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Prüfbericht-Nr.: *Test Report No.:*	**CN21GYRR 001**	**Auftrags-Nr.:** *Order No.:*	244370534	**Seite 1 von 56** *Page 1 of 56*
Kunden-Referenz-Nr.: *Client Reference No.:*	2182037	**Auftragsdatum:** *Order date.:*	Oct 28, 2021	
Auftraggeber: *Client:*	Sungrow Energy Storage Technology Co.,Ltd. No.788 Mingchuan Road, Boyan Technology Park, Hi-tech Zone, Hefei City, 230088 Anhui, P.R. China			
Prüfgegenstand: *Test item:*	Battery Rack			
Bezeichnung / Typ-Nr.: *Identification / Type No.:*	R287-111, R344-111 R578-111, R688-111			
Auftrags-Inhalt: *Order content:*	Test report			
Prüfgrundlage: *Test specification:*	UL 9540A: 2019 (Fourth Edition)			
Wareneingangsdatum: *Date of receipt:*	Nov 15, 2021			
Prüfmuster-Nr.: *Test sample No.:*	Engineering sample			
Prüfzeitraum: *Testing period:*	Nov 15, 2021 ~ Nov 17, 2021			
Ort der Prüfung: *Place of testing:*	See clause 1.1 of main report			
Prüflaboratorium: *Testing laboratory:*	See clause 1.1 of main report			
Prüfergebnis*: *Test result*:*	See main report			

geprüft von / *tested by:*

December 13, 2021 — Marvin Peng&David Zhou / Engineer — Marvin Peng, David Zhou

Datum *Date*	**Name/Stellung** *Name/Position*	**Unterschrift** *Signature*

kontrolliert von / *reviewed by:*

December 13, 2021 — Bowen Dong / Reviewer

Datum *Date*	**Name/Stellung** *Name/Position*	**Unterschrift** *Signature*

Sonstiges / *Other:*

Zustand des Prüfgegenstandes bei Anlieferung: *Condition of the test item at delivery:*

Prüfmuster vollständig und unbeschädigt
Test item complete and undamaged

* Legende:	1 = sehr gut	2 = gut	3 = befriedigend	4 = ausreichend	5 = mangelhaft
	P(ass) = entspricht o.g. Prüfgrundlage(n)		F(ail) = entspricht nicht o.g. Prüfgrundlage(n)	N/A = nicht anwendbar	N/T = nicht getestet
Legend:	1 = very good	2 = good	3 = satisfactory	4 = sufficient	5 = poor
	P(ass) = passed a.m. test specifications(s)		F(ail) = failed a.m. test specifications(s)	N/A = not applicable	N/T = not tested

V04

INTRODUCTION

Model fire codes and energy storage system standards require energy storage systems to comply with UL 9540, which in turn requires battery cells and modules to comply with UL 1973. Compliance with these standards reduces the risk of batteries and battery energy storage systems (BESS) creating fire, shock or personal injury hazards. However, they do not evaluate the ability of the BESS installed as intended and with fire suppression mechanisms in place if necessary, from contributing to a fire or explosion in the end use installations.

To address these fire and explosion hazards associated with the installation of a BESS, the fire and other codes require energy storage systems to meet certain location, separation, fire suppression and other criteria. Those codes also provide a means to provide an equivalent level of safety based on large-scale fire testing of anticipated BESS installations.

UL 9540A is intended to provide a test method that can be used as a basis for validating the safety of a BESS installation in lieu of meeting the specific criteria provided in those codes. The data generated can be used to determine the fire and explosion protection required for installation of a BESS.

The test method is initiated through the establishment of a thermal runaway condition that leads to combustion within the BESS. The test method outlined in UL 9540A consists of several steps – cell level testing, module level testing, unit level testing and installation level testing. The cell and module level testing steps are information gathering steps to inform the unit and installation level testing.

The following outlines the information that may gathered as part of the testing:

a) Cell level – An individual cell fails in a manner that leads to thermal runaway and fire through a suitable method such as external heating. Data such as off-gassing contents, temperatures at venting and temperatures at thermal runaway are recorded.

b) Module level – One or more cells within a BESS module fail in the manner determined during the cell level testing. Data such as fire propagation in the module, temperatures on the failed cells and surrounding cells, off-gassing contents and heat release data are gathered.

c) Unit level – A complete BESS is installed surrounded by target (e.g. dummy) BESS and walls separated at a distance as intended in its installation. The module level test is repeated on a module located in the BESS in the most unfavorable location. Data such as temperature within the BESS, on surrounding walls and target BESS; incident heat flux on walls and target BESS; observation of fire propagation from BESS to target units and walls as well as observance of explosions or evidence of re-ignition within the BESS; and heat release and off-gassing contents are gathered.

d) Installation level – This test is a repeat of the unit level test with the test conducted within a test room and with the intended fire suppression system installed as well as any overhead cables (that can lead to fire propagation) installed. This test is intended to validate the fire suppression system for the BESS installation. Data such as temperature within the BESS, on surrounding walls and target BESS; incident heat flux on walls and target BESS; fire propagation from the BESS to target units, walls or overhead cables and any observable explosion incidents or re-ignition within the BESS; and off-gassing contents (if needed) and heat release are gathered.

Contents

1 General information

1.1 Test specification

Standard: ANSI/CAN/UL 9540A: 2019 (Fourth Edition)

Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems

This report presents the result of unit level tests of UL 9540A: 2019.

All tests were conducted at TUV Rheinland (Shanghai) Co., Ltd. and TUV Rheinland's partner labs that were under supervision of TÜV Rheinland's engineer.

Testing period: Nov 15, 2021 ~ Nov 17, 2021

Refer to Clause 4 for test and measurement instruments.

1.2 General remarks

This report is descriptive and provide the test data only.

The test 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.

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

1.3 List of attachments

Video records of the test from 4 different directions were provided in .mp4 format. Complete records were provided in 4 separate documents, file number listed as below:

NY202111224-1.mp4

NY202111224-2.mp4

NY202111224-3.mp4

NY202111224-4.mp4

1.4 Revision information

New report, not applicable

1.5 Definitions

CELL – The basic functional electrochemical unit containing an assembly of electrodes, electrolyte, separators, container, and terminals. It is a source of electrical energy by direct conversion of chemical energy.

MODULE – A subassembly that is a component of a BESS that consists of a group of cells or electrochemical capacitors connected together either in a series and/or parallel configuration (sometimes referred to as a block) with or without protective devices and monitoring circuitry.

UNIT – A frame, rack or enclosure that consists of a functional BESS which includes components and subassemblies such as cells, modules, battery management systems, ventilation devices and other ancillary equipment.

BATTERY SYSTEM (BS) – Is a component of a BESS and consists of one or more modules typically in a rack configuration, controls such as the BMS and components that make up the system such as cooling systems, disconnects and protection devices.

BATTERY ENERGY STORAGE SYSTEM (BESS) – Stationary equipment that receives electrical energy and then utilizes batteries to store that energy to supply electrical energy at future time. The BESS, at a minimum consists of one or more modules, a power conditioning system (PCS), battery management system (BMS) and balance of plant components.

a) INITIATING BATTERY ENERGY STORAGE SYSTEM UNIT (INITIATING BESS) – A BESS unit which has been equipped with resistance heaters in order to create the internal fire condition necessary for the installation level test (Section 9).

b) TARGET BATTERY ENERGY STORAGE SYSTEM UNIT (TARGET BESS) – The enclosure and/or rack hardware that physically supports and/or contains the components that comprise a BESS. The target BESS unit does not contain energy storage components, but serves to enable instrumentation to measure the thermal exposure from the initiating BESS.

Note: Depending upon the configuration and design of the BESS (e.g. the BESS is composed of multiple separate parts within separate enclosures), the unit level test can be done at battery system level. In such case, the BESS is be read as BS throughout this report.

NON-RESIDENTIAL USE – Intended for use in commercial, industrial or utility owned locations.

RESIDENTIAL USE – In accordance with this standard, intended for use in one or two family homes and town homes and individual dwelling units of multi-family dwellings.

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 gas evolution.

STATE OF CHARGE (SOC) – The available capacity in a BESS, pack, module or cell expressed as a percentage of rated capacity.

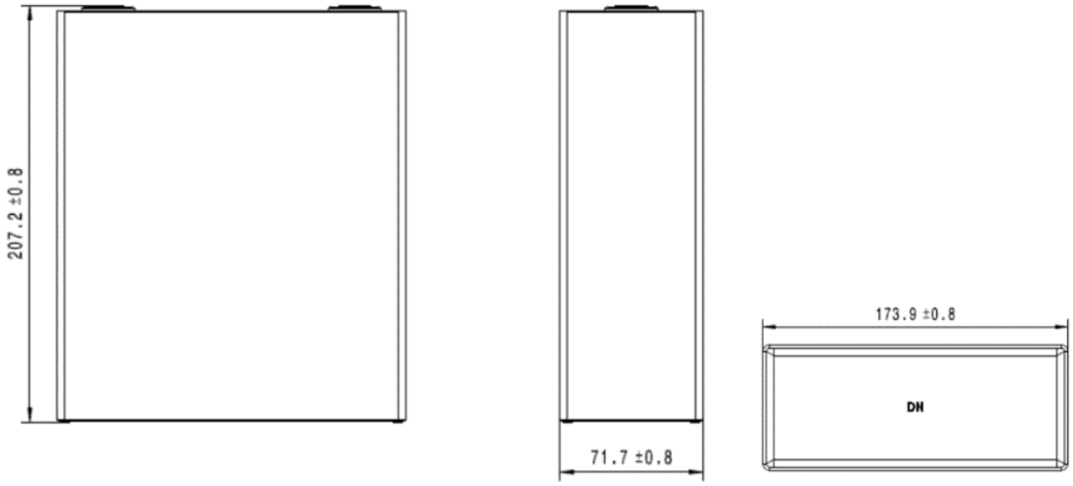
2 General Product Information

The product information and parameters were provided by the client as below.

2.1 Cell

2.1.1 Product information and parameters

Manufacturer ....:	CATL	
Model ....:	CB2W0 CB310	
Chemistry ....:	LiFePO4	
Physical configuration ....:	Prismatic	
	Weight:	5410 ± 300 g
Electrical rating ....:	Rated capacity:	280 Ah
	Nominal voltage:	3.2 V
Standard charge method ....:	Charge current:	280 A
	End of charge voltage:	3.65 V
	Cut off current:	14 A
Standard discharge method ....:	Discharge current:	280 A
	End of discharge voltage:	2.5 V
Diagram with overall dimension		



Model Difference: Cell model CB2W0 is identical to model 001CB310 except for the rated charging/discharging current declared, documented in UL with project No. 4789439215. Models CB2W0 and CB310 are identical to model 001CB310 except for model names, and the declared ratings of pulse charging and discharging current.

2.1.2 Cell level test information

Cell level thermal runaway test information is from CSA cell level test report 80008629 provided by the client.

Thermal Runaway Methodology .... :	External heating method with ceramic heater 1 PCS, rated 220/230V, 500W
Average Cell Surface Temperature at Gas Venting .... :	143.3°C
Average Cell Surface Temperature at Thermal Runaway....................................... :	209.8°C

2.2 Module

2.2.1 Product information and parameters

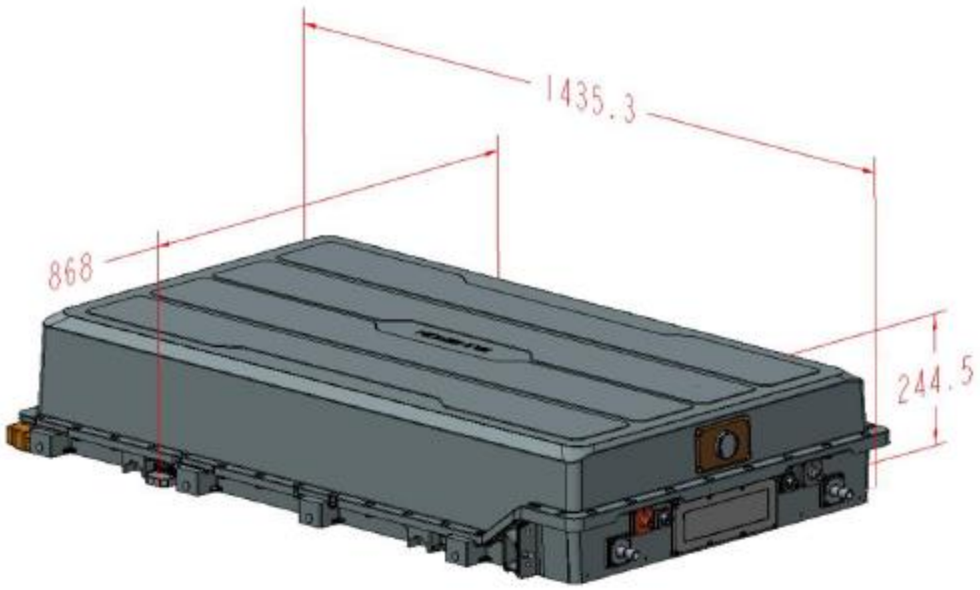
The product information and parameters are provided by the client as below.

