CELL TEST REPORT
UL 9540A
Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems (AACD)

Project Number.....:	**4789795626**
Date of issue.....:	**2021.04.30**
Total number of pages.....:	**39**
UL Report Office .....:	**UL-CCIC Company Limited Guangzhou Branch**
Applicant's name.....:	**EVE POWER Co., Ltd.**
Address .....:	No. 68, Jingnan Avenue, Jingmen Hi-tech Zone Jingmen, CN
Test specification:	4th Edition, Section 7, November 12, 2019
Standard.....:	UL 9540A, Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems
Test procedure .....:	7.1 – 7.8
Non-standard test method .....:	N/A

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General disclaimer:

The test results presented in this report relate only to the sample tested in the test configuration noted on the list of the attachments.

UL LLC did not select the sample(s), determine whether the sample(s) was representative of production samples, witness the production of the test sample(s), nor were we provided with information relative to the formulation or identification of component materials used in the test sample(s).

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Cell level information	
Model No .....:	LF280K
Ratings (Vdc, Ah) .....:	3.2 Vdc, 280 Ah
Chemistry of test item……:	Lithium iron phosphate
Original Equipment Manufacturer (OEM):	**EVE POWER Co., Ltd.**
Branding Manufacturer (if not OEM):	N/A
Was the cell certified? ……:	Yes
Standard test item certified to ……..:	UL1973
Organization that certified test item …….:	UL (MH63503)
Average Vent Temperature, °C:	**146.9**
Average Onset of Thermal Runaway Temperature, °C:	**147.7**
Gas Volume:	**169.7 L**
Lower flammability level (LFL), % volume in air at the ambient temperature	**7.15**
Lower flammability level (LFL), % volume in air at the venting temperature	**6.45**
Burning velocity (S_u) cm/s:	**79**
Maximum pressure (P_{max}) psig:	**102**

Cell Gas composition

Gas		Measured %
Carbon Monoxide	**CO**	**11.191**
Carbon Dioxide	**CO_2**	**27.325**
Hydrogen	**H_2**	**48.013**
Methane	**CH_4**	**6.404**
Acetylene	**C_2H_2**	**0.107**
Ethylene	**C_2H_4**	**3.296**
Ethane	**C_2H_6**	**1.326**
Propadiene (Allene)	**C_3H_4**	**0.000**
Propyne	**C_3H_4**	**0.000**
Propene	**C_3H_6**	**0.948**
Propane	**C_3H_8**	**0.321**
-	**C4 (Total)**	**0.704**
-	**C5 (Total)**	**0.142**
-	**C6 (Total)**	**0.005**
-	**C7 (Total)**	**0.003**
-	**C8 (Total)**	**0.000**
Benzene	**C_6H_6**	**0.014**
Toluene	**C_7H_8**	**0.000**
Dimethyl Carbonate	**$C_3H_6O_3$**	**0.000**
Ethyl Methyl Carbonate	**$C_4H_8O_3$**	**0.201**
Diethyl Carbonate	**$C_5H_{10}O_3$**	**0.000**
Total	**-**	**100**

Cell failure test method performed (summary of method and test clause):

☒ External heating using thin film with 4°C to 7°C thermal ramp.

☐ Nail Penetration

☐ Overcharge

☐ External short circuit (***X*** Ω *external resistance*)

☐ Flow Battery with 2 active electrolyte methods

☐ Flow Battery with 1 active electrolyte methods

☐ Others

Description of method used to fail cells if other than external thin film heater with thermal ramp, : N/A

Summary of testing:

Performance Criteria in accordance with Clause 7.7 and Figure 1.1:

[ ] Thermal runaway was not induced in the cell; and

[ ] The cell vent gas did not present a flammability hazard when mixed with any volume of air, as determined in accordance with ASTM E918 at both ambient and vent temperatures.

Necessity for a module level test

[X] The performance criteria of the cell level test as indicated in 7.7 of UL 9540A 4th edition has not been met, therefore a module level testing in accordance with UL 9540A will need to be conducted on a complete module employing this cell.

[ ] The performance criteria of the module level tests as indicated in 7.7 of UL 9540A 4th edition has been met, therefore a module level testing in accordance with UL 9540A need not be conducted.

Testing Laboratory information

Testing Laboratory and testing location(s):		
Testing Laboratory:	UL(Changzhou) Quality Technical Service Co,. LTD	
Testing location/ address ..... :	21 Longmen Rd, National High-Tech Industrial Development District, Wujin, Changzhou, Jiangsu, China	
Tested by (name, signature) ..... :	Jax Gao	
Witnessed by (for 3rd Party Lab Test Location) (name, signature) ..... :	N/A	
Project Handler (name, signature)..... :	Benjamin Liu	
Reviewer (name, signature) …….:	Rebecca Le	
Gas Analysis Testing Laboratory:	DEKRA Services, Inc.	
Testing location/ address ..... :	Forreston, Illinois	
Project Handler (name, signature)..... :	Abdollah Kashani	
Reviewer (name, signature) …….:	Bernadette N. Reyes	

List of Attachments (including a total number of pages in each attachment):

Attachment A: Cell Conditioning (Charge/discharge) Profiles - (*Pages **17** through **19***)

Attachment B: Cell Instrumentation Photos - (*Pages **20** through **23***)

Attachment C: Cell Temperature Profiles during testing - (*Pages **24** through **26***)

Attachment D: Cell Testing Photos - (*Pages **27** through **36***)

Attachment E: Cell vent gas test chamber photo and profile of chamber gas analysis (O_2 and Pressure) – (*Page **37***)

Attachment F: Cell Gas Analysis Report - (*Pages **38** through **39***)

Photo of cell/Stack:

Test Item Charge/Discharge Specifications:	
• Charge current, A:	140
• Maximum charge voltage, Vdc:	3.65
• Charge temperature range, °C:	0~45
• End of charge current, A:	14
• Discharge current, A:	140
• End of discharge voltage, Vdc:	2.5
• Discharge temperature range, °C:	-20~55

Test item particulars .....:	
Possible test case verdicts:	
- test case does not apply to the test object..... :	N/A
- test object does meet the requirement ..... :	P (Pass)
- test object does not meet the requirement..... :	F (Fail)
- test object was completed per the requirement...:	C(Complete)
- test object was completed with modification……:	M(Modification)
Testing..... :	Cell Model LF280K
Date of receipt of test item ..... :	2021.01.13
Date (s) of performance of tests..... :	2021.01.14 to 2021.02.19

General remarks:

"(See Enclosure #)" refers to additional information appended to the report.
"(See appended table)" refers to a table appended to the report.

Throughout this report a point is used as the decimal separator.

Manufacturer's Declaration of samples submitted for test:

The applicant for this report includes samples from more than one factory location and a declaration from the Manufacturer stating that the sample(s) submitted for evaluation is (are) representative of the products from each factory has been provided.....:	☐ **Yes** ☒ **Not applicable**
Name and address of factory (ies) ..... :	EVE POWER Co., Ltd. No. 68, Jingnan Avenue, Jingmen Hi-tech Zone Jingmen, CN

General product information and other remarks:

The tested cell is a Lithium-ion battery cell, Model LF280K. Each cell has a capacity of 280 Ah and nominal voltage 3.2 Vdc.

The overall dimensions of cell are 207.5 mm by 173.7 mm by 72mm.

The weight of cell is 5420g.

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

5.0	**CONSTRUCTION**		**Verdict**
5.1. 5.4	**Cell/Stack Construction**		—
5.1.1, 5.4.1	Generic Chemistry:	Lithium iron phosphate / C	—
	Electrolyte Chemistry:	LiPF6 with additives	—
	Flow Battery Electrolyte No. 1 Chemistry:		N/A
	Max volume of system electrolyte No. 1, L:		N/A
	Flow Battery Electrolyte No. 2 Chemistry:		N/A
	Max volume of system electrolyte No. 2, L:		N/A
	Separator Melt Temperature, °C:	Not used during test	—
	Format: Cylindrical /Prismatic /Pouch Flow Battery Stack	Prismatic	—
	Overall Dimensions, mm	207.5 x 173.7 x 72	—
	Cell Weight, g	5420 g	—
5.1.2	Cell Certification:		—
	Standard Used for Cell Certification:	UL 1973	—
	Organization that Certified Cell:	UL (MH MH63503)	—
5.1.1, 5.4.1	Cell/Stack Ratings: • Nominal Voltage, Vdc •Nominal Capacity, Ah	3.2 Vdc 280 Ah	— —
5.4.1	Flow Battery: No. of Cells per Stack:		N/A
	Flow battery system manufacturer:		N/A
	Flow battery system model:		N/A
	Flow battery system ratings, Vdc, Ah:		N/A
5.4.2	Flow battery system certified to UL 1973:		N/A
	Organization that certified flow battery system:		N/A
7.0	**PERFORMANCE**		**Verdict**
7.1	**General**		
7.2	**Samples**		
7.2.1	Samples conditioned through charge discharge cycling a minimum of 2 cycles.	See Attachment A for profiles See Table 1 for specifications	P
7.2.2	100% SOC and stabilize from 1h to 8 h before testing		

