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TEST REPORT
ANSI/CAN/UL 9540A:2019
Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems

Report Reference No. ..... :	220801366SHA-001
Tested by (name + signature) ..... :	Chuanhui Xie
Approved by (name + signature) .... :	Robin Xu
Total number of pages ..... :	38
Date of issue ..... :	2022-12-21
Testing Laboratory ..... :	Intertek Testing Services Shanghai
Address ..... :	Building No.86, 1198 Qinzhou Road (North), Shanghai 200233, China
Testing location/ procedure ..... :	Witness testing
Testing location/ address ..... :	No. 158, Changbangcun Road, Fengxian District, Shanghai
Applicant's name ..... :	Zhejiang Narada Energy Technology Co., Ltd
Address ..... :	Room 341, Building 3, No. 368, Jinpeng Street, Sandun Town, Xihu District, Hangzhou, Zhejiang,310000, P.R.China
Test specification:	
Standard ..... :	ANSI/CAN/UL 9540A:2019 (Fourth Edition)+ UL CRD's
Test procedure ..... :	Cell level test (clause 7.1-7.8)
Non-standard test method ..... .:	N/A
Test Report Form No. ..... :	ANSI/CAN/UL 9540A
Test Report Form(s) Originator ..... :	Intertek
Master TRF ..... :	2022-01

Test item description ..... :	Lithium-ion cell
Trade Mark ..... :	Narada
Manufacturer ..... :	Hangzhou Narada Motive Power Science&Technology Co.,Ltd
Model/Type reference ..... :	FE280A
Ratings ..... :	280Ah, 3.2V

List of attachments:

Attachment 1 - Photos

Attachment 2 - Cell conditioning (charge/discharge) profiles

Attachment 3 - Cell thermal runaway record

Attachment 4 - Temperature and voltage profile during the test

Attachment 5 - Cell vent gas capture

Attachment 6 - Cell vent gas composition measurement

Attachment 7 - Lower flammability limit (LFL) of the cell vent gas measurement

Attachment 8 - Vent gas burning velocity (S_u) measurement

Attachment 9 - Cell vent gas maximum pressure (P_{max}) measurement

Attachment 10 – Equipment list

Summary of testing:

Average Vent Temperature (°C)	:	259.9 °C
Average Onset of Thermal Runaway Temperature(°C)	:	357.5 °C
Gas Volume	:	164.6 L
Gas composition	:	CO_2: 26.0% CO: 11.6% H_2: 44.38% Hydrocarbon: 18.02%
Lower flammability level (LFL) at ambient temperature (%)	:	6.0% at 25±1°C and 101±3 kPa.
Lower flammability level (LFL) at cell venting temperature (%)	:	3.4% at 260±3°C and 101±4 kPa.
Burning velocity S_u (m/s)	:	0.685 m/s
Maximum explosion pressure P_{max} (psi)	:	113.1 psi (0.78 Mpa) at 30±3°C and 101±4kPa

Conclusion:

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 need to be conducted on a module employing this cell.

Possible test case verdicts:

- test case does not apply to the test object	:	N/A
- test object was not evaluated for the requirement	:	N/E
- test object does meet the requirement	:	Pass (P)
- test object does not meet the requirement	:	Fail (F)

Testing:

Date of receipt of test items	:	2022-09-23
Date(s) of test performed	:	2022-09-24-2022-11-16

General remarks:

"(see Attachment #)" refers to additional information appended to the report.

"(see appended table)" refers to a table appended to the report.

The tests results presented in this report relate only to the object tested.

This report shall not be reproduced except in full without the written approval of the testing laboratory.

List of test equipment must be kept on file and available for review.

Additional test data and/or information provided in the attachments to this report.

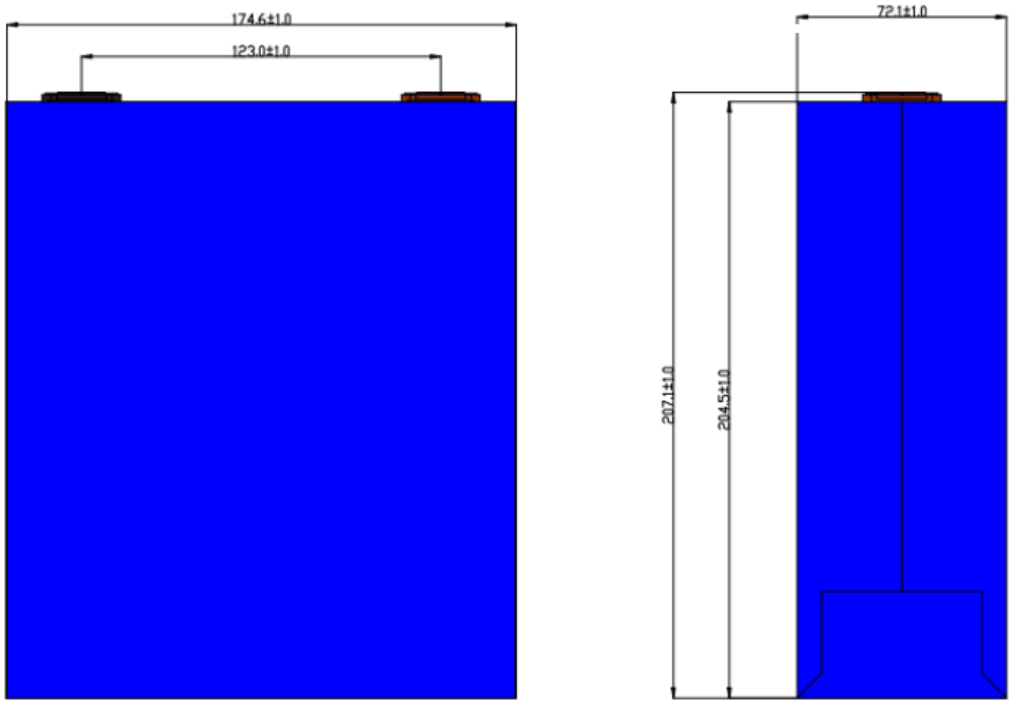
Throughout this report a ☐ comma / ☒ **point** is used as the decimal separator.

Determination of the test results includes consideration of measurement uncertainty from the test equipment and methods.

Production information

Manufacturer	:	Hangzhou Narada Motive Power Science&Technology Co.,Ltd
Factory address	:	No.120 Hongda Road, Yuhang Economic Develpment Zone of Yuhang District, Hangzhou, Zhejiang, 311100 P. R. China
Mode name	:	FE280A
Cell chemistry	:	$LiFePO_4$
Physical configuration	:	Prismatic
Protective measures	:	Vent perforation
Rated capacity (Ah)	:	280 Ah
Nominal voltage (V)	:	3.2 V
Standard charge method		
Charge current (A)	:	140 A
End of charge voltage (V)	:	3.65 V
Cut off current (A)	:	14 A
Standard discharge method		
Discharge current (A)	:	140 A
End of discharge voltage (V)	:	2.5 V
Rest time between charge and discharge	:	0.5 h
Mass of equipment (kg)	:	5.5 kg
Dimension of equipment (mm)	:	204.5±1.0 mm * 72.1±1.0 mm * 174.6±1.0 mm
UL 1973 compliance / certificate number	:	220801367SHA-001

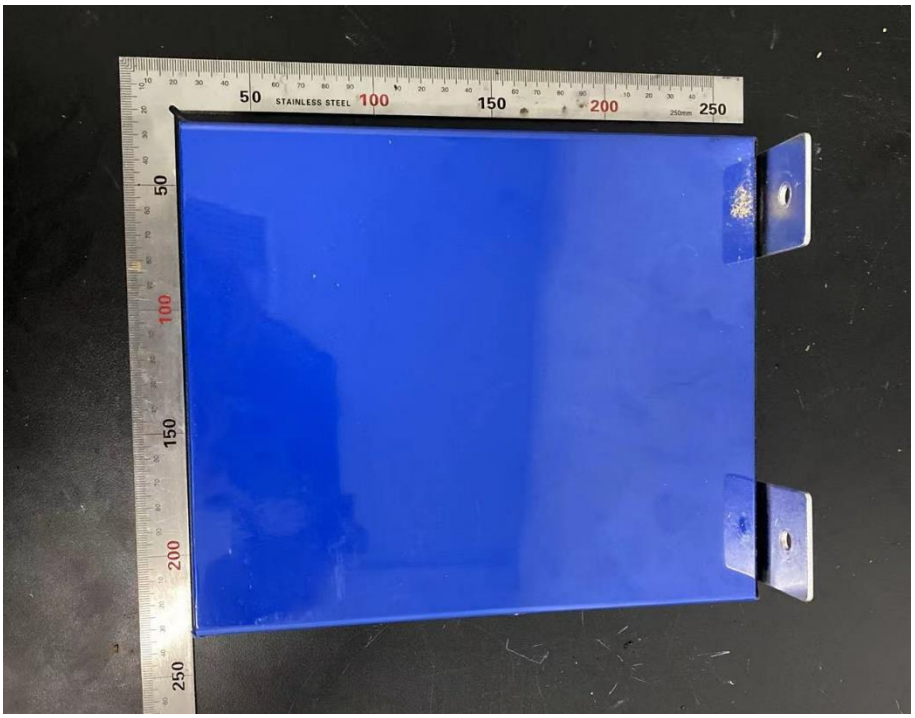
Cell diagram with overall dimension

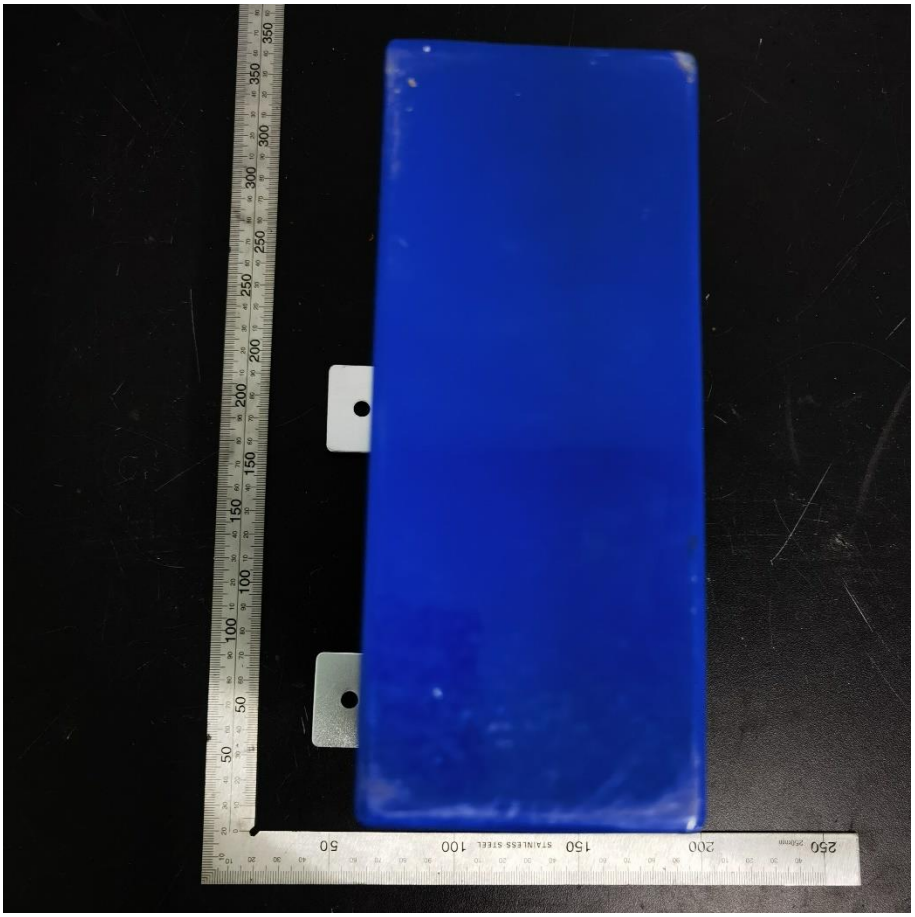


Item	Standard Value	Tolerance
Height (without terminal)	204.5mm (including insulating film and outer ring spacer)	±1.0mm
Height (including terminal)	207.1mm (including insulating film)	±1.0mm
Thickness	72.1mm (including insulating film)	±1.0mm
Width	174.6mm (at bottom fold, including insulating film)	±1.0mm
Terminal Welding Area	Φ16mm (without outer plastic of terminal)	±0.3mm
Distance between center of positive and negative terminal	123.0mm	±1.0mm

Note: The thickness is tested under the pressure of 3000±200N at the large surface.

