UL 9540A Test Method for Evaluating Thermal Runaway Fire Propagation in Cell Energy Storage Systems, Third Edition

Cell Level Test Report
Model V6.0
“Prussian Blue Cell”

Prepared by UL LLC for Natron Energy, Inc.
Issued: December 23, 2019
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Revision notes:

January 14, 2020

- **Page 17, Figure 16 was incorrectly labeled;**
- **Page 24, The hydrogen, carbon monoxide, carbon dioxide, and THC quantification represents 100% of the gas mixture, not just hydrogen & carbon dioxide.**

July 8, 2020 (ULProject# 4789542457)

- **The V6.0 cell capacity rating has been increased from 4.3Ah to 4.6Ah. The increased capacity is a result of the end point cutoff voltage discharge specification being reduced from 1.0V to 0V. This change in end point voltage does not affect the test results as the cell was tested at 100% SOC and the charge voltage rating has not changed.**
  No additional testing considered necessary to update the report to reflect the new capacity rating. The test results portion of this report will not be modified to reflect the new capacity because at the time of the test, this was the recorded value. This revision is to be consistent with the UL1973 certification of the V6.0 cell under UL file number MH63828.
- **Page 4, updated nominal capacity from 4.3Ah to 4.6Ah**
- **Page 5, updated nominal capacity from 4.3Ah to 4.6Ah**

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Introduction

UL defines thermal runaway as follows:

THERMAL RUNAWAY – The incident when an electrochemical cell increases its temperature through self-heating in an uncontrollable fashion. The thermal runaway progresses when the cell's generation of heat is at a higher rate than the heat it can dissipate. This may lead to fire, explosion and gassing.

Scope

The test methodology in this document evaluates the fire characteristics of a cell energy storage system that may undergo thermal runaway.

The data generated will be used to determine the fire and explosion protection required for an installation of a cell energy storage system intended for installation, operation and maintenance in accordance with the International Fire Code (IFC), the Fire Code, NFPA 1, the National Electrical Code, NFPA 70, the National Electrical Safety Code (NESC), IEEE C2, NFPA 855, and other energy storage system codes, and the manufacturer's installation instructions.

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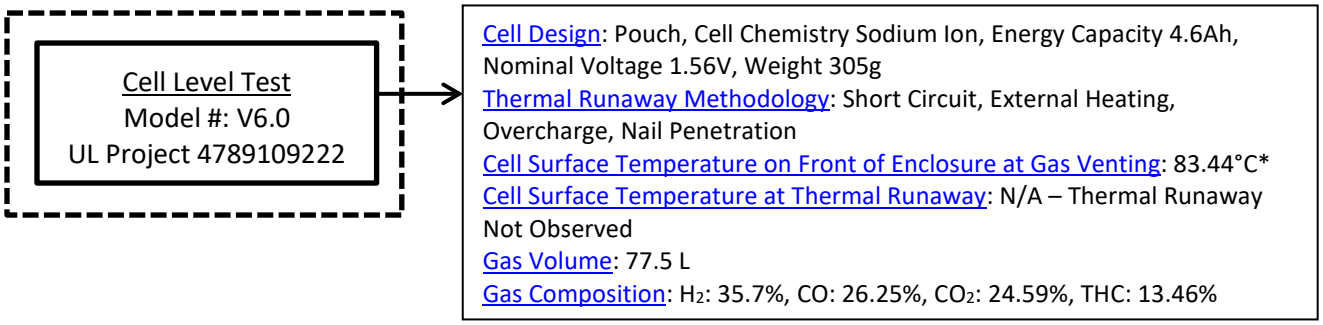
Summary of UL 9540A Test Results



*Cell surface temperature measured during test #6.

For each of the 4 test methods implemented to induce thermal runaway, no thermal runaway was observed with the Natron Energy, Inc model V6.0 cell under test.

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UL 9540A Test Report
for
Natron Energy, Inc.

Cell Energy Storage Description

Cell Energy Storage System Configuration

Table 1 – Product details

Cell	
Manufacturer	Natron Energy, Inc
Model Number	V6.0
Chemistry	Sodium Ion
Electrical Ratings	1.56V 4.6Ah
Dimensions	194 mm x 246 mm x 5.1 mm
Cell Weight	305g
Construction Description	Pouch
UL Certifications	ANSI/CAN/UL 1973, BBGA2/8 File MH63828
	
Figure 1 – Photo of cell	

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Cell Level Test Description

Sample Preparation

Six batteries were prepared according to the requirements specified in UL 9540A Section 6.1.

Cell Conditioning and Stabilization (Section 8.1.4)

The batteries were subjected to a cycle of pre-charge, discharge, charge, discharge, and then final charge. The batteries were charged to 100% state of charge (SOC) per the manufacturer's instructions, summarized in Table 2. Charging profiles are included in Figures 2.

Table 2 – Conditioning parameters

Charging		Discharging	
Current (CC)	80 A	Current (CC)	200 A
Voltage (CV)	1.81 V	Cutoff Voltage	1 V
Cutoff Current	Not Specified		
Charging Time	6 minutes		

The ambient temperature of the space during cell conditioning was maintained within 25±5°C (77±9°F) and 50±25% RH.

Final charge capacity for each cell is presented in Table 3. Individual charge/discharge profiles are included in the Figures 2 & 3 below.

Table 3 – Final cell charge capacities

UL Cell Number	Natron Cell Number	Test Number	Nominal Final Charge (Ah)
1	C14514	1	4.3
2	C14511	2	4.3
3	C13935	3	4.3
4	C14375	4	4.3
5	C14512	5	4.3
6	C13914	6	4.3

The batteries were charged per manufacturer specifications. At a room ambient of 25°C, charging voltage is 1.81V, at 80A. When the 6 minute charge time was reached, charging was stopped.

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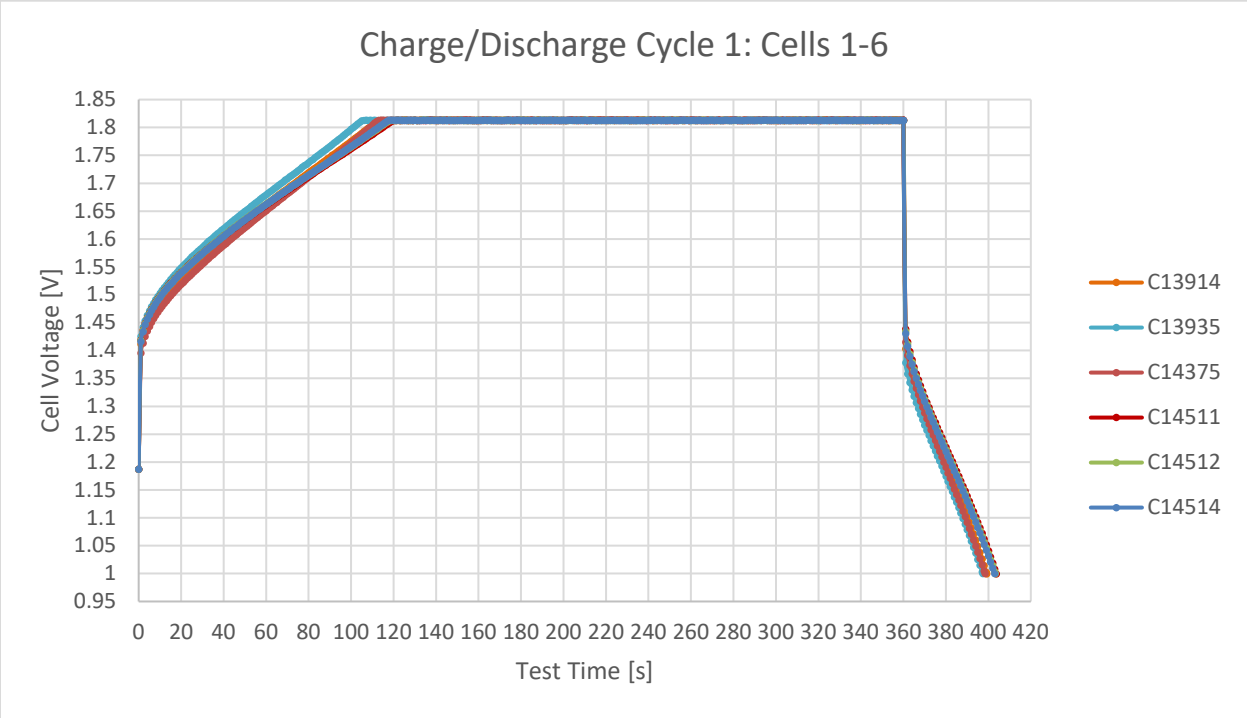