Manufacturer name..............:	SUNGROW ENERGY STORAGE TECHNOLOGY CO., LTD.		
Model number ....:	P573AL-112 P573BL-112	P286BL-112	P573-111 P573B-111
Physical configuration..........:	Metal enclosure with plastic cover		
	Weight: ≤400kg	≤230kg	≤400kg
	Cells in series/parallel: 64 in series	32 in series	64 in series
Cooling method ....:	Liquid Cooling		
Separation between cells ....:	0.45 mm separation between cells by air		
Electrical rating ....:	Rated capacity: 280 Ah	280 Ah	280 Ah
	Nominal voltage: 204.8V	102.4V	204.8V
Standard charge method .....:	Charge current: 280 A	280 A	140A
	End of charge voltage: 233.6 V	116.8 V	233.6 V
	Cut of current: 14 A	14 A	14 A
Standard discharge method :	Discharge current: 280 A	280 A	140A
	End of discharge voltage: 172.8 V	86.4 V	172.8 V

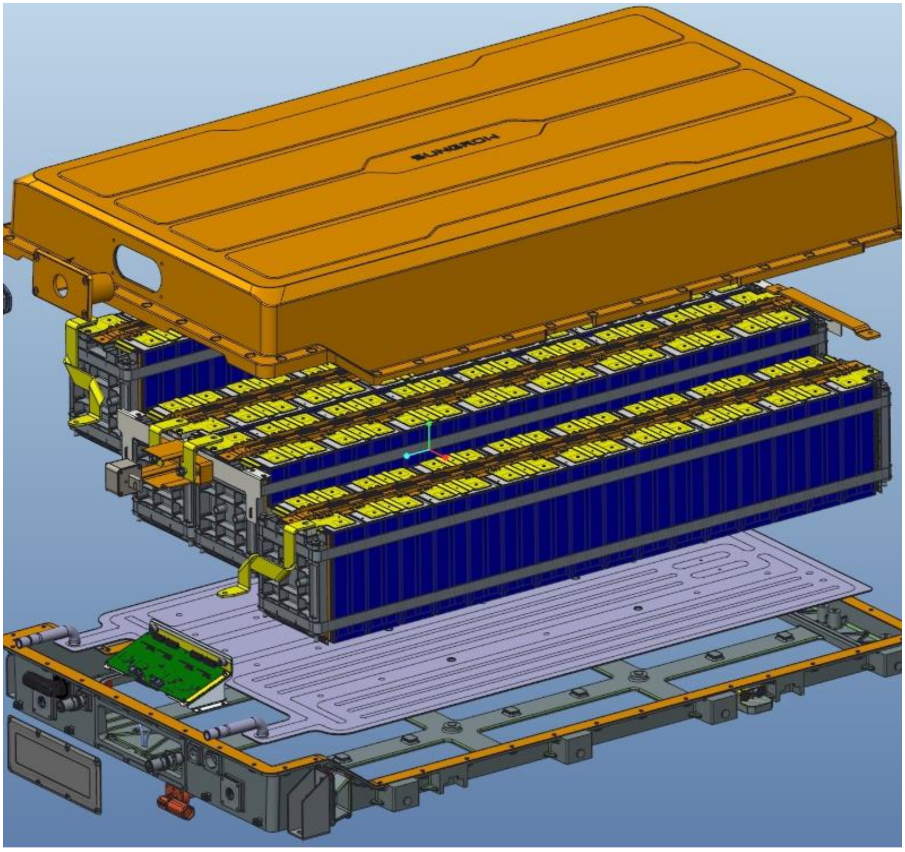
Compliance with UL 1973 ...:	Under certification, not finished

Manufacturer name..............:	SUNGROW ENERGY STORAGE TECHNOLOGY CO., LTD.	
Model number ....:	P537AL-112 P537BL-112	P537AL-111 P537BL-111
Physical configuration..........:	Metal enclosure with plastic cover	
	Weight: ≤384kg	≤384kg
	Cells in series/parallel: 60 in series	60 in series
Cooling method....................:	Liquid Cooling	
Separation between cells ....:	0.45 mm separation between cells by air	
Electrical rating ....:	Rated capacity: 280 Ah	280 Ah
	Nominal voltage: 192V	192V
Standard charge method.....:	Charge current: 280 A	140 A
	End of charge voltage: 219 V	219 V
	Cut of current: 14 A	14 A
Standard discharge method :	Discharge current: 280 A	140 A
	End of discharge voltage: 150 V	150V
Compliance with UL 1973 ...:	Under certification, not finished	

2.2.2 Diagram with overall dimension

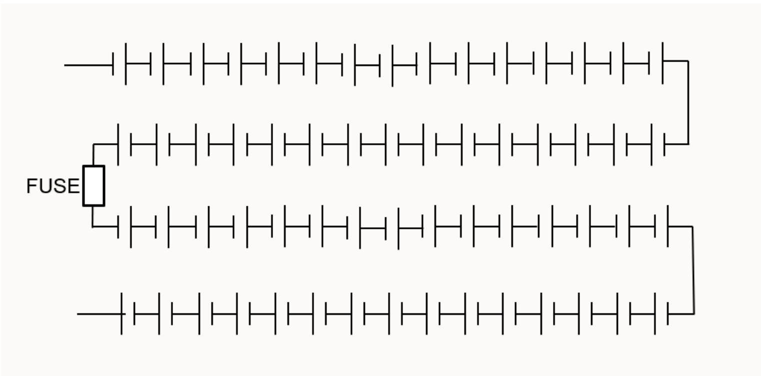


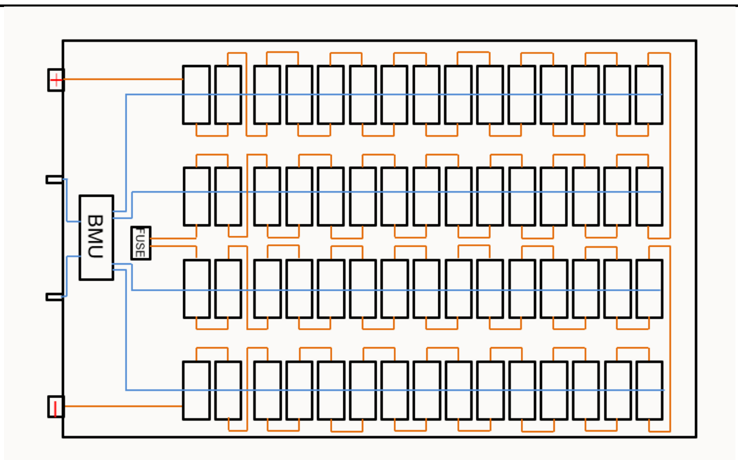
2.2.3 Layout of the module contents



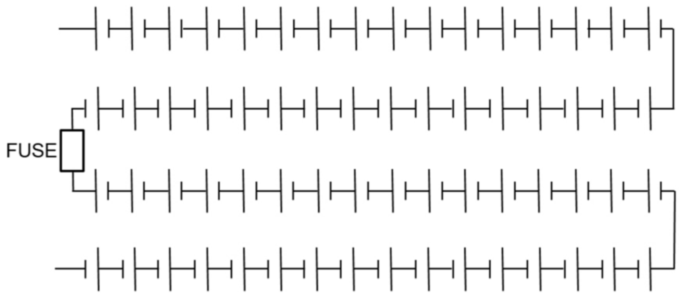
2.2.4 Configuration diagram of the module

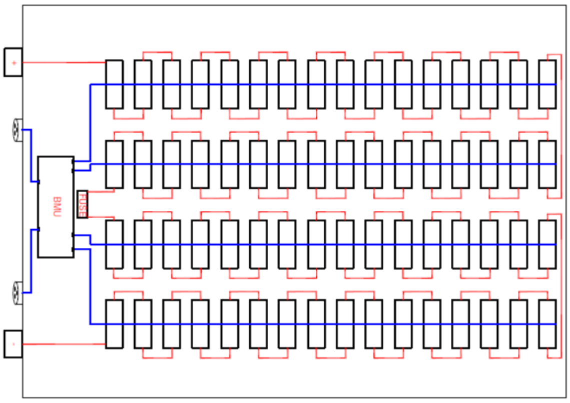
1P60S



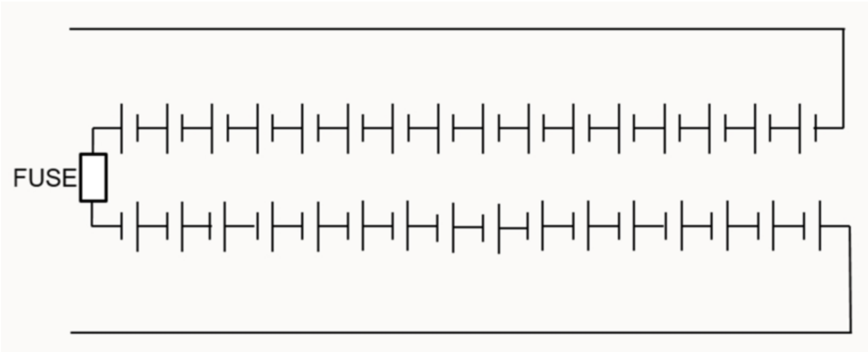


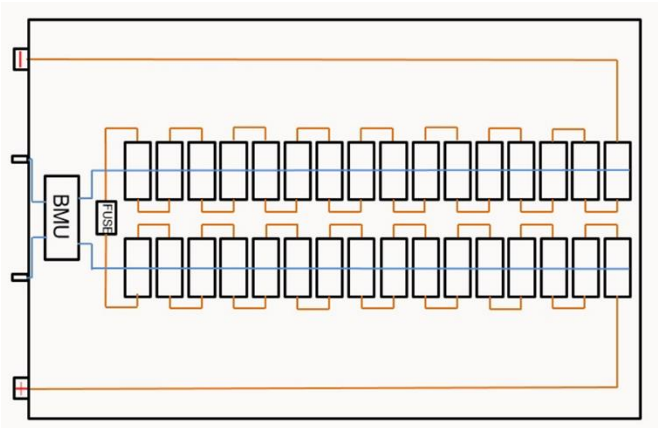
1P64S





1P32S





2.3 Battery system (rack)

2.3.1 Manufacture information and model list

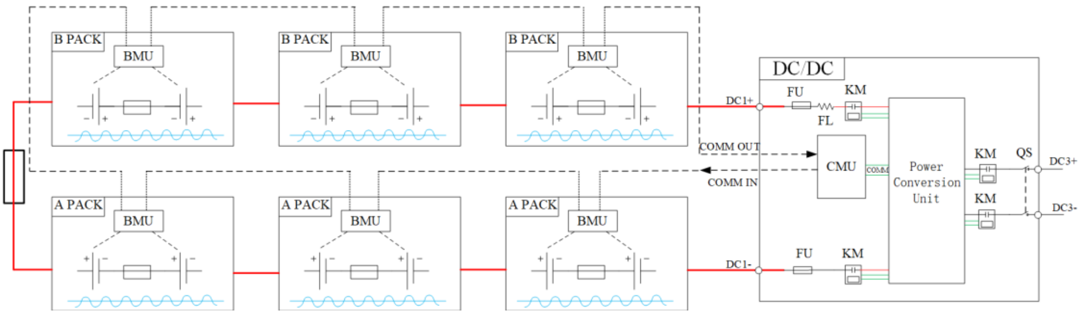
	Battery system	Battery system	Battery system
Product	LFP Lithium Ion Energy Storage System	LFP Lithium Ion Energy Storage System	LFP Lithium Ion Energy Storage System
Type/model	R344-111	R287-111	R688-111
Cell Capacity [Ah]	280	280	280
Cell Quantity	384	320	768
Battery structure	(64S)6S	(64S)5S	((64S)6S)2P
Nominal voltage [V]	1228.8	1024	1228.8
Rated capacity [Wh]	344064	286720	688128
Upper limit charging voltage [V]	1401.6	1168	1401.6
Recommend charging current [A]	140	140	140
Maximum charging current [A]	140	140	140
Recommend discharging current [A]	140	140	140
Maximum discharging current [A]	140	140	140
Discharge cut-off voltage [V]	1036.8	864	1036.8
Temperature range for charging [°C]	0 to 50*	0 to 50*	0 to 50*
Temperature range for discharging [°C]	-30 to 50*	-30 to 50*	-30 to 50*
Temperature threshold for protection	50	-	50
Overcharge protected voltage supply by battery system	≥3.65V /Cell	-	≥3.65V /Cell
Recommend charging method by manufacturer	Charge at constant current 140A until the voltage reaches 1401.6V, then switch to constant voltage 1401.6V till charge current drops to 14A	Charge at constant current 140A until the voltage reaches 1168V, then switch to constant voltage 1168V till charge current drops to 14A	Charge at constant current 140A until the voltage reaches 1401.6V, then switch to constant voltage 1401.6V till charge current drops to 14A
Dimension [mm]	Rack: 3117±10mm(W)×1474±10 mm(D) ×520±10mm(H) DC/DC: 720±5mm(W)×788±5mm(D) ×294±5mm(H)	Rack: 3117±10mm(W)×1474±10 mm(D) ×520±10mm(H) DC/DC: 720±5mm(W)×788±5mm(D) ×294±5mm(H)	Rack: 3117±10mm(W)×1474±10 mm(D) ×1040±10mm(H) DC/DC: 720±5mm(W)×788±5mm(D) ×294±5mm(H)
Weight [kg]	Rack: ≤2400kg DC/DC: 75kg	Rack: ≤2000kg DC/DC: 75kg	Rack: ≤4800kg DC/DC: 75kg
Ingress Protection (IP)	IP65	IP65	IP65
Protective Class	I	I	I
Cooling type	Liquid cooling	Liquid cooling	Liquid cooling
Altitude	4000m	4000m	4000m
*: Constant Power 172kW and max charging and discharging current is 140A when ambient temperature is no more than 45°C, it will start derating when ambient temperature more than 45°C. The battery cell shall be heated first through the liquid cycle when discharging below -20°C.			