Cell photo





ANSI/CAN/UL 9540A			
Clause	Requirement – Test	Result - Remark	Verdict
5	**Constrution – General**		
5.1	**Cell**		**--**
5.1.1	The cells info associated with the BESS include:		Pass
	• cell chemistry (e.g. NMC, LFP);	LFP	Pass
	• the physical format of the cell;	Prismatic	Pass
	• the cell electrical rating in capacity and nominal voltage;	280Ah, 3.2V	Pass
	• the overall dimensions of the cell, and weight.	204.5±1.0 mm * 72.1±1.0 mm * 174.6±1.0 mm 5.5 kg	Pass
5.1.2	The cells associated with the BESS comply with ANSI/CAN/UL 1973 or not.	220801367SHA-001	Pass
5.1.3	Further details included in the cell level test report.	(refer to 7.6.1)	Pass
5.2	**Moudle**		**--**
5.2.1	The modules info associated with the BESS, include:		N/A
	• the generic enclosure material;		N/A
	• the general layout of the module contents;		N/A
	• the electrical configuration of the cells in the modules and the modules in the BESS.		N/A
5.2.2	The modules associated with the BESS comply with UL 1973 or not.		N/A
5.2.3	Further details included in the module level test report.	(refer to 8.3)	N/A
5.3	**Battery energy storage system unit**		**--**
5.3.1	The BESS unit info, include:		
	• the units comply with UL 9540 or not;		N/A
	• the manufacturer and model number;		N/A
	• electrical ratings;		N/A
	• energy capacity of all BESS.		N/A
5.3.2	For BESS units, which UL 9540 compliance cannot be determined, to include:		N/A
	• the number of modules in the BESS;		N/A
	• electrical configuration of the module;		N/A
	• physical layout of the modules in the BESS;		N/A
	• battery management system (BMS); and		N/A
	• other major components of the BESS;		N/A
	• the BESS enclosure overall dimensions and generic material;		N/A
	• battery system(s) may be tested as representative of the BESS;		N/A
	• battery system complies with UL 1973 or not.		N/A

ANSI/CAN/UL 9540A			
Clause	Requirement – Test	Result - Remark	Verdict
5.3.3	Any fire detection and suppression systems that are an integral part of the BESS.		N/A
5.3.4	Further details included in the unit level and if applicable, installation level test reports.		N/A
5.4	**Flow Batteries**		**--**
5.4.1	For flow batteries, to incldue the following info:		N/A
	• the chemistry;		N/A
	• a generic description of the electrolyte (s);		N/A
	• the overall dimensions of the individual stack;		N/A
	• the electrical rating in capacity and nominal voltage of the cell stack.		N/A
	And the Information of the complete flow battery system:		N/A
	• the manufacturer's name and model number of the system;		N/A
	• the electrical rating in volts and rated storage capacity in Ah or Wh;		N/A
	• the number of cells and stacks in the system;		N/A
	• the maximum volume of electrolyte(s) for the system.		N/A
5.4.2	The flow battery system complies with UL 1973 or not.		N/A
5.4.3	Further details included in the flow battery thermal runaway determination level test report.		N/A

6	**Performance – General**		
6.1	The tests in this standard are extreme abuse conditions conducted on electrochemical energy storage devices, which may result in various kind of hazards.		Pass
6.2	At the conclusion of testing, samples discharged in accordance with the manufacturer' specifications.		Pass
	All samples disposed of in accordance with local regulations.		Pass

7	**Cell Level**		
7.1	**General**		**--**
7.1.1	Effective methods for forcing a cell into thermal runaway in a repeatable manner.	External heating with two flexible film heaters (size:173 mm*205mm, rate:220VAC/ 600W) clap on both wide surfaces of the cell	Pass
	Same methods used at the module, unit and installation level of testing.		Pass

ANSI/CAN/UL 9540A			
Clause	Requirement – Test	Result - Remark	Verdict
	The vent gas composition gathered and analyzed.	See attachment 5 and attachment 6	Pass
	Cell temperatures monitored to determine the temperature when the cell vents, and to verify that thermal runaway occurred.	See attachment 3	Pass
7.2	**Sample**		**--**
7.2.1	Cell samples conditioned, prior to testing, through charge and discharge cycles for a minimum of 2 cycles using a manufacturer specified methodology to verify that the cells are functional.	See attachment 2	Pass
7.2.2	The cells charged to 100% SOC and allowed to stabilize for 1 to 8 h before testing.		Pass
7.2.3	Cells with flexible laminate casings be constrained during the test to simulates the constraint in the BESS module to prevent excessive swelling.	Two metal plates clamp the cell to limit the excessive swelling of cell during the testing	Pass
7.3	**Determination of thermal runaway methodology**		**--**
7.3.1	General		Pass
7.3.1.1	Ambient indoor laboratory conditions: 25±5°C and 50±25% RH at the initiation of the test.	See attachment 3	Pass
7.3.1.2	The propensity of the cell to exhibit thermal runaway demonstrated by heating the cell with externally applied flexible film heaters that cover as much of the cell case as possible without covering safety features or terminals, for consistent heating of the internal cell electrode assembly.	See attachment 1 and attachment 3	Pass
	A surface heating rate of 4°C to 7°C per minute applied to the cell.		Pass
	Determination of a maximum surface temperature end point criteria shall be developed based upon a review of cell design and chemistry.	On the center of wide side of the cell	Pass
	If external heating with a flexible film heater does not cause the cell to exhibit thermal runaway, one of the following methods shall be employed to cause thermal runaway:		N/A
	a) Mechanical (e.g. nail penetration);		N/A
	b) Electrical stresses in the form of overcharging, over discharging or external short-circuiting; or		N/A
	c) Use of alternate heating sources (e.g. oven).		N/A
7.3.1.3	When using another cell abuse method to initiate thermal runaway, document the details of it.		N/A
7.3.1.4	In the case of monobloc batteries such as lead acid or nickel cadmium, the monobloc battery can be treated as an individual cell for this testing.		N/A
7.3.1.5	Before testing, determine the approximate surface temperature at which internal short circuiting within the cell will occur that could lead to a thermal runaway condition.		N/A

ANSI/CAN/UL 9540A			
Clause	Requirement – Test	Result - Remark	Verdict
	For Li-ion cells, the surface temperature hold point shall be between 5°C and 15°C greater than the melting temperature of the cell separator material as determined from differential scanning calorimetry (DSC) data of the separator per UL 2591 (UL 746A).	Separator information is not available, heating continuously without a hold point unitl thermal runaway	N/A
	Thermal runaway may occur before this hold point, if thermal runaway is not achieved at this hold point temperature after 4h, the cell heating rate shall be reestablished until thermal runaway occurs or it is demonstrated it is not achievable by heating.		N/A
	Exception: If the separator information is not available or at the manufacturer's discretion, the thermal ramp can be conducted continuously without a hold point until thermal runaway.	(added by UL CRD-2020.5.20)	Pass
7.3.1.6	If using another external heating method, the temperature ramp and max. surface temperature outlined in 7.3.1.2 and 7.3.1.5 shall be used.		N/A
7.3.1.7	The cell's exterior surface temperature measured continuously through the cell test.	See attachment 4	Pass
	At least one thermocouple be located below the heater film at the center of the cell surface and one near the positive cell terminals.	24-gauge or small, type K thermocouple wire used	Pass
7.3.1.8	The temperature at which the cell case vents due to internal pressure rise shall be documented.	See attachment 3	Pass
7.3.1.9	The temperature at the onset of thermal runaway shall be documented.	See attachment 3	Pass
	If there is a transitory temperature dip during the cell venting, the heat input may need to be increased to bring it back to the heating rate range.	See attachment 4	Pass
7.3.1.10	When using methods other than the heater method, the stresses (i.e. electrical or mechanical) shall be applied to the cell until thermal runaway occurs.		N/A
7.3.1.11	If the cell exhibits thermal runaway behavior, 3 additional samples tested using the same method and exhibit thermal runaway to demonstrate repeatability	See attachment 3	Pass
	The vent temperature and thermal runaway onset temperatures shall be averaged over the tested samples (excluding the gas vent capture sample).	See attachment 3	Pass
7.3.2	Flow battery thermal runaway determination tests		N/A
7.3.2.1	For flow battery technology, the propensity for thermal runaway shall be demonstrated by testing the energy reservoir according to the test methods as applicable to the flow battery technology.		N/A
7.3.2.2	The flammability of the electrolytes shall be determined based upon a suitable test method to determine flammability.		N/A
	The test shall be continued to a maximum solution temperature of 200°C or sufficient to determine flammability of the liquid within the boundaries of the test method.		N/A

ANSI/CAN/UL 9540A			
Clause	Requirement – Test	Result - Remark	Verdict
	The flash point temperature shall be recorded for each electrolyte tested. If no flashpoint is observed (i.e. no ignition occurs), this shall be recorded.		N/A
7.3.2.3	For flow battery systems with two electrolytes, the flammability of the liquid electrolytes shall be demonstrated by subjecting each electrolyte to the appropriate test method.		N/A
	If a flash point has been observed in, the ropensity for thermal runaway shall be demonstrated by the test methods of 7.3.2.4 and comparing the temperatures recorded with the flash point temperature determined from 7.3.2.2.		N/A
7.3.2.4	The temperature increase possible due to a flow battery failure where there are two electrolytes shall be demonstrated by charging the energy reservoir in a test flow battery assembly to 100% SOC, and then directly mixing the two electrolyte materials in a closed container within 1min.		N/A
	The mixed solution temperature shall be measured during the test. The test shall conclude when the temperature of the solution stabilizes for a minimum of 1 h. The maximum mixing temperature of the sample shall be recorded and compared with the flash point temperature results from 7.3.2.2.		N/A
	In addition, a test battery representative of the flow battery system shall be subjected to an overcharge test and short circuit test in accordance with UL 1973 while monitoring the temperature of the energy reservoirs. The maximum temperature of the energy reservoirs during the testing shall be recorded and compared with the flash point temperature results from 7.3.2.2.		N/A
7.3.2.5	For flow battery technologies with one active electrolyte containing solid metal particles the appropriate test method is conducted to determine the flash point temperature.		N/A
	The electrolyte tested shall contain the rated concentration of metal particles present in the electrolyte of a fully charged system.		N/A
	If a flash point has been observed in 7.3.2.2, the propensity for thermal runaway shall be demonstrated by the test methods of 7.3.2.6 and comparing the temperatures of the energy reservoir recorded during those tests with the flash point temperature determined from 7.3.2.2.		N/A
7.3.2.6	If a flash point has been observed for a flow battery technology with one active electrolyte containing solid metal particles, a test battery representative of the flow battery system shall be subjected to an overcharge test and short circuit test in accordance with UL 1973 while monitoring the temperature of the energy reservoir.		N/A