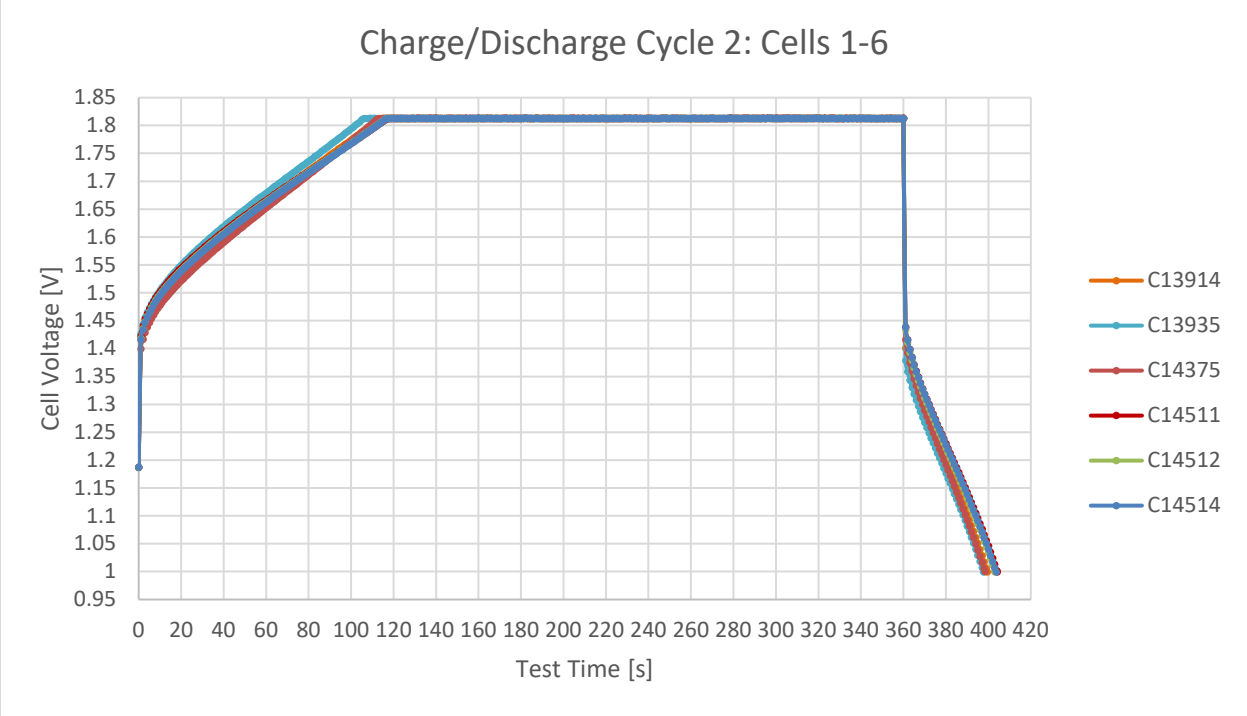

Figures 2-3 – Plots of cell charge and discharge data

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Test Instrumentation

Each initiating cell was instrumented with 5 Type K thermocouples according to the layout illustrated in Figures 4-5.

Table 4 – TC Locations

TC #	Location
TC 1	Top Middle of Cell
TC 2	Bottom Middle of Cell
TC 3	Side of Cell
TC 4	Positive Terminal
TC 5	Expected Vent Location

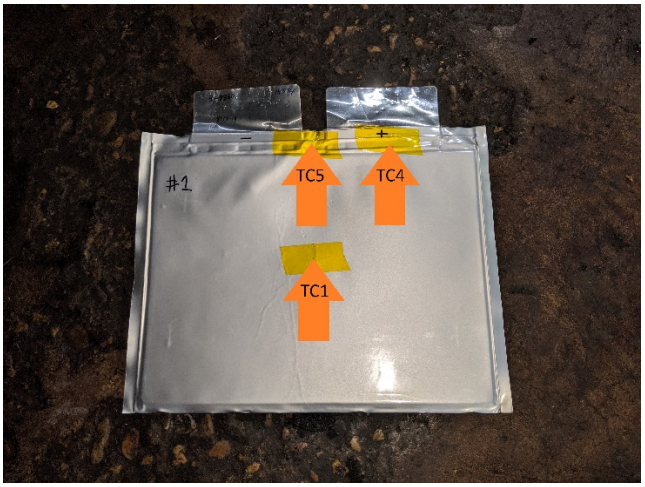

Figure 4 – Initiating thermocouple locations

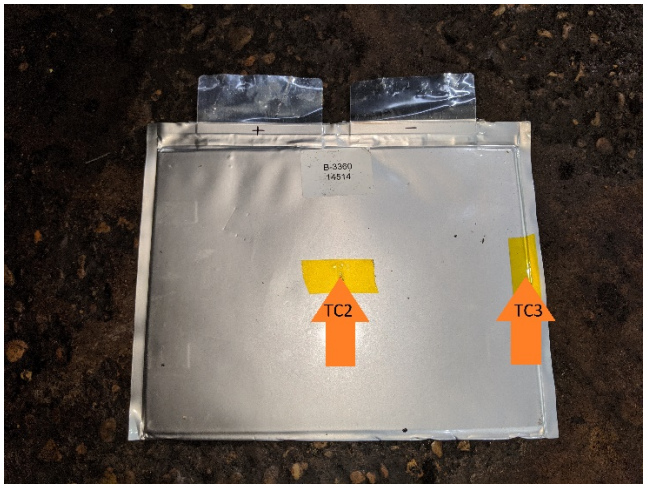

Figure 5 – Additional view of thermocouple locations

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Thermal Runaway Methodology

The propensity for a cell to experience thermal runaway was examined through several different methodologies covering mechanical, thermal, and electrically induced events. The methods and parameters below were intended to place the most stress on the cell to attempt inducing thermal runaway. Thermal runaway is defined as the incident when an electrochemical cell increases its temperature through self-heating in an uncontrollable fashion. The thermal runaway progresses when the cell's generation of heat is at a higher rate than the heat it can dissipate. This may lead to fire, explosion and gassing.

A summary of the evaluated thermal runaway methodologies is included in Table 5.

Table 5 – Thermal Runaway Methodologies

Test	Stress	Methodology	Test Parameters
1	Electrical	Short Circuit	Direct short across positive and negative terminals
2	Thermal	External Heating	4-7°C/min with no holding temperature
3	Electrical	Overcharge	Constant current, voltage increased 1V/min
4	Mechanical	Nail Penetration	Through external casing from short side through internal cell
5	Electrical	Overcharge	Constant current, voltage increased 1V/min
6	Electrical	Overcharge	Gas Composition, same methodology as test 5

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Cell Level Test Results

Test 1 – Demonstration of Thermal Runaway Propensity by Short Circuit

Table 6 – Test initiation details

Test Initiation Details	
Test Date	2019/09/18
Test Start Time	08:41 AM
Initial Lab Temperature	20.5°C
Initial Relative Humidity	46% RH

Figure 6 shows the surface temperatures measured during the test, in which no venting nor thermal runaway was observed. The open circuit voltage prior to the start of the test was 1.77V. A contactor was closed to complete the circuit, at the initiation of the test. The current measured at the initial short circuit was approximately 796A. The current across the short was drastically decreasing through the test. No venting or thermal runway was observed based on visual observations and temperature measurements of the cell enclosure. All temperatures were reducing after the initial short circuit event. At the end of testing, when current was 0 and temperatures were returning to near ambient, at approximately 27 minutes, the contactor was opened.