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict
7.2.3	Pouch Cells constrained per end use during testing.		N/A
7.3	**Determination of thermal runaway methodology**		
7.3.1	**General**		
7.3.1.1	Ambient indoor laboratory conditions: 25 ±5°C (77 ±9°F) ≤50 ±25% RH at the initiation of the test.	See Attachment C and Table 3	
7.3.1.2	Heat the cell to thermal runaway by externally applied flexible film heaters	See Attachment B	P
	Heater Dimension	two pieces 203.0 mm by 152.4 mm heater for each sample	P
	A surface heating rate of 4° C (7.2° F) to 7° C (12.6° F) per minute was applied to the cell.	See Attachment C, D, and E See Table 4.	P
	Maximum surface end point temperature, °C	Not used, heated until thermal runaway achieved	N/A
	The following method(s) was employed to cause thermal runaway: ☐ Mechanical (e.g. nail penetration); ☐ Electrical stress in the form of overcharging, ☐ Electrical stress in the form of over discharging ☐ Electrical stress in the form of external short-circuiting ☐ Use of alternate heating sources (e.g. oven). ☐ Other (explain)	Only external heating using film heaters was used.	N/A
7.3.1.3	Detail of test method when using another cell abuse method to initiate thermal runaway		N/A
7.3.1.4	Monobloc batteries such as a lead acid battery		N/A
7.3.1.5	Estimated surface temperature at which internal short circuiting within the cell will occur that could lead to a thermal runaway condition.	Not used, heated until thermal runaway achieved	N/A
7.3.1.6	The cell was heated until thermal runaway has occurred.	Refer to Attachment C	P
	Another external heating method was used to cause cell thermal runaway		N/A
7.3.1.7	The cell's exterior surface temperature was measured	See Attachment B	P
7.3.1.8	The temperature at which the cell case vents due to internal pressure rise was documented.	See Table 3 and 4 See Attachment C and D	P
7.3.1.9	The temperature at the onset of thermal runaway was documented.	See Table 3 and 4 See Attachment C and D	p

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict
	If cell venting occurs first, the cell was heated continuously until thermal runaway occurs.	See Attachment C	P
7.3.1.10	When using methods other than the heater method, the stresses were applied to the cell until thermal runaway occurs.		N/A
7.3.1.11	3 additional samples were tested using the same method and exhibited thermal runaway	See Table 3, 4 and 5 See Attachment C and D	P
7.3.2	**Flow battery thermal runaway determination tests**		N/A
7.3.2.1	The test methods of 7.3.2.2 through 7.3.2.6 were used for the flow battery technology.		N/A
7.3.2.2	The flammability of the electrolytes was determined		N/A
	For liquids with anticipated higher flashpoints and viscosities at or below 9.5 × 10−6 m2/s (9.5 cSt) at 25°C (77°F): • ASTM D3828 or • ASTM D93 was used.		N/A
	The flash point temperature was recorded for each electrolyte tested.		N/A
7.3.2.3	For flow battery systems with two electrolytes, each electrolyte was subjected to the appropriate test method outlined in 7.3.2.2.		N/A
	The test of 7.3.2.4 was conducted if a flash point had been observed in 7.3.2.2		N/A
7.3.2.4	The energy reservoir in a test flow battery assembly was charged to 100% SOC, and then the two electrolyte materials were mixed in a closed container within approximately 1 min. The mixed solution temperature was measured during the test.		N/A
	A test battery representative of the flow battery system was subjected to an overcharge test and short circuit test in accordance with UL 1973, the temperature of the energy reservoirs during the testing were recorded.		N/A
7.3.2.5	For flow battery technologies with one active electrolyte containing solid metal particles, the appropriate test method of 7.3.2.2 was conducted to determine the flash point temperature		N/A
	If a flash point had been observed in 7.3.2.2, the propensity for thermal runaway was demonstrated by the test methods of 7.3.2.6		N/A

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict
7.3.2.6	If a flash point had been observed, a test battery representative of the flow battery system was subjected to an overcharge test and short circuit test in accordance with UL 1973, and the maximum temperature of the energy reservoir during testing was recorded.		N/A
7.4	**Cell vent gas composition test**		
7.4.1	Cell vent gas was generated and captured by forcing a cell into thermal runaway with the methodology developed in 7.3, inside a pressure vessel	Size of pressure vessel used: 100L (26.4gal) Refer to Attachment E	P
	The test was initiated with an initial condition of atmospheric pressure and less than 1% oxygen by volume.	Refer to Attachment E Atmospheric pressure (psig): 0.1 psig above the atmospheric pressure	P
		Oxygen concentration measured (% volume): <0.1%	
		Inert gas used: Nitrogen	
7.4.2	Cell vent gas composition was determined using Gas Chromatography (GC)	Refer to Table 6 Refer to Attachment F	P
	Hydrogen gas was measured	Refer to Table 6	P
	The initial atmospheric conditions prior to testing were noted.	Refer to Table 3 and 6 Refer to attachment C and E	P
7.4.3	The lower flammability limit of the cell vent gas was determined on samples of the synthetically replicated gas mixture in accordance with ASTM E918, testing at both ambient and cell vent temperatures.	Refer to Table 6 and 7 Refer to attachment F	P
7.4.4	The gas burning velocity of the synthetically replicated cell vent gas was determined in accordance with the Method of Test for Burning Velocity Measurement of Flammable Gases Annex in ISO 817.	Refer to Table 6 and 7 Refer to attachment F	P
7.4.5	P_{max} of the synthetically replicated cell vent gas was determined in accordance with EN 15967.	Refer to Table 6 and 7 Refer to attachment F	P
7.5	**Off gas composition for flow battery systems**		N/A

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict
7.5.1	The off gas composition from the flow battery testing of 7.3.2 was determined by conducting the test method of 7.3.2.2: • In a closed container and capturing the off gasses generated, and • By collecting the off gasses generated at vent openings and vent ducts during the overcharge and short circuit testing of 7.3.2.4 and 7.3.2.6.		N/A
	Gas composition and flammability limit were determined through the methods outlined in 7.4.2 and 7.4.3 at both ambient temperature and the maximum temperature measured.		N/A
7.5.2	The volume of flammable gases measured during the testing were scaled to the maximum energy reservoir for the intended flow battery system		N/A
7.6	**Cell Level Test Report Information**		
7.6.1	Minimum information provided in the report for items a) through m)		P
7.6.2	Minimum information of items a) through k) was provided in the report for flow battery		N/A
7.7	**Performance – cell level test**		
7.7.1	a) Thermal runaway cannot be induced in the cell; and	'F' in this clause indicates that module level testing is required	F
	b) The cell vent gas does not present a flammability hazard when mixed with any volume of air, at both ambient and vent temperatures.	'F' in this clause indicates that module level testing is required	F
7.8	**Performance – flow battery thermal runaway determination tests**		
7.8.1	a) The electrolyte(s) subjected to the test method in accordance with 7.3.2.2 does not ignite; or		N/A
	b) The flash point temperature(s) measured in the test of 7.3.2.2 exceed the maximum temperature measured on the energy reservoir during the overcharge and short circuit tests of 7.3.2.4 or 7.3.2.6 by at least 5°C (9°F); and		N/A

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict
	c) The flash point temperature(s) measured in the test of 7.3.2.2 exceed the maximum temperature of the mixed solution measured in accordance with 7.3.2.4 by at least 5°C (9°F) for systems with two active electrolytes.		N/A

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Clause	Requirement + Test	Result - Remark	Verdict

Table 1 – Specified conditioning parameters			
Charging:		**Discharging**	
Current (CC), A	140	**Current (CC), A**	140
Max Charge Voltage (CV), Vdc	3.65	**Voltage at start of discharge, Vdc**	3.65
End of charge current, A	14	**End of discharge voltage, Vdc**	2.5
Charging Test Ambient, °C	0-45	**Discharging Test Ambient, °C**	-20~55
Refer to Attachment A for charge/discharge profiles for each cell.			

Table 2 – Charge completion and cell test initiation times			
Cell Test Number	**Cell Number**	**Charge Completion Date and Time**	**Cell test Date and Time**
1	3589311-001	2021/01/14 07:55 AM	2021/01/14 04:27 PM
2	3589311-003	2021/01/20 06:27 AM	2021/01/21 03:05 PM
3	3589311-004	2021/01/22 06:02 AM	2021/01/22 03:54 PM
4	3589311-006	2021/02/08 03:35 PM	2021/02/08 06:27 PM
5	3589311-008	2021/02/17 11:58 PM	2021/02/19 05:05 PM

Table 3 - Test Initiation Details					
	Cell Test 1	**Cell Test 2**	**Cell Test 3**	**Cell Test 4**	**Cell Test 5**
Test Date	2021/01/14	2021/01/21	2021/01/22	2021/02/08	2021/02/19
Test Start Time	04:27 PM	03:05 PM	03:54 PM	06:27 PM	05:05 PM
Initial Lab Temperature	22.3	22.1	23.5	23.2	22.1
Initial Relative Humidity	31.2	35.7	34.6	32.1	35.4

Table 4 - Thermal Runaway Results					
	Cell Test 1	**Cell Test 2**	**Cell Test 3**	**Cell Test 4**	**Cell Test 5**
OCV at start of test, Vdc	3.39	3.36	3.39	3.36	3.37
Average Heating Rate, °C/min	4.3	4.3	4.3	4.3	4.3
Venting Time after the test start, secs	3067	2853	2922	2861	3965
Venting Temperature, °C	158.4	142.7	147.4	139.1	187.0
Thermal Runaway Time after the test start, secs	3114	2909	2954	2899	4039
Thermal Runaway Temperature, °C	163.5	161.4	148.2	147.7	192.5
Refer to Attachment C for surface temperature profiles during testing See attachment E for datasheets					

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

Table 5 – Average Vent and Thermal Runaway Temperatures#	
Average of Cell Vent Temperatures, °C	146.9
Average of Cell Thermal Runaway Temperatures, °C	147.7
#Averages of cell tests other then the gas analysis test	