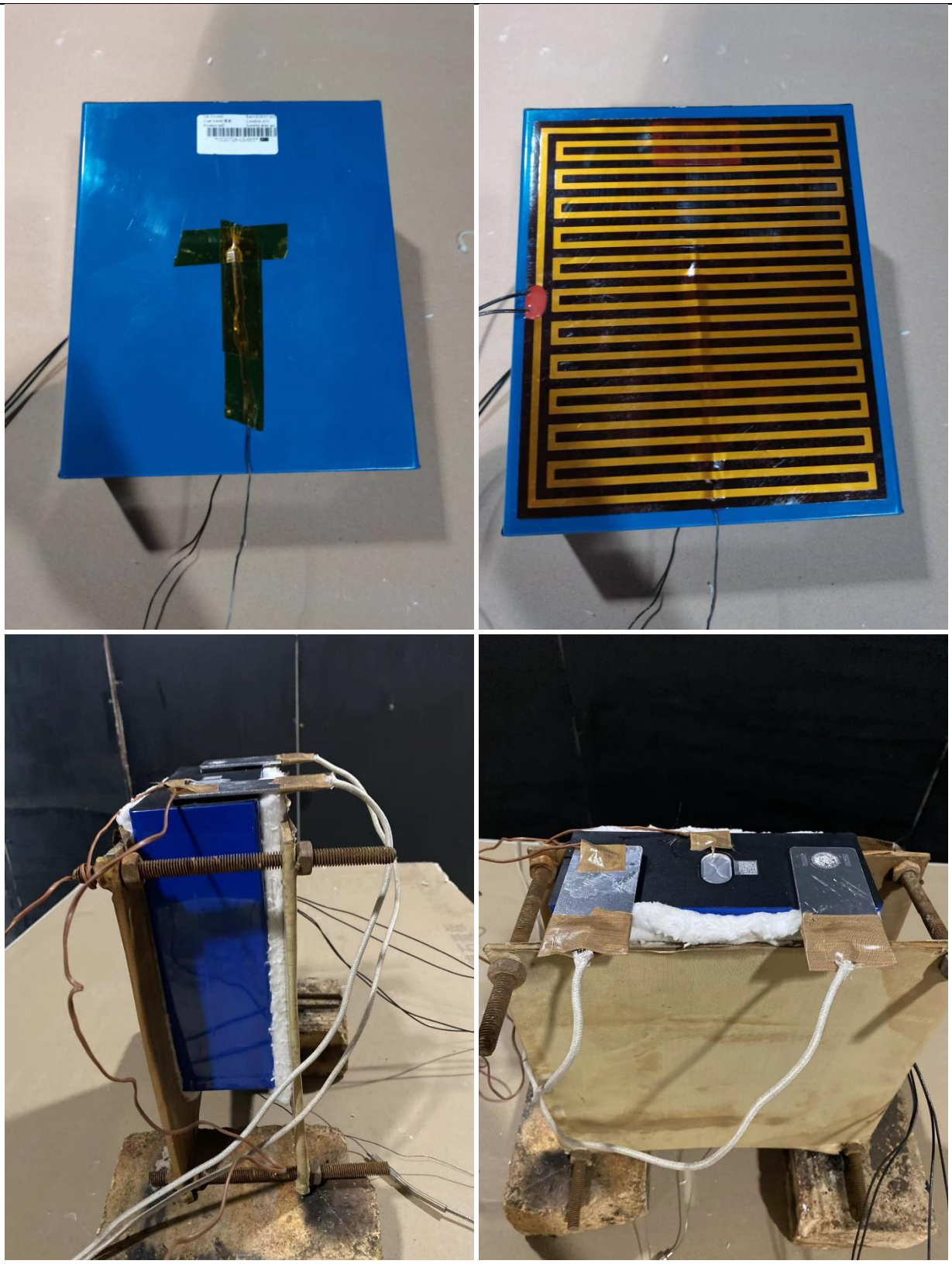
ANSI/CAN/UL 9540A			
Clause	Requirement – Test	Result - Remark	Verdict
	The maximum temperature of the energy reservoir during testing shall be recorded and compared with the flash point temperature results from 7.3.2.2.		N/A
7.4	**Cell vent gas composition test**		**--**
7.4.1	Cell vent gas shall be generated and captured by forcing a cell into thermal runaway inside a pressure vessel.	A 82.0 L pressure vessel used	Pass
	The test shall be initiated with an initial condition of atmospheric pressure and less than 1% oxygen by volume.	Oxygen content by volume: 0.09%	Pass
	The initial atmospheric conditions prior to testing.	Pressure inside: 101.3kPa	Pass
7.4.2	Cell vent gas composition	See attachment 6	Pass
	Hydrocarbon gases that represent an ignition or explosion hazard as well as other additional gases.		Pass
	Hydrogen gas shall be measured with a sensor capable of measuring in excess of 30% by volume.		Pass
7.4.3	The lower flammability limit of the cell vent gas, samples of the synthetically replicated gas mixture in accordance with ASTM E918.	See attachment 7	Pass
7.4.4	The synthetically replicated gas mixture used to determine gas burning velocity in accordance with the Method of Test for Burning Velocity Measurement of Flammable Gases.	See attachment 8	Pass
7.4.5	The synthetically replicated gas mixture used to determine Pmax in accordance with EN 15967.	See attachment 9	Pass
7.5	**Off gas composition for flow battery systems**		**--**
7.5.1	The off gas composition from the flow battery testing 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.		N/A
	Composition of these captured gases and their flammability limit.		N/A
7.5.2	The volume of flammable gases measured during the testing shall be scaled to the maximum energy reservoir for the intended flow battery system in order to determine the potential total flammable gas that can be produced by the system under a fault condition that leads to off gassing.		N/A
7.6	**Cell level test report**		**--**
7.6.1	The report on cell level testing shall include the following:		Pass
	a) Cell manufacturer name and cell model number;	See production information	Pass
	b) Cell details per 5.1 (and whether UL 1973 compliant);	See production information	Pass
	c) Energy storage technology (and whether UL 9540 compliant);	UL 9540 certificate not provided	Pass

ANSI/CAN/UL 9540A			
Clause	Requirement – Test	Result - Remark	Verdict
	d) The rated energy storage capacity of the cell;	See production information	Pass
	e) Voltage and current obtained during conditioning of the cell;	See attachment 1	Pass
	f) Open-circuit voltage of the cell at initiation of test;	See Attachment 3	Pass
	g) Methods attempted and used to initiate thermal runaway;	See Attachment 3	Pass
	h) Surface temperature at which gases are first vented and the average temperature of the samples tested excluding the gas collection sample;	See Attachment 3	Pass
	i) Surface temperature (and location of maximum temperature) prior to thermal runaway and average temperature of the samples tested excluding the gas collection sample;	See Attachment 3	Pass
	j) Flammable gas generation and composition measurements;	See Attachment 5 and attachment6	Pass
	k) The lower flammability limit of the cell vent gas;	See attachment 7	Pass
	l) Burning velocity of the cell vent gas; and	See attachment 8	Pass
	m) Pmax of the cell vent gas.	See attachment 9	Pass
7.6.2	The report on flow battery thermal runaway determination testing include the following:		N/A
	a) Flow battery system manufacturer name and model No. (and whether UL 1973 compliant);	Not flow battery system	N/A
	b) Cell stack details per 5.4;		N/A
	c) Energy storage technology (and whether UL 9540 compliant);		N/A
	d) The rated energy storage capacity of the flow battery (e.g. Ampere-hours or Watt-hours);		N/A
	e) Electrolyte(s) composition and quantity in the system;		N/A
	f) Flash point temperatures of each electrolyte;		N/A
	g) Highest temperatures measured during abnormal conditions of:		N/A
	1) Mixed electrolytes for two electrolyte systems; and		N/A
	2) Electrolyte during the battery system overcharge and short circuit test;		N/A
	h) Flammable off gas generation and composition measurements;		N/A
	i) The lower flammability limit of the flammable off gas at both ambient and abnormal test temperatrues;		N/A
	j) Burning velocity of the flammable off gas; and		N/A
	k) Pmax of the flammable off gas.		N/A
7.7	**Performance – cell level test**		**--**

ANSI/CAN/UL 9540A			
Clause	Requirement – Test	Result - Remark	Verdict
7.7.1	Module level testing is not required if the following performance conditions are met:		Fail
	a) Thermal runaway cannot be induced in the cell; and	Thermal runaway induced	Fail
	b) The cell vent gas does 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.	Vent gas is flammable	Fail
7.7.2	BESS contain cells that all comply with the criteria in 7.7.1 shall be suitable for installation in residential dwelling units.		Fail
7.8	**Performance – flow battery thermal runaway determination tests**		**--**
7.8.1	For flow batteries, no further testing is required if the following performance conditions are met during the flow battery thermal runaway determination test:		N/A
	a) The electrolyte(s) subjected to the test method in accordance with 7.3.2.2 does not ignite; or	(not flow battery system)	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
	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
7.8.2	Flammable off gassing during the abnormal tests are addressed as outlined in 7.5.2 by scaling the results in accordance with the largest anticipated flow battery energy reservoir.		N/A

Attachment 1 Photos

Sample Preparation for thermal runaway test



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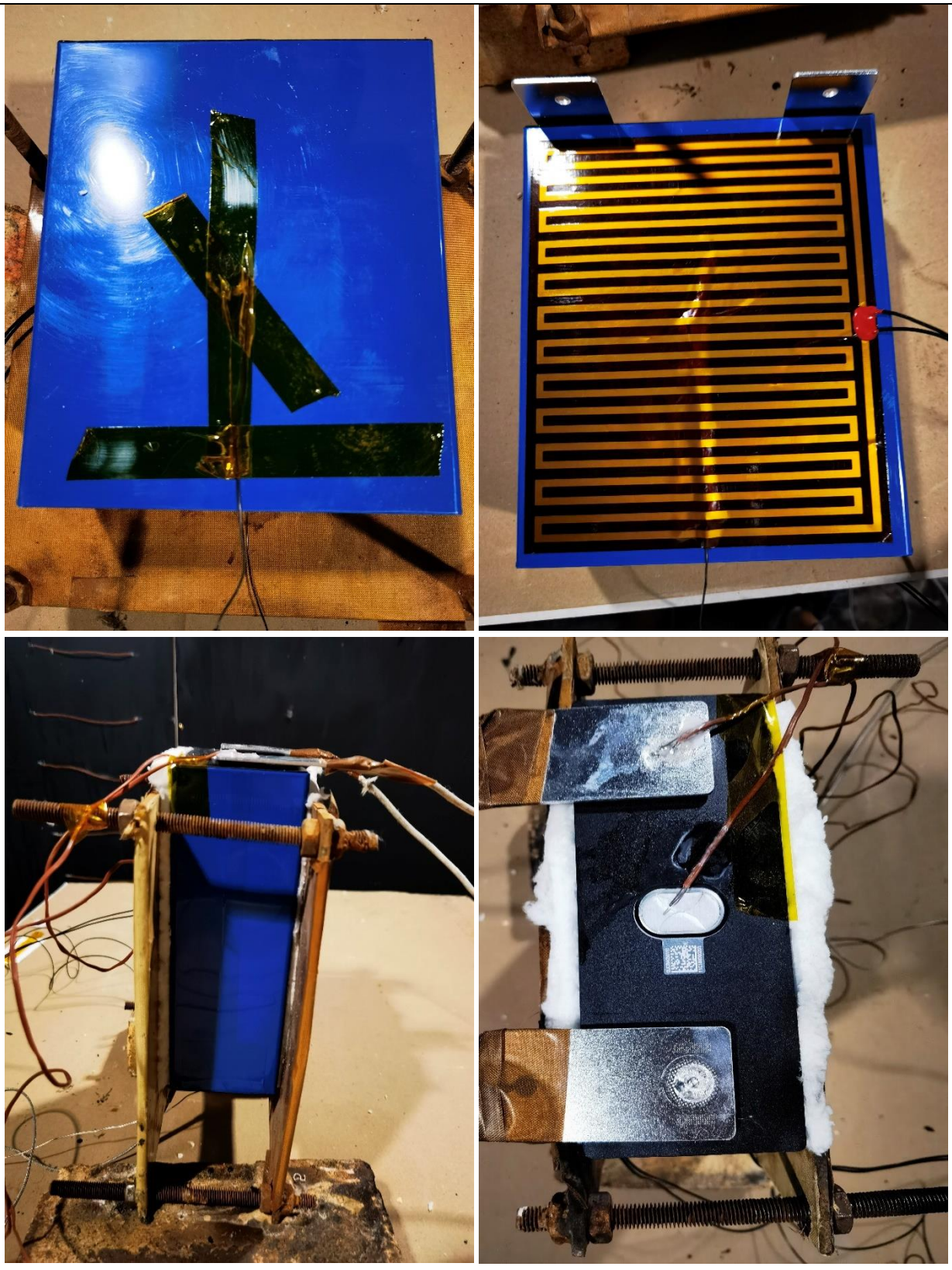

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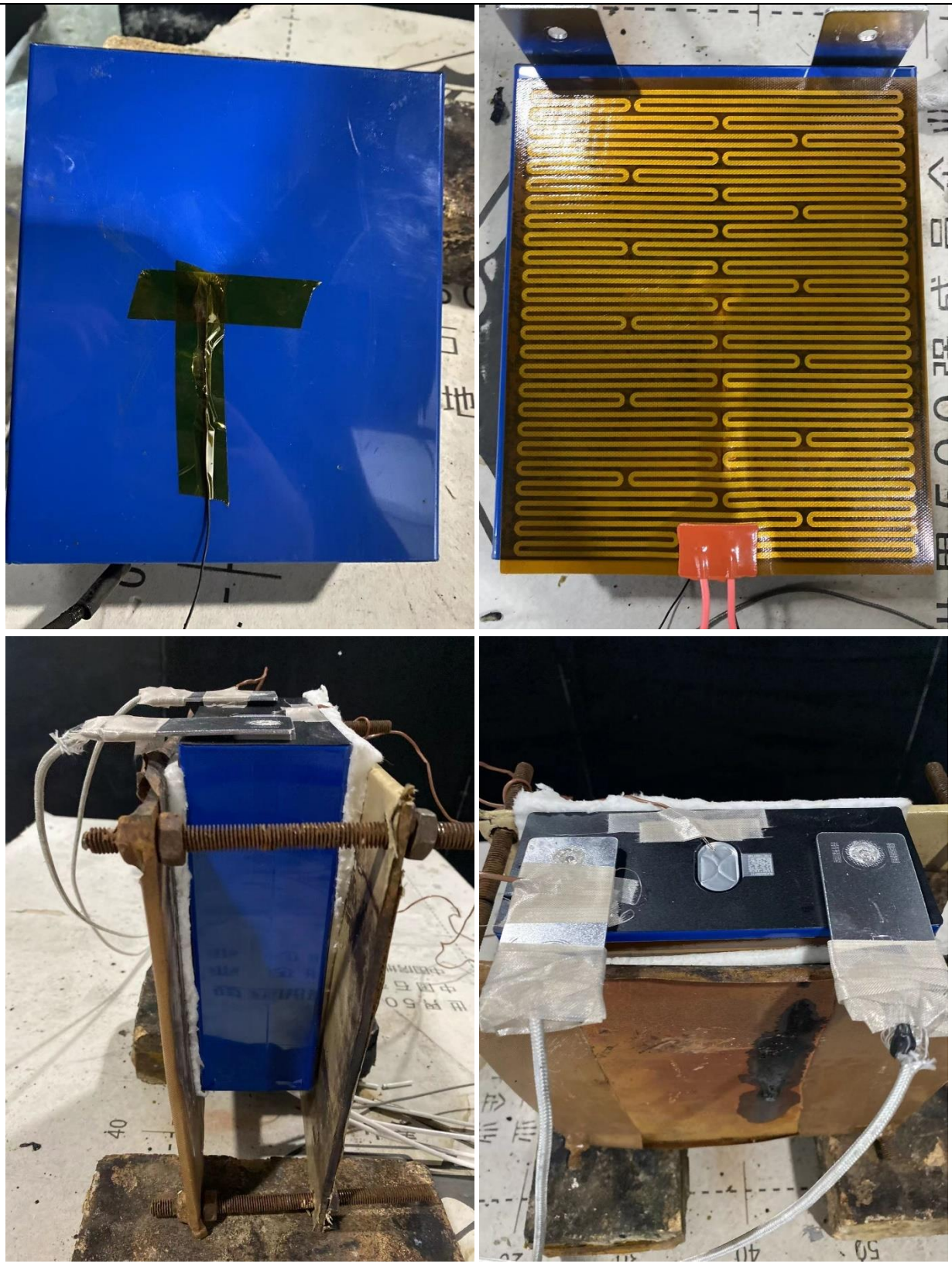

