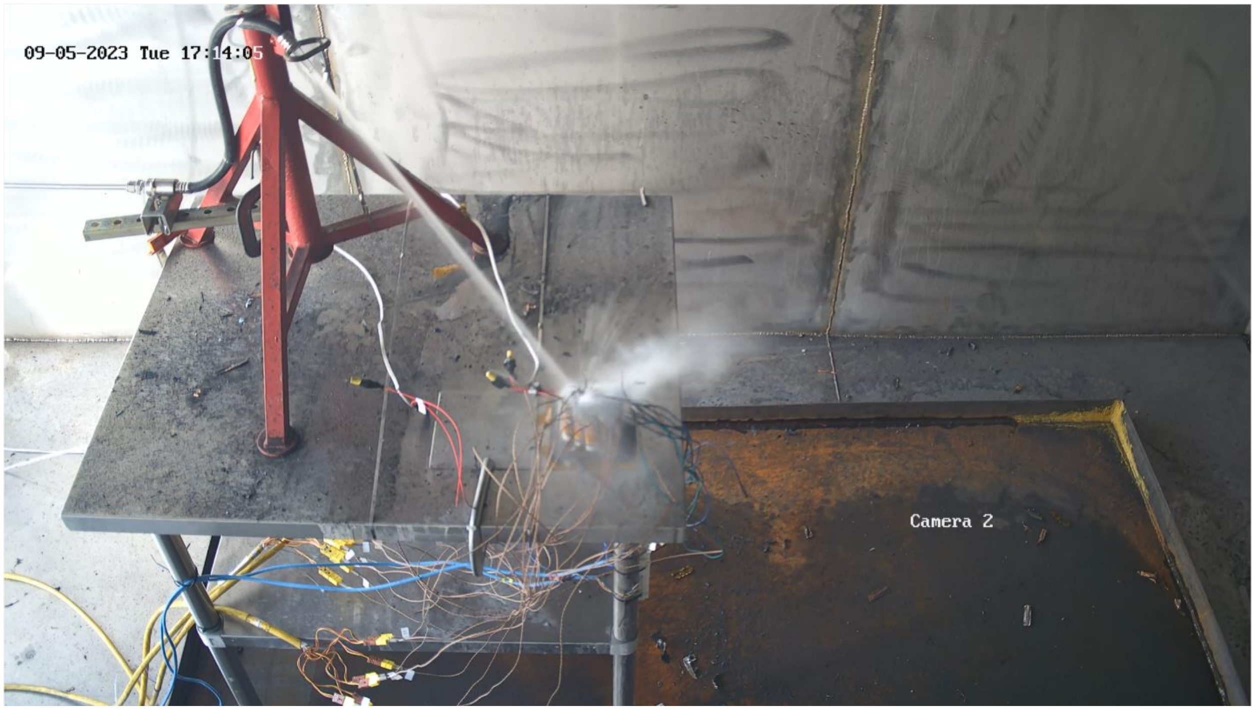

Figure 29. Second application of FSS.

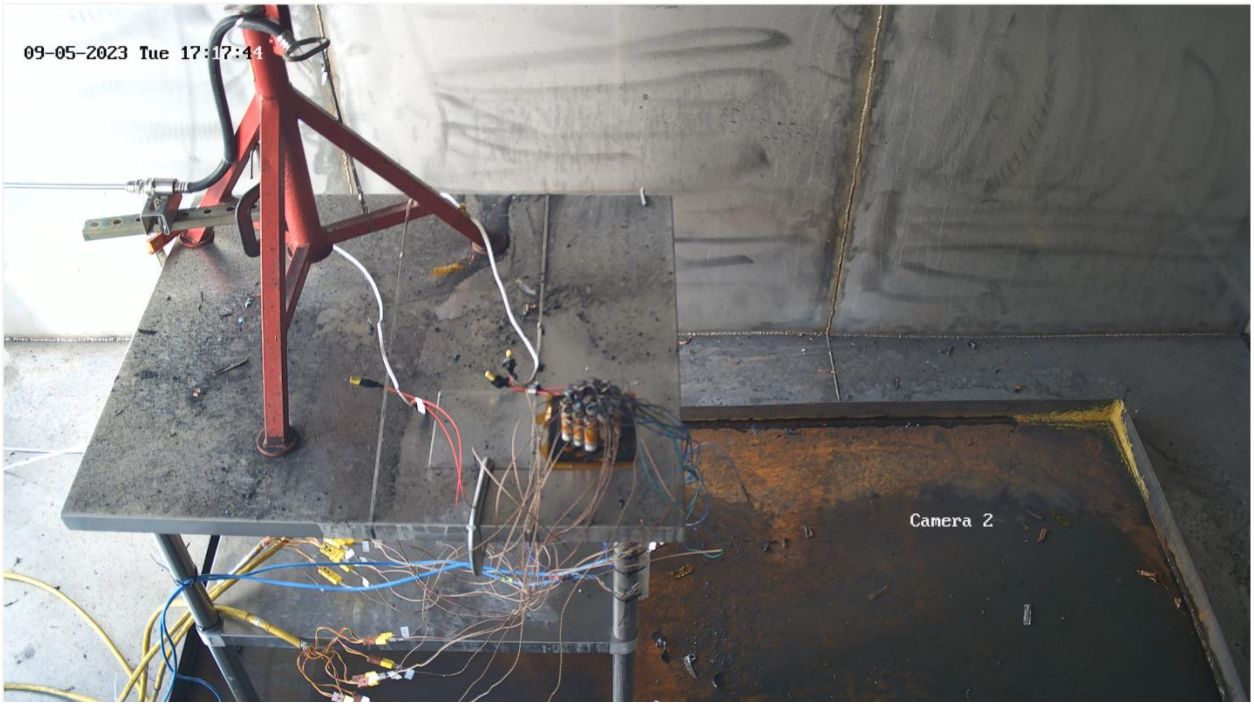

Figure 30. End of test for FCL FSS.

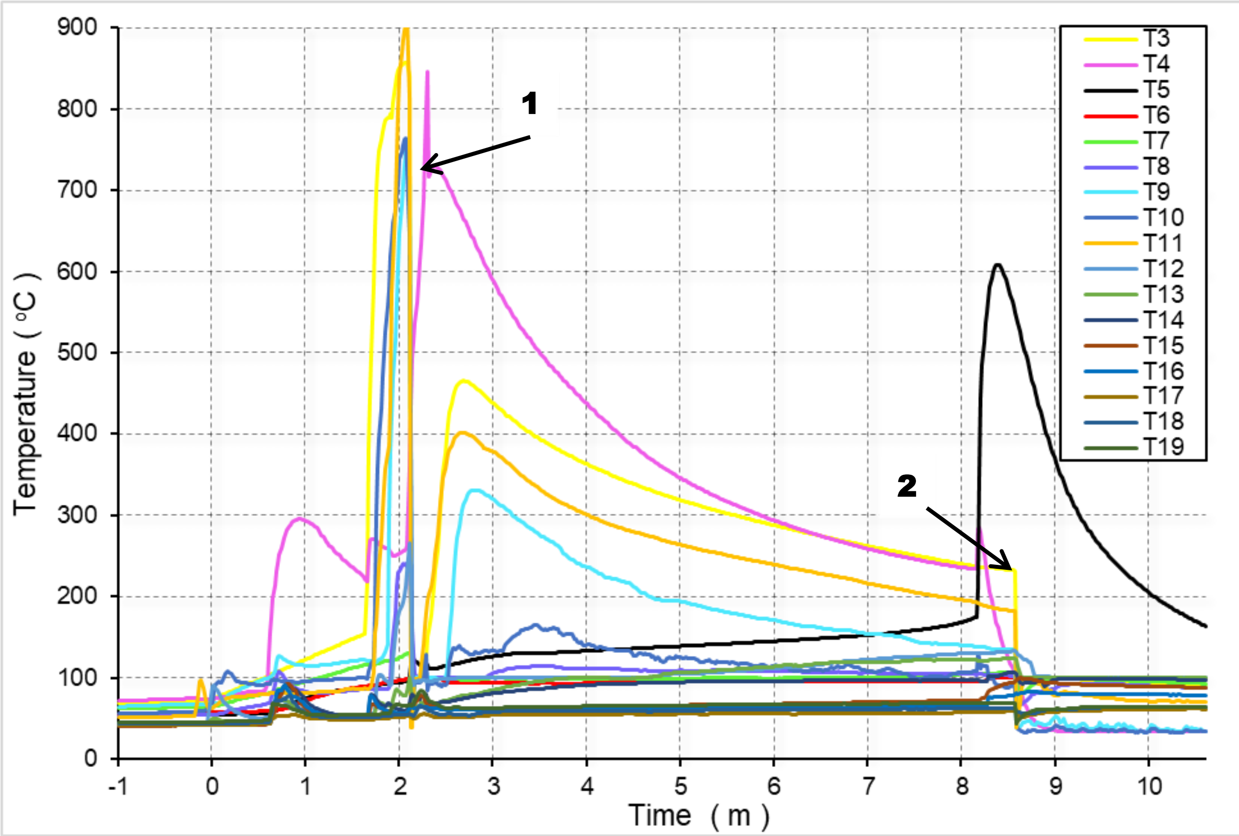

Figure 31. Graph of cell temperatures with FCL FSS as an extinguishing agent.

Notes:

1. First time FSS was applied
2. Second time FSS was applied

D. Control

At t=09:16 five cells had propagated within the control group; this is the same trigger in other tests when EA would have been deployed. At t=26:55 all cells propagated. At approximately t=36:00 all thermocouples were consistently trending downward and below 120 degrees Celsius **(Figure 32 and 33)**.

Figure 32. First cell experiencing thermal runaway in the control group.

Figure 33. All cells having experienced thermal runaway.