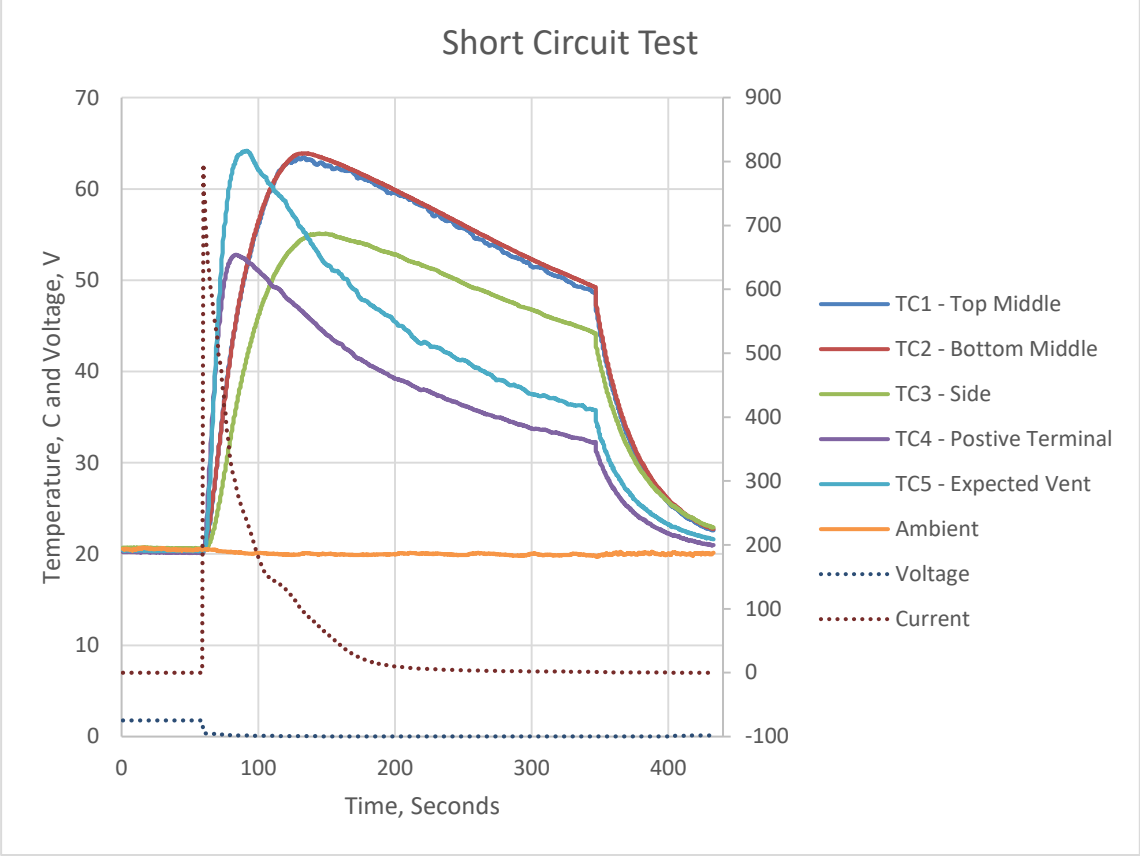

Figure 6 – Surface temperatures measured on cell

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Figure 7 – Photograph of cell after test

Figure 8 – Photograph of cell after test

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Test 2 – Demonstration of Thermal Runaway Propensity by External Heating

Table 7 – Test initiation details

Test Initiation Details	
Test Date	2019/09/18
Test Start Time	1:29 PM
Initial Lab Temperature	20.5°C
Initial Relative Humidity	46% RH

Figure 9 shows the surface temperatures measured during the test, in which cell venting was observed through the seams of the cell pack but thermal runaway was not observed. The open circuit voltage of the cell prior to the test was 1.78V. Heaters were place on both faces of the cell. Kapton tape was used to secure the heaters to the cell. TC5, just outside of the heater on the case, was heated at a rate of 4-7°C per minute until the heater reached approx. 400C. At this time the heater failed causing the heater itself to catch on fire. The heater power supply was shut off and the cell temperatures were further monitored. There was no observance of fire from the cell internally.