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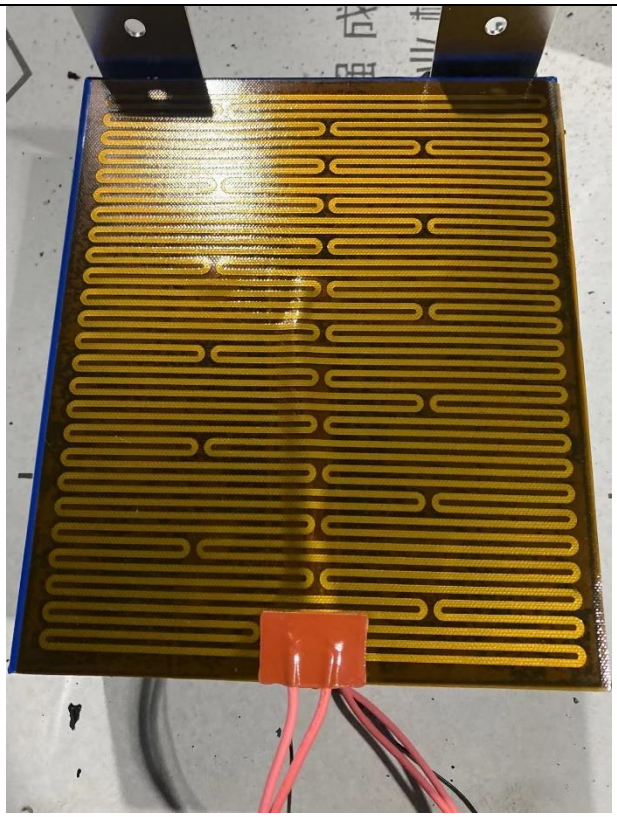
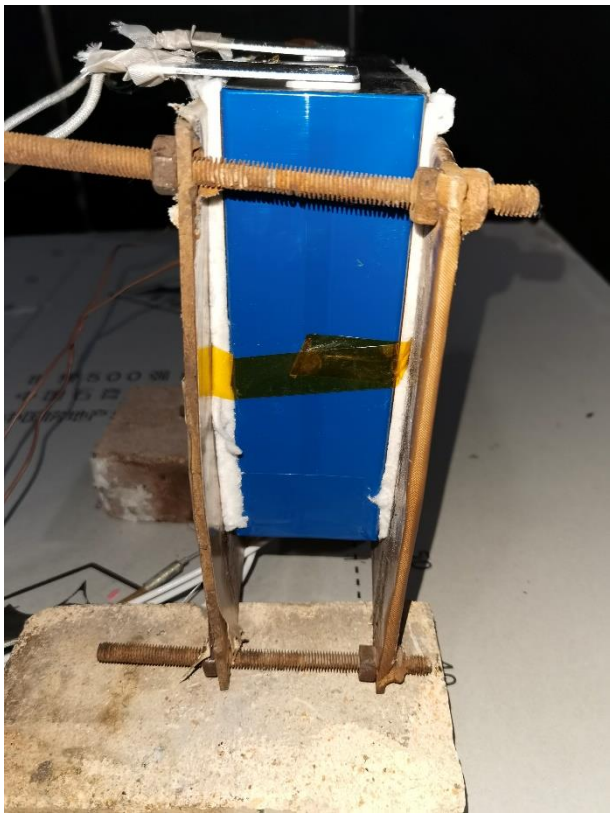
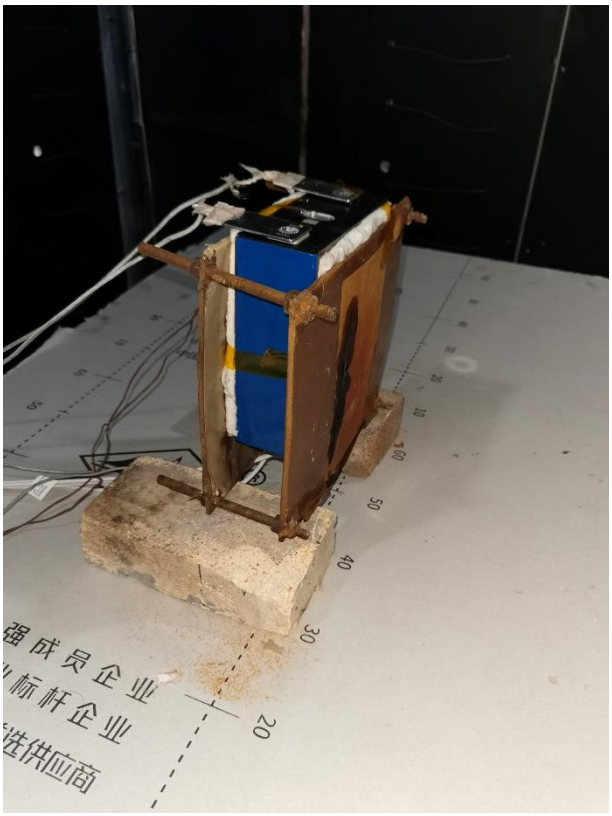

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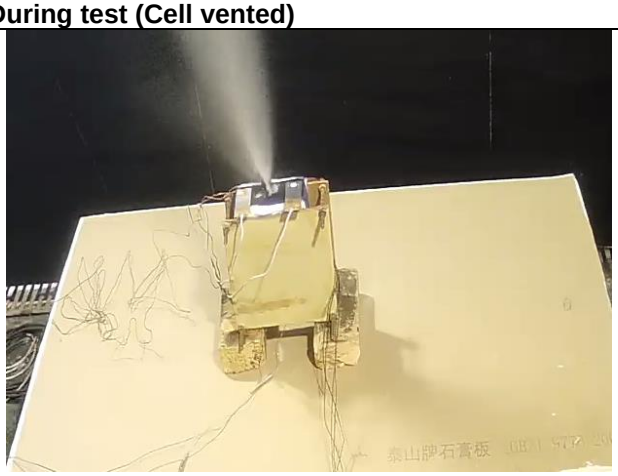
During test (Cell vented)



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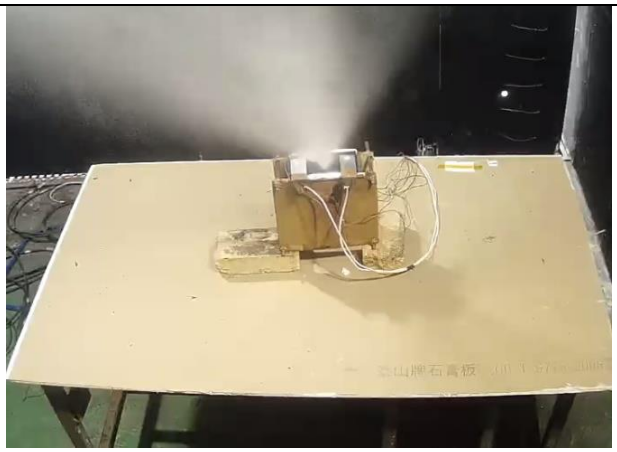

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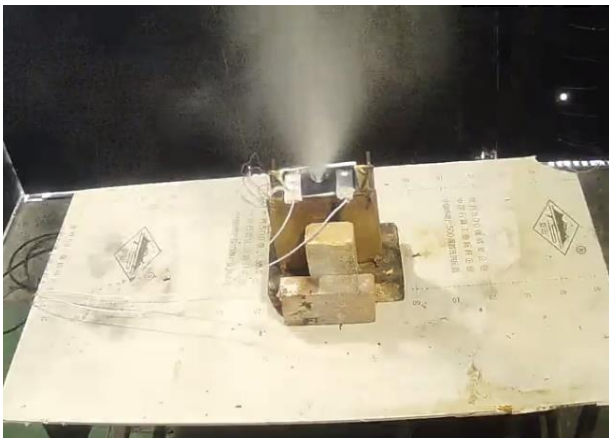
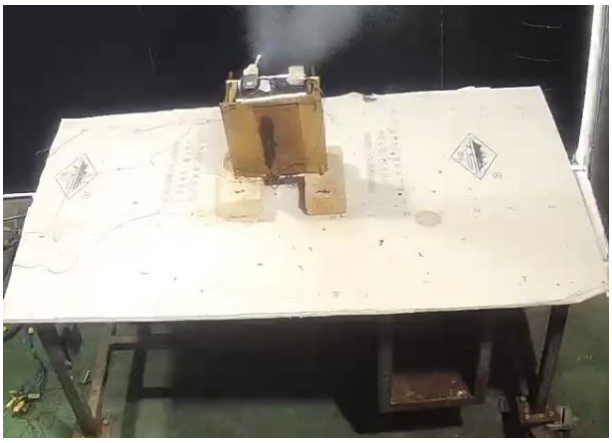
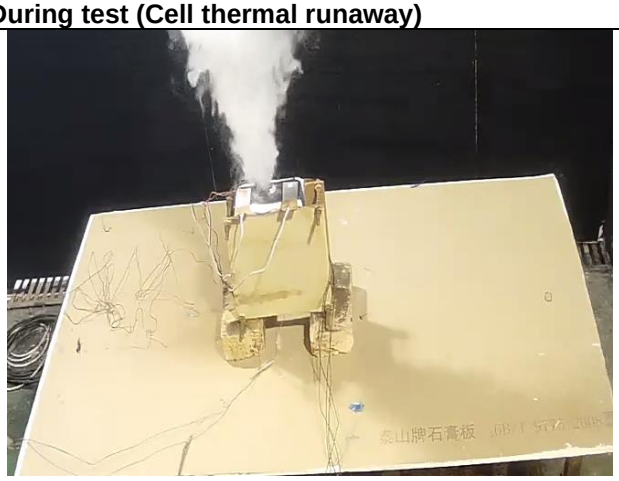


3#



4#

During test (Cell thermal runaway)



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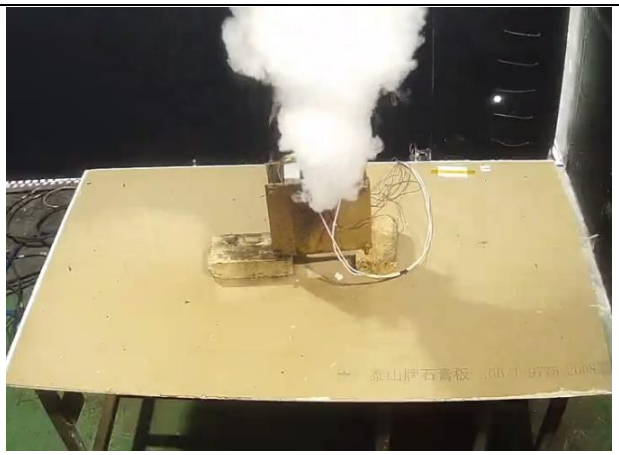
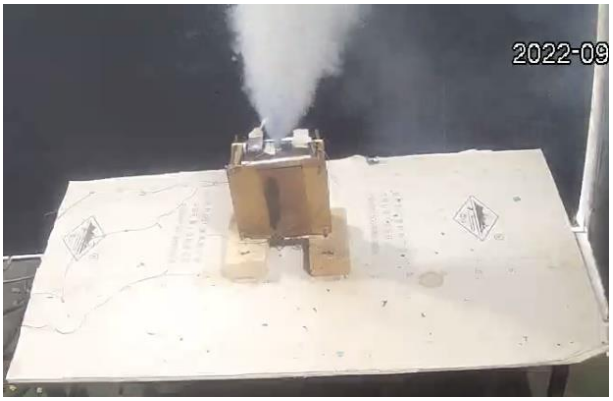