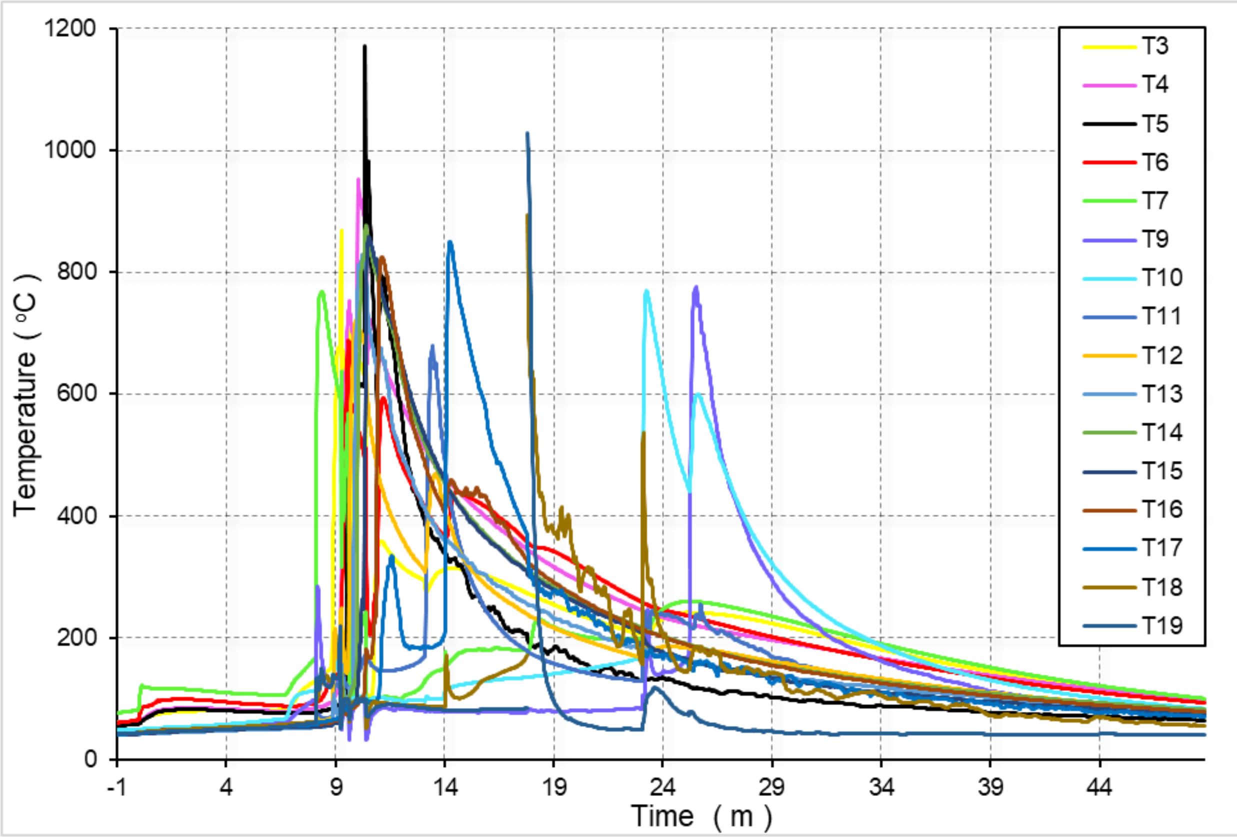

Figure 34. Graph of cell temperatures for control group.

Note:

1. T8 was removed due to being damaged

E. Gas Data

Gasses generated from the test set up were monitored with real time Fourier Transform Infrared Spectrometry (FTIR). All gasses listed in Table 1 were monitored for but only Methane, ethylene, CO, CO2, and HCl were validated to be present at levels high enough to be detected **(Figures 35 through 37)**. HF was measured but in all situations was below detectable limits. All levels are relatively the same with minimal differences. Considering the total number of cells that underwent thermal runaway, chemical levels were still similar to those before they were extinguished. In this small-scale test, the levels of HCL between the different EAs does not differ significantly and repeat or larger scale testing is needed before drawing final conclusions. Lastly, it was observed that hydrogen was present at extremely low levels during each of the four tests but was not significantly different than background hydrogen levels in the atmosphere.

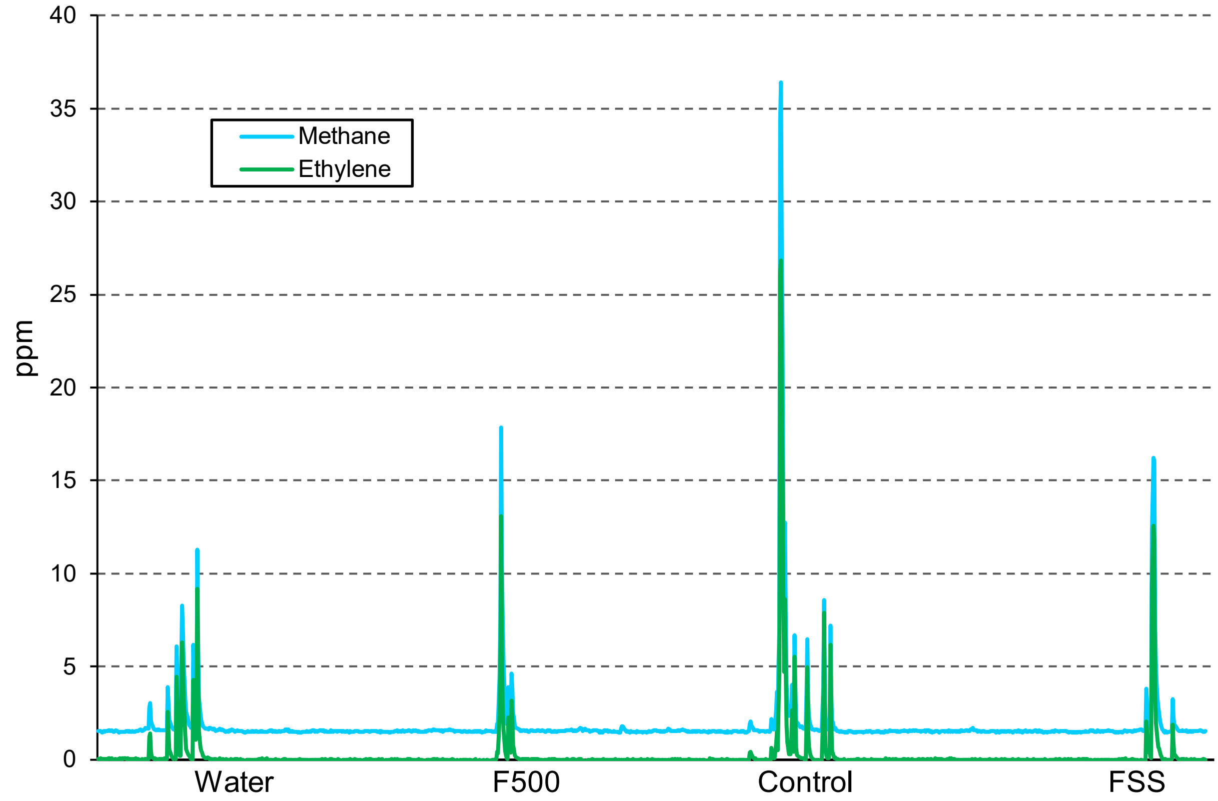

Figure 35. Graph of methane and ethylene in ppm across all four tests.

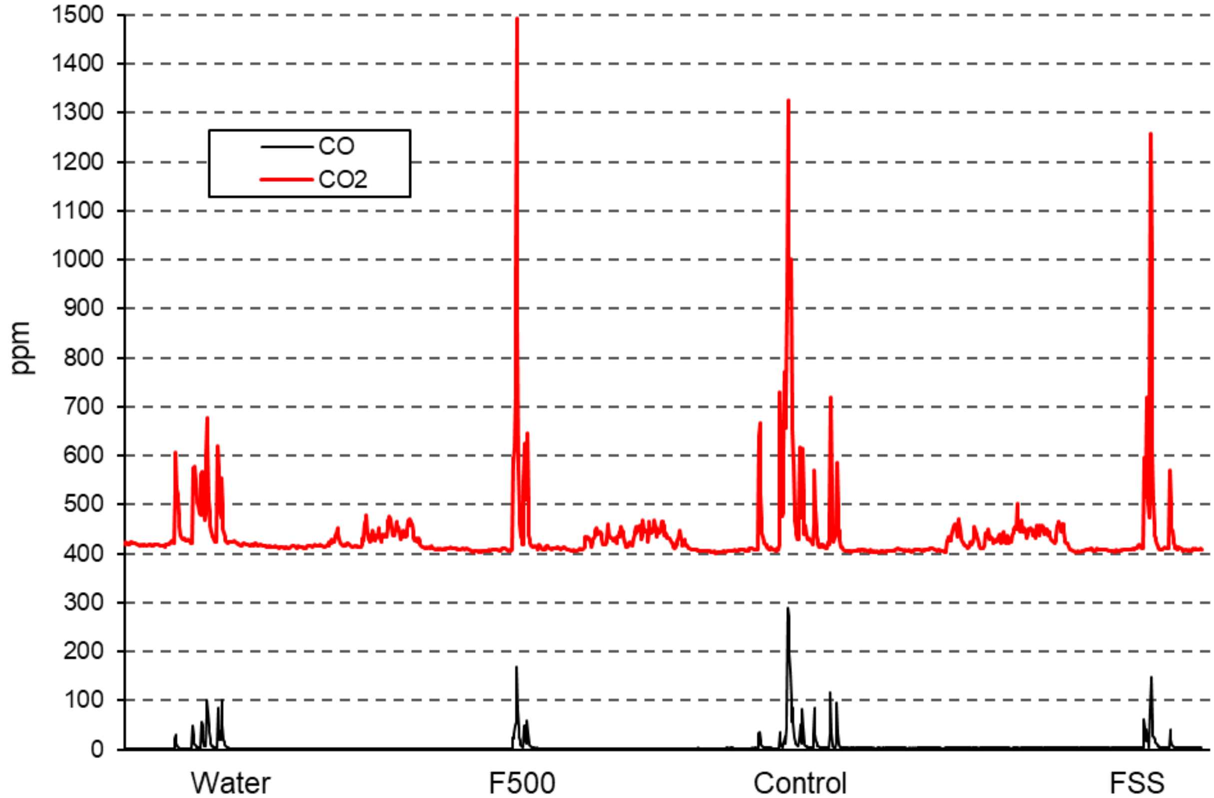

Figure 36. Graph of carbon monoxide and carbon dioxide in ppm across all four tests.