Table 6 – Results of Gas Analysis			
Gas		**Measured %**	**Component LFL**
Carbon Monoxide	**CO**	**11.191**	**10.9**
Carbon Dioxide	**CO_2**	**27.325**	**N/A**
Hydrogen	**H_2**	**48.013**	**4.0**
Methane	**CH_4**	**6.404**	**4.4**
Acetylene	**C_2H_2**	**0.107**	**2.3**
Ethylene	**C_2H_4**	**3.296**	**2.4**
Ethane	**C_2H_6**	**1.326**	**2.4**
Propadiene (Allene)	**C_3H_4**	**0.000**	**1.9**
Propyne	**C_3H_4**	**0.000**	**1.8**
Propene	**C_3H_6**	**0.948**	**1.8**
Propane	**C_3H_8**	**0.321**	**1.7**
-	**C4 (Total)**	**0.704**	**N/A**
-	**C5 (Total)**	**0.142**	**N/A**
-	**C6 (Total)**	**0.005**	**N/A**
-	**C7 (Total)**	**0.003**	**N/A**
-	**C8 (Total)**	**0.000**	**N/A**
Benzene	**C_6H_6**	**0.014**	**1.2**
Toluene	**C_7H_8**	**0.000**	**1.0**
Dimethyl Carbonate	**$C_3H_6O_3$**	**0.000**	**N/A**
Ethyl Methyl Carbonate	**$C_4H_8O_3$**	**0.201**	**N/A**
Diethyl Carbonate	**$C_5H_{10}O_3$**	**0.000**	**N/A**
Total	**-**	**100**	**-**

Table 7 – Properties of Vent Gas Analysis	
Lower Flammability Analysis at Ambient Temperature, 25°C (% vol in air)	7.15
Lower Flammability Analysis at Vent Temperature, [147 °C] (% vol in air)	6.45
Flow Batteries, LFL scaled to maximum electrolyte volume of system, 25°C (% vol in air)	N/A
Flow Batteries, LFL scaled to maximum electrolyte volume of system, [°C] (% vol in air)	N/A
Burning Velocity Measurement, S_u cm/sec	79
Maximum Pressure P_{max}, psig	102

	TABLE 8: Critical components information	

UL 9540A, Edition 4,			
Clause	Requirement + Test	Result - Remark	Verdict

Object / part No.	**Manufacturer/ trademark**	**Type / model**	**Technical data**	**Standard**	**Mark(s) of conformity[1)]**
Cell Model	EVE Power Co.，Ltd.	LF280K	3.2Vdc，280Ah，LFP	UL1973	UL (MH MH63503)
Separator	Hebei Gellec New Energy Science & Technology Joint Stock Co., Ltd	JP07-465-05-194.5mm	PE and Boehmite, Dimensions：18753mmx194.5mmx0.016mm	UL1973	UL(MH62190)
Electrolyte	Zhuhai Smoothway Electronic Materials Co., Ltd	JD10-447-02	$LiPF_6$, EMC, DMC, EC	—	—
Case	NINGBO ZHENYU TECHNOLOGY Co.,LTD	72174204 |0.6mm	AL3003, Dimensions 174mmx72mmx204mm. Thickness of front 0.6mm, thickness of side 0.8mm, thickness of bottom 1.2mm.	—	—
Insulators/ location in cell	HUI ZHOU TONMAX NEW ENERGY MATERIALS Co.,LTD	72174200|DM	PP	—	—
CID	NINGBO ZHENYU TECHNOLOGY Co.,LTD	顶盖组件(手板件) |72174| 中心距 123mm	MFX2-O 0.85±0.2Mpa	—	—

Attachment A: Cell Conditioning (Charge/discharge) Profiles - (*Pages **17** through **19***)