	Battery system
Product	LFP Lithium Ion Energy Storage System
Type/model	R573-111
Cell Capacity [Ah]	280
Cell Quantity	640
Battery structure	((64S)5S)2P
Nominal voltage [V]	1024
Rated capacity [Wh]	573440
Upper limit charging voltage [V]	1168
Recommend charging current [A]	140
Maximum charging current [A]	140
Recommend discharging current [A]	140
Maximum discharging current [A]	140
Discharge cut-off voltage [V]	864
Temperature range for charging [°C]	0 to 50*
Temperature range for discharging [°C]	-30 to 50*
Temperature threshold for protection	50
Overcharge protected voltage supply by battery system	≥3.65V /Cell
Recommend charging method by manufacturer	Charge at constant current 140A until the voltage reaches 1168V, then switch to constant voltage 1168V till charge current drops to 14A
Dimension [mm]	Rack: 3117±10mm(W)×1474±10mm(D) ×1040±10mm(H) DC/DC: 720±5mm(W)×788±5mm(D) ×294±5mm(H)
Weight [kg]	Rack: ≤4000kg DC/DC: 75kg
Ingress Protection (IP)	IP65
Protective Class	I
Cooling type	Liquid cooling
Altitude	4000m

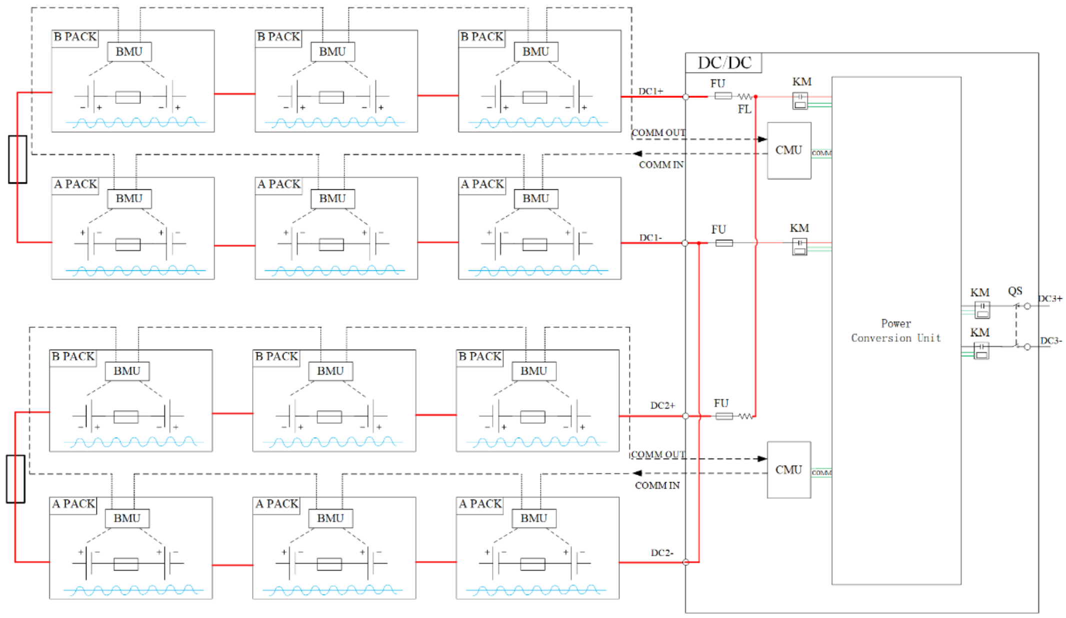
2.3.2 Product information

This product is used for Energy Storage System.
The EUTs covered by this report are 4 models of LFP lithium ion battery energy storage systems which include one DC-DC converter box and several battery packs in series(parallel) connection. The number of battery packs are 5, 6, 10,12 for model R287-111, R344-111, R573-111 and R688-111.

Block diagram for R344-111 is as below (R287-111 is the same except for one less pack) :



Block diagram for R688-111 is as below (R573-111 is the same except for two fewer packs) :

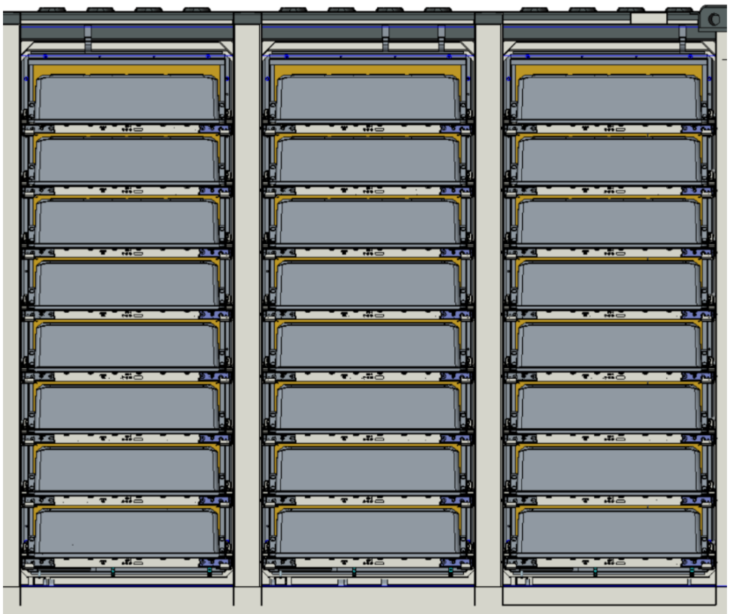


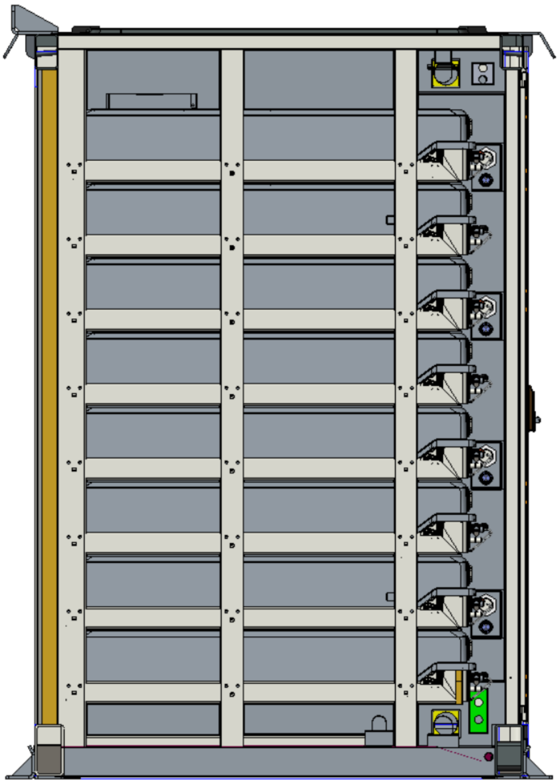
Each battery pack contains 64 cells in structure 64S. And it contains one BMU board for measuring and collecting the cell parameters and uploading the information of cell voltage and temperature to CMU in DC-DC converter box.
DC-DC box: Including CMU function and DC-DC converter which is certified with UL 1741.

The EUTs are indoor type. The insulation between the DC circuit and the metal enclosure is basic insulation. And the insulation between the DC circuit and communication ports is reinforced insulation or double insulation.
BMS functional safety was evaluated according to IEC 60730-1 Annex H by TÜV Rheinland.

Compliance with UL9540 .... :	without
Compliance with UL1973 .... :	Yes, (repot number: CN21XPKR 001)
Integrated fire protection system in the unit .... :	No integrated fire protection system

Diagram with dimension of R688-111





2.4 Photo

Module

Battery Rack

3 Unit level test (section 8 of UL 9540A)

3.1 General

Unit level testing corresponds with the testing anticipated by fire codes and other codes impacting energy storage system installations to evaluate the large scale fire performance of BESS units installed in, on or adjacent to buildings or in other areas and their resultant performance to qualify for exceptions to limits in the codes imposed on these installations. The limitations where exceptions may be sought are limitations on the size of the individual BESS units, the total number of BESS units installed within a room, and the separation distances between BESS units and between BESS units and walls of the building.

In this test the initiating BESS unit is placed a set distance from target BESS units simulating BESS units identical to the initiating BESS unit, and from simulated walls representative on the installation. A thermal runaway is induced in cells, using the same approach as used in the module level testing within one of the modules in the initiating BESS, and a variety of measurements are taken. The results are intended to be used to verify that a fire within a single BESS unit will not spread to other units, nor breach the walls or the BESS enclosure (if provided), and there shall be no flying debris or explosive discharge of gases.

The test arrangement include the largest (energy) BESS unit for the installation to be represented by the test, and minimum spacing to adjacent walls and BESS units. The BESS may be tested with an internal fire suppression system provided by the manufacturer if that fire suppression system is required to be installed in the BESS. Optional internal fire suppression systems are not included in the unit level testing.

The test monitors the fire behavior of the BESS unit and measures heat release rates (convective and chemical); gas generation and composition; smoke release rate; maximum heat flux on the target BESS units, wall surfaces and within the accessible means of egress; maximum surface temperatures of the walls and modules within the target BESS units; and documents any explosions, deflagrations and flying debris from the BESS under test.

3.2 Unit sample preparation

The battery system is constructed with open rack without enclosure. One series of the rack with 6 complete modules was considered as a unit for purposes of the test.

All 6 module samples were conditioned together as a unit, through 3 charge/ discharge cycles per the manufacturer's instructions to verify that the module was functional.

The Charge/discharge was performed at 140A. Each cycle was defined as a charge to 100% SOC and allowed to rest 60 minutes and then discharged to an end of discharge voltage (EODV) determined by the module specification. Refer to section 2.2 for the end of the condition of charge and discharge.

Cycling was conducted on Sep 16, 2021 under ambient temperature 25°C ± 3°C and R.H. 70% ± 5%.

3.3 Setup of the test

3.3.1 Battery system installation information

The installation information was provided by the client as below.

Intended use location .... :	☐ Residential	☒ Non-residential
	☐ Non-residential rooftop	
	☐ Non-residential open garage use	
Type of installation .... :	☒ Indoor	☐ Outdoor
	☒ Floor/ground mounted	☐ Wall mounted
Row(s) of installation	☐ Single	☒ Multiple

3.3.2 Test site setup

Two instrumented walls with 3.8 m height and 3.55 m width form a right angle. Walls were constructed of 5/8 in gypsum painted flat black.

Three racks were used for the purpose of the test. As specified by the manufacture, the two target racks will be installed up and down of the initial unit. All racks were positioned facing instrumented wall A. See Figure 1 and 2 and photos on page 47.

The initiating unit (unit A) was positioned at the middle, adjacent to the two instrumented wall sections.

The minimum separation distance from the rack to wall and between racks were defined by the client. Subject to the actual conditions of the testing environment, there was 1cm tolerance in the actual setup.

Figure 1 was the test site setup diagram with separation distance.

The test side setup was located under the smoke collection hood of the calorimeter measurement system.

Figure 1. Test site setup diagram with separation distance. (Top view)

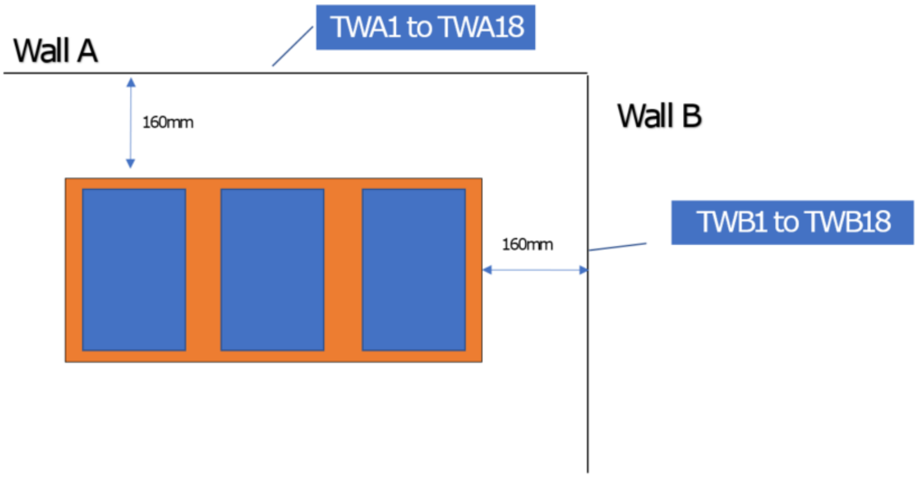
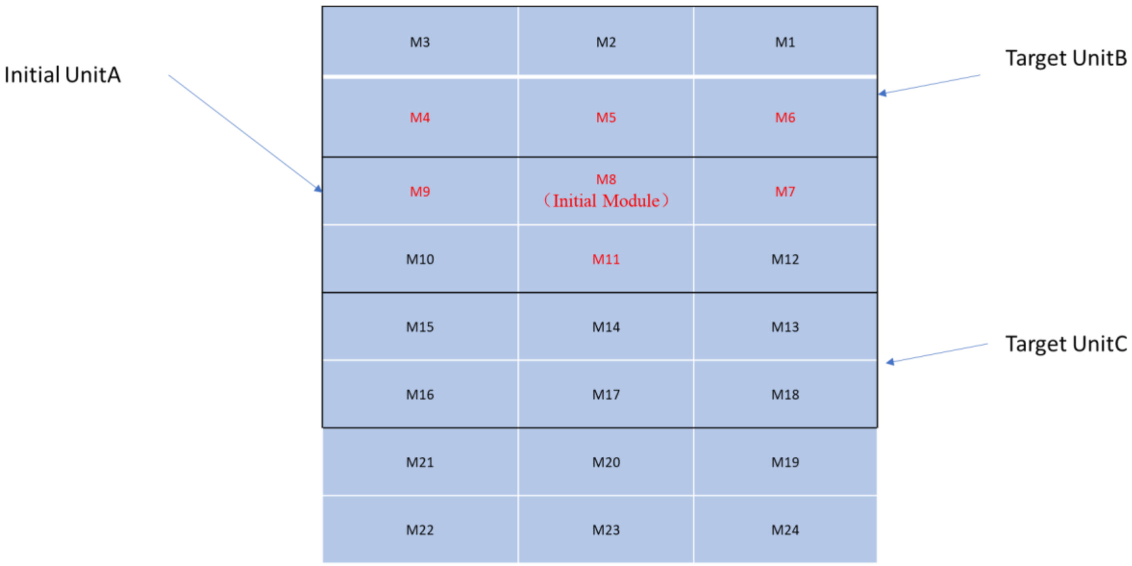


Figure 2. Test site setup diagram with separation distance. (Front view)



For the purpose of this test, the modules were numbered according to the electrical continuity.