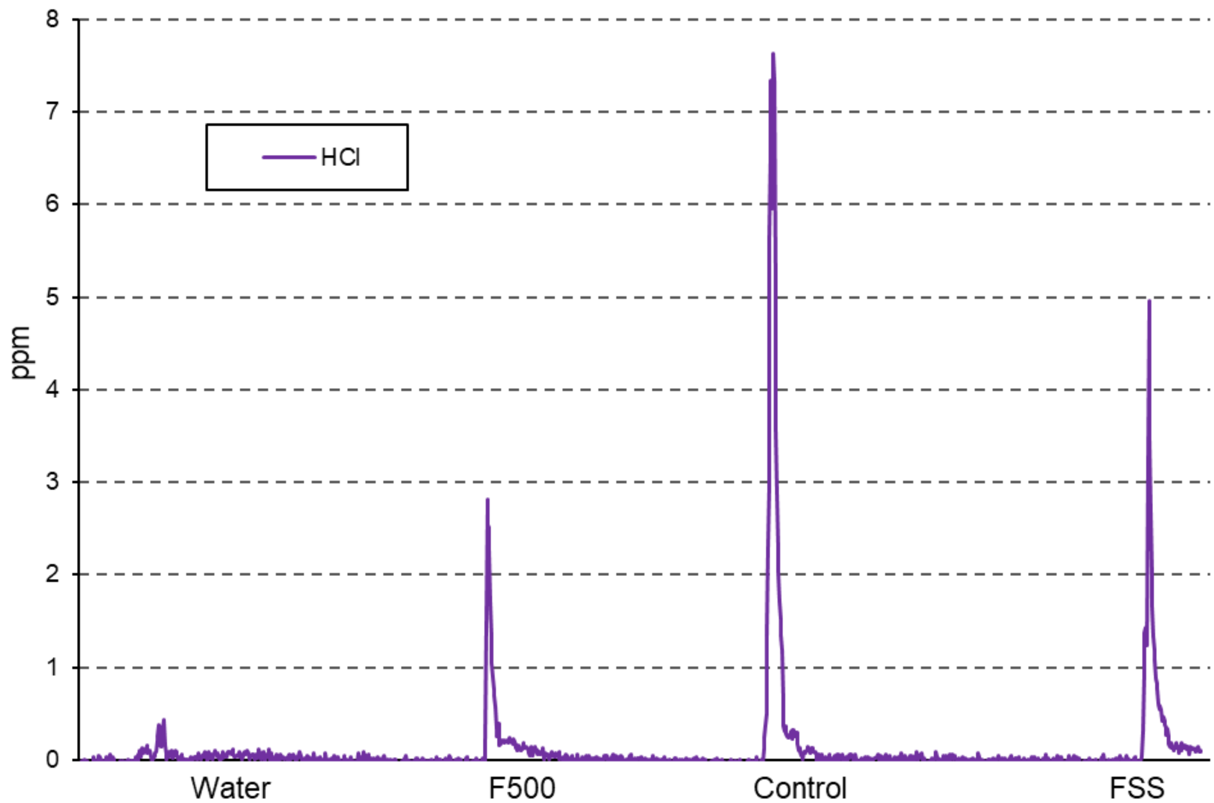

Figure 37. Graph of hydrochloride in ppm across all four tests.

VI. STAGE 2 CONCLUSION

Despite some variations in observed temperatures, the number of cells experiencing thermal runaway remained remarkably similar across all three EA tests. While surface temperature readings differed by up to 400°C, it's likely that actual cell temperatures within the battery remained quite close. Small discrepancies in thermocouple placement relative to flame jets and gas expulsion points likely account for the observed disparities in recorded high temperatures.

The trigger point for EA application – propagation of thermal runaway to five cells – highlights the potential for uncontrolled propagation within the cell cluster without intervention. Notably, the time it took for the fifth cell to undergo thermal runaway varied across tests, demonstrating the inherent unpredictability of inter-cell propagation. Minor adjustments in cell position and orientation relative to their neighbors can significantly influence both the pattern and speed of spread. Ensuring consistent progression to full thermal runaway in the control group (all 19 cells) underlines the severity of uncontrolled escalation in such scenarios.

Cells continued to heat up and go into thermal runaway in all three tests. This can be attributed to the current testing limitations, which do not allow for precise repositioning and direct aiming of the EA at flames. Significant residual heat may persist within cells despite no external signs like flames. This raises concerns about potentially insufficient EA application for thorough heat dissipation. This can be seen in Figure 34 where T5 is slowly increasing while all the surrounding cells are decreasing after the application of the EA.

Beyond pure evaporation and heat dissipation, additional factors appear to be at play in F500 and FSS, leading to significantly reduced cool-down times. Whether these involve active ingredients or other specific properties within the formulations requires further investigation to identify their rapid cooling mechanisms.

Overall, these findings showcase the efficacy of extinguishing agents in mitigating small-scale lithium-ion battery fires, especially F500 and FCL FSS with their rapid cool-down properties **(Table 2)**. However, further research is crucial to address reignition and potential propagation, optimize application strategies, and gain a deeper understanding of the differences between F500 and FCL FSS for small scale lithium-ion fires.

A. Table

Table 2

	Number of Cells entered into TR	Highest recorded Temp C	Quantity of EA used	Time of cool down below 120C° after last application of EA (mm:ss)
Water	7	1244	2.6 lbs	13:28
F500 (3%)	7	822	2.3 lbs	05:13
FCL FSS	6	916	2.25 lbs	04:35
Control	19	1170	NA	18:33[1]

Notes:

1. From last temperature peak for control group

VII. STAGE 3 TEST CONFIGURATION

The test was conducted in accordance with the "***Suggested Test Method for Evaluating Extinguishing Agents on Secondary Lithium-Ion Batteries Undergoing Thermal Runaway*" protocol.** This protocol was developed to replicate current industry standards for lithium-ion propagation testing as well as fire suppression certification testing outlined in *UL 9540A 4th edition* and *UL 711 8th edition*. Testing protocol was adjusted based upon lessons learned from Stage 2 Testing. Instead of having a fixed suppression nozzle as in Stage 2 Test, a trained firefighter was used the extinguishing canister as they would in a real-world scenario.

A. Equipment

Stage 3 increased the size of the batteries up to a 960 Wh Electric Bike (E-Bike) battery. This battery is one of the largest on the current market. It is made up of 48x18650 NMC cells. The E-Bike batteries were purchased from a local bike shop who specializes in electric bikes, trikes, and scooters.

Each battery was outfitted with one PLM-203/10-P flexible Kapton film heater. The heater was installed internally between the cells and the battery metal casing with wires routed out of the gasket between the front face plate and the body.

Type K thermocouples (24 gauge) were attached internally and externally to monitor temperatures and heaters **(Figure 38 through 41)**. Lastly, a 2.5-gallon stainless steel fire extinguisher was used for each of the three extinguishing agents. Each extinguishing agent had its own canister to prevent any cross contamination between agents.

B. Installation

The E-bike battery was placed on the ground in the middle of the burn test chamber. All thermocouples were connected to data acquisition and heaters connected to power. A firefighter stood just outside the test chamber waiting to apply the EA to the battery once propagation had occurred.

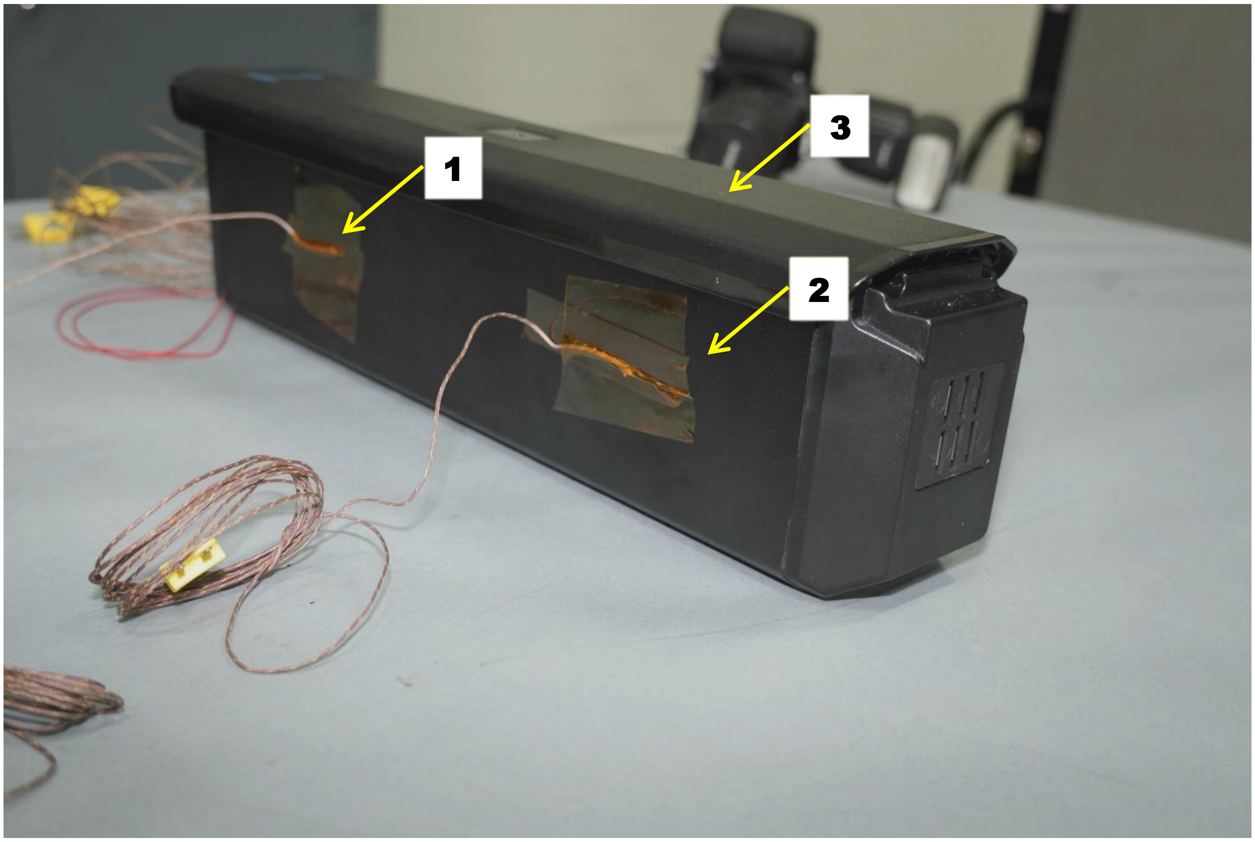

Figure 38. E-Bike battery.