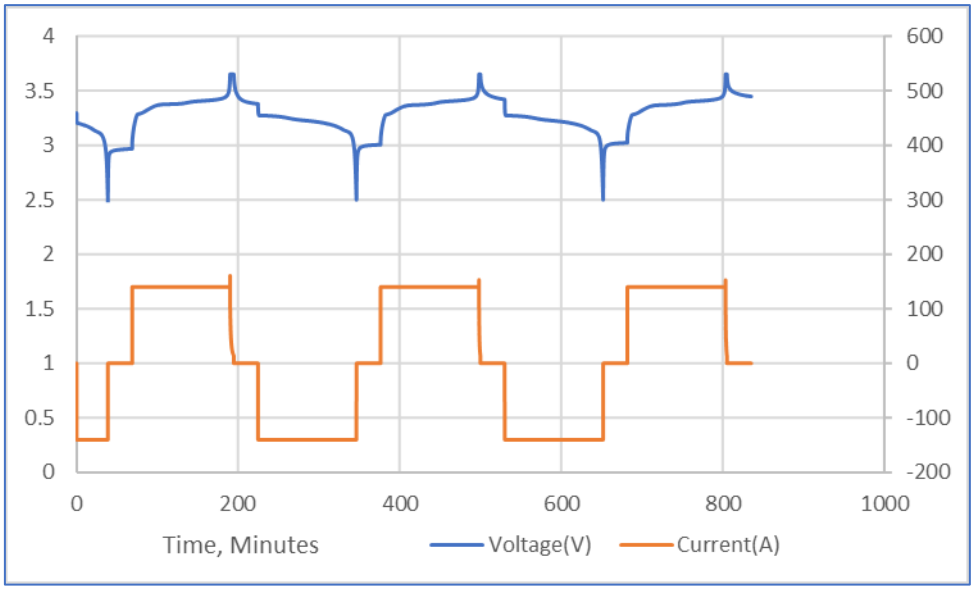


Figure 1: Cell 1 Conditioning (Charge/discharge) Profiles

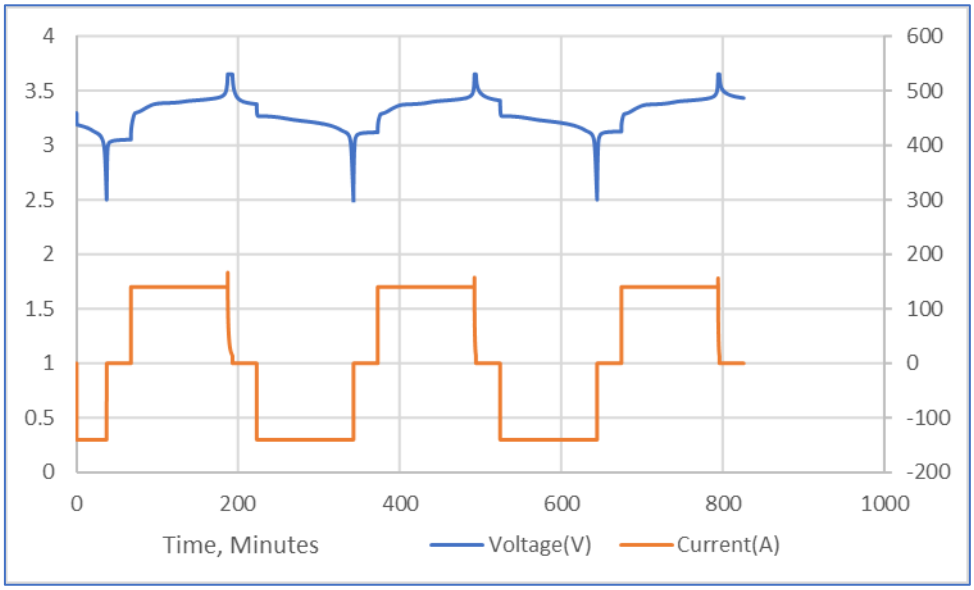


Figure 2: Cell 2 Conditioning (Charge/discharge) Profiles

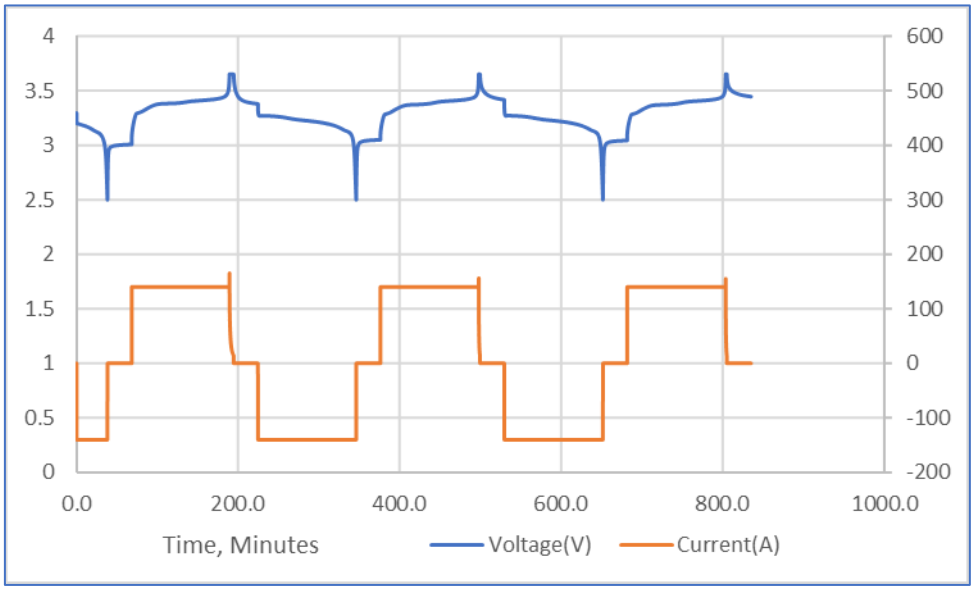


Figure 3: Cell 3 Conditioning (Charge/discharge) Profiles

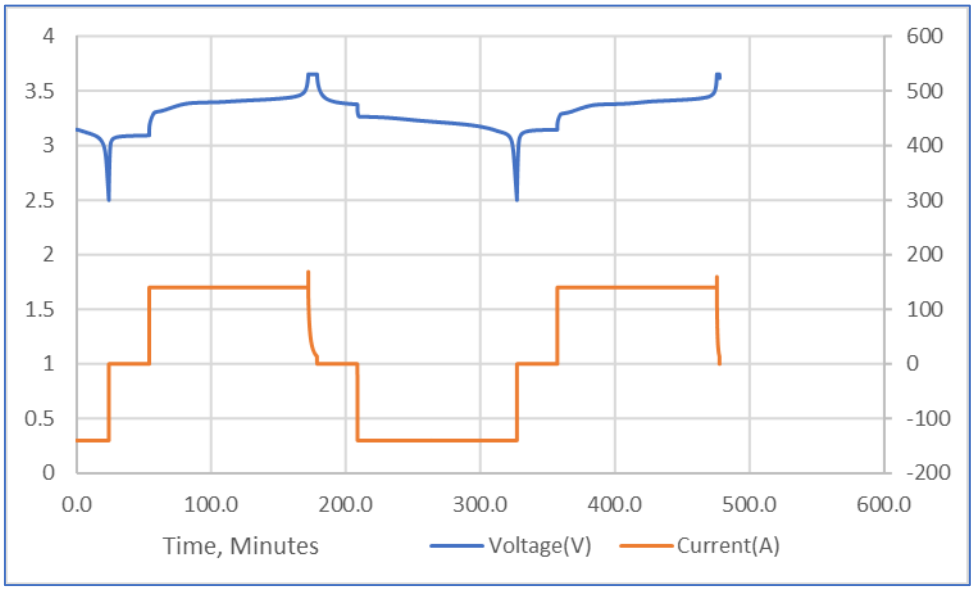


Figure 4: Cell 4 Conditioning (Charge/discharge) Profiles

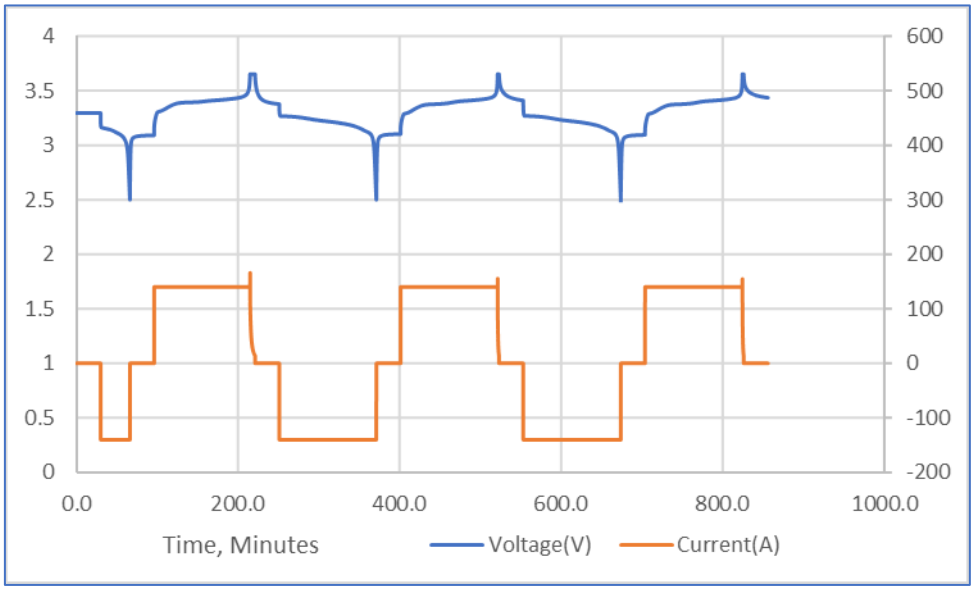


Figure 5: Cell 5 Conditioning (Charge/discharge) Profiles

Attachment B: Cell Instrumentation Photos - (*Pages **20** through **24***)

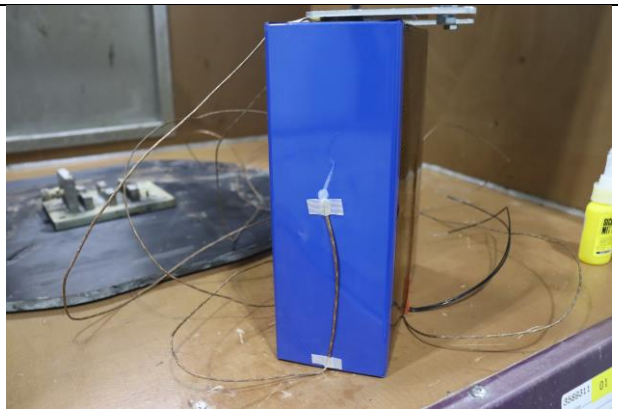
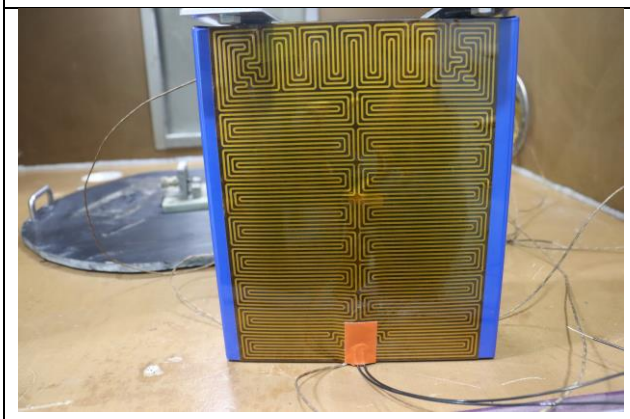
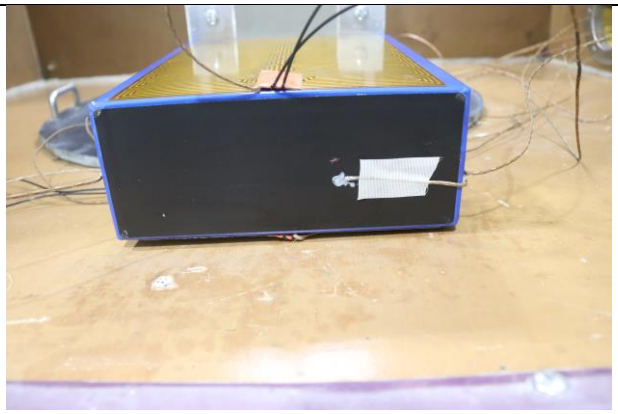




Figure 6: Sample 1 Instrumentation Prior to Test

Note: heaters were placed on two sides of cell after thermocouple adhered.

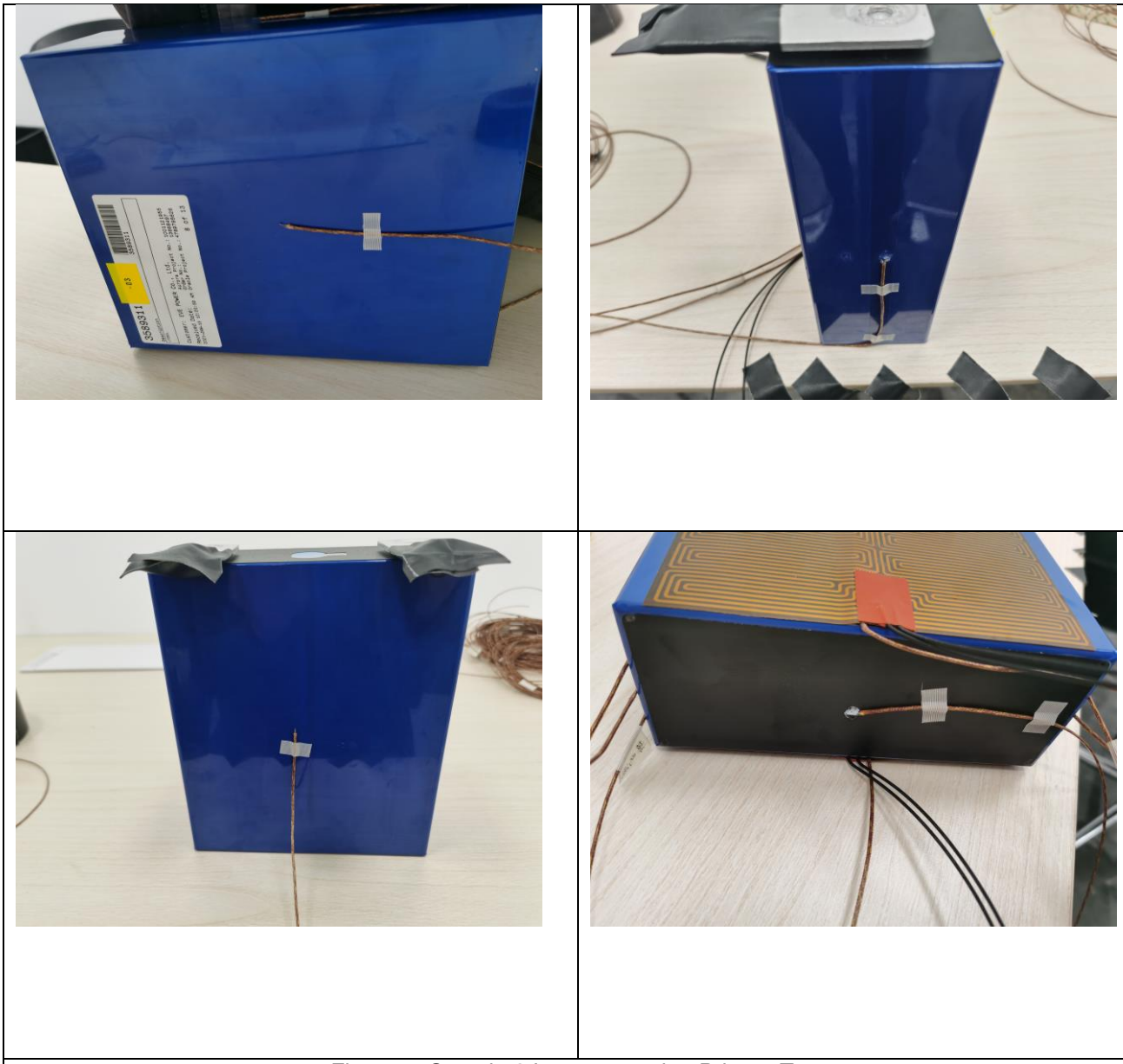


Figure 7: Sample 2 Instrumentation Prior to Test

Note: heaters were placed on two sides of cell after thermocouple adhered.