In Initial Unit A, modules numbers from M7 to M12.

In Target Unit B, modules numbers from M1 to M6 which was the target unit situated above the Initial Unit A.

In Target Unit C, modules numbers from M13 to M18 which was the target unit situated below the Initial Unit A.

See Figure 3.

4 complete modules were used for unit A (M7 to M9 and M11).

3 complete modules were used for unit B (M4 to M6) to check the possible propagation form unit to unit.

Empty modules without cells were used for the other modules.

Figure 3. Module numbering in units showing fully populated modules in red.

M3	M2	M1
M4	M5	M6
M9	M8 (Initial Module)	M7
M10	M11	M12
M15	M14	M13
M16	M17	M18
M21	M20	M19
M22	M23	M24

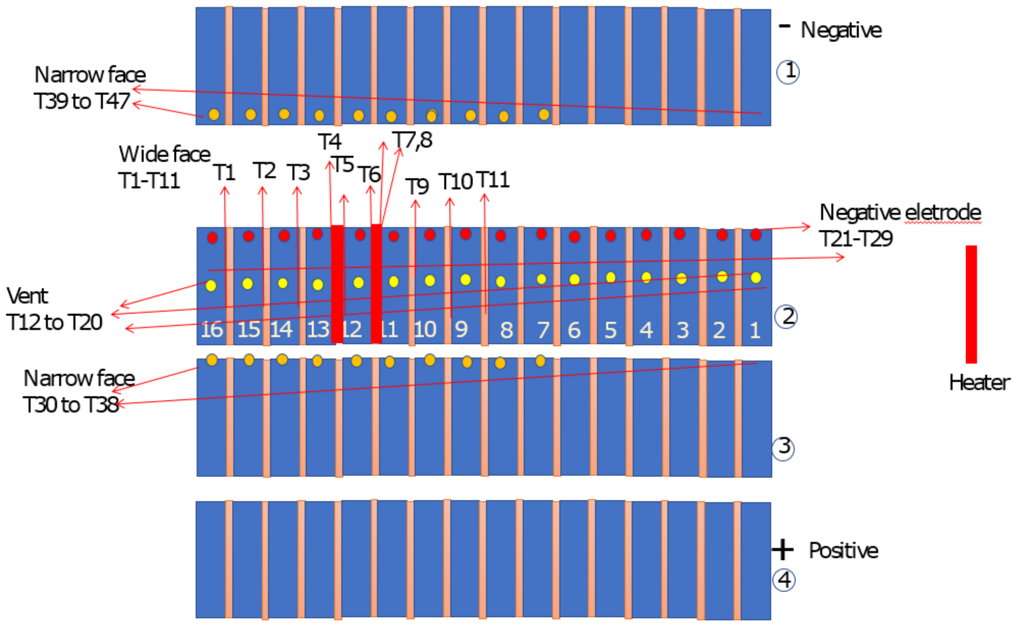
3.3.3 Thermal runaway setup

External heating method, agreed with the client, was used to initiate the thermal runaway within the module.

Module M8 was prepared with two heaters inside. Same as the method in module level test.

Cells inside the module were numbered from 1 to 16 as Figure 3.

Figure 3. Cell numbering inside the initiating module



Consider the unit level installation and airflow of the liquid cooling in the module. #11, #12 and #13 cell located in the back of the module were chosen as target cell to be forced into thermal runaway.

The cell #12 was heated by two external heater on each wide side, the cell #11 and cell#13 was heated by one external heater on wide near cell #12. The heater is rated 220VAC/500 W (size 207*174*4mm).

11 glass fiber thermocouples Type K, 24 AWG were attached to the center of the wide surface of #1 to #16 cells. 20 glass fiber thermocouples Type K, 24 AWG were attached on the center of narrow surface of opposite cells near #7 to #16 cells.

The initiating module M8, internal voltage sample wire and signal wire covered by glass fiber tube. The BMS control board was disabled during the test.

A PID controller was used to control the voltage supply to the heater and maintain a 5.5°C/min heating rate. When heater temperature reached to 180°C (T-set), hold about 60min (10:10 to 11:10), then continue to heat and maintain a 4°C/min to 7°C/min heating rate.

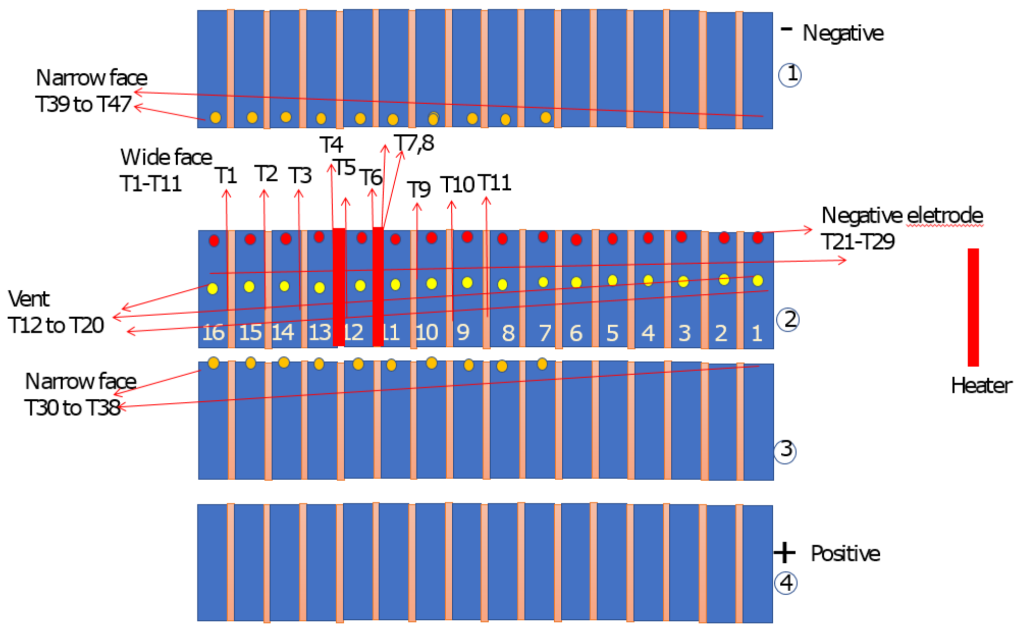
Once thermal runaway was observed, the heaters were immediately de-energized.

Four thermocouples(located below the heater at the wide surface center of #11,#12,#13 cell and two thermocouples located below the heater at the wide surface center of #4 cell were used to feedback the temperature to the controller.

6 glass fibers insulated thermocouples on the center of the wide surface of #14 to #16, #8-#10 cell s to check the possible propagation from cell to cell.

Voltage of the module are monitored during the test.

Figure 5: Thermocouples on module M8



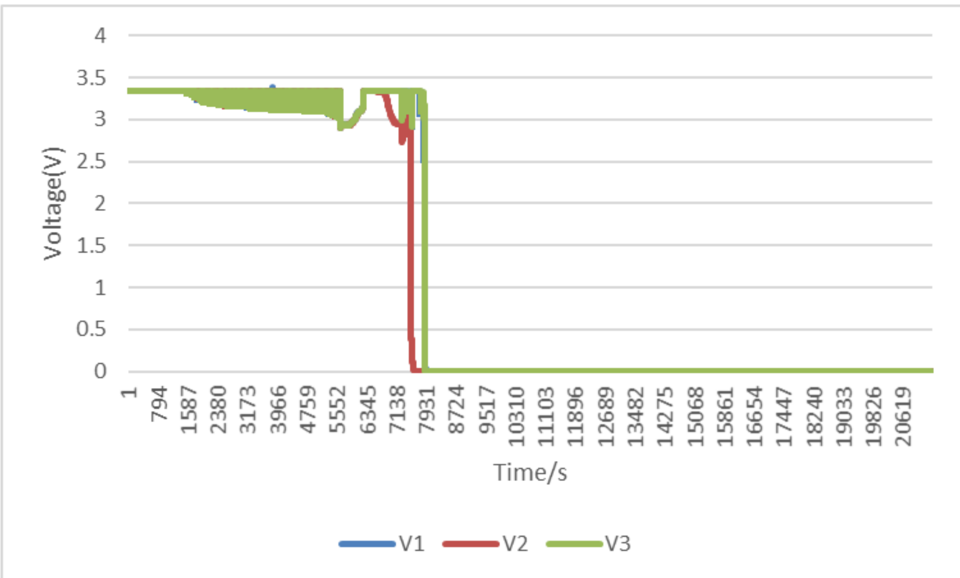
3.4 Observations and records

Before the test, the initiating module was 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.

The ambient condition at the initiation of the test was 25°C, 66% RH.

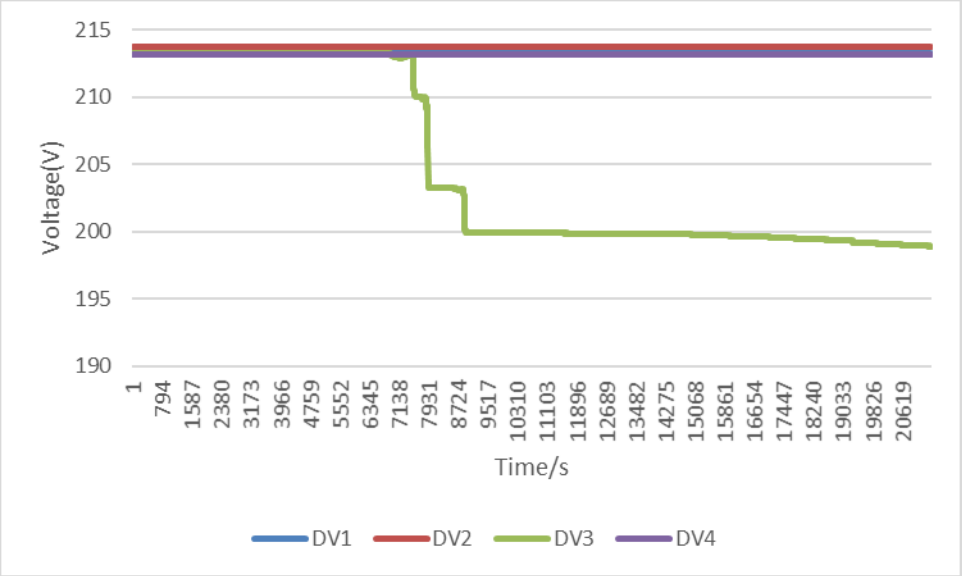
The voltage of the modules was recorded as below:

Figure 6: Voltage record of cells during the test



V1: Cell voltage of #13
V2: Cell voltage of #12
V2: Cell voltage of #11

Figure 7: Voltage record of Modules during the test



DV1: Module voltage of #4
DV2: Module voltage of #5
DV3: Module voltage of #6
DV4: Module voltage of #8

Tests were performed on Sep 16, 2021, started at 09:40 AM.

Observations during the test:

Audible pop was heard on 11:14 AM (the pressure relief valve burst), followed by smoke release after several seconds.

A large amount of white smoke was observed after thermal runaway.

Cell to cell propagation was observed in the initial model.

Module to module propagation was not observed.

No flying debris or explosive discharge of gases observed during test.

No sparks, electrical arcs, or other electrical events observed during test.

No external flaming was observed during the test.

Observations after the test:

Leakage outside the initiating module enclosure was observed. See photos in page 46~54.

No damage and contamination on the instrument walls.

No damage and contamination on the modules of target units.

The plastic top enclosure near the initial cell of module M8 was melted and significantly damaged. Module voltage of M8 was 198.6 Vdc.

Four cells inside the initial module M5 was damaged. Cell to cell propagation was observed on cell #14 after receiving thermal energy from cell #13. Voltage measured on each remaining undamaged in other sub-modules were 3.33Vdc.

Weight loss of the initiating module was 1.7 kg (before test 401.5kg, after test 399.8kg)

See photos in page 53.