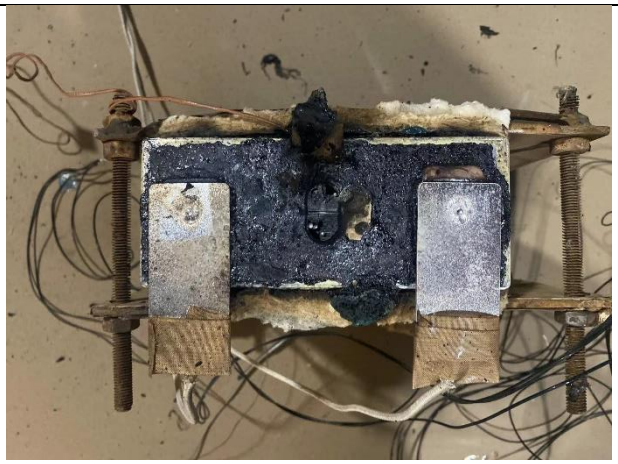
2#

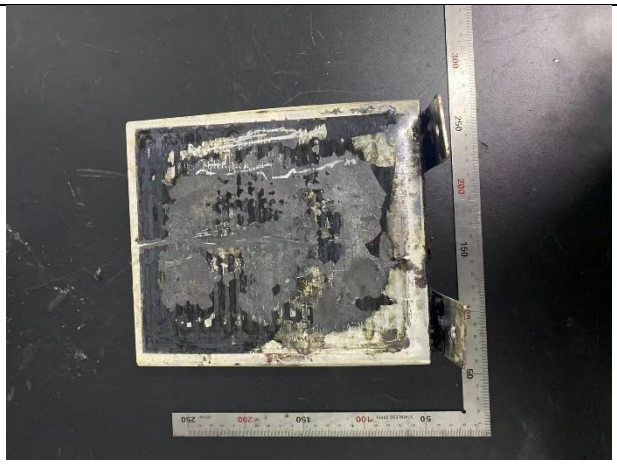
3#



4#

After test





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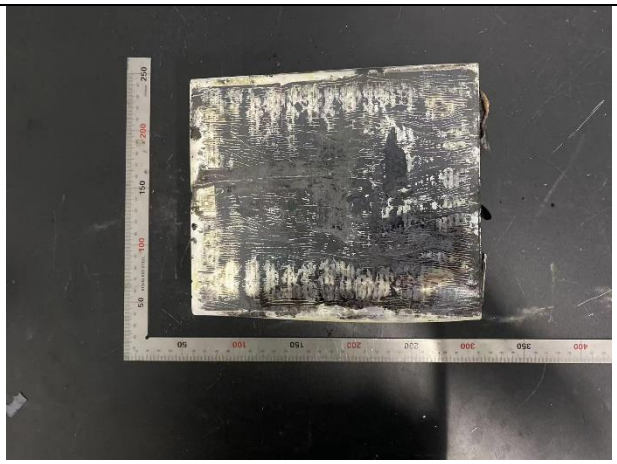
2#

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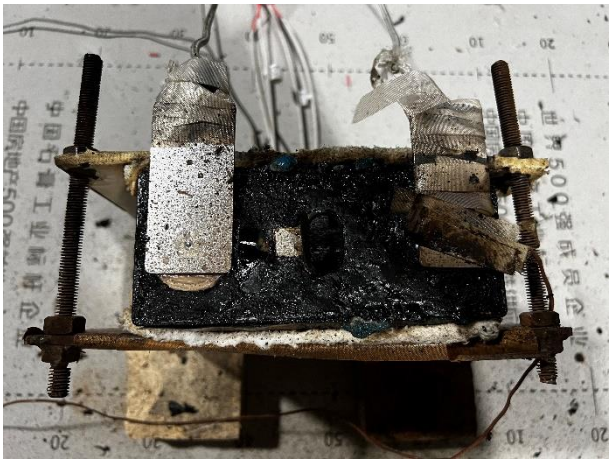
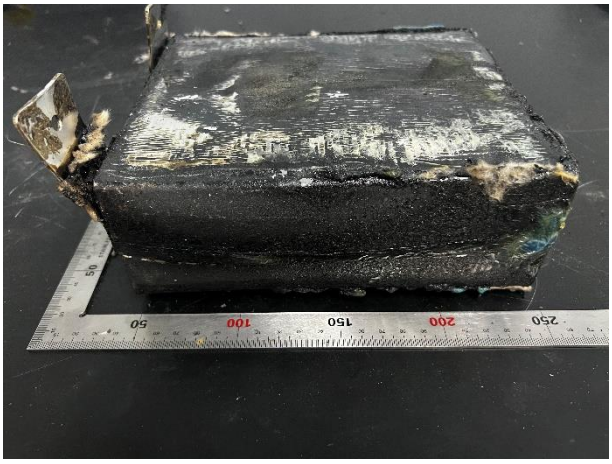
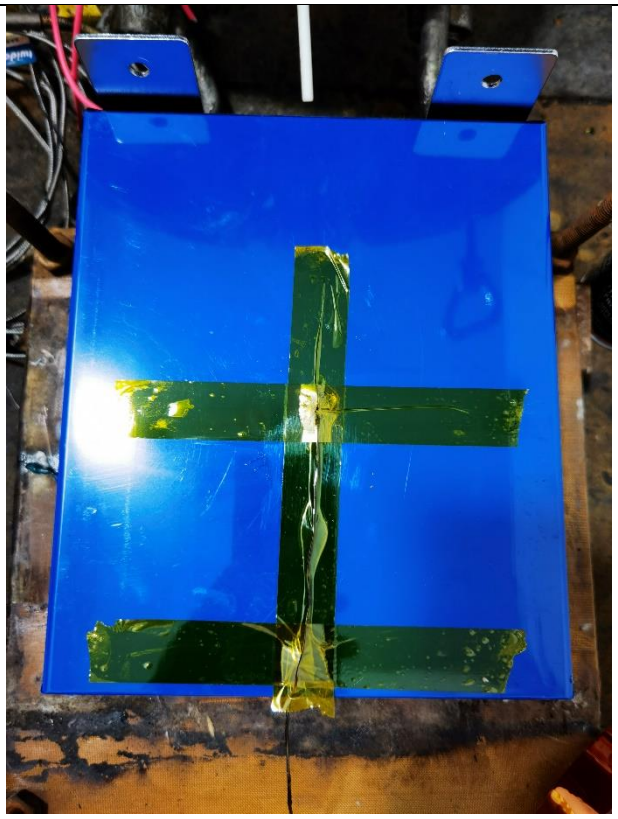
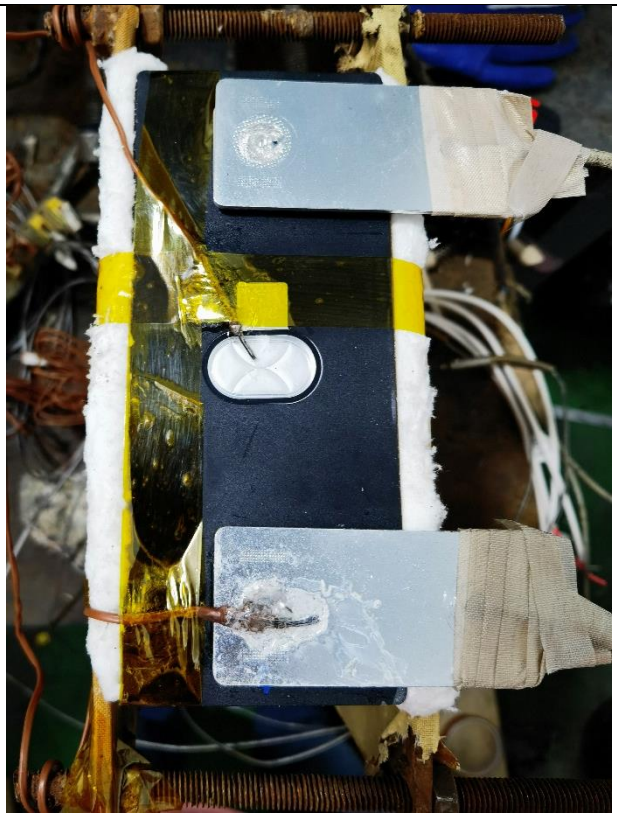



4#

Cell vent gas capture (5#)

Before test

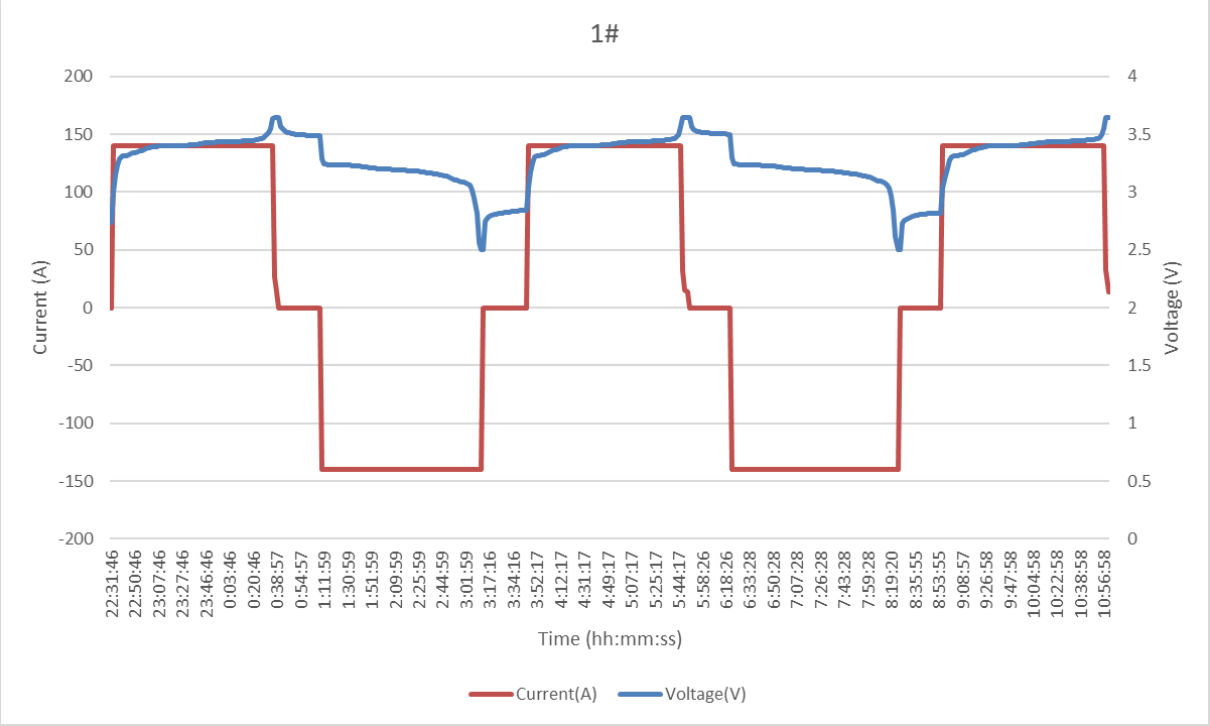

After test

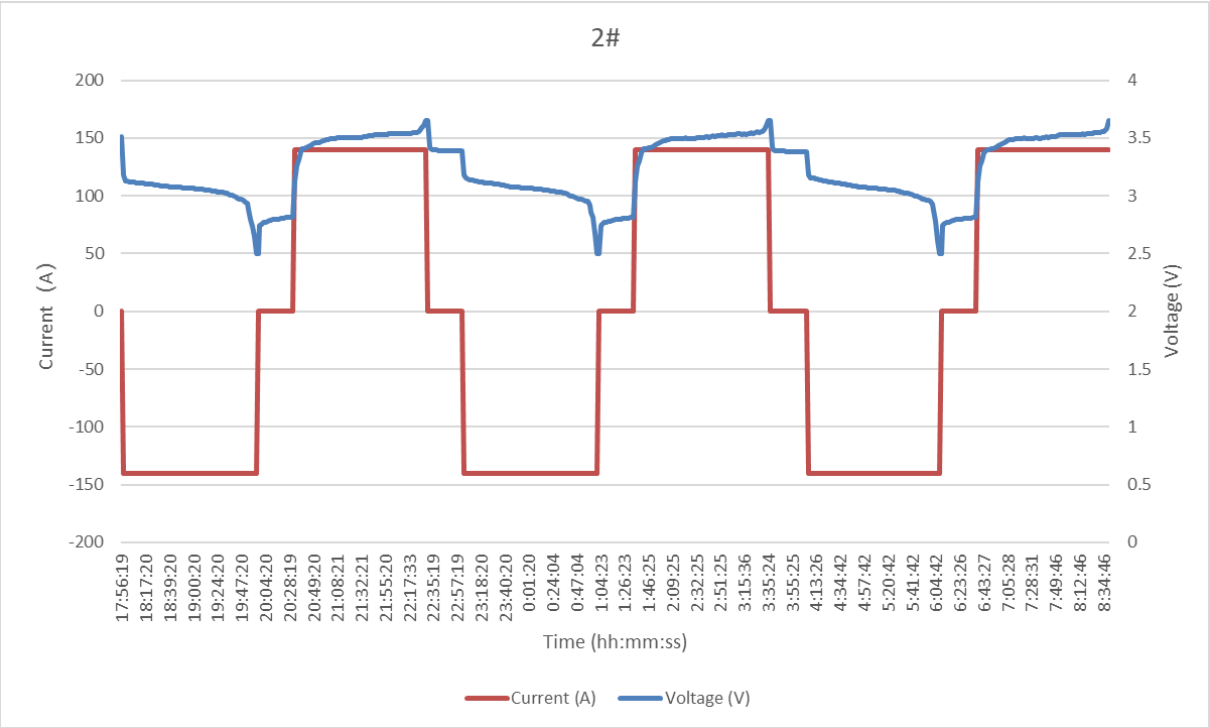
Attachment 2 Cell conditioning (charge/discharge) profiles