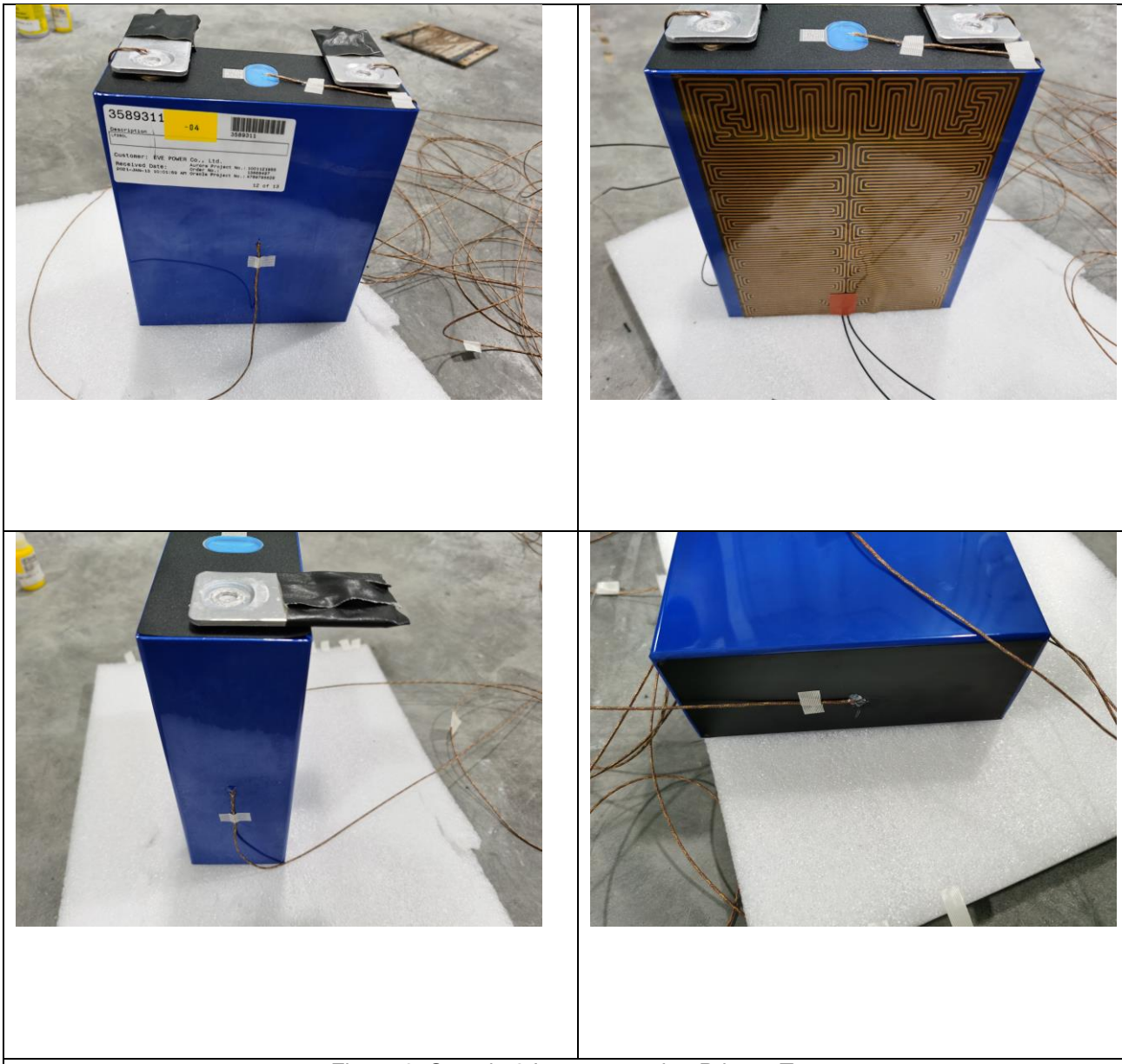
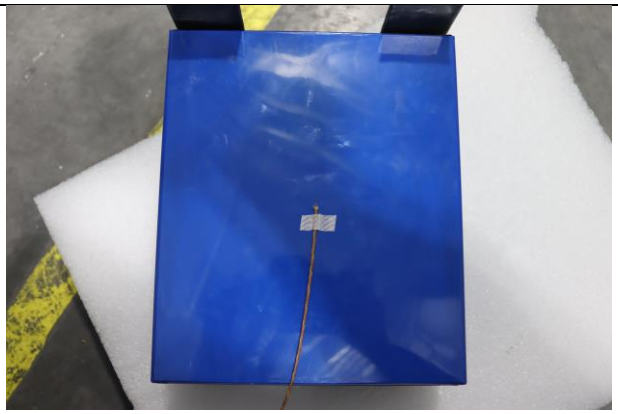


Figure 8: Sample 3 Instrumentation Prior to Test

Note: heaters were placed on two sides of cell after thermocouple adhered.



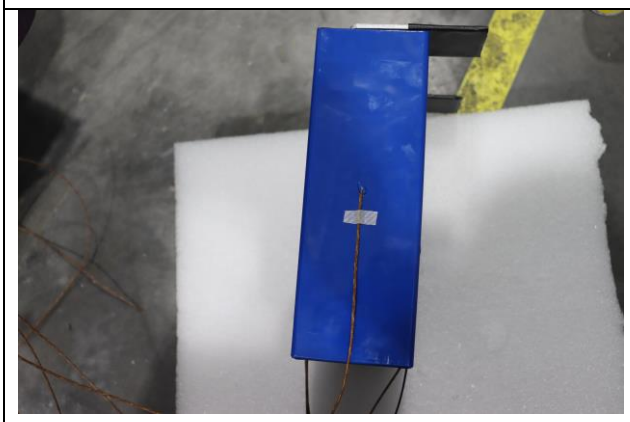


Figure 9: Sample 4 Instrumentation Prior to Test

Note: heaters were placed on two sides of cell after thermocouple adhered.

Attachment C: Cell Temperature Profiles during testing - (*Pages **24** through **26***)

Note: TC01 under heater; TC02 on the cell positive; TC03 at the cell bottom; TC04 on the cell body not cover by heater; TC05 Ambient temperature; V1 cell voltage