3.5 Temperature measurements

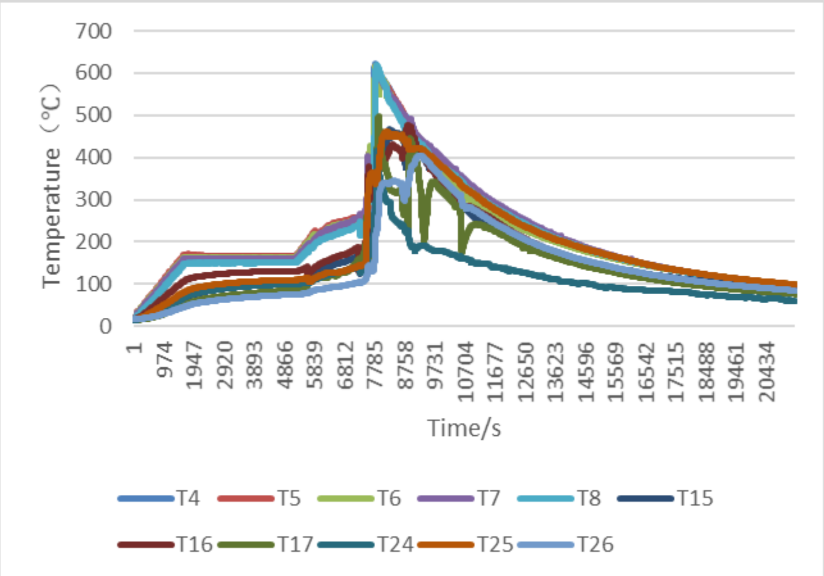
3.5.1 Temperature measurement of initiating cells

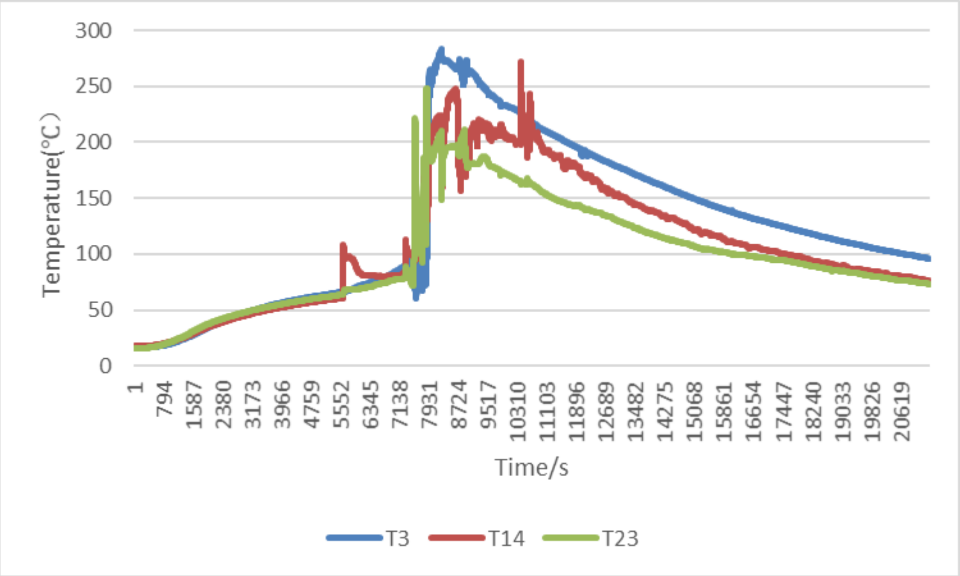
Surface temperature of cells #8 - #16 was recorded during the test. Cell to cell propagation occured during the test. See Figure 6 for the temperature vs time curve.

Cell thermal runaway occurred on cell #12, #13, #11 in turn at around 11:46, 11:50, 11:52 Maximum temperature 617.4°C, 623.7°C,619.5°C were measured on the cell #12, #13, #11 surface.

Cell to cell thermal runaway propagation occurred on cell #14. Maximum temperature 283.8°C was measured on the cell #14 surface.

Figure 8. Surface temperatures of thermal runaway cells on module M8





Cell in other sub-module did not go to thermal runaway, maximum temperature 108.2°C, 131.7°C, 553.8°C, 353.5°C, 646.6°C, 566.6°C, 133.7°C, 142.7°C, 163.7°C were measured on narrow surface center of cell near cells #8 - #16 in sub-modules 1 and 3.

Figure 9. Surface temperatures of no thermal runaway cells on sub-module 3 of module M8

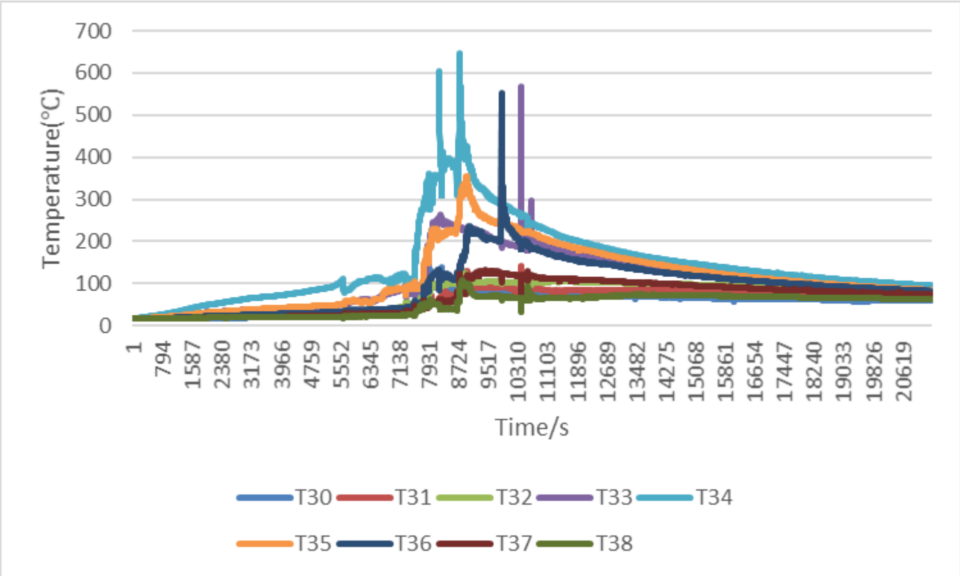
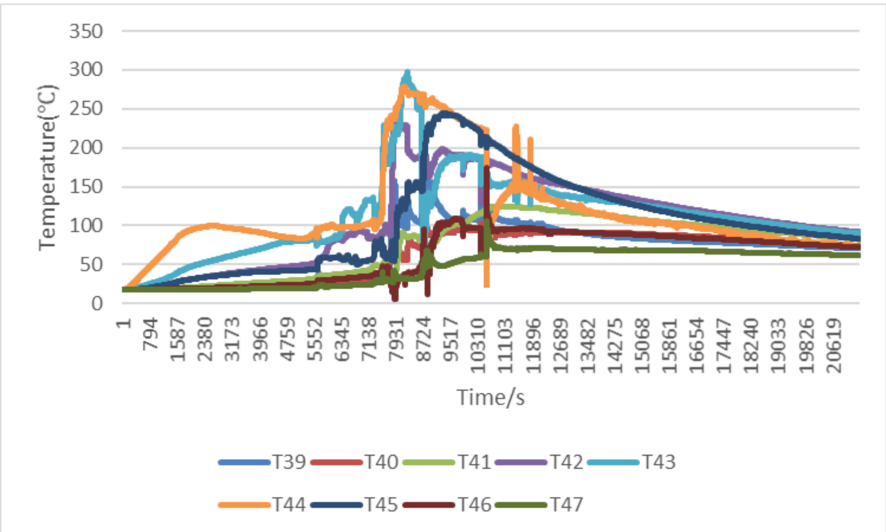


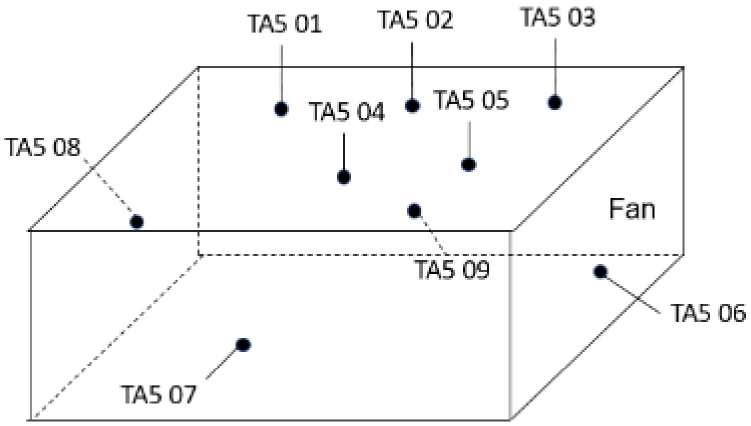
Figure 10. Surface temperatures of no thermal runaway cells on sub-module 1 of module M8



3.5.2 Temperature measurement of units

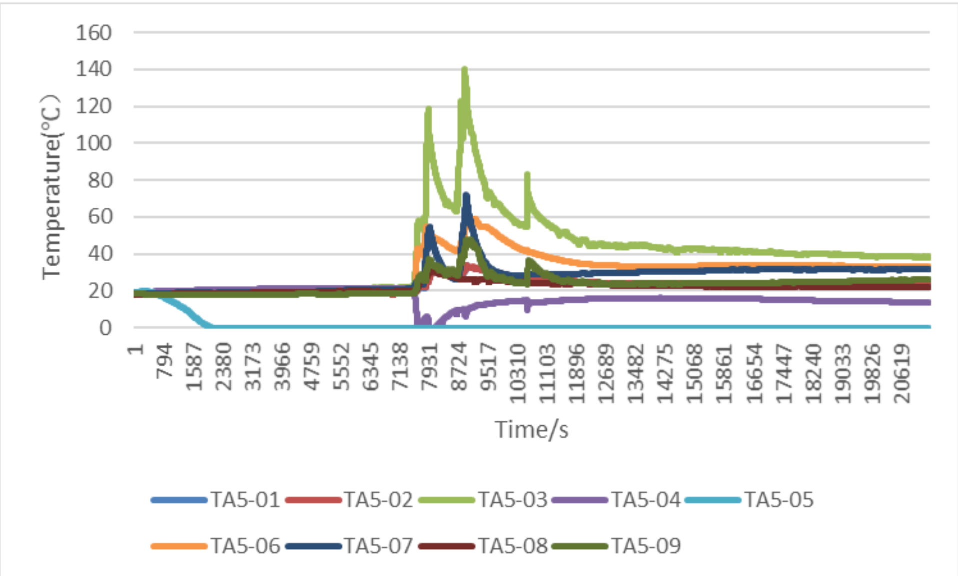
9 glass fiber insulated thermocouples (TA5 01~TA5 09), Type K, 24 AWG were attached to the external surface of module M8, as below Figure 11.

Figure 11. thermocouple of module M5 surface



TA5 01~TA5 03 were located on the top surface above cell in sub-module2. TA5 04, TA5 05 were located on the top surface above cell in sub-module3. TA5 06 was located in front of module, TA5 07 was located on the left side surface, TA5 08 located on the rear side, TA5 02 was located on the right side surface. Maximum temperature 407.3°C was measured on top of the module near #4 cell.

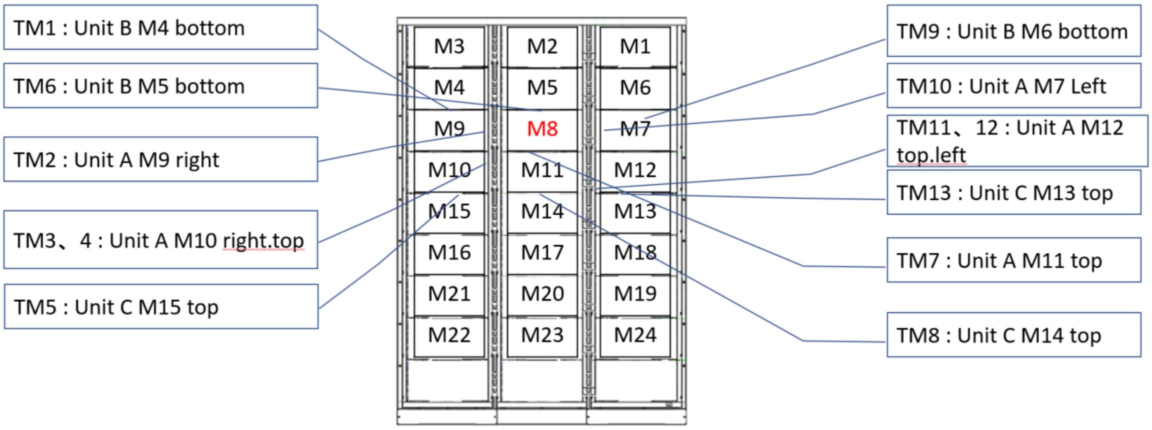
Figure 12. Surface temperatures of initiating module M8



13 glass fiber insulated thermocouples (TM1 to TM13), Type K, 24 AWG were attached to the center of the top surface of modules M4 to M15.

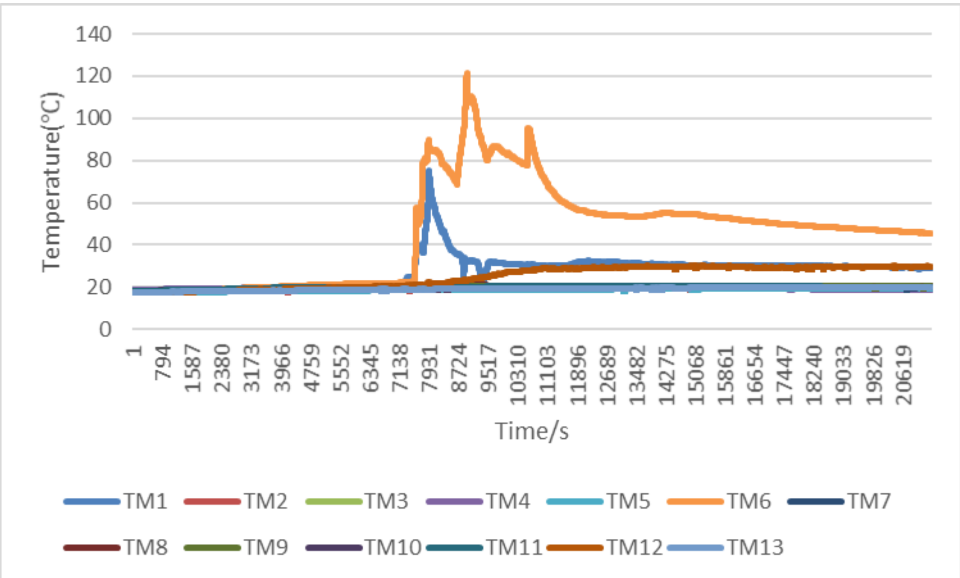
Maximum temperature 121.5°C was measured on bottom of the module M5.