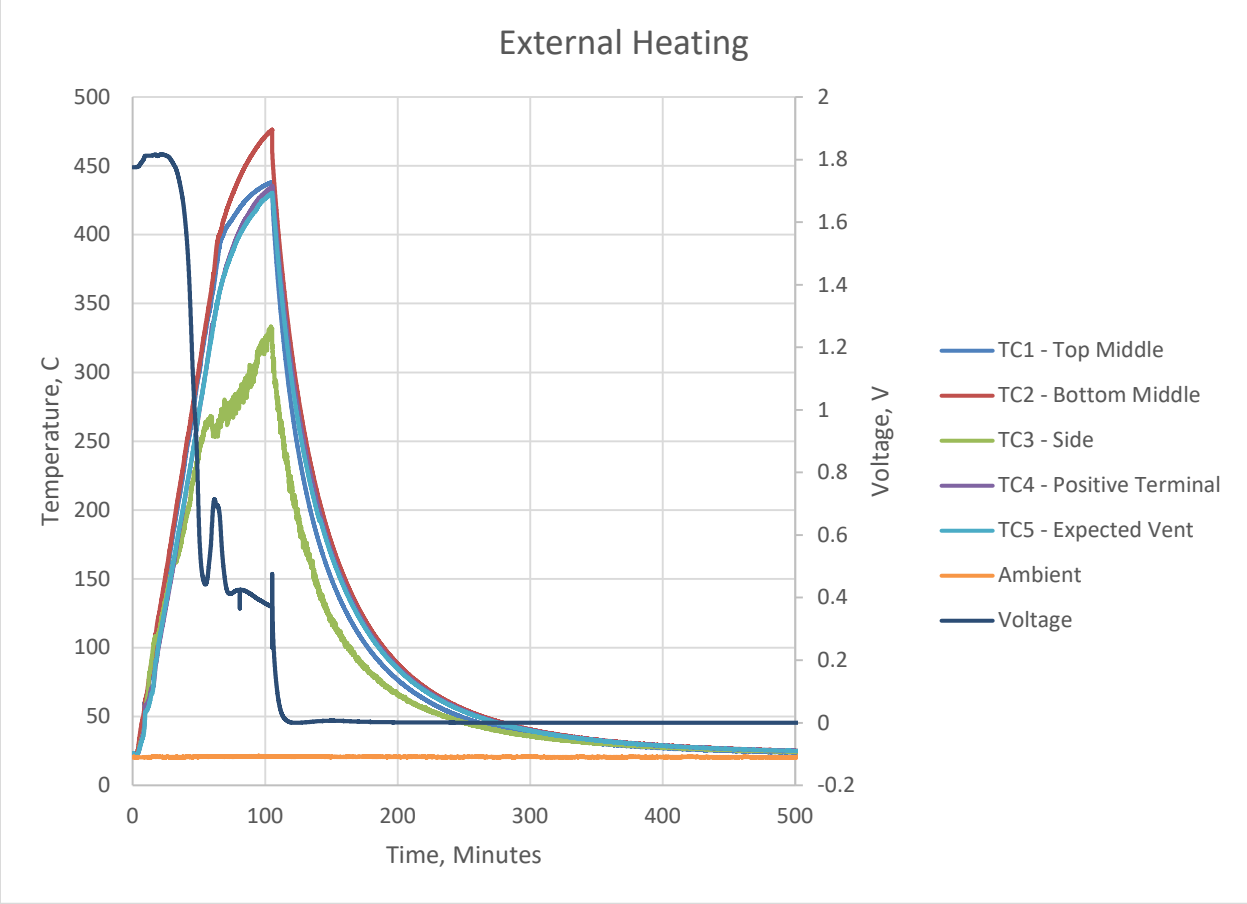

Figure 9 – Surface temperatures and electrical parameters measured on cell

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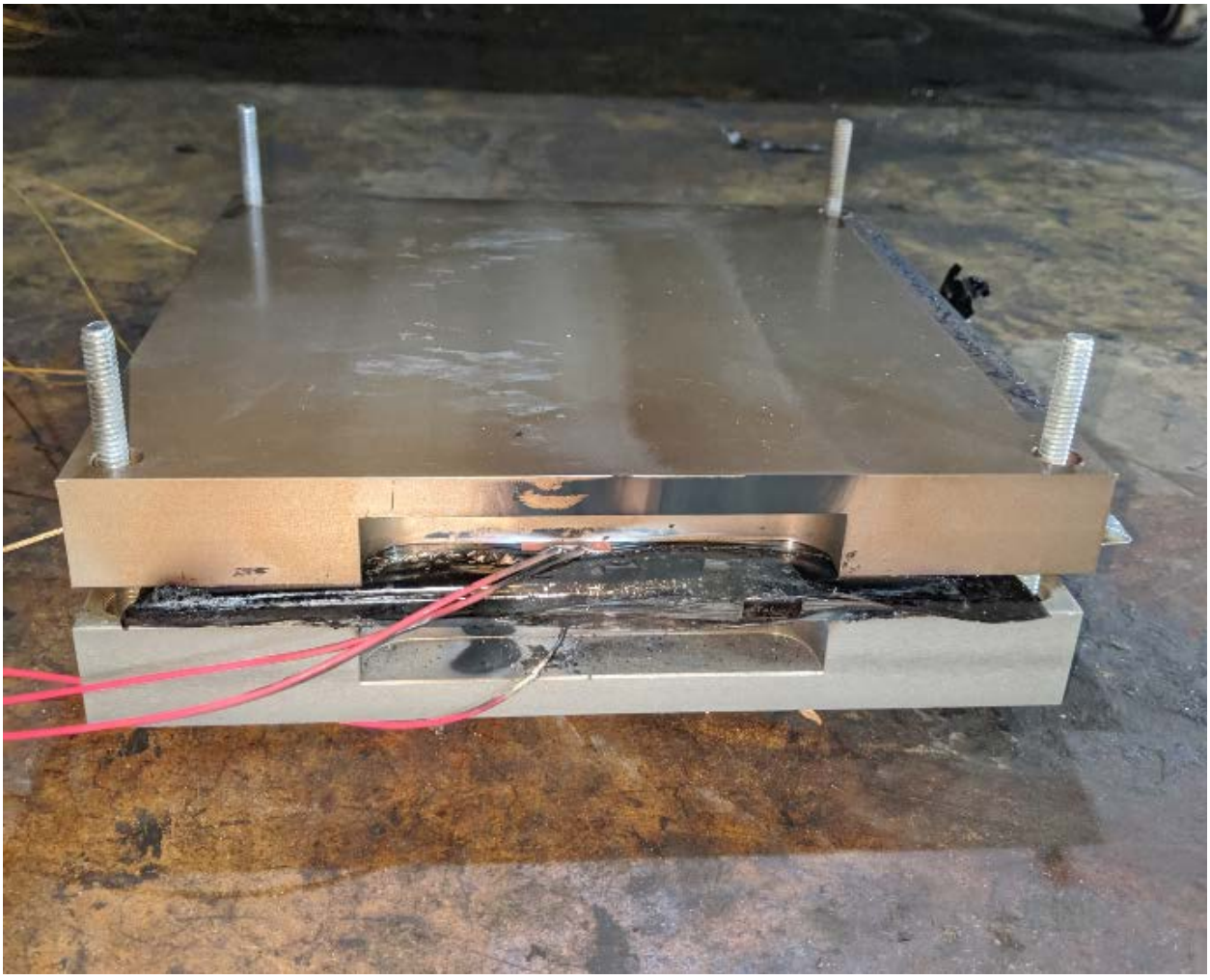
Smoking was observed approx. 50 minutes into the test when the TC1 was approx. 294°C. Since there was no uncontrolled increase in temperature, the heaters proceeded to increase at a rate of 4-7°C per minute.

Figures 10-12 - Photographs of the cell after the external heating test.



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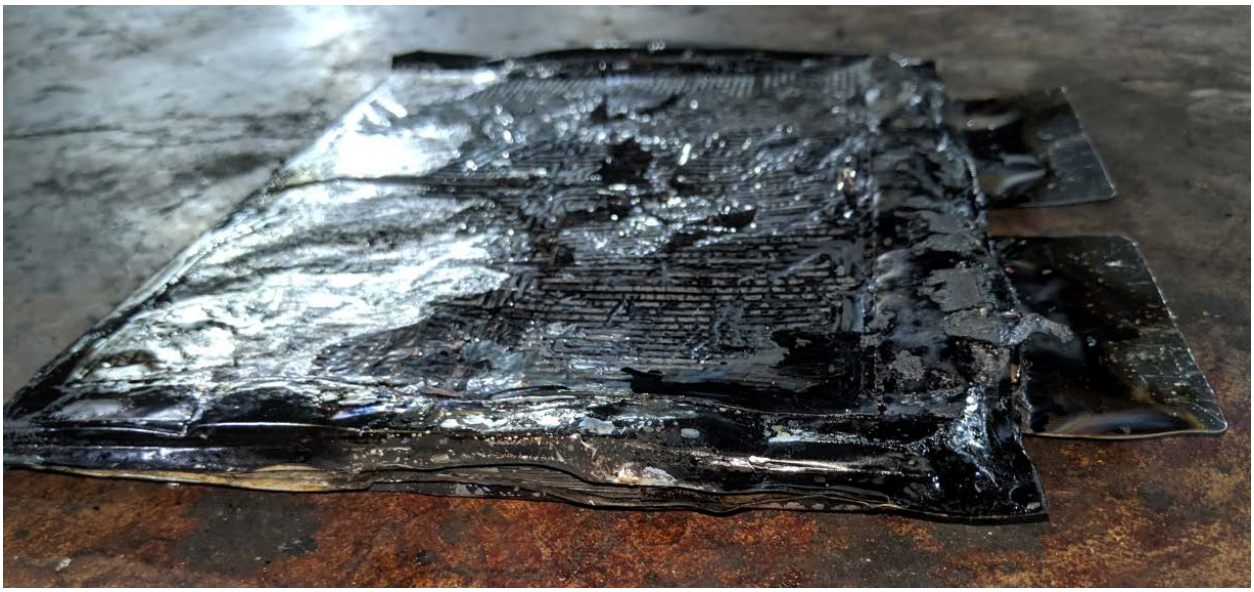

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Test 3A – Demonstration of Thermal Runaway Propensity by Overcharge #1

Table 8 – Test initiation details

Test Initiation Details	
Test Date	2019/09/19
Test Start Time	08:18 AM
Initial Lab Temperature	21.0°C
Initial Relative Humidity	47% RH

Figure 13 shows the surface temperatures measured during the test, in which cell venting was observed through the seams of the cell pack but thermal runaway was not observed. The open circuit voltage of the cell prior to the test was 1.73V. The power supply used to charge the cell was placed in a constant voltage mode, where the voltage was increased by 1V every minute. During the test, the cell enclosure breached and a flame was observed in the cell when the supply was at 26V. This occurred at approx. 26 minutes into the test. The power supply was left on for an additional 10 minutes after the initial breach was observed. When the power supply was turned off at approx. minute 35, the flames self extinguished. Due to this, a second heating test was performed under Test #5 shown later in the report where the power supply was immediately turned off upon observation of the cell enclosure breaching.