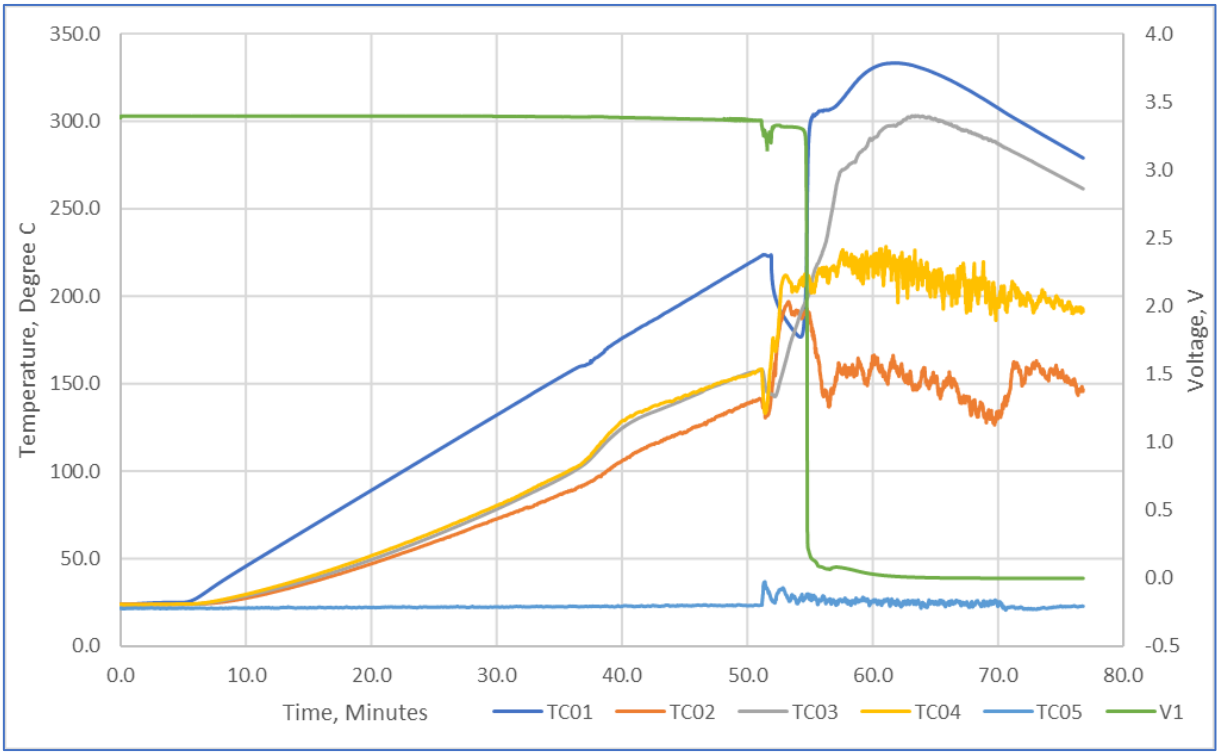


Figure 10: Cell 1 – External Heating 4.3°**C** per minute

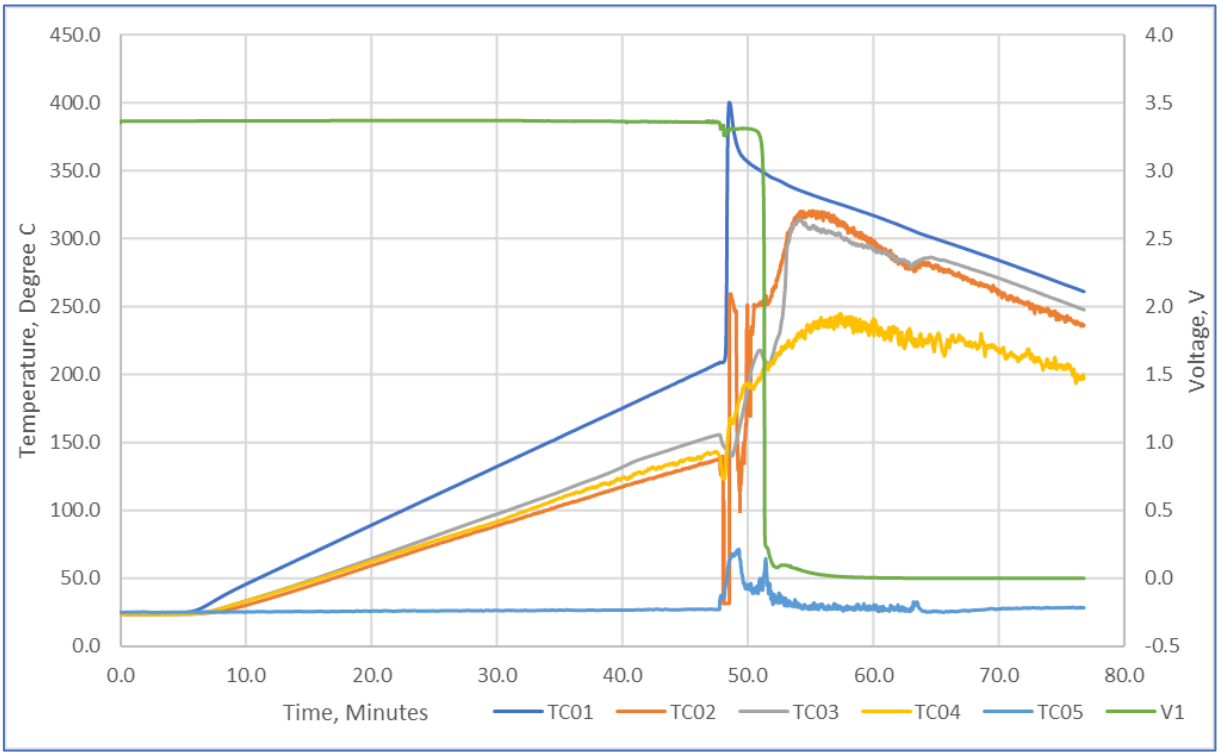


Figure 11: Cell 2 – External Heating 4.3°**C** per minute

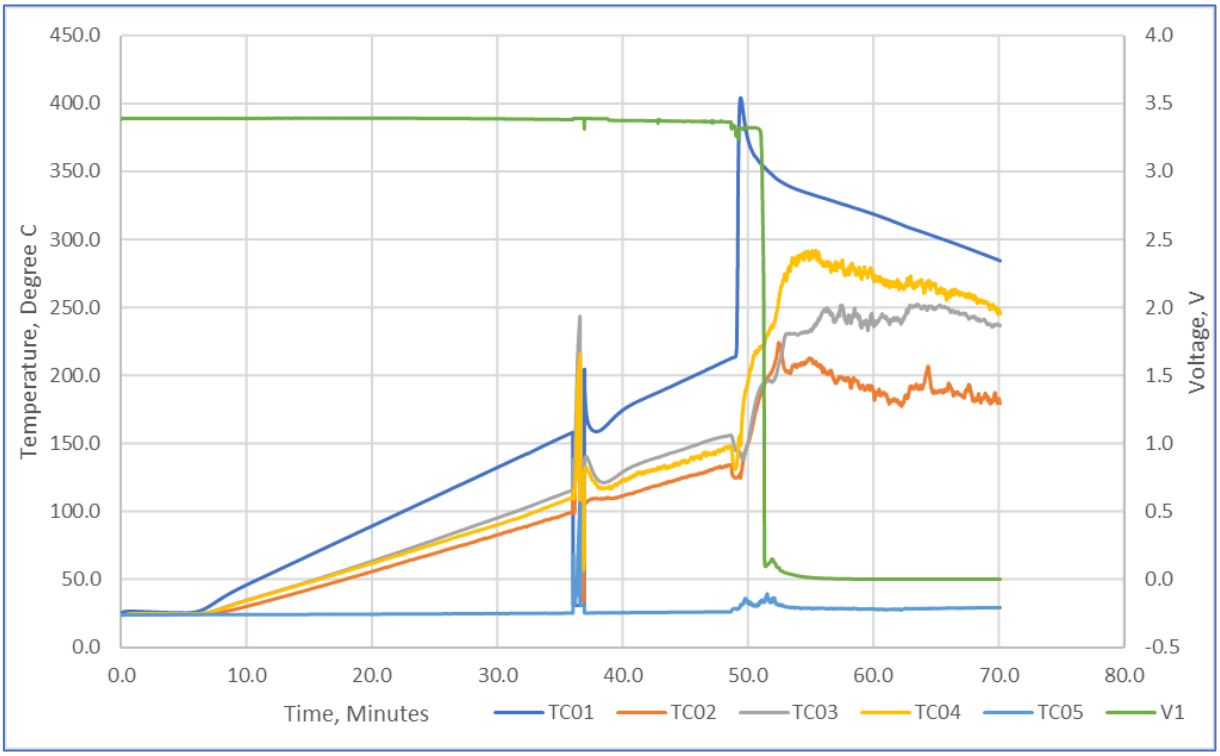


Figure 12: Cell 3 – External Heating 4.3°**C** per minute

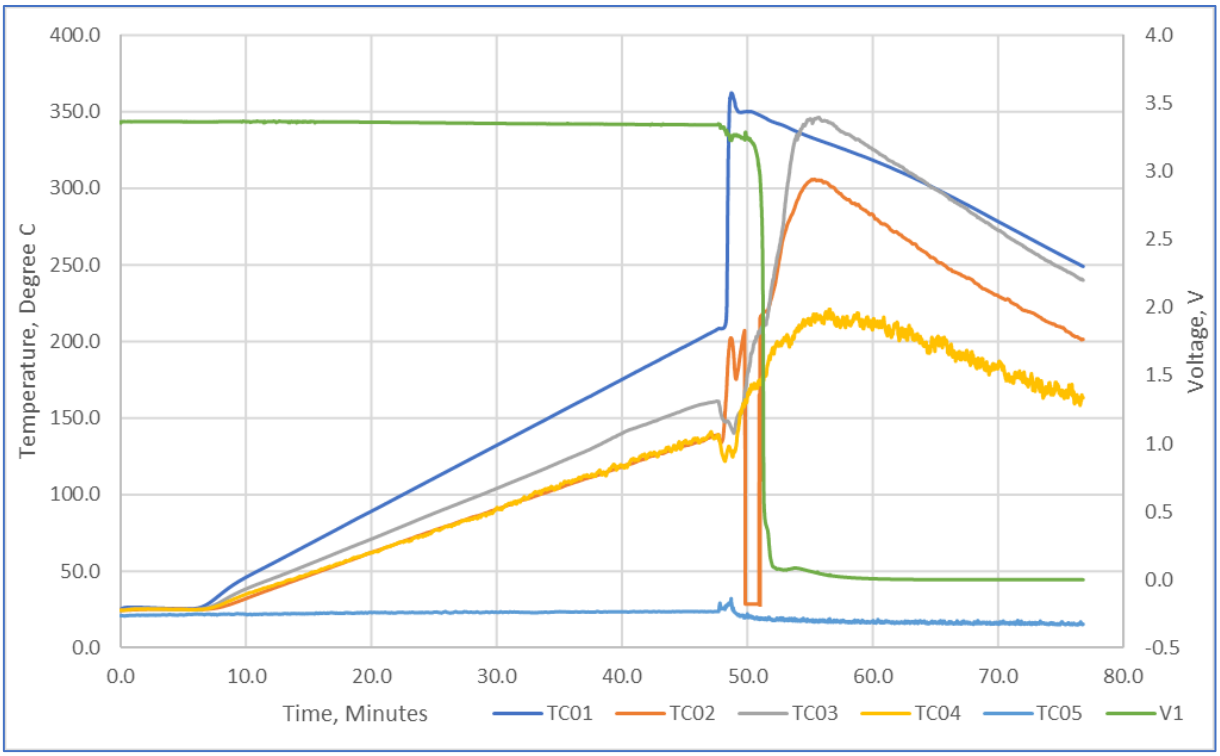


Figure 13: Cell 4 – External Heating 4.3°**C** per minute

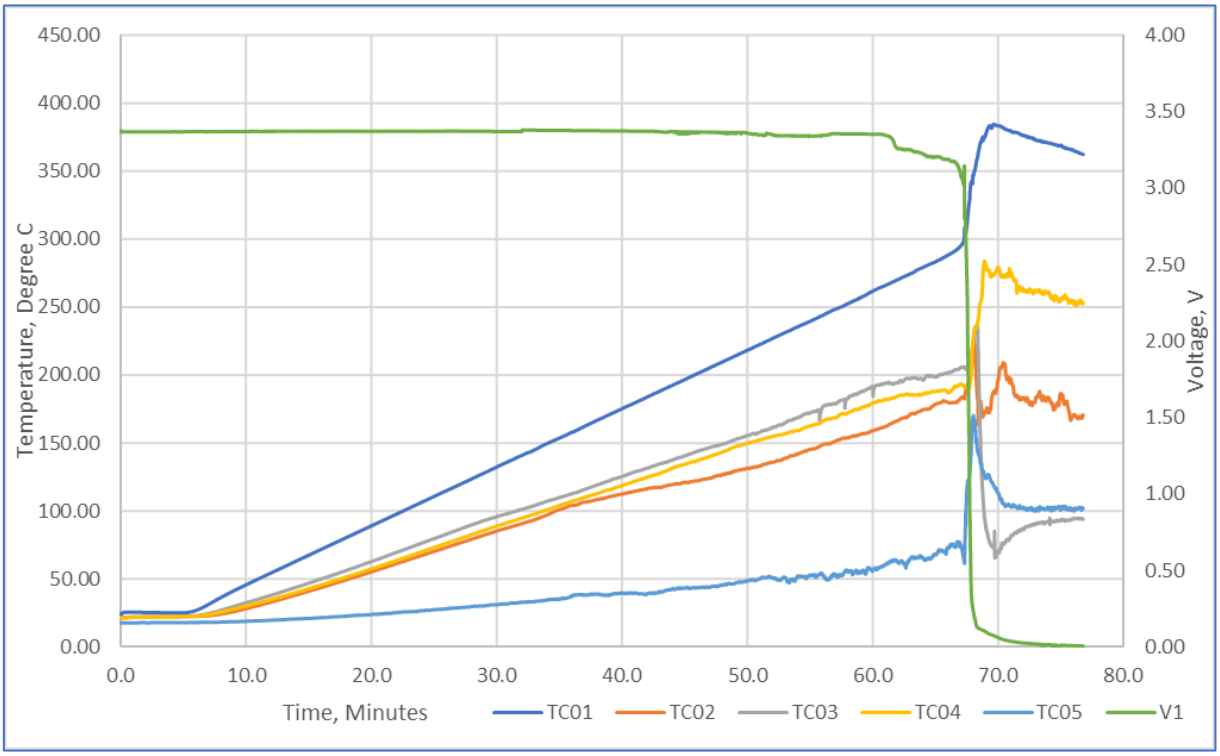


Figure 14: Cell 5 – External Heating 4.3°**C** per minute

Attachment D: Cell Testing Photos - (*Pages **27** through **36***)

Cell Sample 1 – below figure shows highlights of cell testing. Cell venting and thermal runaway were observed, however no evidence of fire. Figure on next page shows photos of cell after testing.

(a) Test Start
[00:00]

(b) Cell Venting
[46:05]

(c) Thermal runaway behavior
[46:52]

Figure 15: Highlights of Cell 1 Testing

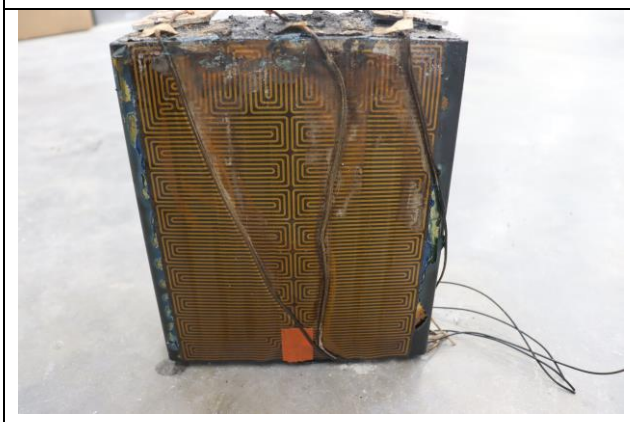
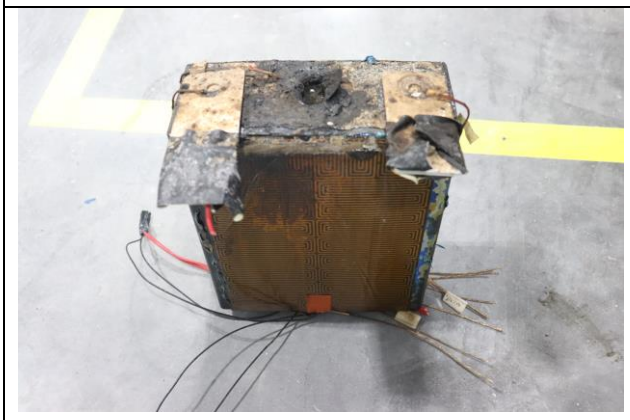


Figure 16: Sample 1 Post Test Photos

Cell Sample 2 – below figure shows highlights of cell testing. Cell venting and thermal runaway were observed, however no evidence of fire. Figure on next page shows photos of cell after testing.