Figure 13. Thermocouple location on modules in units A,B,C (Rack 1)



View direction: towards instrument wall A with reference to Figure 2

Figure 14. Surface temperatures of modules from M4 to M15

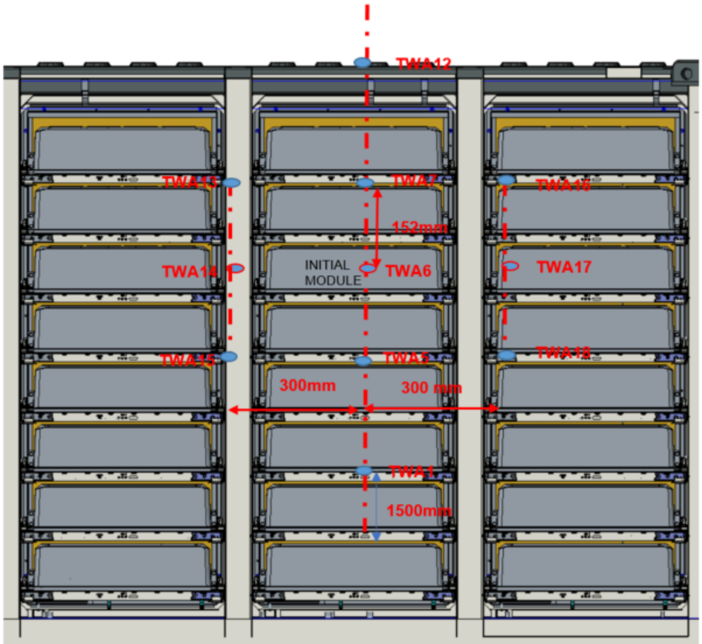


Maximum temperature 121.4°C was measured on side surface of the module M5 of Unit B.

Maximum temperature 21.2°C was measured on rear surface of the module M14 of Unit C.

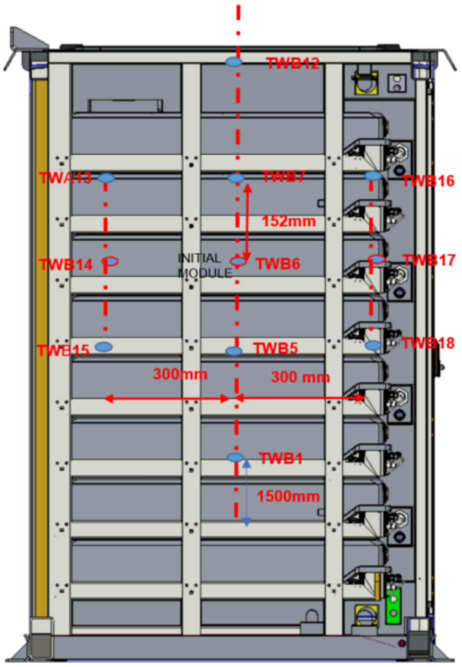
Figure 15. Thermocouple location on the back side of Wall A

View direction: from instrument wall A with reference to Figure 2



On the back side of wallA

Figure 16. Thermocouple location on the left side of wall B



On the left side of wall B

View direction: towards instrument wall B with reference to Figure 2

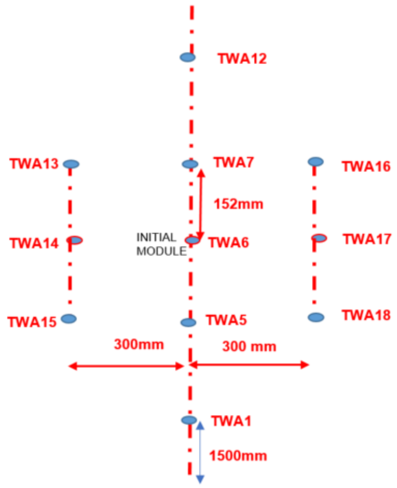
3.5.3 Temperature measurement of instrumented walls

Wall surface temperatures were measured in vertical arrays at 152 mm intervals for the full height of the instrumented wall sections using Type K, 30 AWG thermocouple. The thermocouple arrays were collinear with the centre line of Initial Unit A. The red line in Figure 12 shows the thermocouple arrays on the wall.

The first thermocouple starts from 1500 mm from ground. Total 36 thermocouples were used for each array. The thermocouples were numbered from low to high as TWA1 to TWA18 for wall A and TWB1 to TWB18 for wall B.

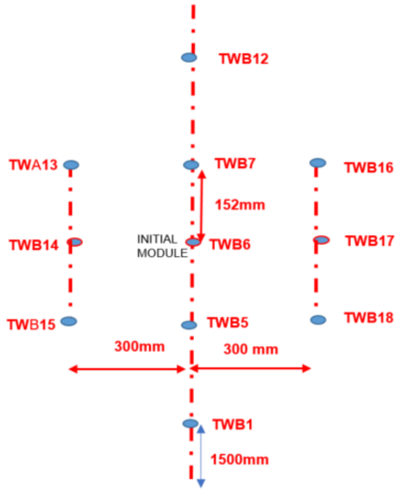
Figure 17. Vertical position of the thermocouples on the wall

Instrumented wall A



View direction: towards instrument wall A with reference to Figure 2

Instrumented wall B



View direction: towards instrument wall B with reference to Figure 2

Additional 6 thermocouples were positioned horizontally near the initial module M8 300 mm away from the vertical array each side, on instrumented wall A and wall B. See Figure 18.

Maximum temperature measured on instrument wall A was 21.4°C at TWA13, temperature curve see figure 18 for detail.

Maximum temperature measured on instrument wall B was 24.6°C at TWB10, temperature curve see figure 19 for detail.

Figure 18. Horizontal position of the thermocouples on the wall A and wall B

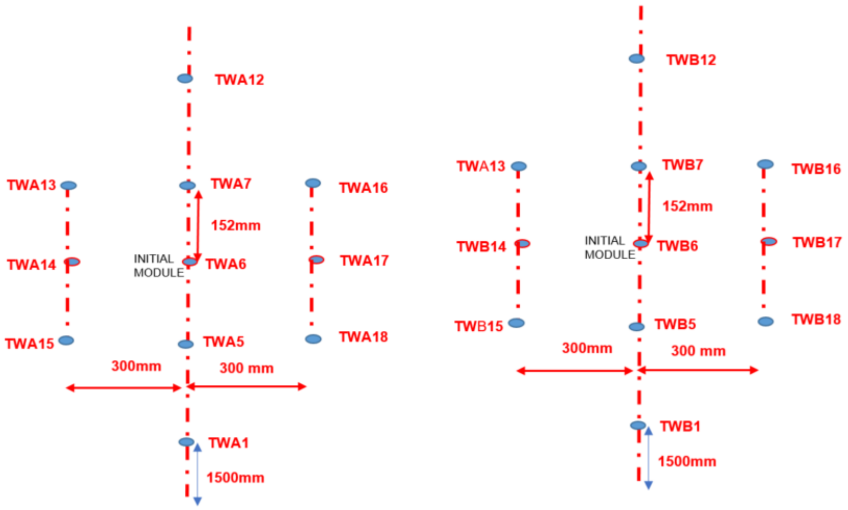


Figure 19. Temperatures on instrument wall A.

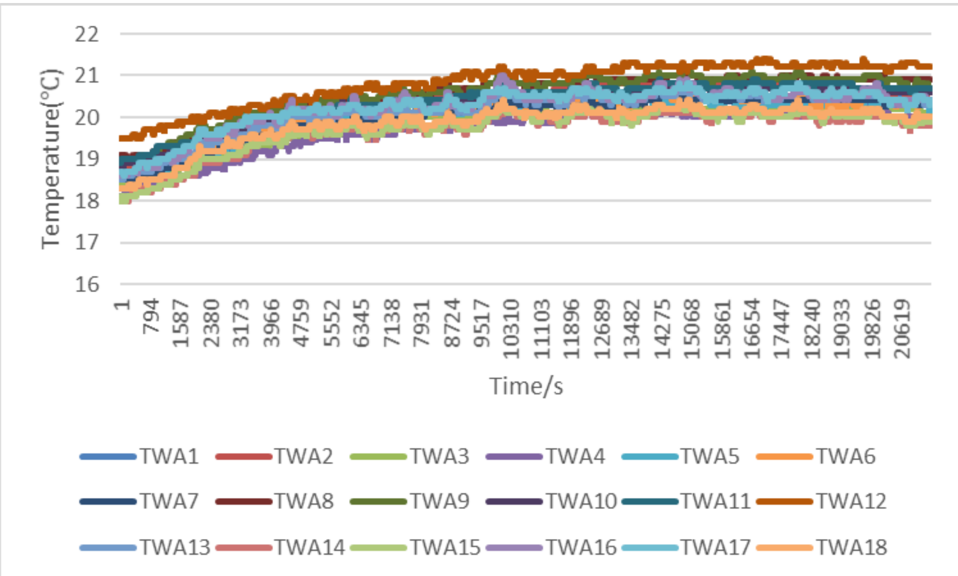
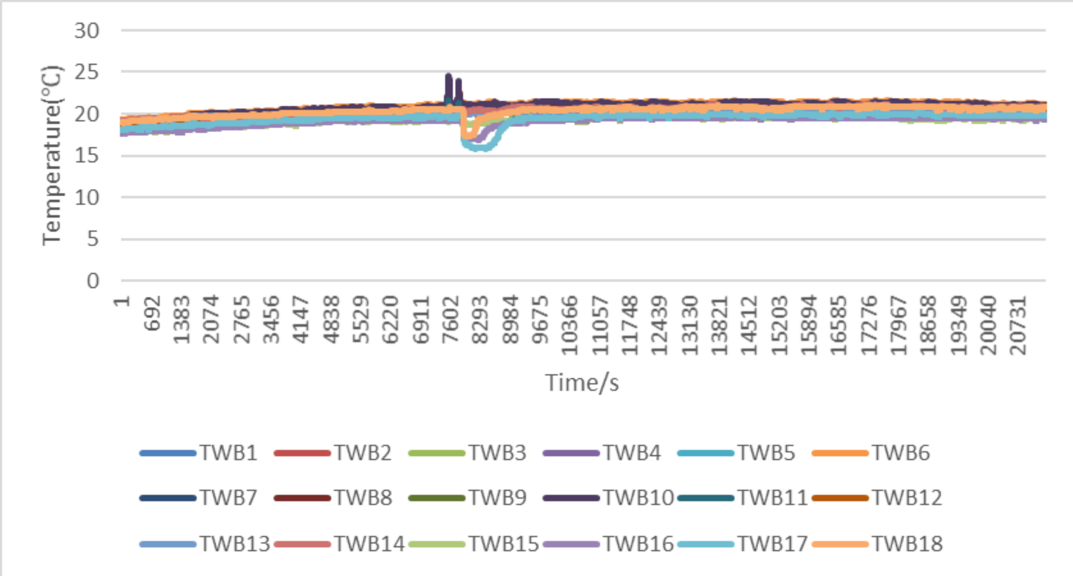


Figure 20. Temperatures on instrument wall B.



3.6 Heat flux measurement

Two sensors were placed on the surface of instrumented wall A, wall B and adjacent unit A that faces the initiating unit.

The sensors were collinear with the vertical thermocouple array. One was positioned at the height equivalent to module M8 top edge, which was estimated to receive the greatest heat flux due to the thermal runaway of the initiating module within the initiating unit. Another was positioned at the height equivalent to module M11 top edge, which was estimated to receive the greatest surface heat flux due to the thermal runaway of the initiating unit.

Figure 21 shows the positions of the sensors. Sensor H1 & H2 were positioned at unit A; All sensors were numbered from low to high.