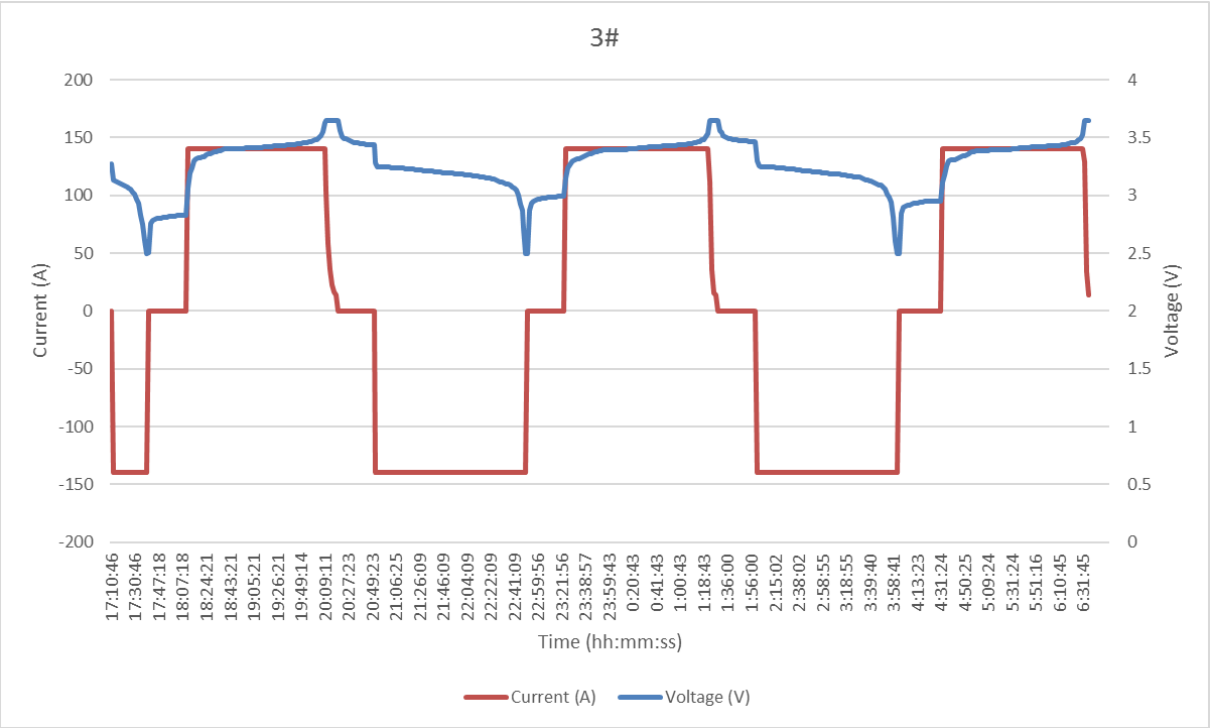
The cells were conditioned, prior to testing, through charge and discharge cycles for at least 2 cycles using a manufacturer specified methodology to verify that the cells are functional.

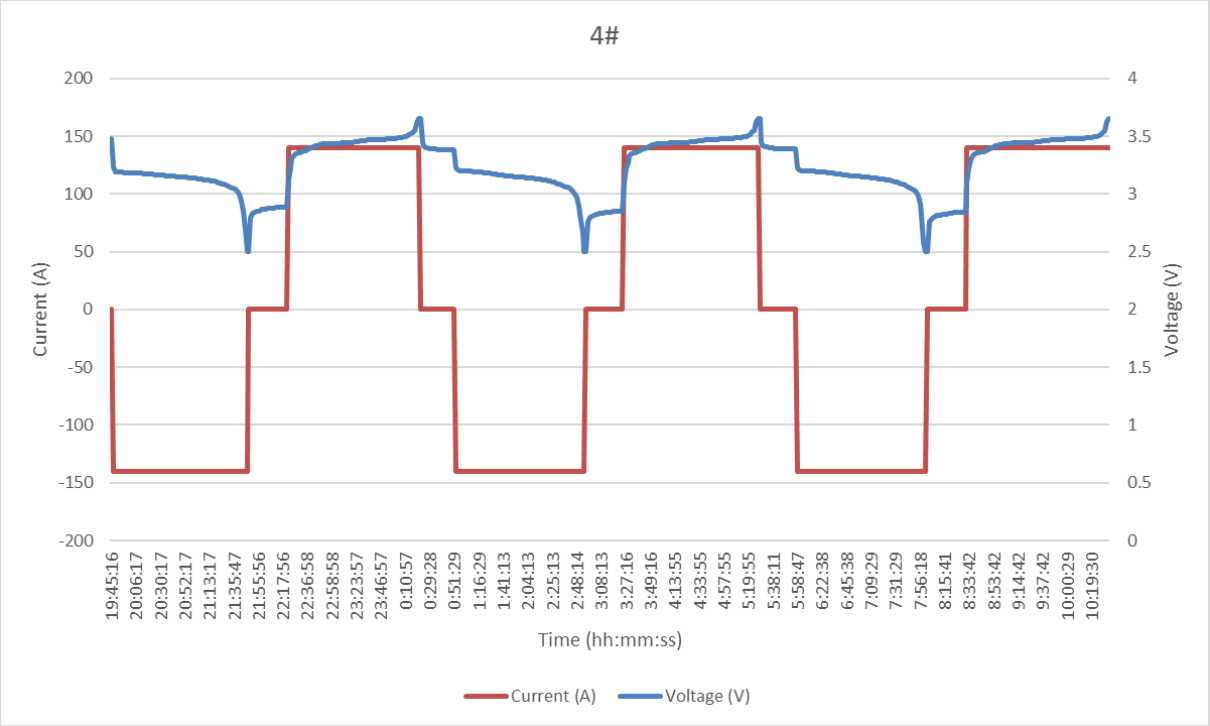
As manufaturer specified, Each cycle the cell was charge to end of charge voltage 3.65V with charge current 140A and then rest 30 minutes, then cell was discharge to end of discharge voltage 2.5V with discharge current 140A and then rest 30 minutes.

During conditioning the ambient temperature maintained in 25 ±5°C and 50 ±25% RH.The curves of cell voltage and current during the cell conditioning are shown below.




2#
200
150
100
50
0
-50
-100
-150
-200
Current (A)
4
3.5
3
2.5
2
1.5
1
0.5
0
Voltage (V)
17:56:19
18:17:20
18:39:20
19:00:20
19:24:20
19:47:20
20:04:20
20:28:19
20:49:20
21:08:21
21:32:21
21:55:20
22:17:33
22:35:19
22:57:19
23:18:20
23:40:20
0:01:20
0:24:04
0:47:04
1:04:23
1:26:23
1:46:25
2:09:25
2:32:25
2:51:25
3:15:36
3:35:24
3:55:25
4:13:26
4:34:42
4:57:42
5:20:42
5:41:42
6:04:42
6:23:26
6:43:27
7:05:28
7:28:31
7:49:46
8:12:46
8:34:46
Time (hh:mm:ss)
Current (A)
Voltage (V)


3#
Current (A)
Voltage (V)
Time (hh:mm:ss)
Current (A)
Voltage (V)


4#
Current (A)
Voltage (V)
Time (hh:mm:ss)
Current (A)
Voltage (V)


5#
Current (A)
Voltage (V)
Time (hh:mm:ss)
Current (A)
Voltage (V)

Attachment 3 cell thermal runaway record

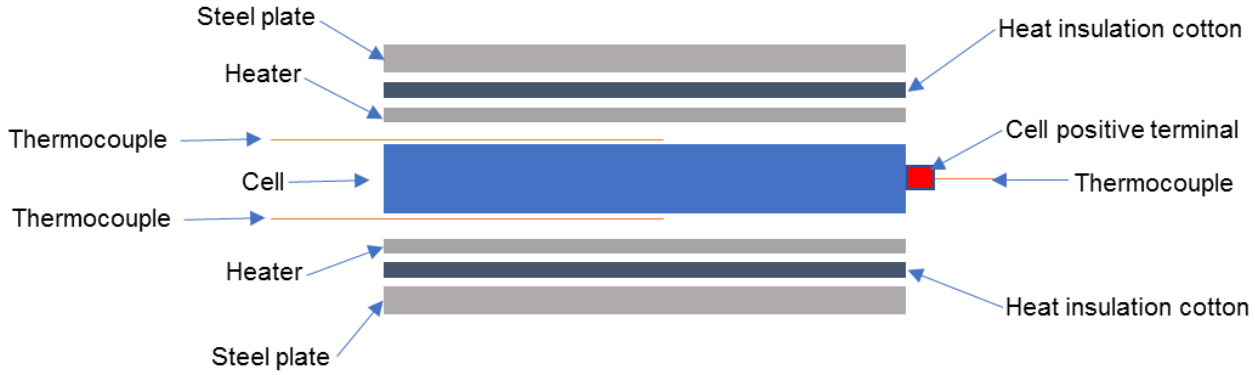
The cells to be tested were charged to 100% SOC and allowed to stabilize for a minimum of 1 h and a maximum of 8 h before the start of the test.

External 2 flexible film heaters (rate: 220VAC/600 W, size: 173mm*205mm) were attached on the cell wide sides to induce the cell thermal runaway.

The cell sample and heaters were clamped by two steel plate together using blots during test to simulate the constraint in the BESS module to prevent excessive swelling during the test. Two layers heat insulation cotton sheet were placed between the steel plate and heater to limit the heat loss during the test.

Two type K thermocouples were located below the heater, one at the centre of the cell wide surface and this one was also used as feedback of the heat controller. Another one was at the centre of opposite side of the cell surface. Additional one thermocouple was located on the positive terminals. Open voltage of the cell was also monitor during the test.

Figure below is an illustration of sample preparation for thermal runaway test.



The cell was maintained a 4-7°C/min heating rate (monitored by thermocouple on centre of cell wide side) until thermal runaway was observed.

The cell exhibits thermal runaway behaviour by heating the wide sides of cell. And 3 additional samples were repeated to demonstrate repeatability.

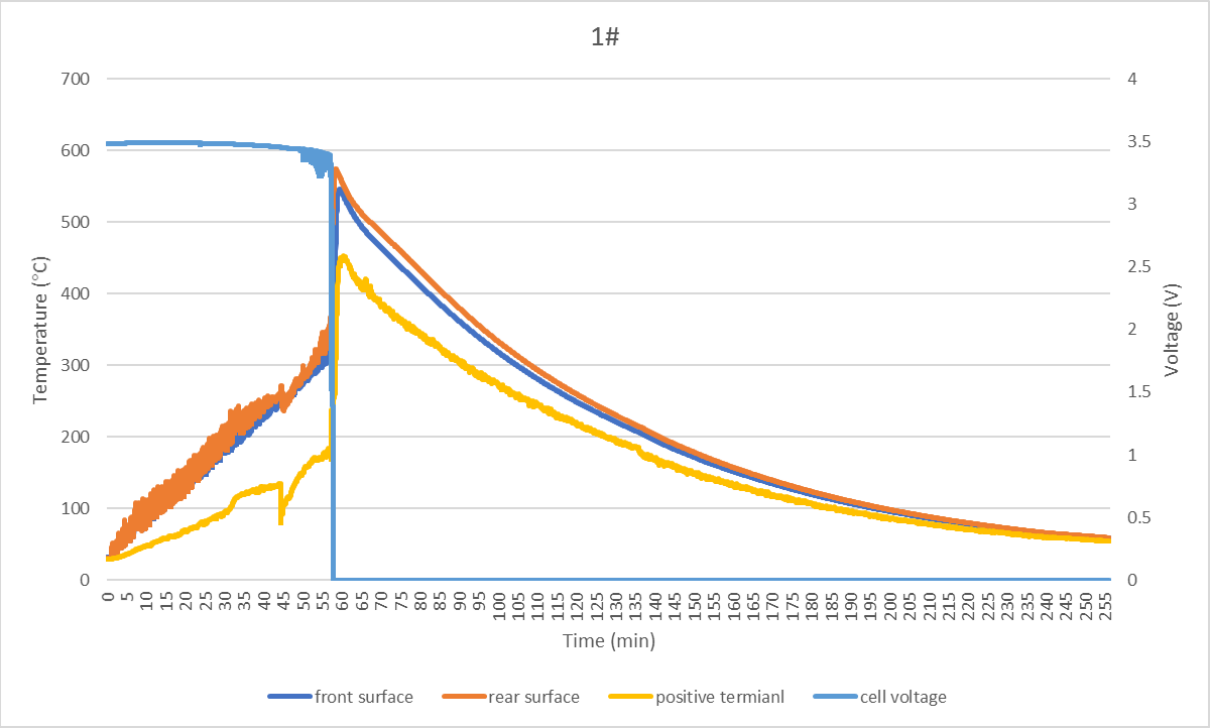
The vent temperature and thermal runaway onset temperatures were averaged over the tested 4 samples.