Notes:

1. Thermocouple 7
2. Thermocouple 8
3. Thermocouple 3, internal

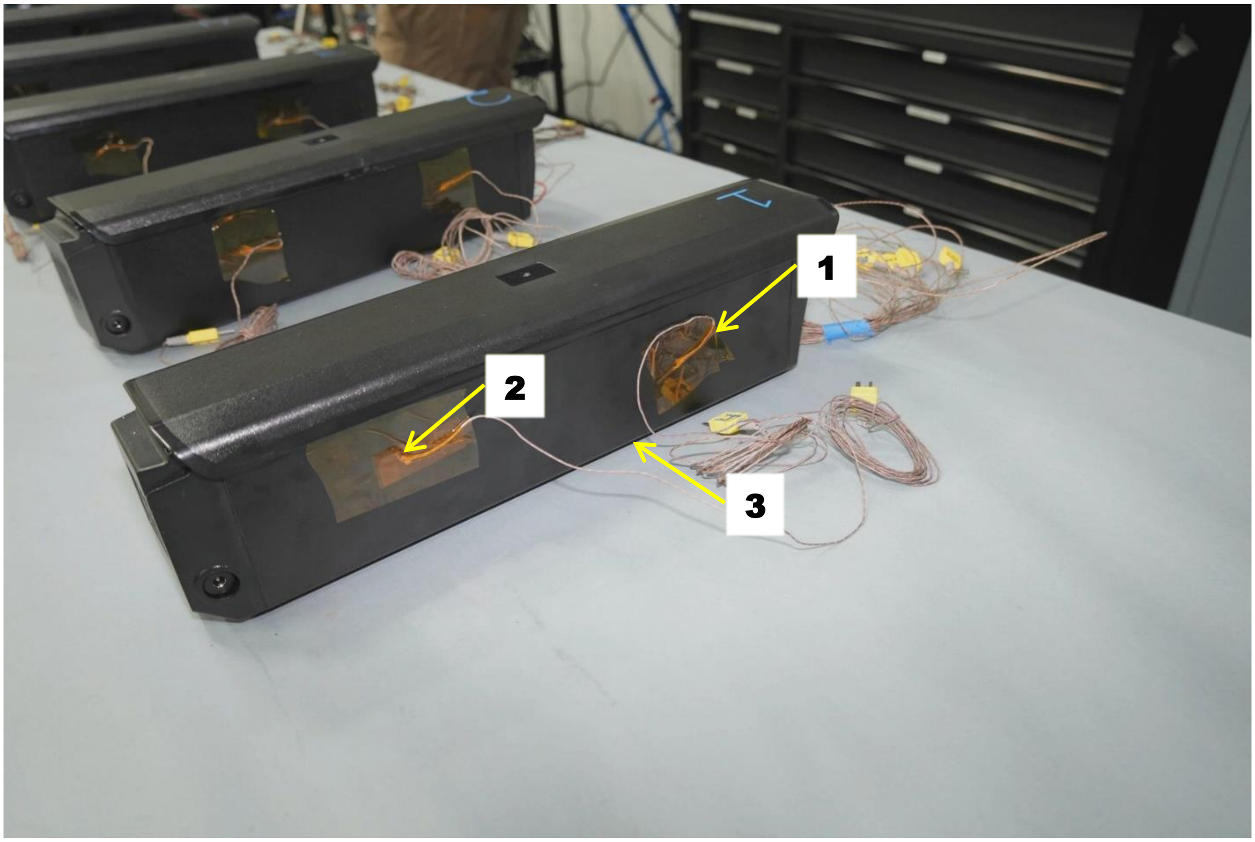

Figure 39. Side view of the E-Bike batteries.

Notes:

1. Thermocouple 5
2. Thermocouple 6
3. Thermocouple 2, internal

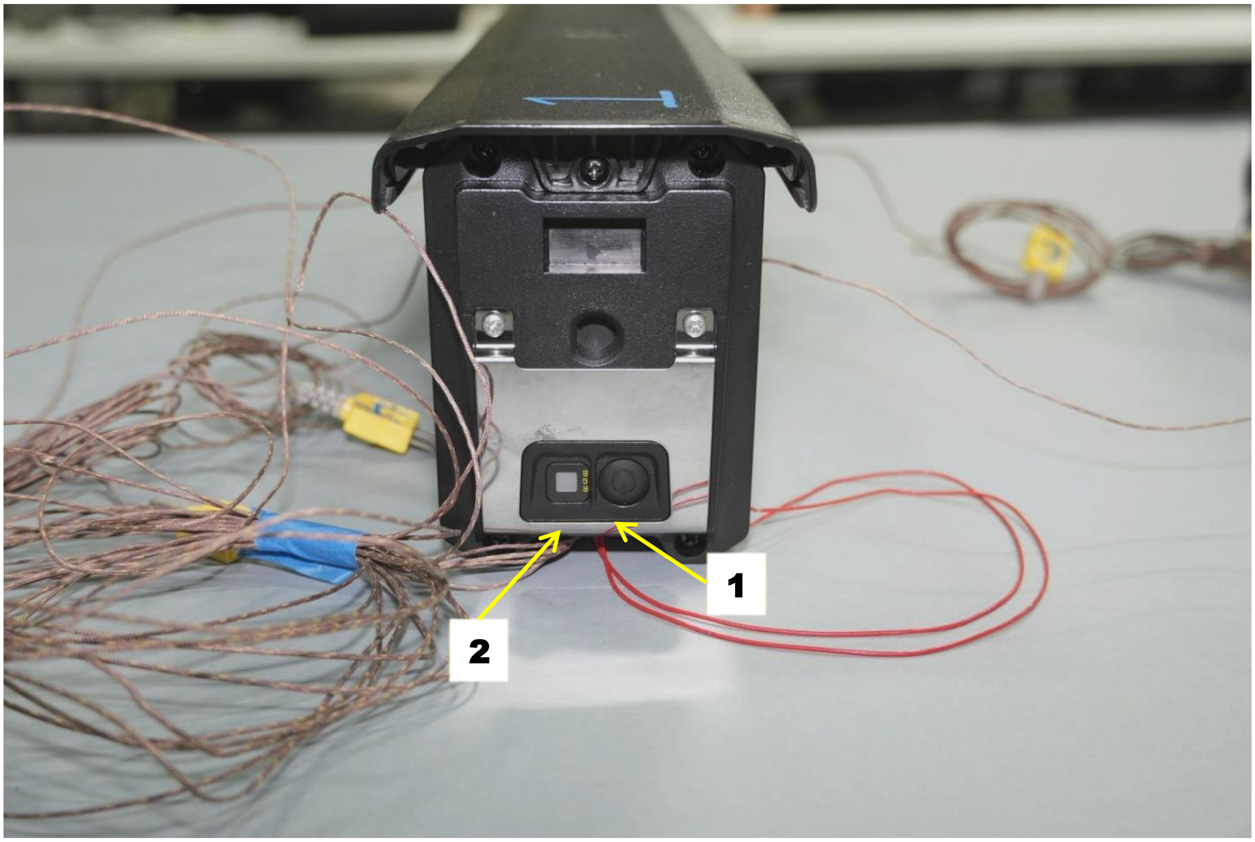

Figure 40. Front view of the E-Bike battery.

Notes:

1. Heater location, internal
2. Thermocouple 1A and 1B located underneath the heater

Figure 41. Bottom label of the E-Bike battery, 48V, 20 Ah, 960Wh.

C. Instrumentation

Except for the E-Bike charger, the instrumentation used for this test was calibrated and used in accordance with SAFE Labs' ISO 17025 accreditation. The instrumentation for this test consisted of the equipment listed below. The E-Bike Batteries were charged with the manufacturers recommended charger. All the same equipment was used that was described in section IV.A Equipment. The charger was the only difference.

D. Procedure

The initiating film heater was set to max heating at 120 V and .7 A. The heaters were allowed to stay on until thermal runaway was achieved. Extinguishing agents (EA) were only applied after propagation to multiple cells was observed. A firefighter deployed the EA by squeezing the handle of the canister until all visible flames were extinguished (approximately 5-8 seconds). Cells were monitored for reignition and if reignition was observed, the EA was deployed again until the flames were no longer visible. Temperatures were monitored until all thermocouples were trending downward and below 120 C^{o}.

VIII. STAGE 3 RESULTS

The first observations of thermal runaway for each test are referred to as t=00:00 (mm:ss), throughout this report. At the start of the test, the outdoor temperature was 68.3 degrees Fahrenheit with approximately 53% relative humidity and a 2-mph wind speed.

A. Water

The first cells went into thermal runaway at t=00:00. Water was first applied at t=00:31 after multiple cells went into thermal runaway. Water was applied for a duration of 6 seconds. Reignition was observed at t=01:05. Water was applied for a second time at t=02:25 for a duration of 7 seconds. The battery module reignited for a second time at t=05:08 and at t=05:49 water was applied for the third and final time for a duration of 28 seconds. Progression of the test can be seen in **Figure 42 through Figure 57**. Post photos can be seen in **Figure 58 through Figure 62** with a temperature graph shown in **Figure 63**.

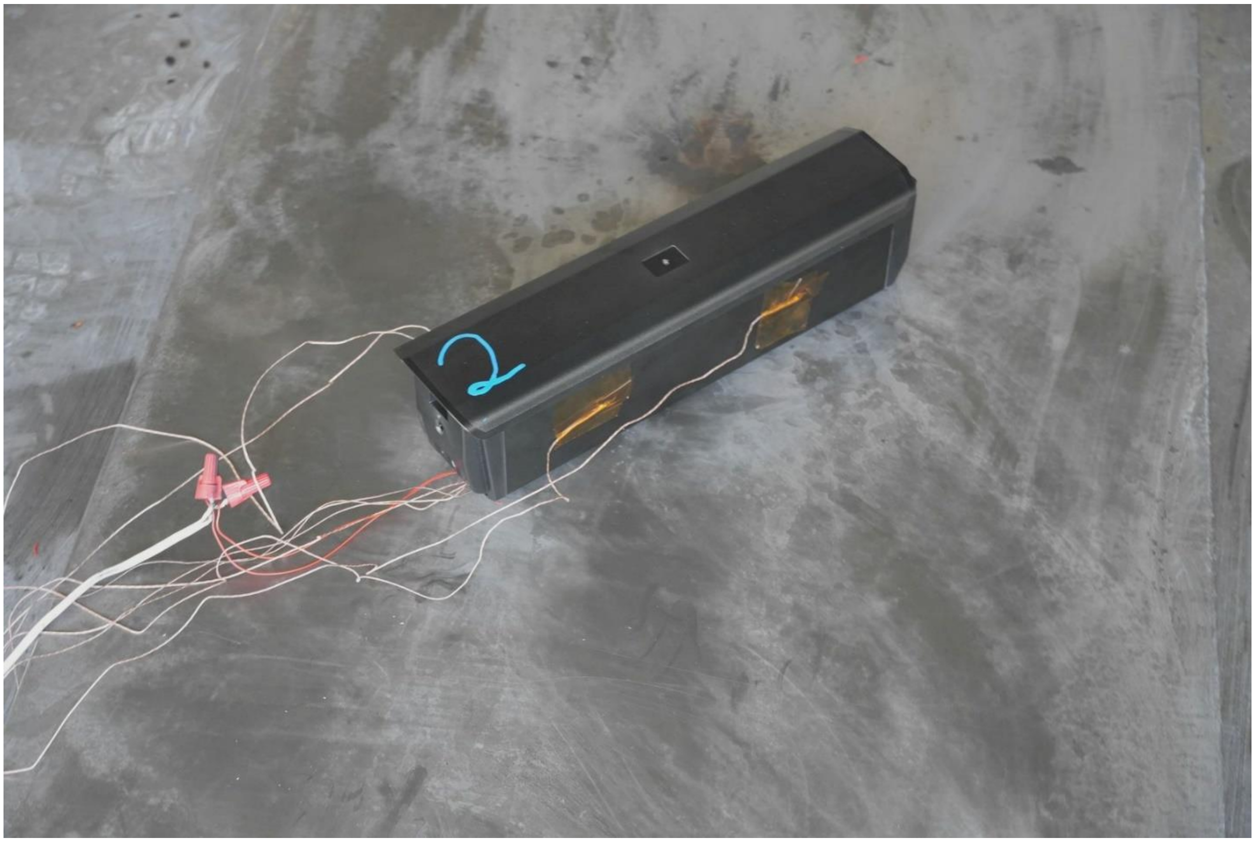

Figure 42. Start of the test for water as an extinguishing agent.