<table>
<tr><td> </td><td> </td></tr>
<tr><td>(a) Test Start
[00:00]</td><td>(b) Cell Venting
[47:33]</td></tr>
<tr><td> </td><td></td></tr>
<tr><td>(c) Thermal runaway behavior
[48:29]</td><td></td></tr>
<tr><td colspan="2">Figure 17: Highlights of Cell 2 Testing</td></tr>
</table>



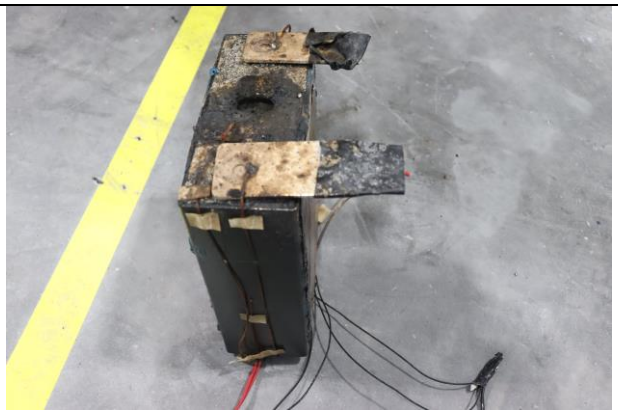
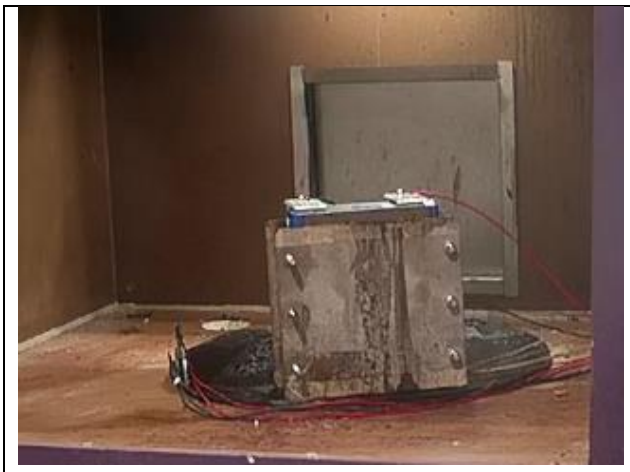


Figure 18: Sample 2 Post Test Photos

Cell Sample 3 – below figure shows highlights of cell testing. Cell venting and thermal runaway were observed, however no evidence of fire. Figure on next page shows photos of cell after testing.

<table>
<tr><td>  </td><td> </td></tr>
<tr><td>(a) Test Start
[00:00]</td><td>(b) Cell Venting
[48:42]</td></tr>
<tr><td> </td><td></td></tr>
<tr><td>(c) Thermal runaway behavior
[49:14]</td><td></td></tr>
<tr><td colspan="2">Figure 19: Highlights of Cell 3 Testing</td></tr>
</table>

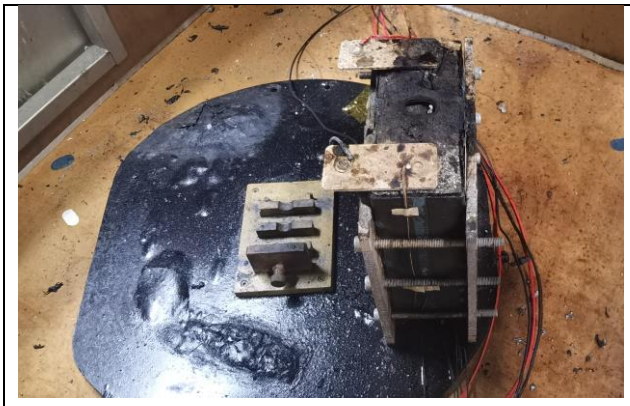


Figure 20: Sample 3 Post Test Photos

Cell Sample 4 – below figure shows highlights of cell testing. Cell venting and thermal runaway were observed, however no evidence of fire. Figure on next page shows photos of cell after testing.