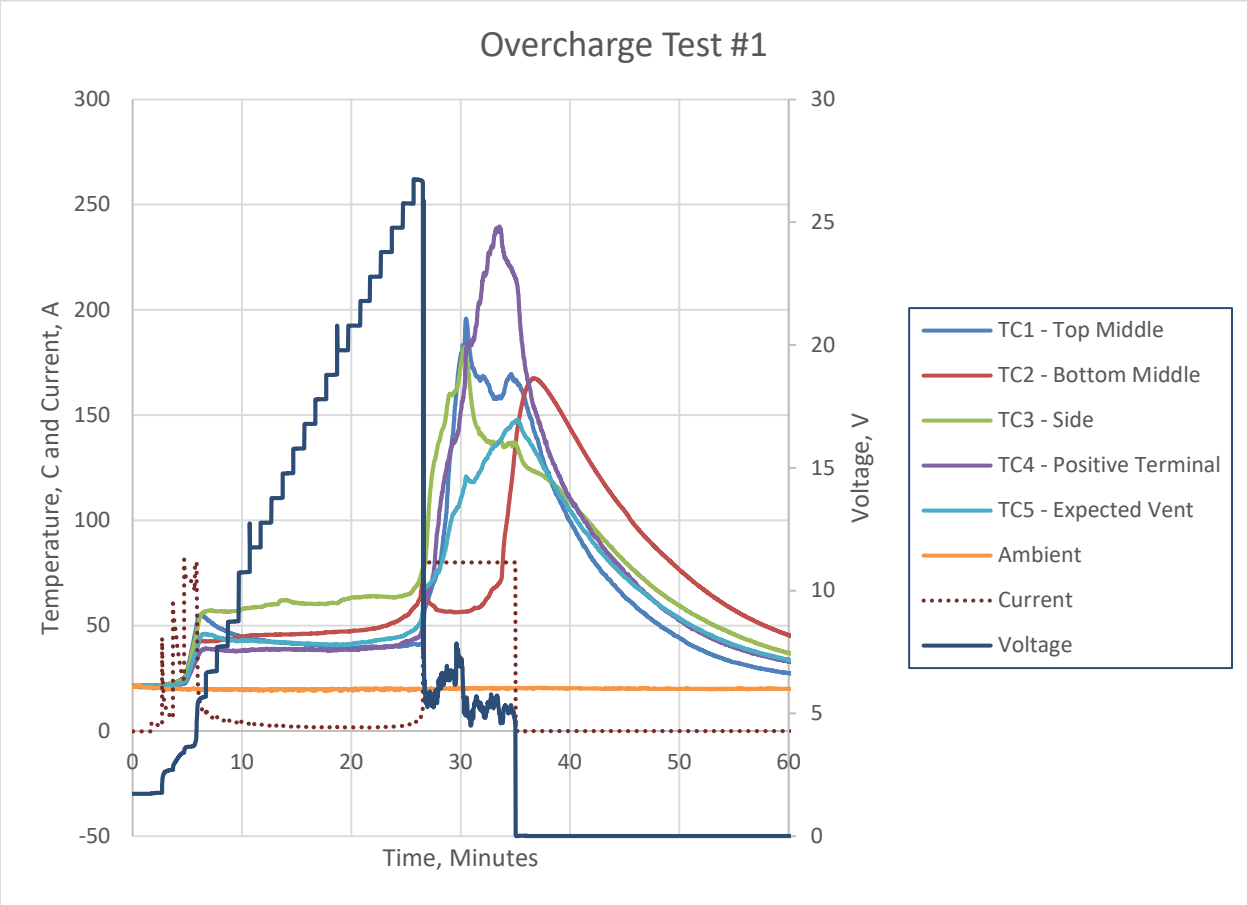

Figure 13 – Surface temperatures measured on cell

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Figure 14 – Photograph of cell top after test

Figure 15 – Photograph of cell bottom after test

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Test 4 – Demonstration of Thermal Runaway Propensity by Nail Penetration

Table 9 – Test initiation details

Test Initiation Details	
Test Date	2019/09/19
Test Start Time	01:01 PM
Initial Lab Temperature	21.0°C
Initial Relative Humidity	47% RH

Figures 16 show the surface temperatures measured during the test, in which no cell venting nor thermal runaway was observed. The open circuit voltage prior to the start of the test was 1.77V. An 8 mm diameter nail , 125 mm long, was used to penetrate through the side of the cell in order to puncture through the entire cell. The nail increased in temperature slightly due to the friction of the nail as it passed through the cell. There was no change in status after nail penetration. The test was concluded after 38 minutes.