Figure 43. Right before the first cell experienced thermal runaway.

Figure 44. First cell experienced thermal runaway.

Figure 45. Progression view of multiple cells experiencing thermal runaway.

Figure 46. The E-Bike battery experiencing propagation from cell to cell.

Figure 47. Water being applied to the battery.

Figure 48. End of the first application of water.

Figure 49. Battery continues to smoke and off gas after water was applied.

Figure 50. Reignition.

Figure 51. Post reignition.

Figure 52. Water applied after reignition.

Figure 53. End of the second application of water, 7 seconds.

Figure 54. Second reignition.

Figure 55. Third time applying water.

Figure 56. End of third application of water.

Figure 57. No visible smoke from battery.

Figure 58. Photo of the E-Bike battery after third application of water.

Figure 59. Close-up photo of the E-Bike battery after the third application of water.

Figure 60. Right side of the E-Bike battery.

Figure 61. Left side of the E-Bike battery.

Figure 62. Front of the E-Bike battery.

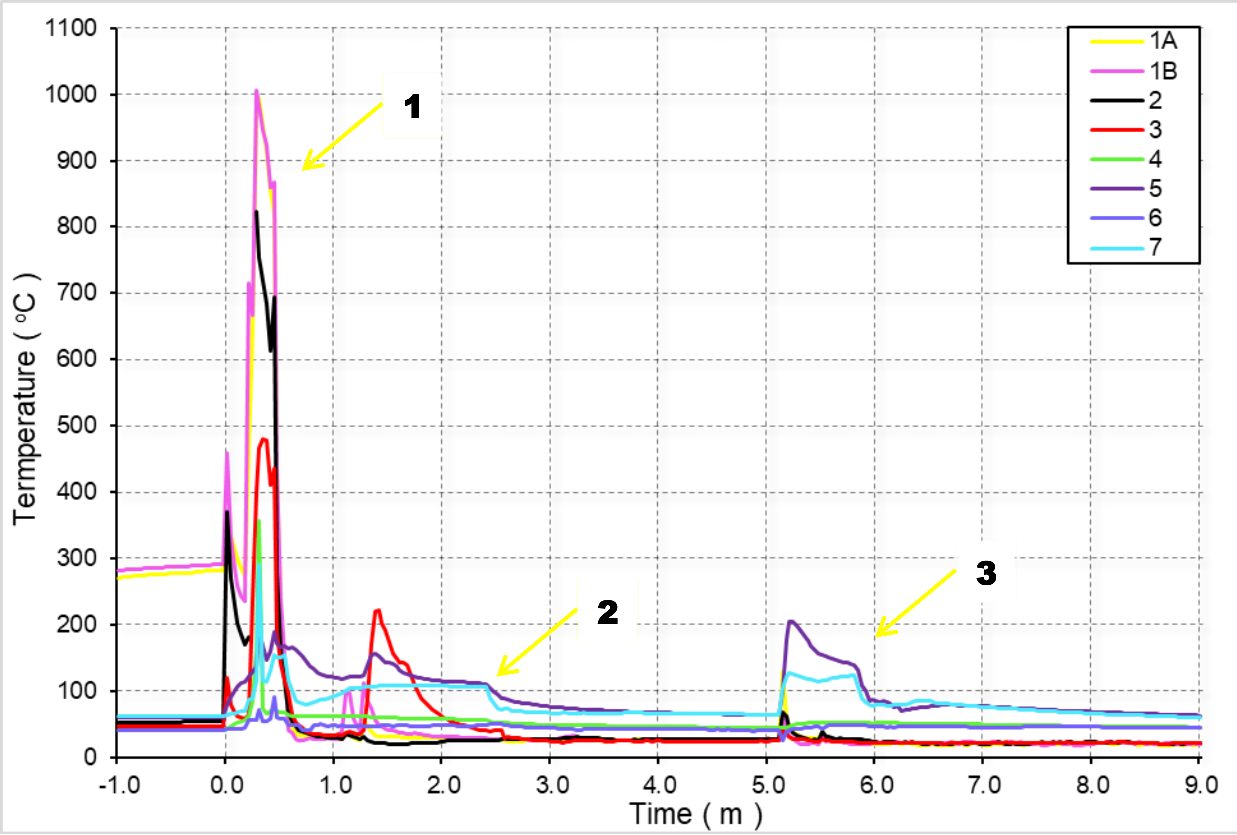

Figure 63. Temperatures of the E-Bike battery with water applications.

Notes:

1. First application of water
2. Second application of water
3. Third application of water

B. F500

After the first cell went into thermal runaway at t=00:00, it took several minutes for propagation to occur. After multiple cells had undergone thermal runaway, at t=05:56 F500 was applied for a duration of 8 seconds. Smoke and gas were observed from the battery for several minutes following the application of F500 but no reignition was observed. Below a progression of the test can be seen in **Figure 64 through Figure 71**. Post photos can be seen in **Figure 72 through Figure 75** with a temperature graph shown in **Figure 76**.

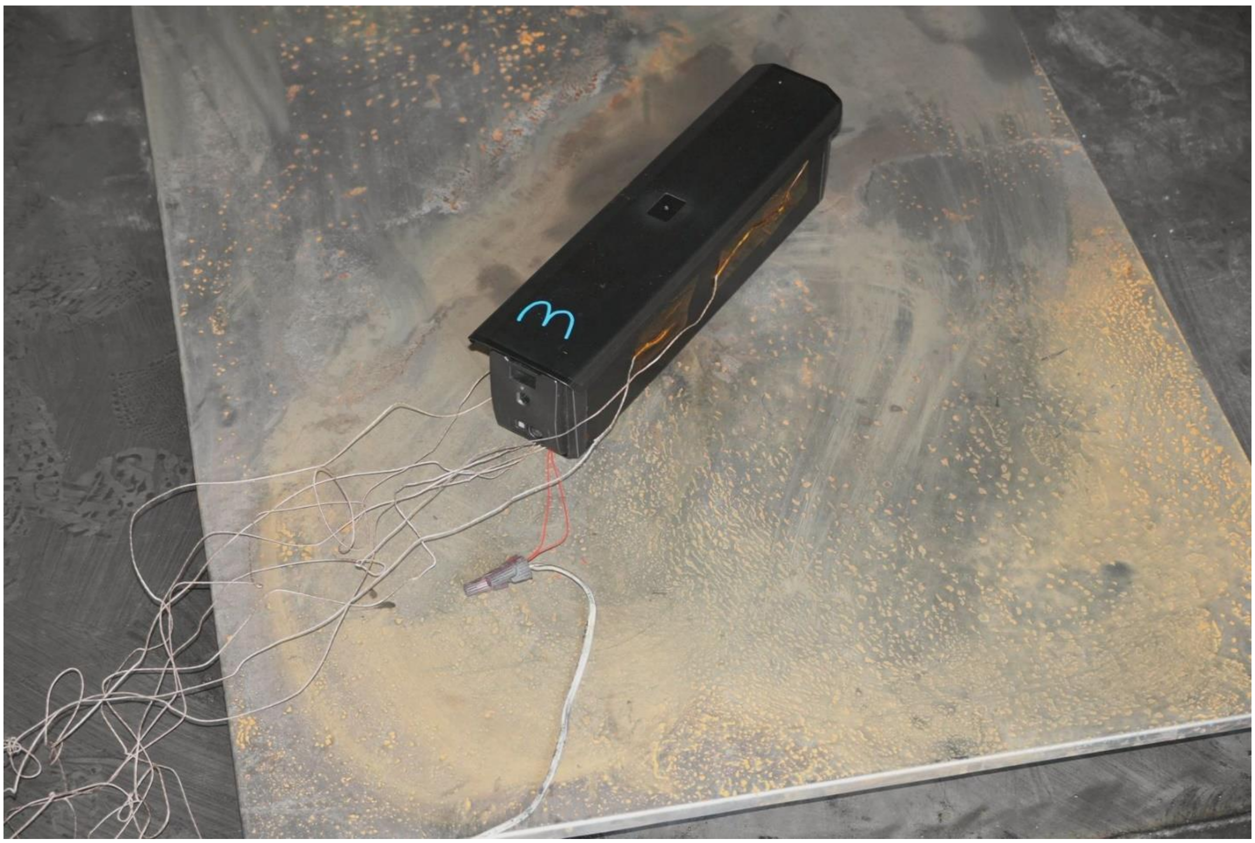

Figure 64. View of test set-up where F500 was used as an extinguishing agent.

Figure 65. View immediately before the first cell experienced thermal runaway.

Figure 66. Thermal runaway.

Figure 67. E-Bike battery still off gassing and smoking.

Figure 68. Cell to cell propagation within the battery.

Figure 69. Smoke and gas from propagation.

Figure 70. Application of F500.

Figure 71. No smoke or gas visible from the battery post application of F500.