Figure 21. Heat flux sensor locations on unit

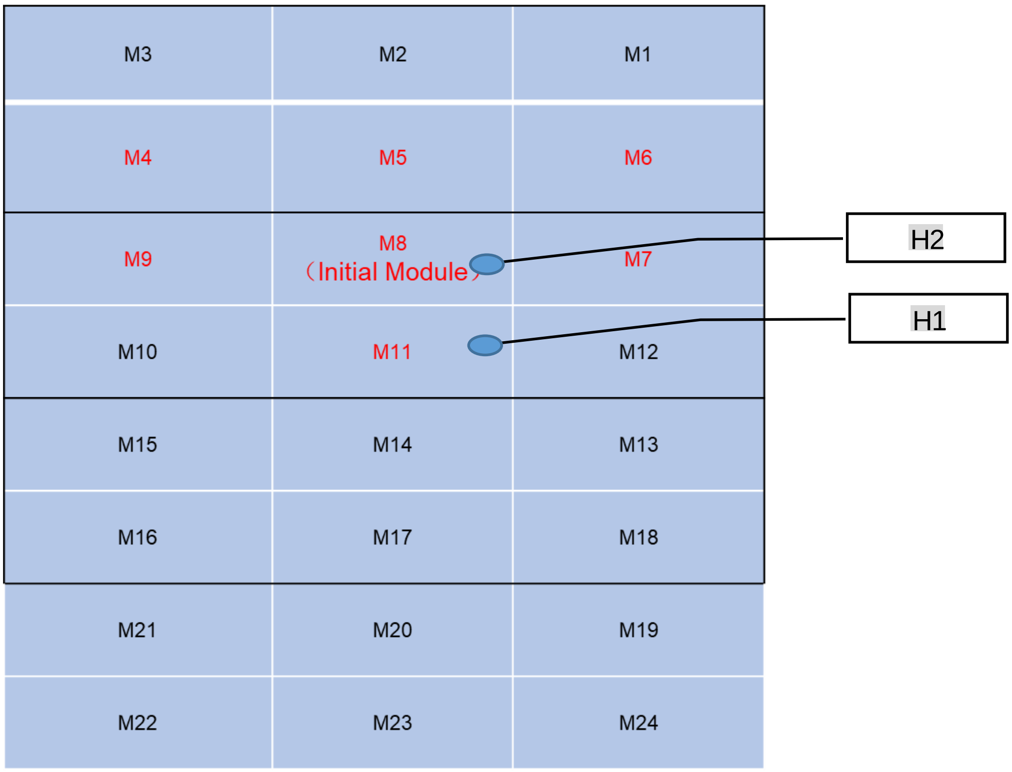
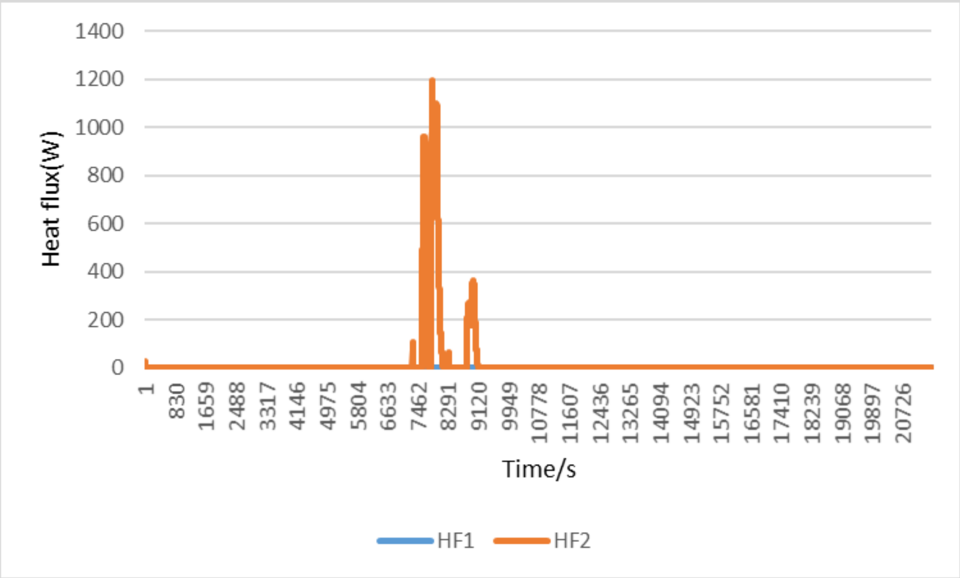


Figure 22. Measured heat flux of target wall and target units



3.7 Chemical heat release rate measurement

The chemical heat release rates were measured by an oxygen consumption calorimeter measurement system consisting of a paramagnetic oxygen analyzer, non-dispersive infrared carbon dioxide and carbon monoxide analyzer, velocity probe, and a Type K thermocouple.

The instrumentations are located in the exhaust duct of the heat release rate calorimeter.

The chemical heat release rate was calculated at each of the flows as follows:

$$HRR_1 = \left[E \times \varphi - (E_{co} - E) \times \frac{1-\varphi}{2} \times \frac{X_{co}}{X_{O_2}}\right] \times \frac{\dot{m}_e}{1+\varphi \times (\alpha - 1)} \times \frac{M_{O_2}}{M_a} \times (1 - X^o_{H_2O}) \times X^o_{O_2}$$

In which:

HRR_t = total heat release rate, as a function of time (kW)

E = Net heat released for complete combustion per unit of oxygen consumed (adjusted for oxygen contained within cell chemistry, 13,100 kJ/kg)

E_{CO} = Net heat released for complete combustion per unit of oxygen consumed, for CO (adjusted for oxygen contained within cell chemistry, 17,600 kJ/kg)

φ = Oxygen depletion factor (non-dimensional), where:

$$\varphi = \frac{X^o_{O_2} \times [1 - X_{CO_2} - X_{CO}] - X_{O_2} \times [1 - X^o_{CO_2}]}{X^o_{O_2} \times [1 - X_{O_2} - X_{CO_2} - X_{CO}]}$$

X_{CO} = Measured mole fraction of CO in exhaust flow (non-dimensional)

X_{CO_2} Measured mole fraction of CO_2 in exhaust flow (non-dimensional)

$X°_{CO_2}$ = Measured mole fraction of CO_2 in incoming air (non-dimensional)

$X°_{H_2O}$ = Measured mole fraction of H_2O in incoming air (non-dimensional)

X_{O_2} = Measured mole fraction of O_2 in exhaust flow (non-dimensional)

$X°_{O_2}$ = Measured mole fraction of O_2 in incoming air (non-dimensional)

α = Combustion expansion factor (non-dimensional; normally a value of 1.105)

M_a = Molecular weight of incoming and exhaust air (29 kg/kmol)

M_{O_2} = Molecular weight of oxygen (32 kg/kmol)

$\dot{m}_e$ = Mass flow rate in exhaust duct (kg/s), in which:

$$\dot{m}_e = C \times \sqrt{\frac{\Delta p}{T_e}}$$

or

$$\dot{m}_e = 26.54 \times \frac{A \times k_c}{f(\mathrm{Re})} \times \sqrt{\frac{\Delta p}{T_e}}$$

C = Orifice plate coefficient (in $kg^{1/2}m^{1/2}K^{1/2}$)

Δp = Pressure drop across orifice plate or bidirectional probe (Pa)

T_e = Combustion gas temperature at orifice plate or bidirectional probe (K)

A = Cross sectional area of the duct (m^2)

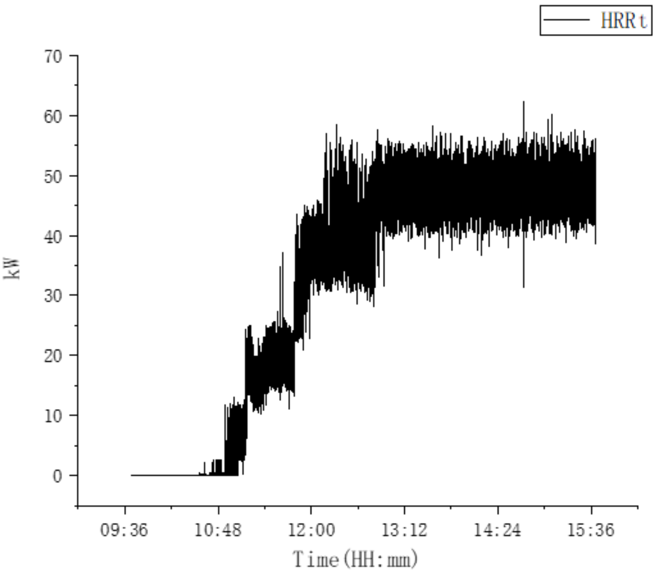
k_c = Velocity profile shape factor (non-dimensional)

f (Re) = Reynolds number correction (non-dimensional)

The heat release rate measurement system was calibrated at 50kW and 70kW heat release rate using a standard propane burner before the test. The calibrations were performed using flows of 1078mg/s and 1510mg/s of propane.

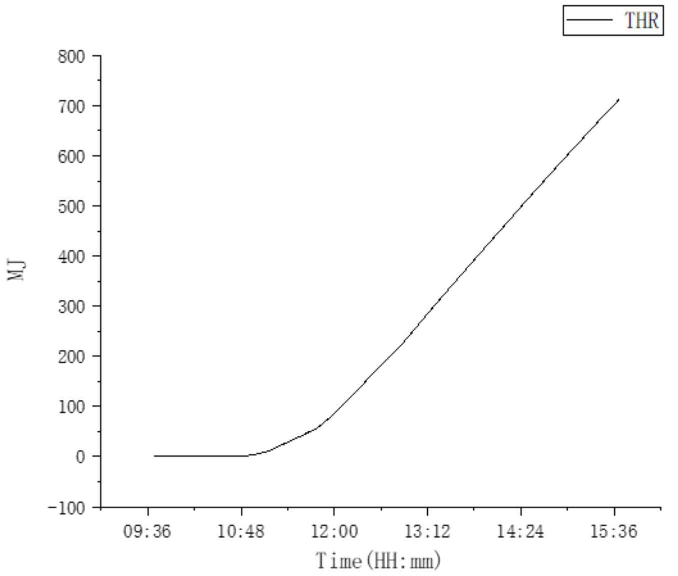
Measured peak chemical heat release rate HRR_t was 62.37kW

Figure 23. HRRt curve



Measured total heat release THR through the test was 712.474 MJ

Figure 24. THR curve



3.8 Convective heat release rate measurement

The convective heat release rate was measured using thermopile, a velocity probe, and a Type K thermocouple, located in the exhaust system of the exhaust duct.

The convective heat release rate was calculated at each of the flows as follows:

$$HRR_c = V_e A \frac{353.22}{T_e} \int_{T_o}^{T} C_p dT$$

Where:

HRR_c = The convective heat release rate (kW)

V_e = The exhaust velocity (m/s)

A = The exhaust duct cross sectional area (m^2)

T_e = The temperature at the location where exhaust velocity is measured (K)

$353.22/T_e$ = The density of air at the velocity measurement location (kg/m^3)

T_o = The ambient temperature (K) in the test room

T = The thermopile temperature (K)

$$\int_{T_o}^{T} C_p dT = A_0(T - T_o) + A_1/2(T^2 - T_o^2) + A_2/3(T^3 - T_o^3) + A_3/4(T^4 - T_o^4)$$

Cp = Specific heat of air (kJ/kg-K), given as $\mathbf{C_p = A_0 + A_1 T + A_2 T^2 + A_3 T^3}$, where:

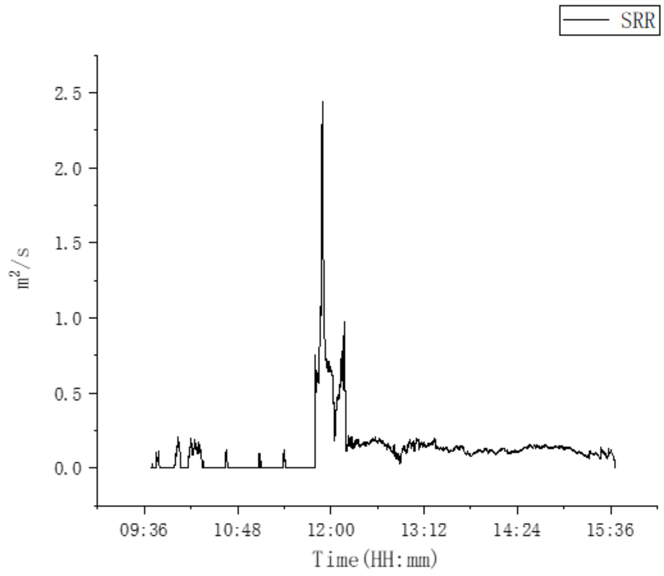
A_0 = 0.9950

A_1 = -5.29933E-05

A_2 = 3.21022E-07

A_3 = -1.22004E-10

Figure 25. Peak smoke release rate SRR: 22.5863 m2/s



3.9 Gas generation measurement

The composition, velocity and temperature of the vent gases were measured within the calorimeter's exhaust duct.

Gas compositions were measured using a Fourier-Transform Infrared Spectrometer with a resolution of 1 cm^{-1} and a path length of 4.2 m within the calorimeter's exhaust duct.

The total hydrocarbon content of the vent gas was measured using flame ionization detection.

Hydrogen gas was measured with electrochemical method.

Composition, velocity and temperature measurement instrumentation were collocated with heat release rate calorimetry instrumentation.

3.10.1 Total gas release

The flow rates of various gases were integrated over the test duration and the total cumulative volume of gas calculated for the total test duration (09:05 ~ 16:20) was presented in the below table.

The total cumulative volume of gases before cell venting (09:05 ~ 10:06) was also presented in the table for reference. Which may be considered as ambient gases background before the test.

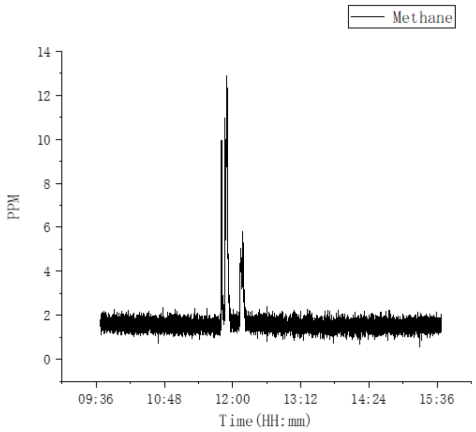
Gas type	Gas components		Total volume of gas (L)	
			Before cell venting	Throughout the test
Hydrocarbon species	Methane	CH_4	0.5	26.1
	Ethylene	C_2H_4	0.7	15.2
	Ethane	C_2H_6	0.2	6.5
	Propane	C_3H_8	0.1	36.3
	Propylene	C_3H_6	0	69.1
Hydrogen halide species	Hydrogen Fluoride	HF	0	12.2
Nitrogen containing species	Nitrous Oxide	NO	0.2	6.8
Others	Carbon Monoxide	CO	0	60.1
	Carbon Dioxide	CO_2	20670.4	54337.6
	Hydrogen	H_2	0	164.8
	Dimethyl carbonate(DMC)	$C_3H_6O_3$	0.3	177.2
	Ethylmethyl carbonate	$C_4H_8O_3$	0.1	30.7
	Oil as octane		0	5.9
Total Hydrocarbons				262.3

Note:
1) The collection time is from 09:40 to 16:20;
2) The carbon dioxide in the air during this period1) was also counted;
3) Total hydrocarbon gas volume was measured by flame ionization detection (FID);
4) Total volume of carbon monoxide (CO) and carbon dioxide (CO2) was measured using nondispersive infrared spectroscopy (NDIR);
5) The volume of hydrogen (H2) was measured using electrochemical with MODEL5000 sensor.