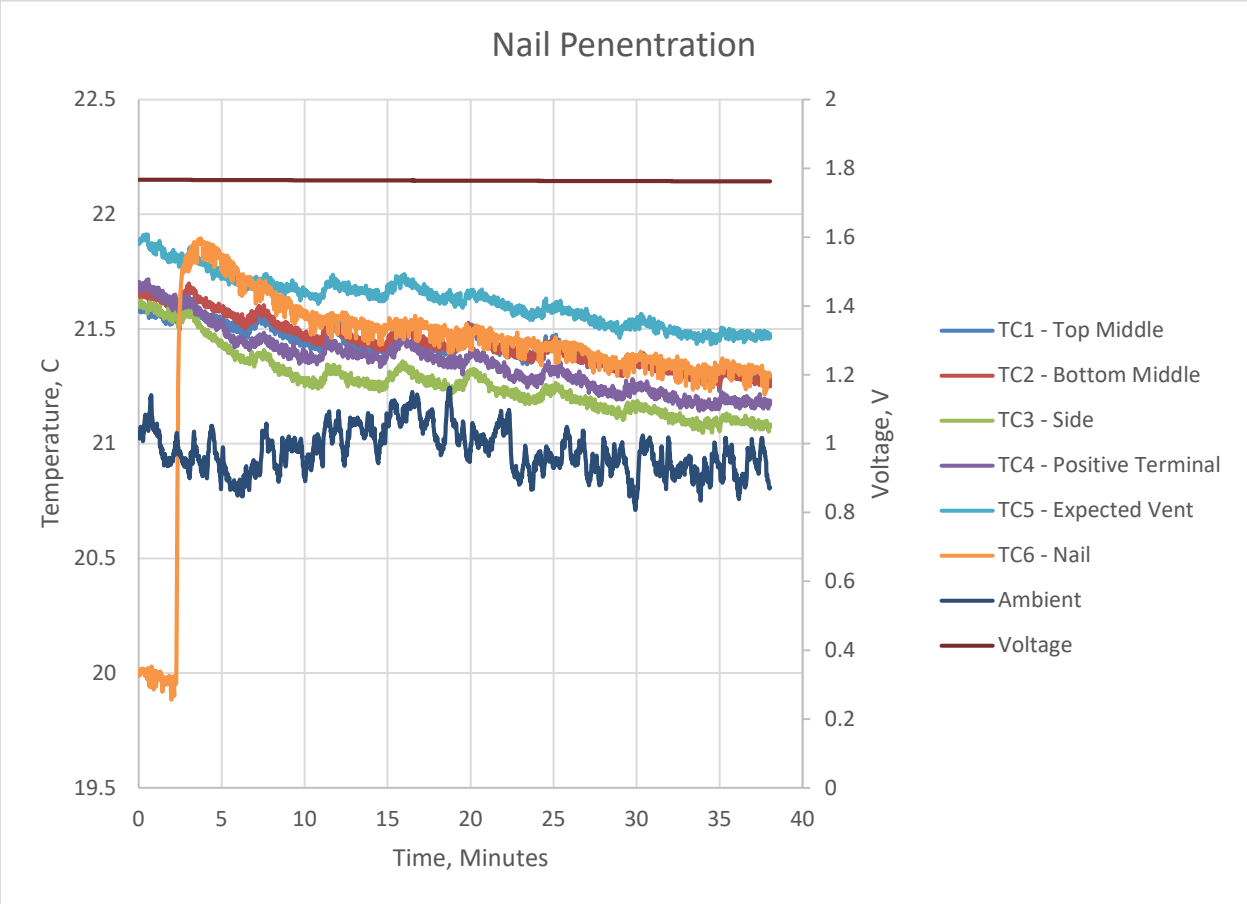

Figure 16 – Surface temperatures measured on cell

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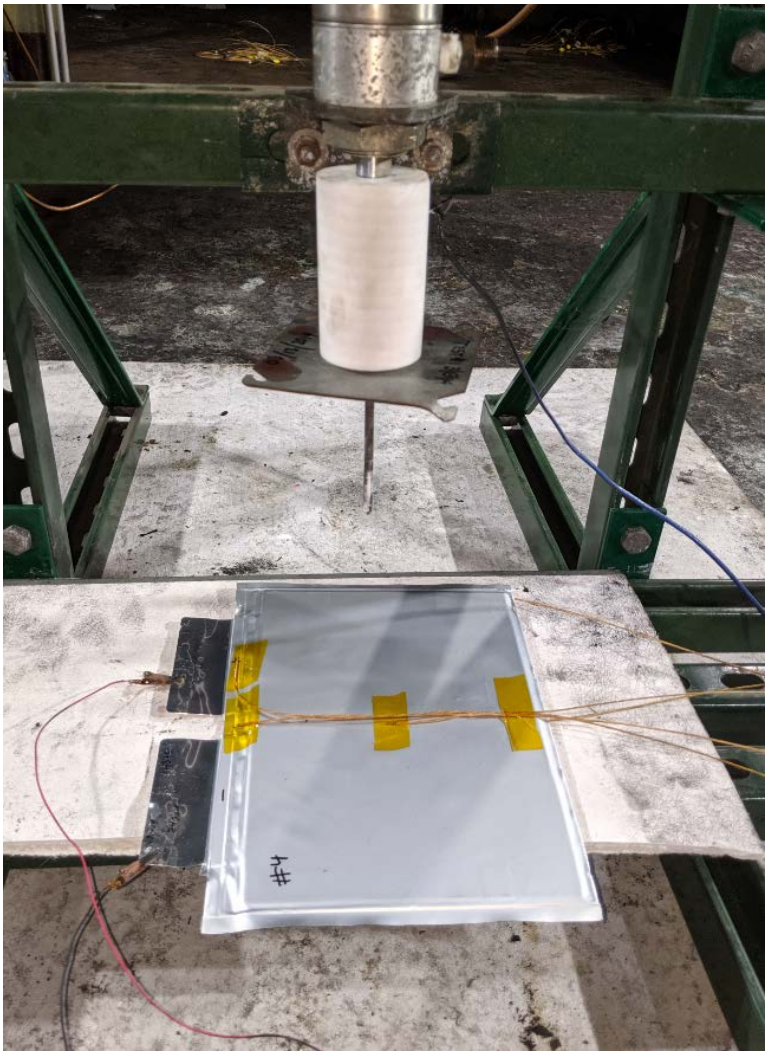

Figure 17 – Nail Penetration Setup

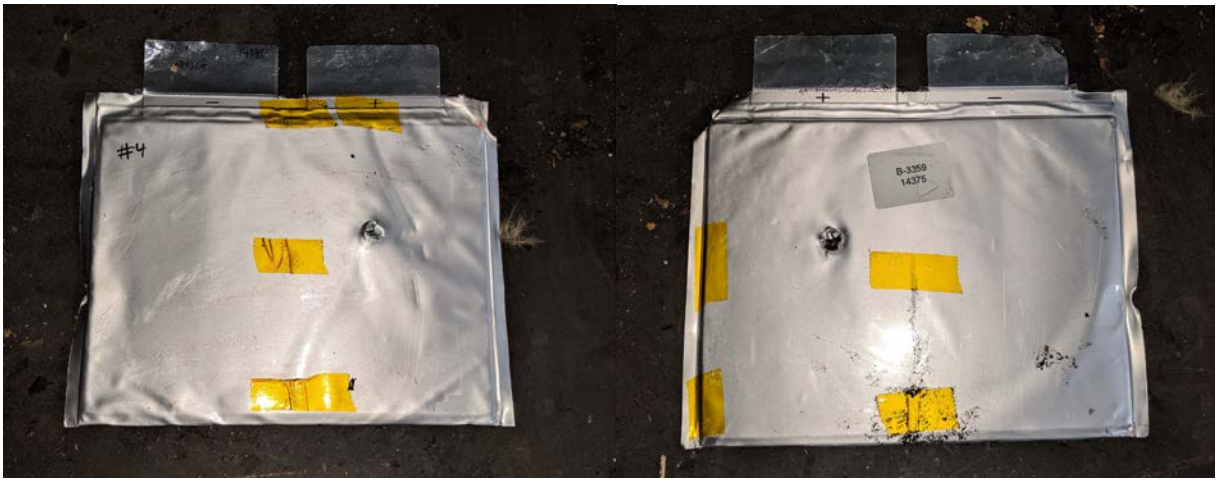

Figure 18 – Nail Entry and Exit

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Test 5 – Demonstration of Thermal Runaway Propensity by Overcharge #2

Table 10 – Test initiation details

Test Initiation Details	
Test Date	2019/09/19
Test Start Time	02:03 PM
Initial Lab Temperature	22.5°C
Initial Relative Humidity	47% RH

Figure 19 shows the surface temperatures measured during the test, in which cell venting was observed through the seams of the cell pack but thermal runaway was not observed. The open circuit voltage of the cell prior to the test was 1.76V. The power supply used to charge the cell was placed in a constant voltage mode, where the voltage was increased by 1V every minute. During the test, the cell enclosure breached and a flame was observed in the cell when the supply was at 32V. This occurred at approx. 35 minutes into the test. The power supply was immediately shut off after the initial breach was observed with flaming. When the power supply was turned off, the flames self extinguished.