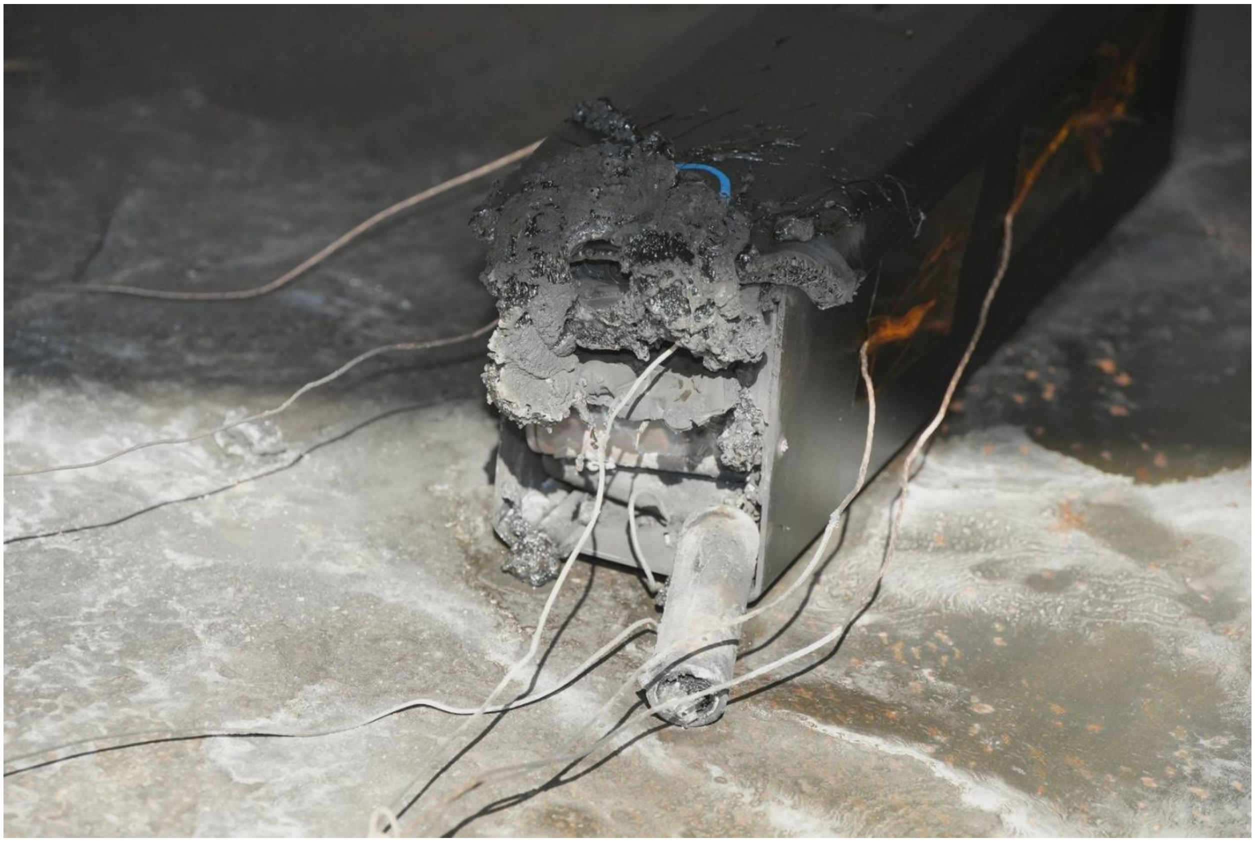

Figure 72. Post photos of the front of the E-Bike battery.

Figure 73. Right side of the E-Bike battery.

Figure 74. Left side of the E-Bike battery.

Figure 75. Close-up view of the front of the E-Bike battery.

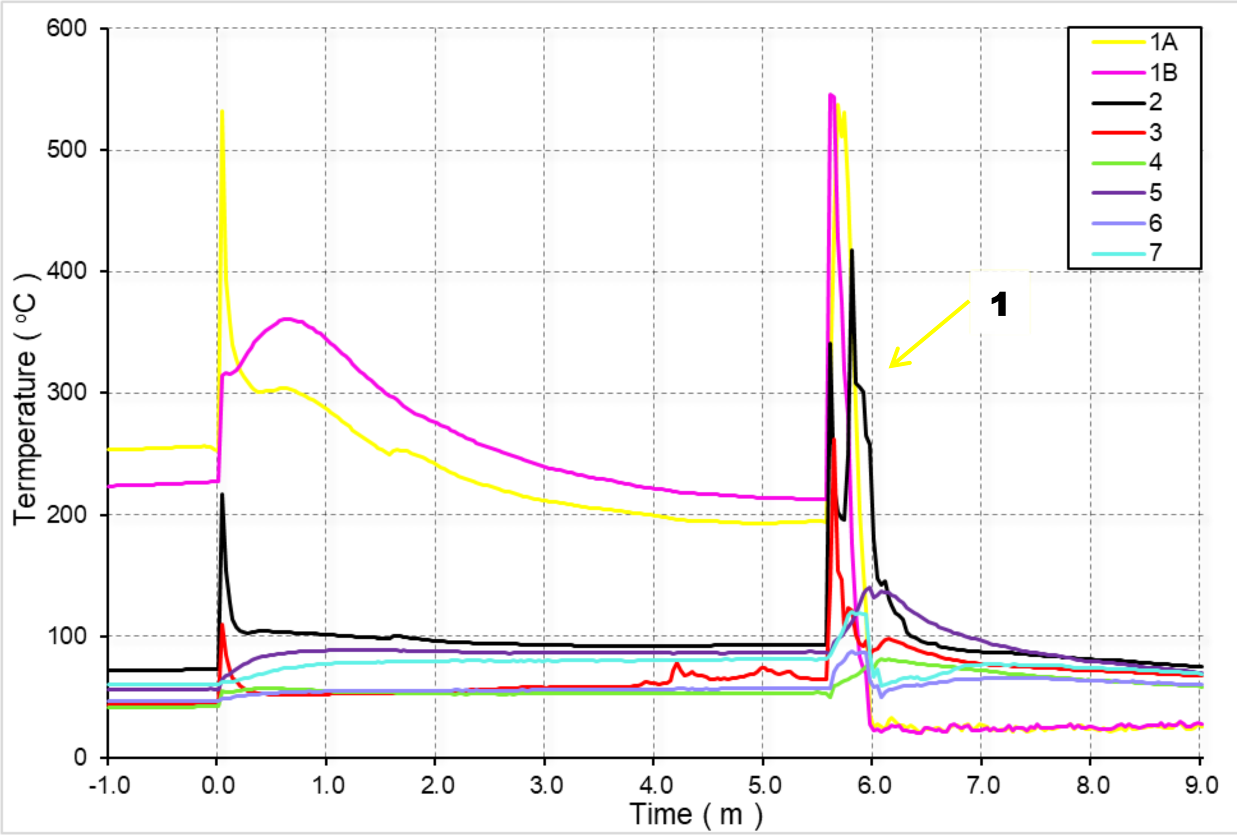

Figure 76. Temperatures of with F500 as an extinguishing agent.

Notes:

1. Application of F500

C. FCL FSS

Several cells entered thermal runaway within the first couple minutes of the test. At t=02:50 FCL FSS was applied for a duration of 4 seconds. Smoke and gas were observed from the battery for only a few seconds following the application of FCL FSS but no reignition was observed. Below a progression of the test can be seen in **Figure 77 through Figure 86**. Post photos can be seen in **Figure 87 through Figure 89** with a temperature graph shown in **Figure 90**.

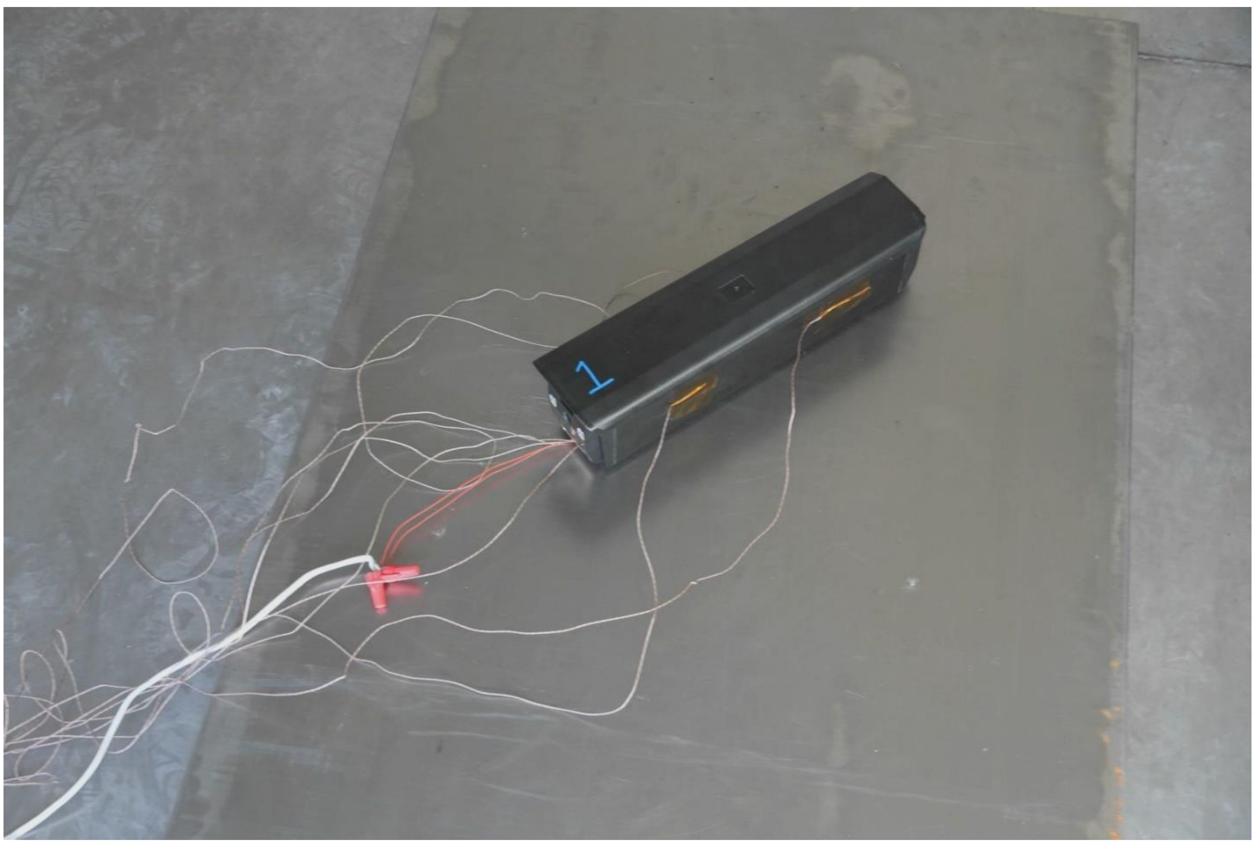

Figure 77. Before the start of the test for FCL FSS as an extinguishing agent.

Figure 78. View immediately before the first cells experienced thermal runaway.

Figure 79. Thermal runaway.

Figure 80. Continued flame.

Figure 81. Propagation to other cells within the E-Bike battery.