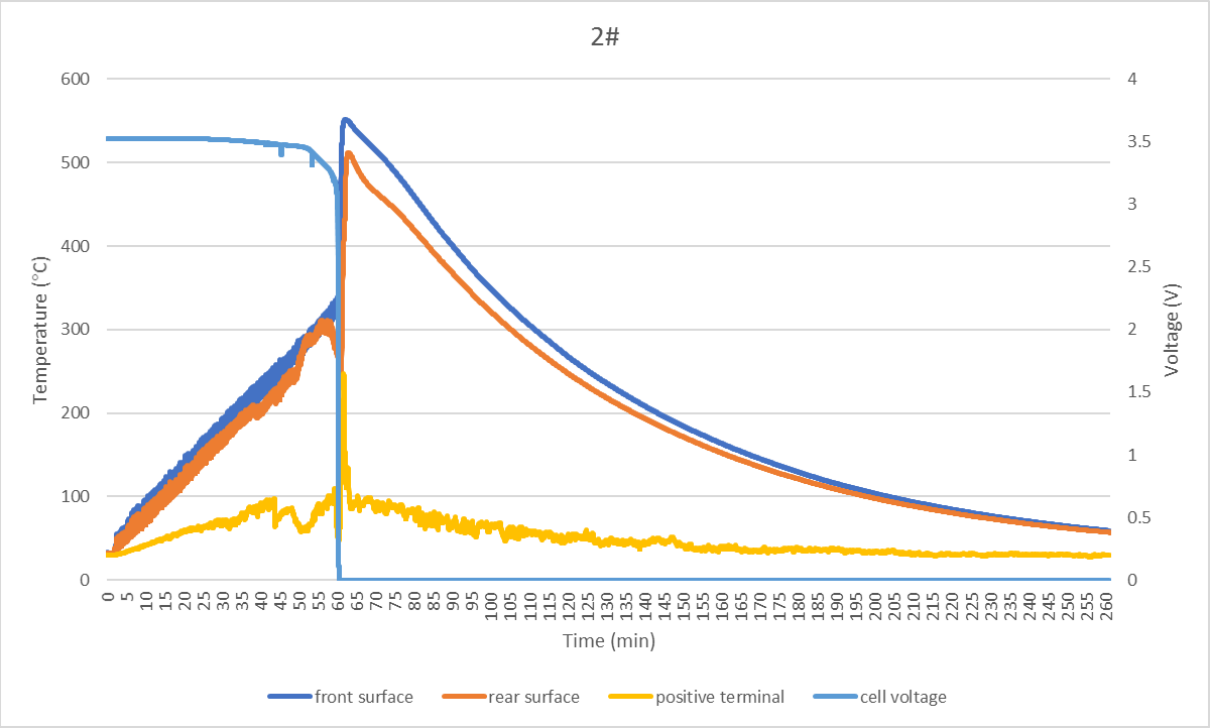
The test result is shown in table below.

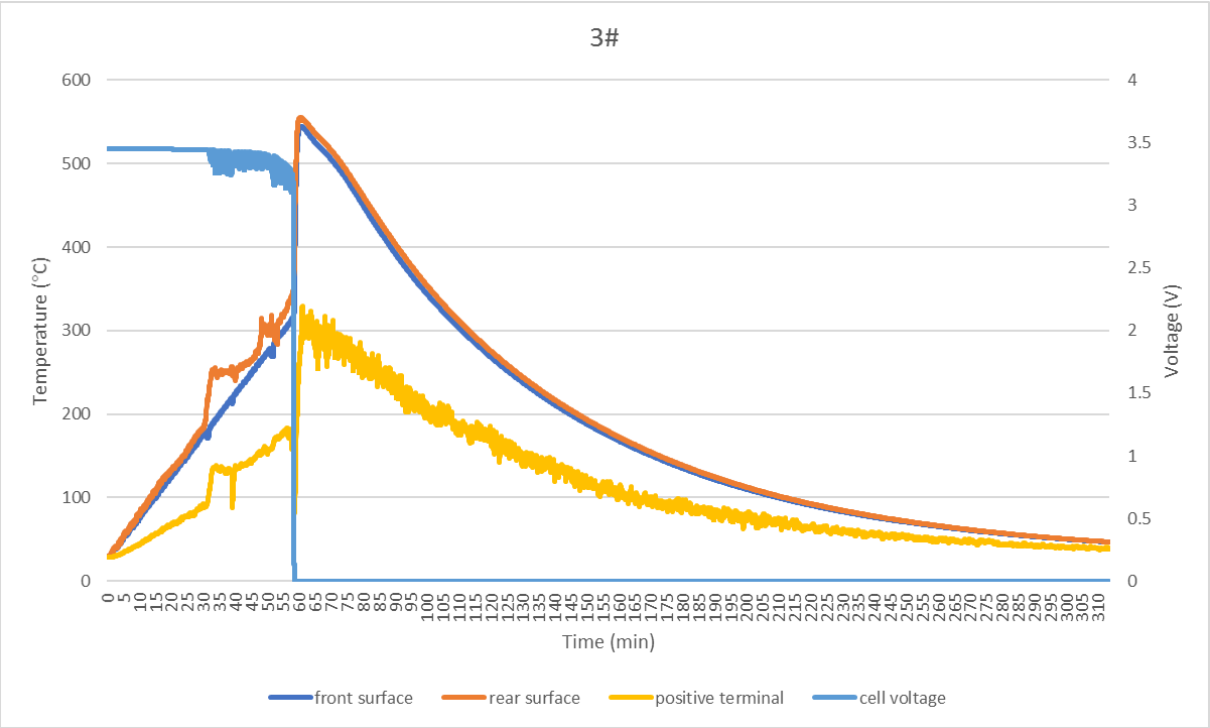
Sample No.	1#	2#	3#	4#
Ambient conditions at the initiation of the test	26 °C, 47%RH	25 °C, 67%RH	25 °C, 64%RH	25 °C, 71%RH
Open circuit voltage before test (V)	3.48	3.523	3.44	3.37
Weight before the test(g)	5598	5597	5599	5595
Weight after the test(g)	4298	4294	4298	4289
Cell vent temperature (°C)	271.2	251.7	255	262
Cell vent time (min)	44	43	39	48
Measured max surface temperature of controlled surface (°C)	574.9	551	555	539.4
Measured max surface temperature of opposite surface (°C)	545.8	512	543.9	539.2
Measured max temperature near positive terminal (°C)	453.2	246.8	329.2	413
Thermal runaway onset temperature(°C)	371.8	339.4	351	368
Thermal runaway onset time (min)	57	60	58	70
Average measured cell vent temperature (°C)	259.9			
Average measured thermal runaway onset temperature (°C)	357.5			

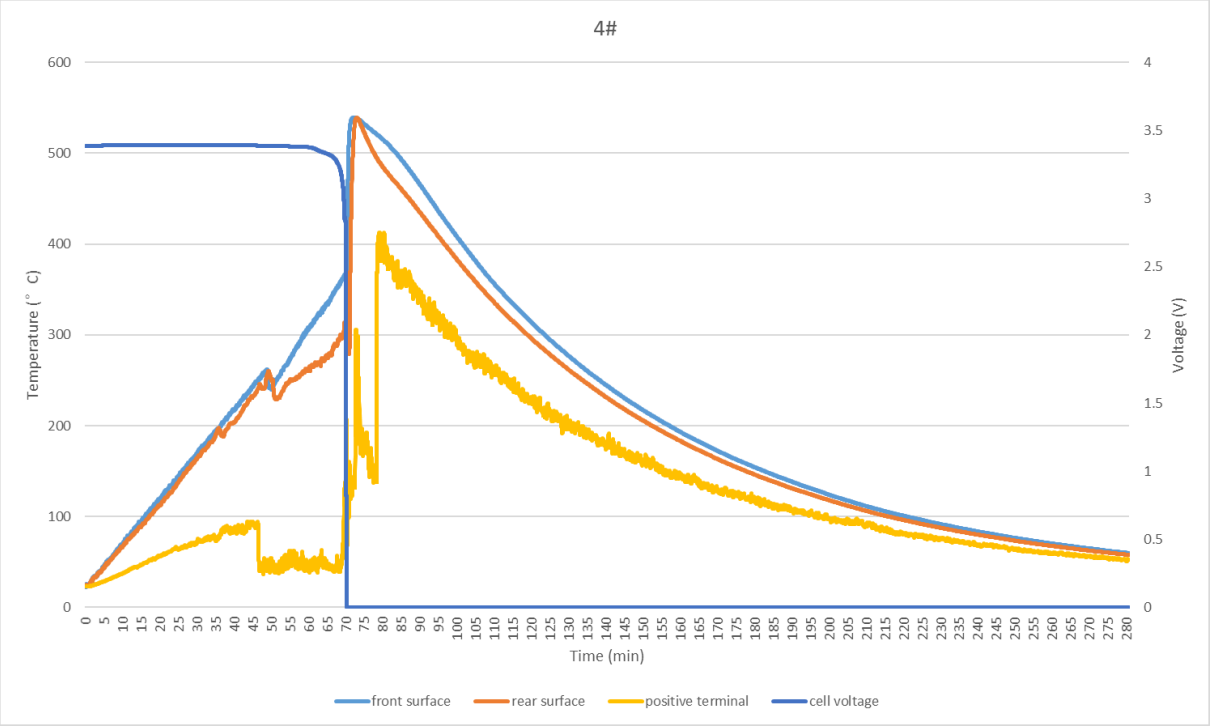
Attachment 4 temperature and voltage profile during the test

The curves of temperature and voltage during the test are shown in figures below





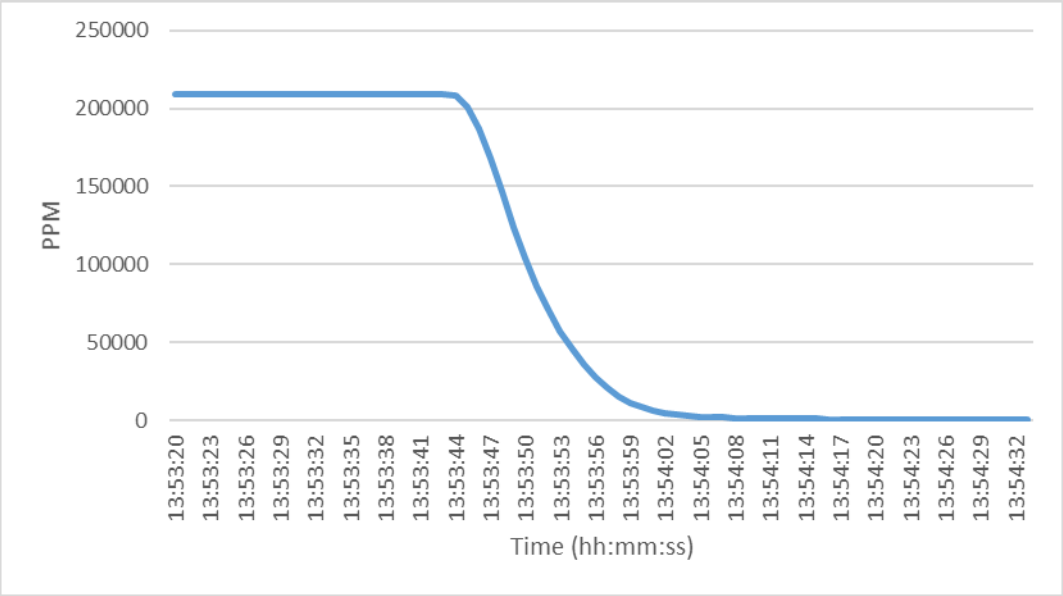

3#
Temperature (°C)
Voltage (V)
Time (min)
front surface
rear surface
positive terminal
cell voltage


4#
Temperature (° C)
Voltage (V)
Time (min)
front surface
rear surface
positive terminal
cell voltage

Attachment 5 cell vent gas capture

The cell was conditioned prior to the test (see Attachment 2), and force into thermal runaway by the method determined in the thermal runaway test (see Attachment 3).