<table>
<tr><td> </td><td> </td></tr>
<tr><td>(a) Test Start
[00:00]</td><td>(b) Cell Venting
[47:41]</td></tr>
<tr><td> </td><td></td></tr>
<tr><td>(c) Thermal runaway behavior
[48:19]</td><td></td></tr>
<tr><td colspan="2">Figure 21: Highlights of Cell 4 Testing</td></tr>
</table>

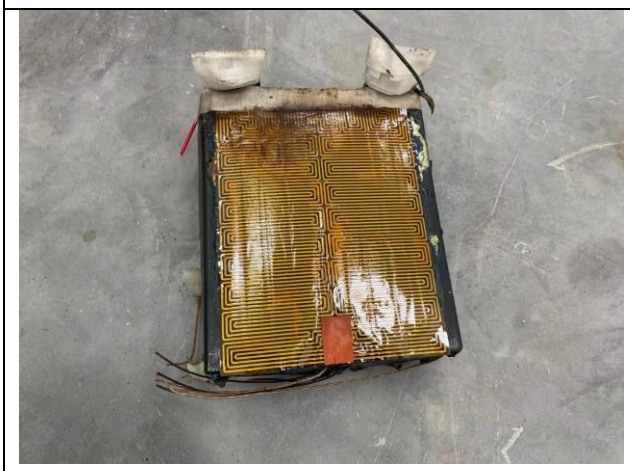


Figure 22: Sample 4 Post Test Photos

Cell Sample 5 – below figure shows highlights of cell testing. Cell venting and thermal runaway were observed, however no evidence of fire. Figure on next page shows photos of cell after testing.

The camera cannot record properly during test due to cell reaction inside test chamber, no photo provided.

Figure 23: Highlights of Cell 5 Testing

Figure 24: Sample 5 Post Test Photos

Attachment E: Cell vent gas test chamber photo and profile of chamber gas analysis (O_2 and Pressure) - *(Page **37**)*

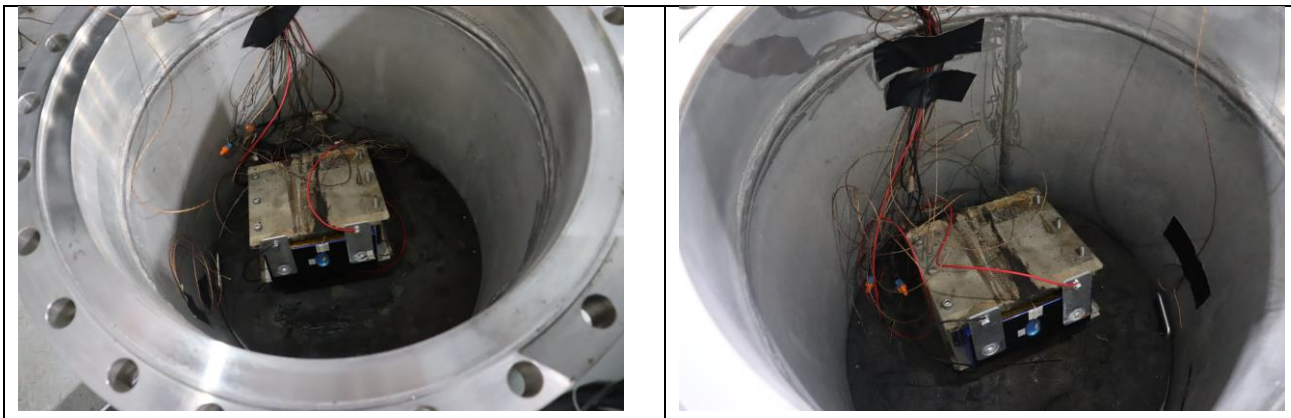


Figure 25: Sample 5 instrumented and inside gas test chamber

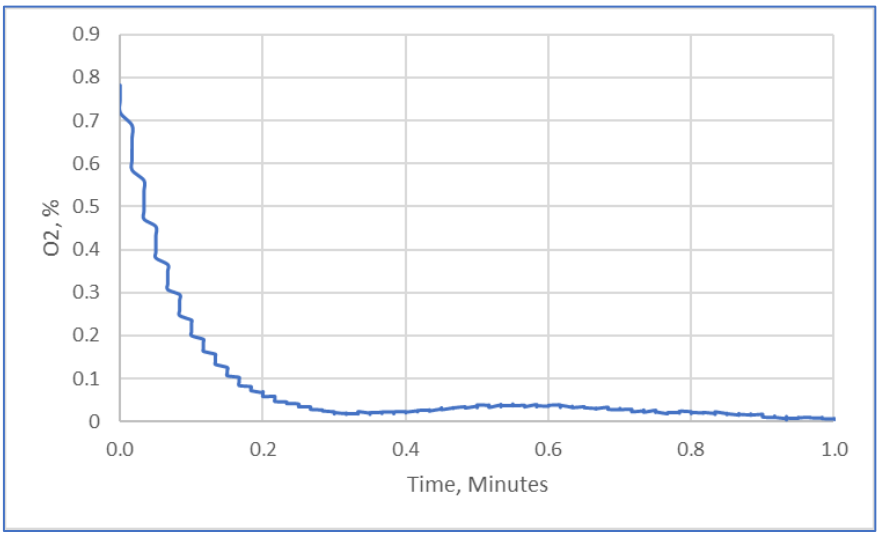


Figure 26: Profile of gas test chamber (O_2 Concentration before test)

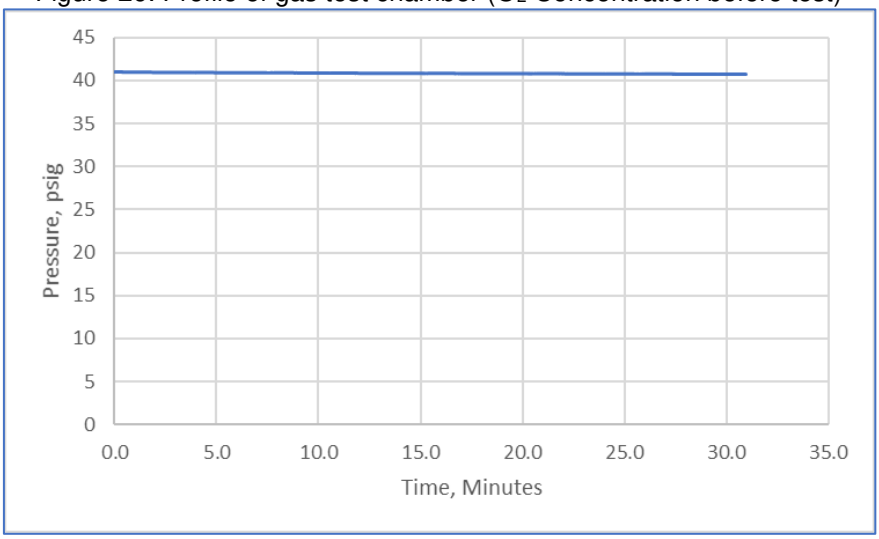


Figure 27: Profile of gas test chamber (Pressure maintenance before test)

Attachment F: Cell Gas Analysis Report - (*Pages **38** through **39***)

Table Re-normalized Gas Quantification, excluding N_2 and O_2, and unknown compounds.

Item	Measure	Chemical formula	Conc.(%)
1	Carbon Monoxide	CO	11.191
2	Carbon Dioxide	CO_2	27.325
3	Hydrogen	H_2	48.013
4	Methane	CH_4	6.404
5	Acetylene	C_2H_2	0.107
6	Ethylene	C_2H_4	3.296
7	Ethane	C_2H_6	1.326
8	Propadiene (Allene)	C_3H_4	0.000
9	Propyne	C_3H_4	0.000
10	Propene	C_3H_6	0.948
11	Propane	C_3H_8	0.321
12	C4 (Total)	-	0.704
13	C5 (Total)	-	0.142
14	C6 (Total)	-	0.005
15	C7 (Total)	-	0.003
16	C8 (Total)	-	0.000
17	Benzene	C_6H_6	0.014
18	Toluene	C_7H_8	0.000
19	Dimethyl Carbonate	$C_3H_6O_3$	0.000
20	Ethyl Methyl Carbonate	$C_4H_8O_3$	0.201
21	Diethyl Carbonate	$C_5H_{10}O_3$	0.000
	Total	Measurement result	100.000

Figure 28: Gas composition analysis result

Table 1-3: Executive Summary of Lower Flammability Limit Test Results

Sample Name	LFL at Ambient Temp (vol.%)	LFL at 147°C (vol.%)
Custom Gas Mix Ref #4789795626	7.15	6.45

Figure 29: Flammability characteristics test result – Lower flammability level (LFL)

Material Tested: Gas-Mixture Part # SG HYULMX28-150A, Cylinder/Serial # 91005145
Certification of Analysis (COA): *COA of Gas mixture formulation is shown in section 4 below)*
Reference Material Tested: *R-32 (difluoromethane)*

Parameter Tested/Analyzed	
Explosion Severity Output	***Results***
Maximum Pressure (psig)	**102**
Maximum Pressure Rise Rate (psi/sec)	**9387**
Maximum Reaction Temperature in chamber (°C)	**204**
Deflagration Index; K_G *(bar·m/sec)*	**111**
Flame Speed and Burning Velocity	
Gas Mixture Linear Flame Speed (cm/sec)	**171**
Gas Mixture Burning Velocity (cm/sec)	**79**
R-32 Linear Flame Speed (cm/sec)	**25.0**
R-32 Burning Velocity (cm/sec)	**6.67**

Figure 30: Flammability characteristics test result – Maximum pressure (P_{max}) and Burning velocity (S_u)