Figure 82. View of thermal runaway before the application of FCL FSS.

Figure 83. Start of the application of FCL FSS.

Figure 84. End of application of FCL FSS.

Figure 85. Small amount of smoke visible after application of FCL FSS (yellow arrow).

Figure 86. No smoke or gas visible.

Figure 87. Photo of E-Bike battery post application of FCL FSS as an extinguishing agent.

Figure 88. Close-up view of E-Bike battery.

Figure 89. Front picture of E-Bike battery.

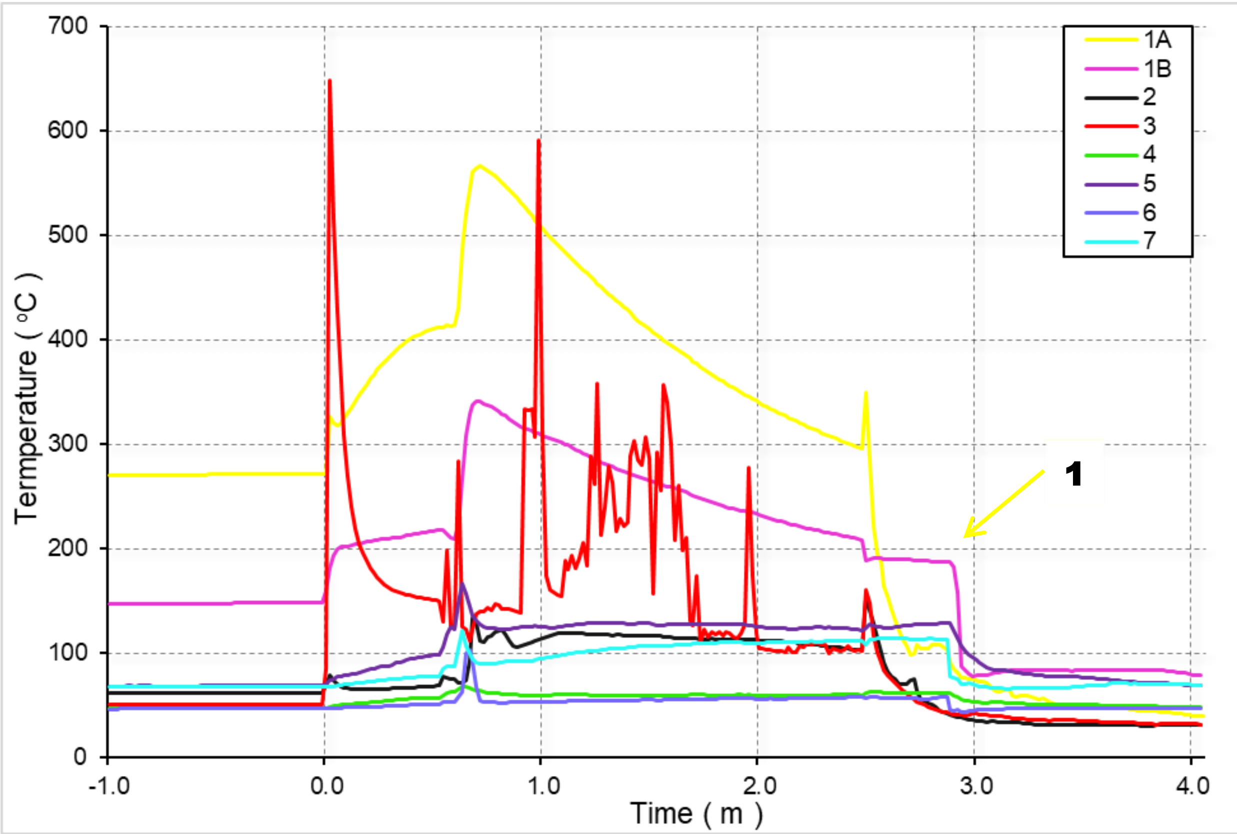

Figure 90. Temperatures of with FCL FSS as an extinguishing agent.

Notes:

1. Application of FCL FSS

D. Control

During the control group the same ignition source was used as the other three iterations of the test. This time the battery cells were allowed to continue to propagate without intervention. A total of 48 cells went into thermal runaway between t=00:00 and t=31:20. The force of the cells venting pushed the E-Bike battery around the test chamber and a significant amount of debris was scattered. Holes were burned through the metal casing of the battery as can be seen in **Figure 106** and **Figure 108**. Progression of the test can be seen in **Figure 91 through Figure 103**. Post photos can be seen in **Figure 104 through Figure 110** with a temperature graph shown in **Figure 111**.

Figure 91. Picture before the test for the control group.

Figure 92. Immediately before thermal runaway.

Figure 93. View of thermal runaway.

Figure 94. Progression photo of control battery.

Figure 95. Progression photo of control battery with sustained flame.

Figure 96. Progression photo of control battery experiencing thermal runaway.

Figure 97. Control battery begins to move from force of cells going into thermal runaway.

Figure 98. Control moves to the right edge of the test stand.

Figure 99. Progression photo of control battery.

Figure 100. Each additional cell going into thermal runaway moves the whole battery.

Figure 101. Further view of progression of the control battery.

Figure 102. Final cells going into thermal runaway.

Figure 103. End of control test.

Figure 104. Post photos of the control burn.

Figure 105. Debris from the inside of the E-Bike battery.

Figure 106. Metal case of the battery with visible holes.

Figure 107. Close-up of the debris from the inside of the battery.

Figure 108. View of E-Bike case with visible holes post control test.

Figure 109. View of E-Bike case with no cells visible within the battery.

Figure 110. Dents visible on the opposite side of the metal case.

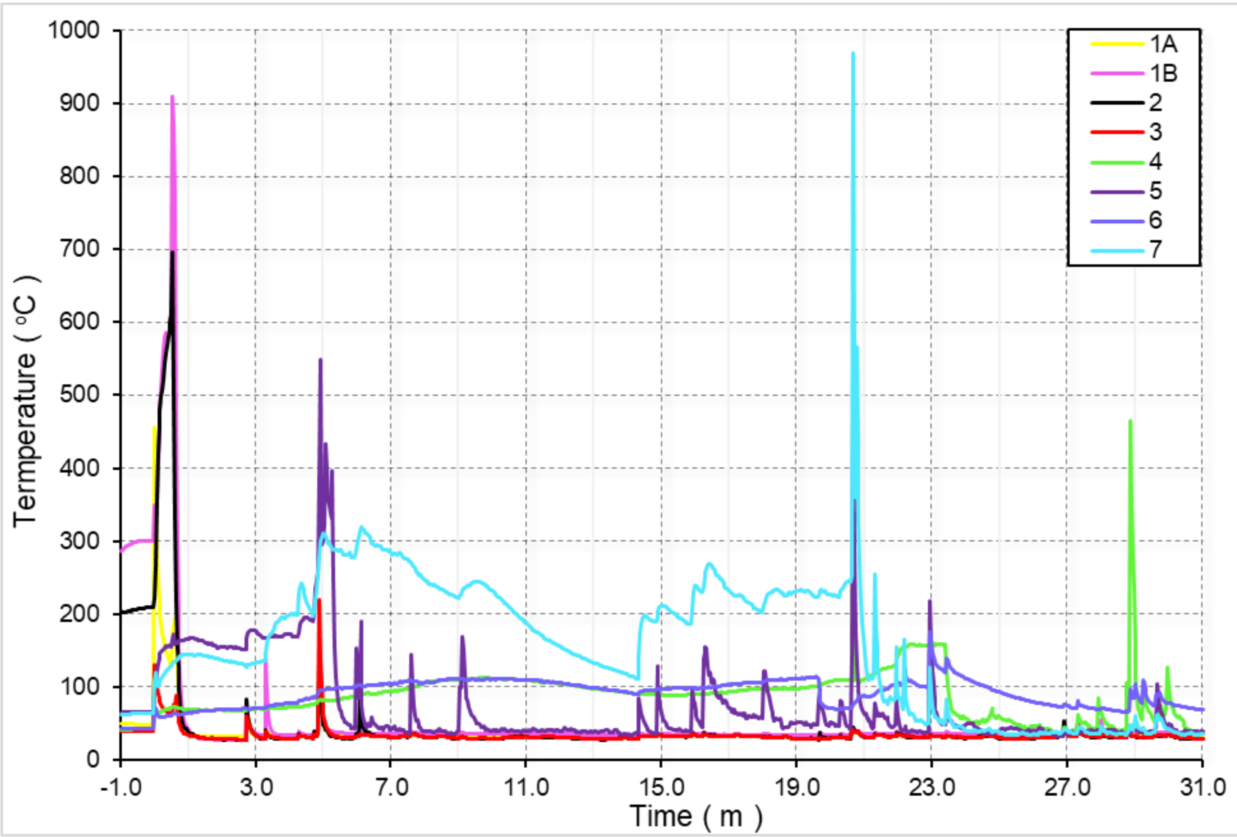

Figure 111. Temperatures of the control burn.

E. Gas Data

Gasses generated from the test set up were monitored with real time Fourier Transform Infrared Spectrometry (FTIR). Methane, ethylene, CO, CO2, and HCl were validated to be present at levels high enough to be detected **(Figure 112 through Figure 114)**.

Lastly, it was observed that hydrogen was present at extremely low levels during each of the four tests but was not significantly different than background hydrogen levels in the atmosphere.