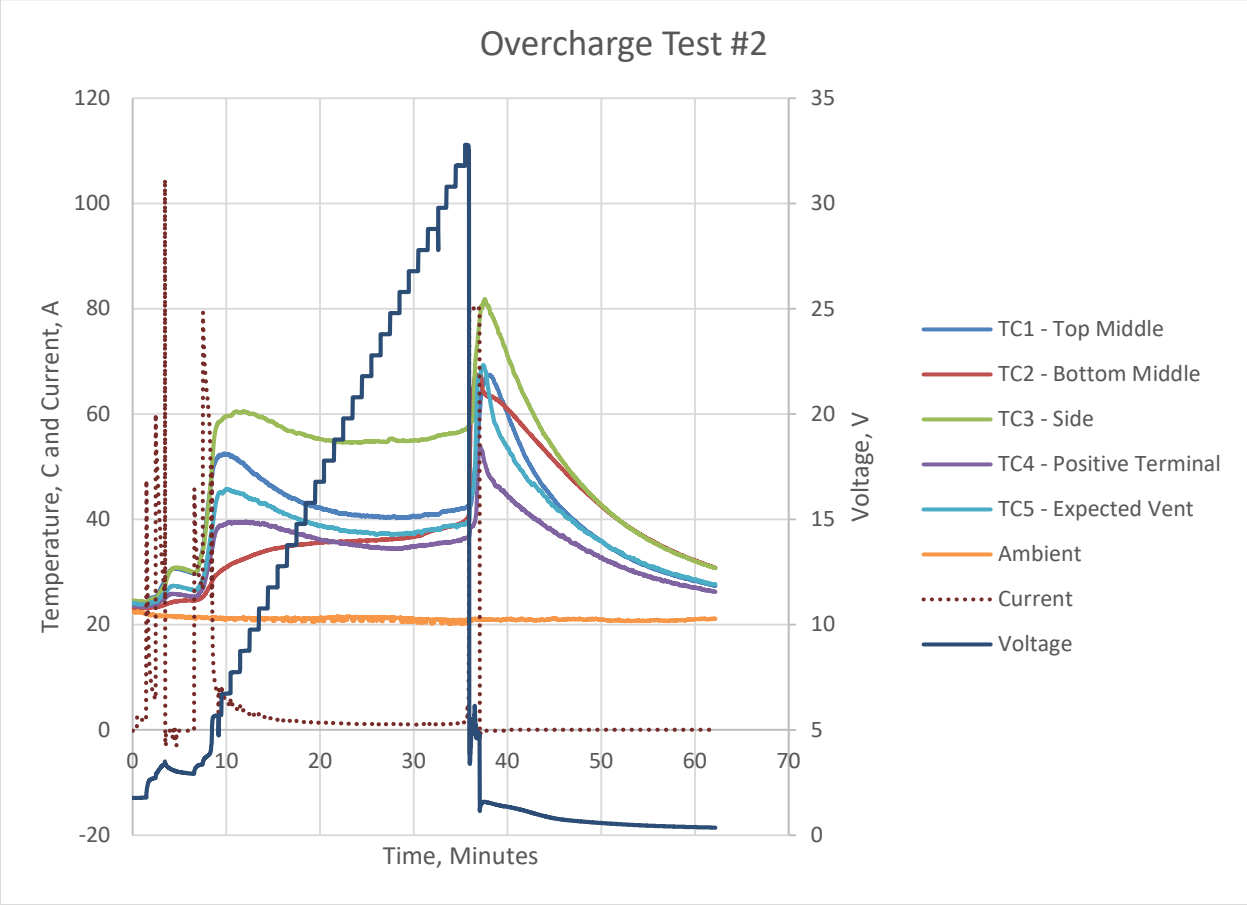

Figure 19 – Surface temperatures measured on cell

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Figure 20 – Photograph of cell top after test

Figure 21 – Photograph of cell bottom after test

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Test 6 – Gas Composition

The gas composition test was conducted with the cell inserted into the cell gas composition test chamber and the chamber was sealed. The cell gas composition test chamber is an 82 L pressure vessel and is shown in Figures 22. The method used for inducing venting was overcharging. From all 5 tests, none resulted in thermal runaway. The external heating and overcharging did cause the cell to vent. Venting and flames were not present in the external heating test until the heater failed and caught fire. Once the heater power was disconnected, the cell ceased to increase in temperature and self extinguished. During the overcharge tests, the cell expanded in size and eventually vented. Upon venting, there was a flame observered in each case. The flame present seemed to be sustained due to the additional energy provided by the power supply, not the cell itself. Under both tests, the cell self extinguished within seconds of the power supply turning off. It was determined that turning off the power supply immediately after venting was observered was the more accurate method as to not supply the cell with external power. The overcharging #2 methodology was employed as was demonstrated in Test 5.

Figure 22 – Cell gas composition test chamber

Prior to initiating venting for the gas collection, the chamber's atmosphere was purged until a condition of less than 1% oxygen by volume, as shown in Figure 23. Following the purge of the chamber atmosphere, the chamber pressure was relieved to 0 psig, Figure 24.

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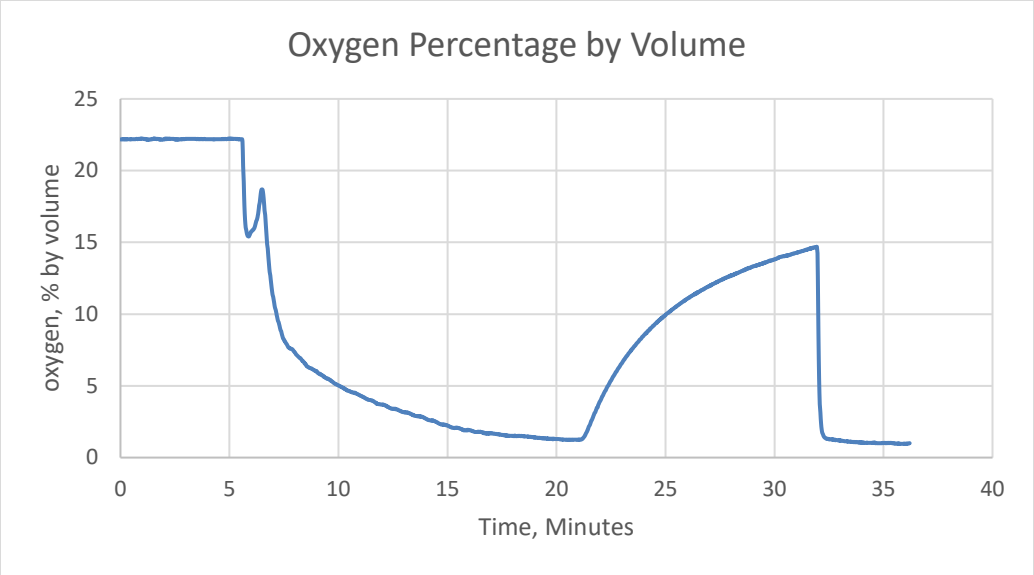

Figure 23 – Oxygen concentration during purge of cell gas composition test chamber prior to start of test

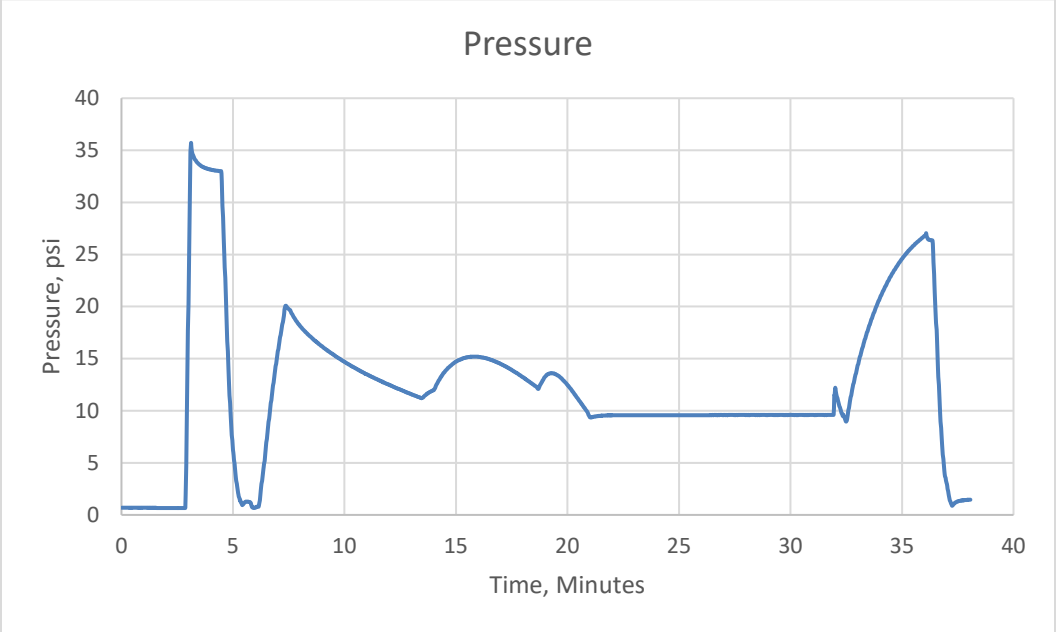

Figure 24 – Pressure inside the cell gas composition test chamber before overcharging

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Table 11 – Test initiation details

Test Initiation Details	
Test Date	2019/09/25
Test Start Time	01:23 PM
Initial Lab Temperature	22.6°C
Initial Relative Humidity	49% RH

Table 12 – Gas composition results

Venting for Gas Collection Results*	
Venting Time	19:46
Temperature on Top Middle Surface	83.44°C
Thermal Runaway Time	No thermal runaway, only venting
Thermal Runaway Temperature	No thermal runaway, only venting
*These results are not a direct comparison with the results from Cell Tests 1-4, as this test was conducted inside a pressure vessel with an inert gas atmosphere.	