The cell was tested in an 82.0L pressure vessel, before the test, the air in the vessel was replaced with N_2 to reduce the oxygen content below 1% by volume. See oxygen content figure below



After the cell forced into thermal runaway, the mixed gas in the vessel was collected to test cell vent gas composition.

The cell vent gas capture test result is shown in table below.

Sample number	5#
Temperature in the vessel before the test (°C)	25.3
Temperature in the vessel after the test (°C)	35.3
Atmospheric pressure in the vessel before the test (kPa)	101.3
Atmospheric pressure in the vessel after the test (kPa)	328.9
Initial oxygen content by volume (%)	0.09
Total vent gas volume (L)	163

Attachment 6 cell vent gas composition measurement

Cell vent gas composition was determined using Gas Chromatography (GC) with detection techniques for quantifying component gases.

Test method was reference to ISO 6143: 2001 Gas analysis — Comparison methods for determining and checking the composition of calibration gas mixtures

Measured gas components and concentration was shown in tables below

Vent gas components (including O_2 and N_2 and other gas components)	
Gas component	Concentration %
CH_4 (Methane)	5.325
C_2H_6 (Ethane)	0.974
C_2H_4 (Ethylene)	3.410
C_3H_8 (Propane)	0.260
C_3H_6 (Propylene)	2.003
C_4H_{10} (Isobutane)	0.033
C_4H_{10} (n-Butane)	0.068
C_4H_8 (1-butylene)	0.135
C_5H_{12} (Isopentane)	0.018
C_5H_{12} (n-Pentane)	0.139
C_5H_{10} (1-pentene)	0.040
H_2 (Hydrogen)	30.585
CO (Carbon Monoxide)	7.990
CO_2 (Carbon Dioxide)	17.923
N_2 (Nitrogen)	31.207
O_2 (Oxygen)	0.652

Normalized gas compositions by removing the N_2, O_2 and other gas components contributions was shown in table below.

This was used to synthetically replicated gas mixture for further flammability character parameter tests.

Vent gas components (excluding O_2 and N_2 and other gas components)	
Gas component	Concentration %
CH_4 (Methane)	7.73
C_2H_6 (Ethane)	1.41
C_2H_4 (Ethylene)	4.95
C_3H_8 (Propane)	0.38
C_3H_6 (Propylene)	2.91
C_4H_{10} (Isobutane)	0.05
C_4H_{10} (n-Butane)	0.10
C_4H_8 (1-butylene)	0.20
C_5H_{12} (Isopentane)	0.03
C_5H_{12} (n-Pentane)	0.20
C_5H_{10} (1-pentene)	0.06
H_2 (Hydrogen)	44.38
CO (Carbon Monoxide)	11.60
CO_2 (Carbon Dioxide)	26.00
Total	100

Attachment 7 lower flammability limit (LFL) of the cell vent gas measurement

Upon determination of the cell vent gas composition, 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.

Synthetically replicated gas mixture identifies with same component and concentration in Attachment 6 gas quantification excluding O_2, N_2 and other gas concentration was produced by standard gas manufacturer.

Table below is the information of synthetically replicated gas mixture

Sample information			
Name of Sample	Synthetically replicated gas mixture		
Cylinder volume	8L	Filling pressure	90bar@15°C
Certification date	2022-10-13	Expiry date	2023-10-12
Certification number	202210130003	Relative expanded uncertainty	±1%
Calibrated sample composition			
Gas component	Concentration %	Gas component	Concentration %
CH_4	7.63%	C_4H_8 (1-butylene)	0.148%
C_2H_6	1.38%	C_5H_{12} (Isopentane)	0.036%
C_2H_4	5.02%	C_5H_{12} (n-Pentane)	0.190%
C_3H_8	0.370%	C_5H_{10} (1-pentene)	0.056%
C_3H_6	2.85%	CO (Carbon Monoxide)	11.7%
C_4H_{10} (Isobutane)	0.054%	CO_2 (Carbon Dioxide)	26.0%
C_4H_{10} (n-Butane)	0.116%	H_2 (Hydrogen)	balance
Remark The information above is provided by the gas manufacturer. Coverage factor of the expanded uncertainty is *k*=2; equivalent to coverage probability (VIM name is level of confidence) is 95%.			

According to ASTM E918-19, the lower flammability limit (*LFL*) of the cell vent gas at both ambient and cell vent temperatures are shown in table below

Test Item	Flammable(explosion) limits of gas and vapours—*LFL*
Test Method	ASTM E918-19 Standard Practice for Determining Limits of Flammability of Chemicals at Elevated Temperature and Pressure
Remark	The symbols used in this test are defined as below except otherwise defined: c_s = Concentration of sample. T_i = Initial temperature in each trial. p_i = Initial pressure in each trial. p_{ex} = Overpressure in each trial. L_1 = The minimum sample concentration that gives flame propagation. L_2 = The maximum sample concentration that does not give flame propagation. *LFL* = Lower flammable limit； $LFL = (L_1 + L_2)/2$. p_{max} = maximum explosion pressure. S_u = Burning velocity. It is considered explosion occurred, if $p_{ex} / p_i \geq 1.07$. Concentration defined in this test means volume percentage.
Test Item	Flammable(explosion) limits of gas and vapours—*LFL*
Test Conditions	Initial Temperature: 25±3 °C; Initial Pressure: 101±3 kPa
Ambient Conditions	Ambient Temperature: 20~26 °C, Relative Humidity: 32~65%

Part of Test Data

No.	c_s [%]	T_i [°C]	p_i [kPa]	p_{ex} [kPa]	p_{ex} / p_i	Ignition?
1	6.1	25.2	98.4	142.4	1.45	Y
2	5.9	22.5	101.6	107.6	1.06	N
3	5.9	23.4	102.3	105.9	1.04	N
4	5.9	26.1	100.9	102.7	1.02	N
Test result	*L1*=6.1%, *L2*=5.9%, *LFL*=6.0% at 25±3°C and 101±3kPa.					

Test Conditions	Initial Temperature: 260±3°C; Initial Pressure: 101±4kPa
Ambient Conditions	Ambient Temperature: 20~26°C, Relative Humidity: 32~65%

Part of Test Data

No.	c_s [%]	T_i [°C]	p_i [kPa]	p_{ex} [kPa]	p_{ex} / p_i	Ignition?
1	3.5	259.6	103.8	114.7	1.10	Y
2	3.3	257.4	104.2	104.6	1.00	N
3	3.3	261.1	102.0	103.8	1.02	N
4	3.3	261.0	100.7	103.5	1.03	N
Test result	*L1*=3.5%, *L2*=3.3%, *LFL*=3.4% at 260±3°C and 101±4kPa.					

Attachment 8 vent gas burning velocity (S_u) measurement

Same synthetically replicated gas mixture was used to determine gas burning velocity in accordance with the Method of Test for Burning Velocity Measurement of Flammable Gases Annex in ISO 817.

Vent gas burning velocity (*Su*) test record is shown in tale below

Test Item	Burning velocity of flammable gases			
Test Method	ISO 817:2014 Refrigerants - Designation and safety classification			
Test Conditions	Initial Temperature: Room Temperature Initial Pressure: Atmospheric Pressure			
Ambient Conditions	Ambient Temperature: 20-26°C Relative Humidity: 32-57%			
Remark	The symbols used in this test are defined as below except otherwise defined: c_s = Concentration of sample. S_S = Flame propagation speed. a_f = Cross-sectional area of flame bottom. A_f = Flame surface area. S_u is calculated as: $S_u = S_S \times \frac{a_f}{A_f}$ Concentration defined in this test means volume percentage.			
Part of Test Data				
No.	c_s [%]	S_S [m/s]	a_f/A_f /	S_u [m/s]
1	20.0	1.350	0.452	0.610
2	21.0	1.350	0.456	0.616
3	22.1	1.425	0.481	0.685
4	22.1	1.200	0.552	0.662
5	23.1	1.200	0.469	0.563
6	24.1	1.050	0.456	0.478
Test result	S_u= 0.685m/s at room temperature and atmosphere pressure.			

Attachment 9 Cell vent gas maximum pressure (P_{max}) measurement

Same synthetically replicated gas mixture shall be used to determine P_{max} in accordance with EN 15967.

Maximum pressure (P_{max}) test record is shown in table below

Test Item	Maximum explosion pressure of gases and vapours
Test Method	EN 15967:2011 Determination of maximum explosion pressure and the maximum rate of pressure rise of gases and vapours
Test Apparatus	Test Vessel: 20L closed sphere. Ignition system: Fusing Wire.
Preparation of Test Mixture	Partial pressure method used inside the vessel
Test Conditions	Initial Temperature: 21±4°C. Initial Pressure: 101±4kPa.
Ambient Conditions	Ambient Temperature: 18-25°C. Relative Humidity:10-48%
Remark	The oxidant used in this test is Synthetic air The symbols used in this test are defined as below except otherwise defined: c_s = Concentration of sample. $p_{ex,n}$ = Explosive overpressure in the nth ignition test at a certain concentration $p_{ex,max}$ = The average value of the explosion overpressure at a certain concentration. p_{mean} = Lowest explosion pressure in 5 (resp. 3) tests. $p_{highest}$ = Highest explosion pressure in 5 (resp. 3) tests. p_{max} is expressed as the maximum value of $p_{ex,max}$. Concentration defined in this test means volume percentage.

Part of Test Data

No.	c_s [%]	p_{ex1} [MPa]	p_{ex2} [MPa]	p_{ex3} [MPa]	p_{ex4} [MPa]	p_{ex5} [MPa]	p_{mean} [MPa]
1	18.0	0.745	0.737	0.717	/	/	0.733
2	19.0	0.734	0.742	0.724	/	/	0.733
3	20.0	0.745	0.748	0.742	/	/	0.745
4	20.4	0.747	0.736	0.739	/	/	0.741
5	20.6	0.781	0.771	0.754	/	/	0.769
6	20.8	0.726	0.759	0.748	/	/	0.744
7	21.0	0.737	0.739	0.772	/	/	0.749
8	22.0	0.721	0.721	0.711	/	/	0.718

Test Item	Maximum explosion pressure of gases and vapours				
Determination of the explosion pressure					
No.	c_s [%]	P_{Lowest} [MPa]	$P_{Highest}$ [MPa]	P_{Mean} [MPa]	P_{ex} [MPa]
1	18.0	0.717	0.745	0.733	0.75
2	19.0	0.724	0.742	0.733	0.74
3	20.0	0.742	0.748	0.745	0.75
4	20.4	0.736	0.747	0.741	0.75
5	20.6	0.754	0.781	0.769	0.78
6	20.8	0.726	0.759	0.744	0.76
7	21.0	0.737	0.772	0.749	0.77
8	22.0	0.711	0.721	0.718	0.72
Determination of the maximum explosion pressure					
Content of flammable substance	20.6% volume				
Smallest flammable substance content increment	0.2% volume				
Maximum explosion pressure	0.78Mpa				
Test result	P_{max}=*0.78*MPa at 21±4°C and 101±4kPa				

Attachment 10 Equipment list

No.	Equipment		Model	Rating	Inventory no.	Last Cal. date
1.	Ambient monitor		WSB-2-H1	0~40°C, 10~90%RH	S-055	2022-07-11
2.	Electronic scale		HC311	0-6000g	S-047	2022-03-25
3.	Digital multi-meter		FLUKE101	0-600V	S-038	2022-02-23
4.	Heating control equipment		DTB4824	0-1000°C,	S-060-3	2022-07-11
5.	Data acquisition equipment		ADAM-4117 ADAM-4118	0-10V 0-1000°C,	S-060-1 S-060-2	2022-07-11 2022-07-11
6.	Charge/discharge equipment		RCDS-10V300A	10V/300A	S-057	2022-07-11
7.	Gas acquisition system 82L	Thermopile	WRNK-191 K	0-1000°C,	S-020-1~10	2022-02-26
		Pressure sensor	BD-801KZ	0.02/0.08/0.15MPa	S-020-11	2022-02-23
		Data acquisition equipment	DTM DTM	0-1000°C, 0-10V	S-020-12 S-020-14	2022-03-25
8.	Oxygen analyser		HM-BX-02	0-20.9%	S-014	2022-06-10
9	Gas Chromatography		PE Clarus680	——	T-177	2022-11-16
10	Gas Chromatography		GC-2014C	——	T-251	2022-01-24
11	Digital pressure meter		YB-80A	0 -300kPa	PC 239	2022-11-03
12	Barometer		DYM3	800-1060 hPa	PC201	2022-09-14
13	Pressure sensor		601CAB	10-1000Hz	PC174	2022-06-14
14	Pressure sensor		601CAB	10-1000Hz	PC173	2022-06-14
15	Ruler		1000mm	1000 mm	LC101	2022-08-01
16	Oxygen analyzer		MiniMP 5200	0 ~ 100% ±0.1%	AC123	2022-01-28

- End of test report