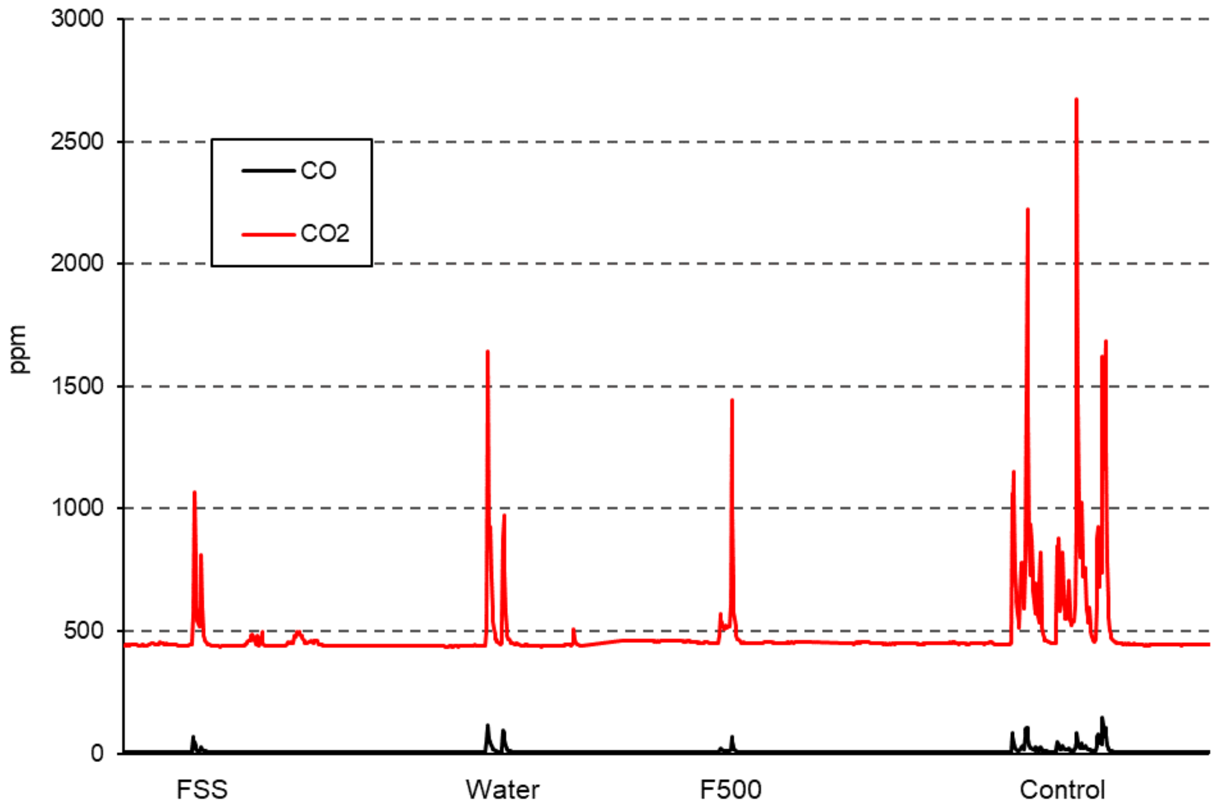

Figure 112. Graph of CO and CO_2.

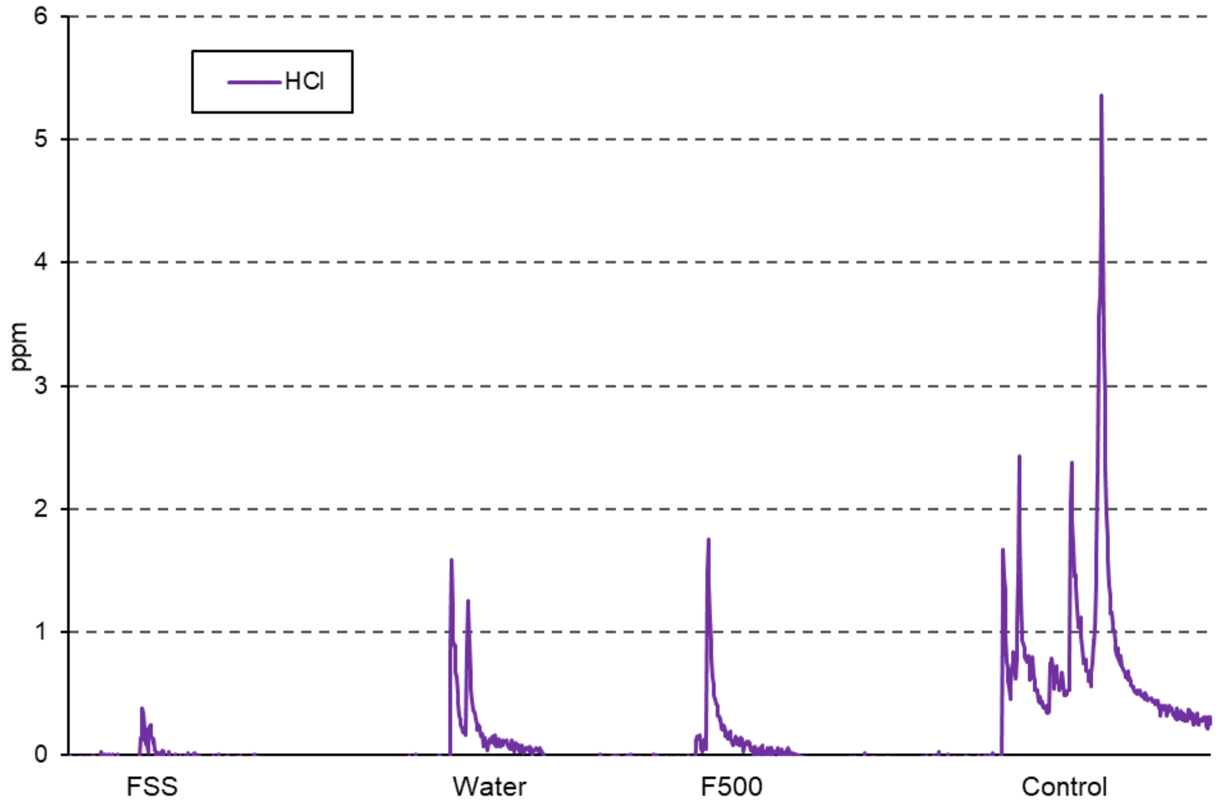

Figure 113. Graph of HCL.

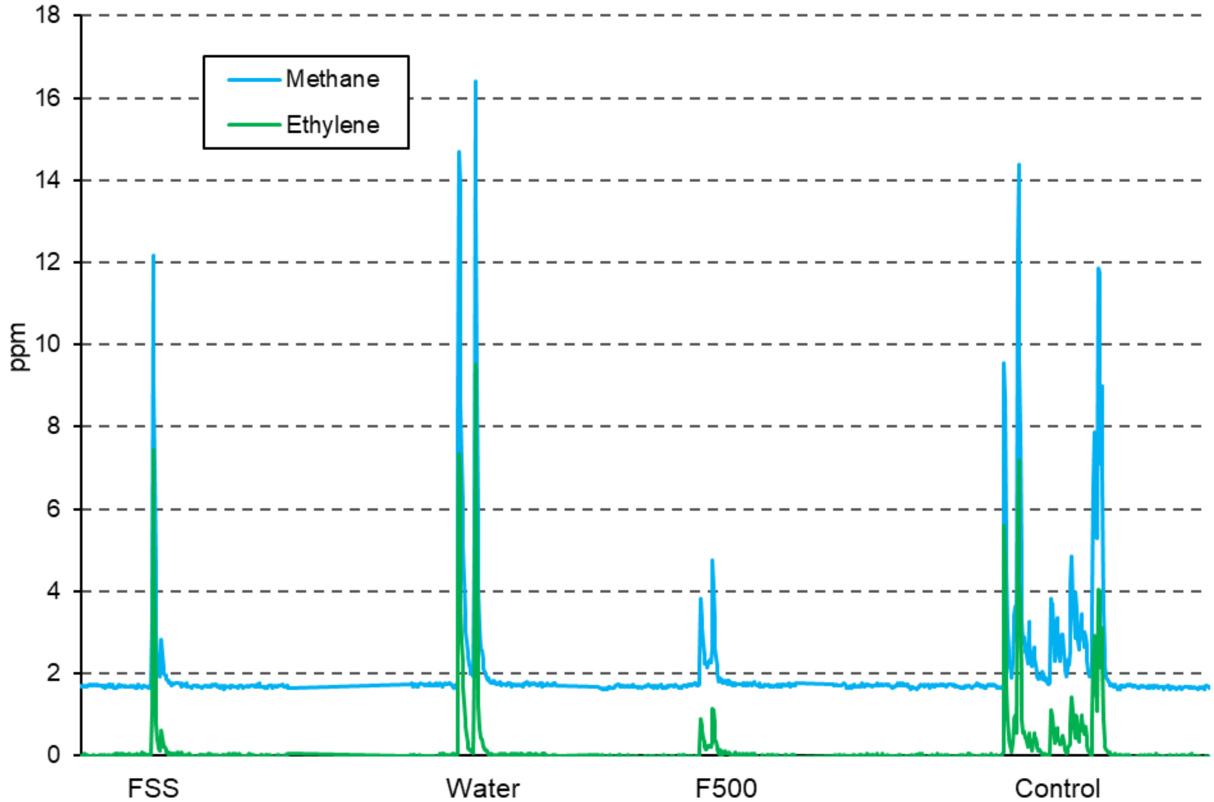

Figure 114. Graph of hydrocarbons.

IX. STAGE 3 CONCLUSIONS

Scaling up to a larger 960 Wh E-Bike battery in Stage 3 served not only to amplify differences between EA performance, but also to bring us closer to a real-world fire scenario. In this regard, several key variables were chosen to mirror the observations and decision-making processes of a firefighter. By focusing on these firefighter-centric variables, Stage 3 aimed to bridge the gap between laboratory testing and practical application.

First responders gauge the effectiveness of their intervention by the rate at which a fire cools. It is noteworthy that FCL FSS demonstrated an order of magnitude faster cool-down time compared to F500, highlighting its potential for rapid fire control in real-world settings **(Table 3)**.

Another crucial variable is smoke generation and visibility. Firefighters rely on visibility to assess fire progression and determine their next steps. Reflecting this real-world approach, Both F500 and water experienced prolonged smoke even though they both extinguished the E-Bike fire.

It is crucial to consider potential application variables introduced by the firefighter in Stage 3. Application times varied, with F500 taking significantly longer than FCL FSS despite using less product by weight. This likely reflects inherent differences in how firefighters operate extinguishers, potentially influencing dose and coverage.

Firefighter observations provided valuable insights by mimicking real-world decision making and identifying the natural endpoint for applying the agent. Although acknowledging the limitations of subjective parameters is essential, incorporating firefighter perspectives enriched the understanding of fire control dynamics and paves the way for improved testing methodologies in future investigations.

As the test scale increases, differentiating the extinguishing agents becomes easier. Therefore, extensive larger scale testing is crucial to comprehensively evaluate the efficacy and nuanced differences between each agent. Additionally, future investigations should explore various deployment techniques to refine and optimize practical application scenarios.

Table 3

	Starting Voltage VDC	Highest recorded Temp C	Quantity of EA used	Total time EA was sprayed	Number of Applications of Extinguishing Agent	Time to cool down below 120 C^O from first application	Smoke observations after final application of EA
Water	54.12	1005	>10 lbs	41 sec	3	05:38	02:29 [1]
F500 (3%)	53.77	545	1.9 lbs	8 sec	1	00:46	03:15
FCL FSS	54.14	648	2.7 lbs	4 sec	1	00:02	00:28
Control	54.10	969	NA	NA	0	30:00+ [2]	All Cells propogated

Notes:

1. After third application of water
2. Time from when an EA would have been applied compared to other tests