Figure 25 shows the surface temperatures measured during the test, in which cell venting was observed, but no indication of thermal runaway was observed. As thermal runaway was not observed in any iteration of the tests 1-5, the intent of this gas composition testing is to measure components of the vent gas release, and not thermal runaway gas release.

Upon completion of the venting event, the internal pressure was approx. 4psi. In order to obtain the cell vent gas, an inert gas was added to the vessel to increase the internal pressure to a suitable value to allow for transfer to a gas bottle. The gas compositon shown in Table 14 does not include the inert gas added.

All of the gas events documented after the “Nitrogen Added” event mark in Figure 25 were not a result of the cell venting.

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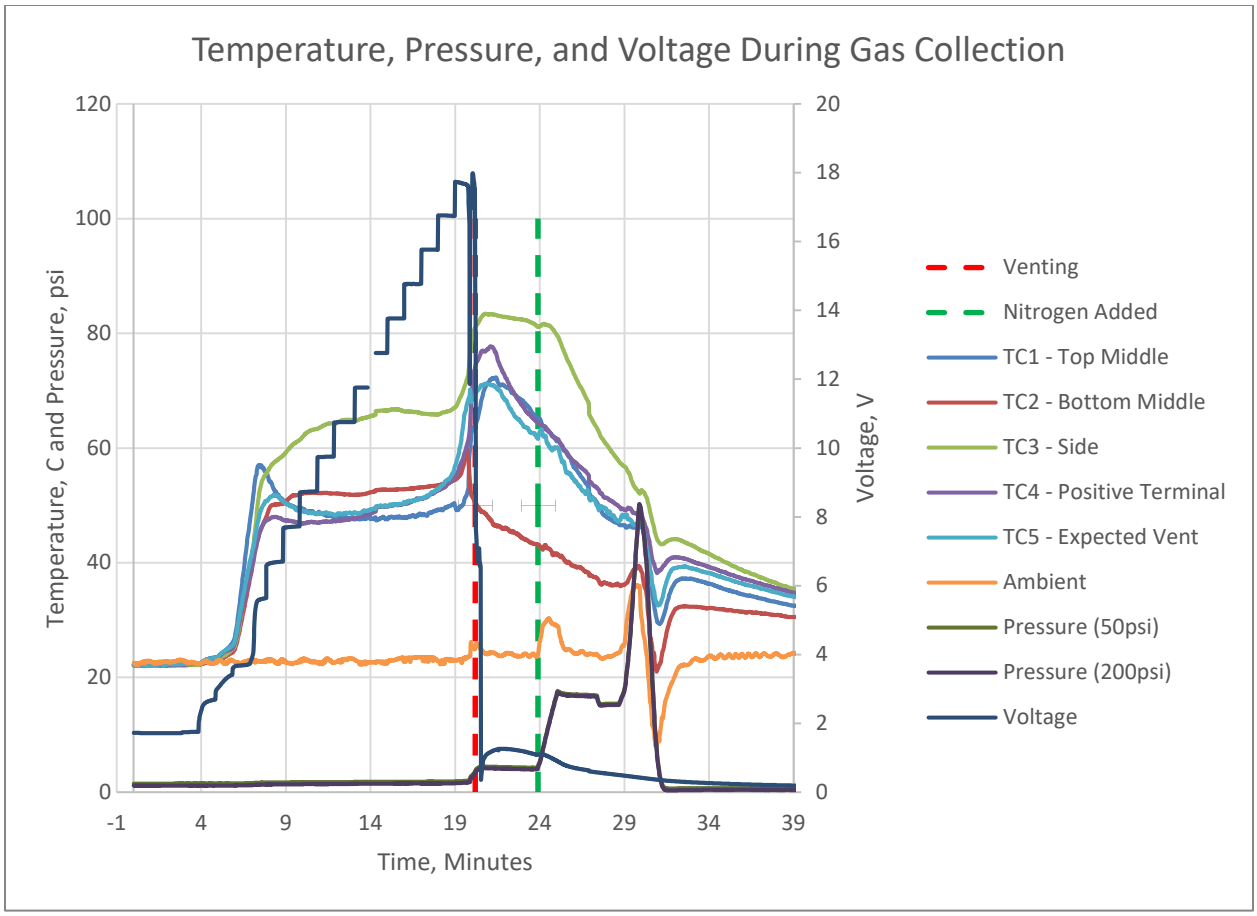

Figure 25 – Surface temperatures measured on cell

Table 13 – Gas composition test

Gas Composition Test	
Volume of Gas Generated (NTP Conditions)	77.5 L

Gas that vented from the cell in Test 6 was collected and analyzed using gas chromatography. Table 14 summarizes the results of the types and volume fractions of gases identified. Though the gas chromatography measurements did not resolve specific C4 hydrocarbons, the elution of the gas sample through the gas chromatograph was effective in determining the bulk components of the vented cell gas. The hydrogen, carbon monoxide, carbon dioxide, and THC quantification represents 100% of the gas mixture within the limitation of 2 digits of precision.

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Table 14 – Components measured in vented cell gas

Gas		Measured %
Hydrogen	H_2	35.70
Carbon Monoxide	CO	26.25
Carbon Dioxide	CO_2	24.59
Methane	CH_4	4.36
Ethylene	C_2H_4	3.91
Ethane	C_2H_6	0.83
Propylene	C_3H_6	2.57
Propane	C_3H_8	0.33
Propadiene	C_3H_4	0.02
-	C_4 (Total)	1.28
Pentane	n-C_5H_{12}	0.11
Isopentane	C_5H_{12}	0.03
Hexane	C_6H_{14}	0.02
Total	-	100

Analysis of lower flammability limit (LFL), maximum pressure rise (P_{max}), burning velocity (S_u) of the cell venting gases was conducted using the methodologies specified in UL 9540A. Please refer to Appendix A for testing details. The results are as follows:

- LFL: 5.24%
- Pmax: 121.1 psig
- S_u: 85 cm/sec

Post Test Thermal Runaway and Re-Ignitions

Additional thermal runaway behavior or re-ignitions were not observed during post test observation, disassembly, and disposal of the sample.

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Summary of Cell Test Results

Cell Vent and Thermal Runaway Results

A summary of cell venting times and temperatures, and thermal runaway time and temperatures are presented in Table 15.

Table 15 – Summary of measurements collected in Cell Level Tests 1 - 6

Test	Test Method	Venting Time (mm:ss)	Venting Temperature (°C)	Thermal Runway Time (mm:ss)	Thermal Runway Temperature (°C)
1	Short Circuit	Not Observed	N/A	Not Observed	N/A
2	Heating	64:05	476.14*	Not Observed	N/A
3	Overcharge #1	26:34	239.6**	Not Observed	N/A
4	Nail Penetration	Not Observed	N/A	Not Observed	N/A
5	Overcharge #2	35:55	81.85	Not Observed	N/A
6	Gas Composition (Overcharge)	19:46	83.44	Not Observed	N/A

*The increased temperature was due to the heater being increased to 475°C

**The increased temperature was due to the sustained fire when the power supply for charging was left on.

Thermal runaway was not observed in any of the 5 tests, therefore repeat tests were not required.

Cell Venting Gas Analysis

The total amount of gas collected from the cell after venting was 77.5 L at Normal Tempreature and Pressure (NTP), over a period of approximately 4 minutes. Flammability properties were determined empirically:

- LFL: 5.24%
- Pmax: 121.1 psig
- S_u: 85 cm/sec

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