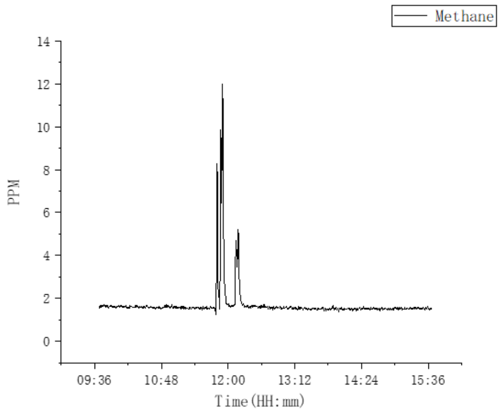
3.10.2 Gas components

Concentrations of the gases were scaled based on the measured flow rate of the exhaust system and were presented in the standard volume flow rate of gas ventilated in below figures.

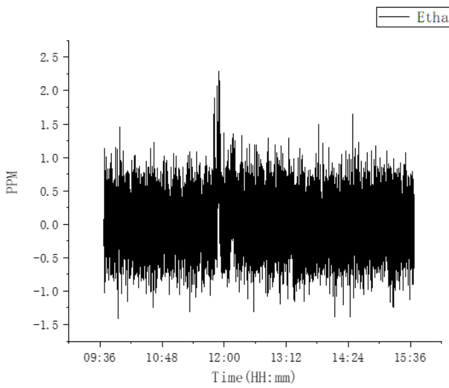
Figure 26. Hydrocarbon species



Raw original data



Savitzky-Golay filtered data



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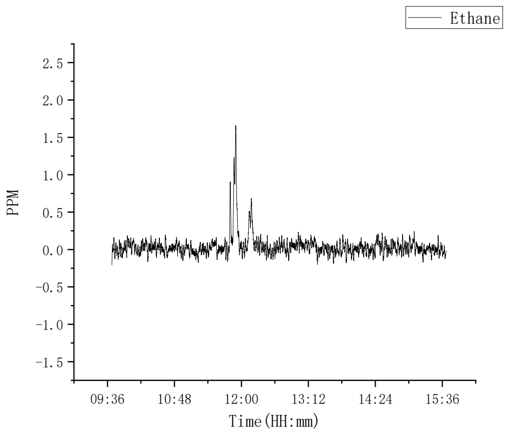
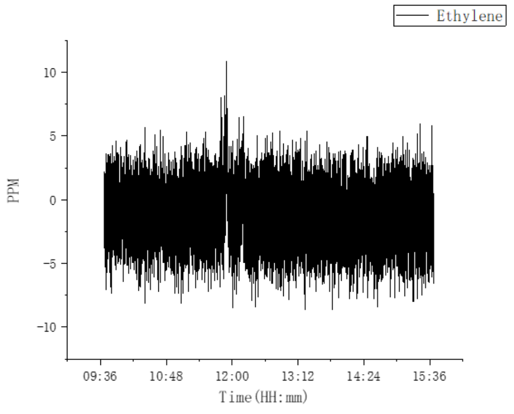


Savitzky-Golay filtered data



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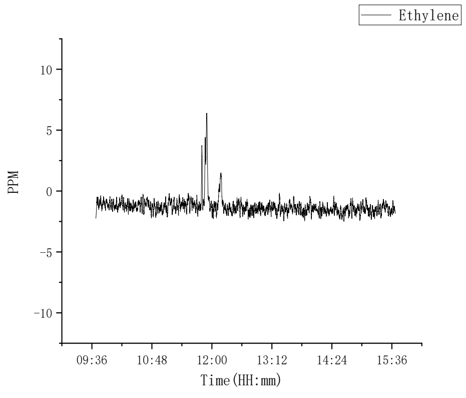

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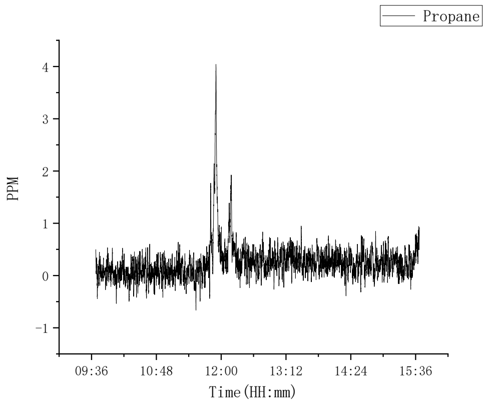

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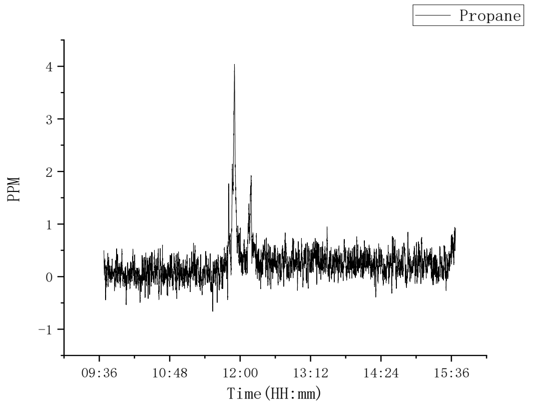
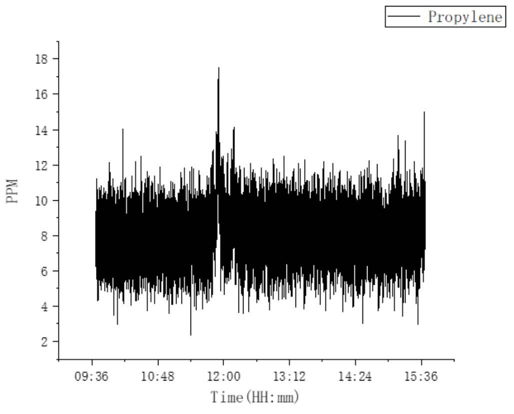


Savitzky-Golay filtered data



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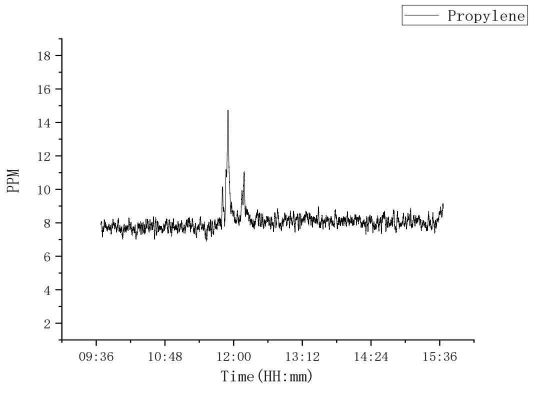
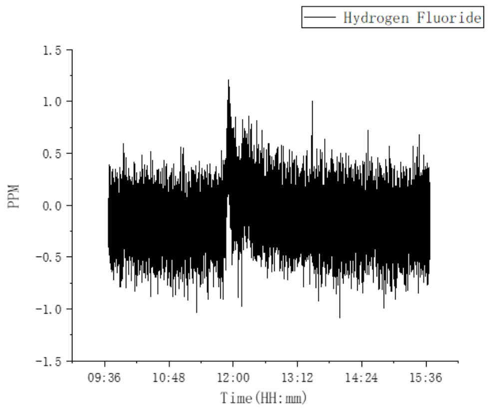
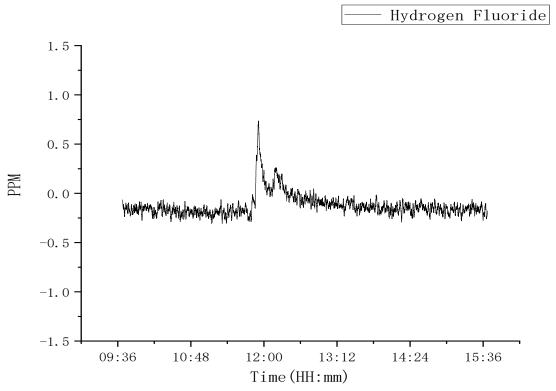


Savitzky-Golay filtered data

Figure 27. Hydrogen halide species



Raw original data



Savitzky-Golay filtered data

Figure 28. Nitrogen containing species

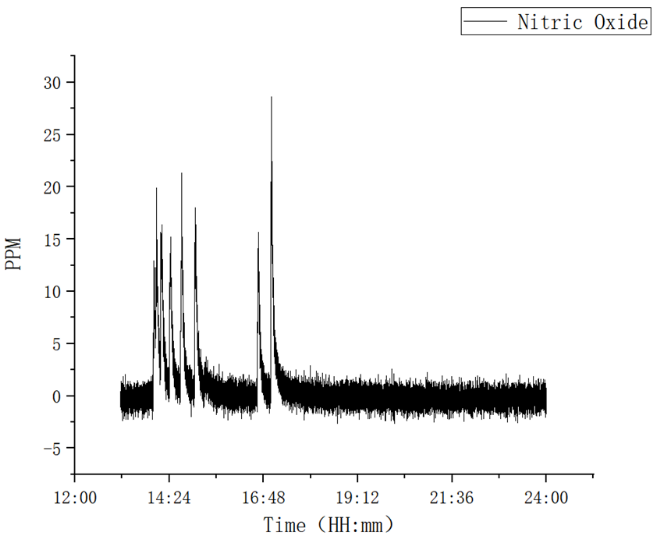


Figure 29. H_2 containing species

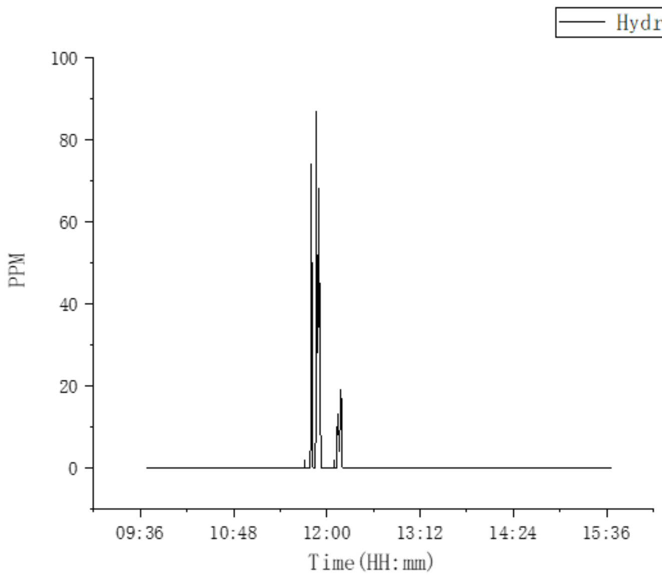
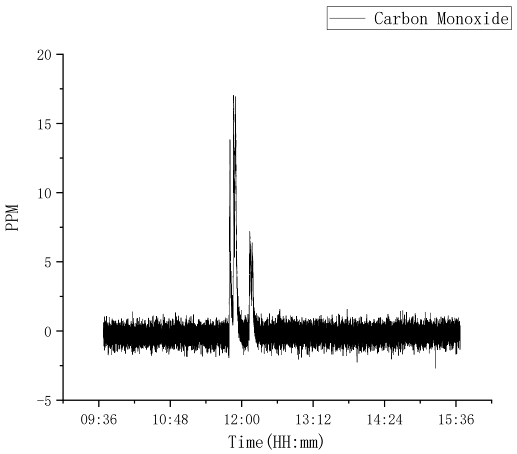
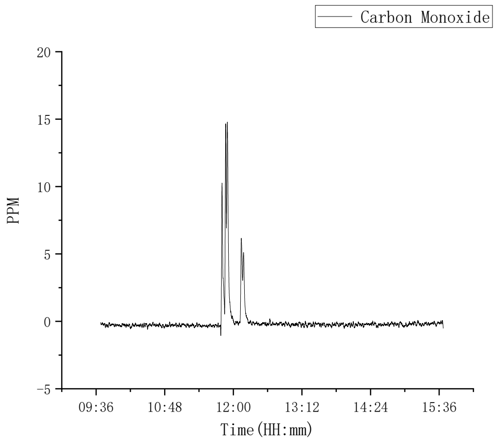


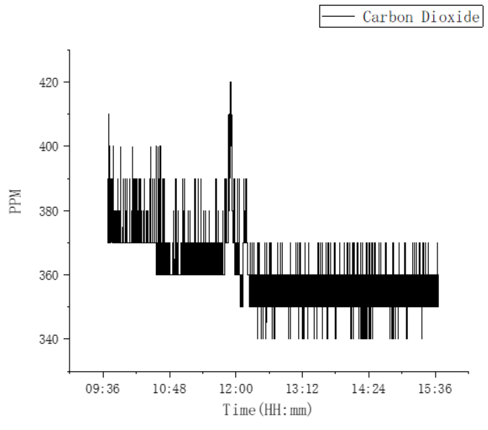
Figure 30. CO, CO_2 containing species



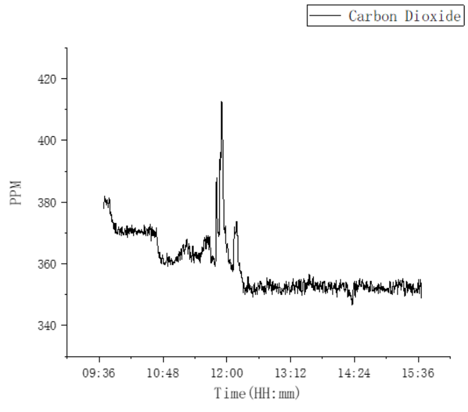
Raw original data



Savitzky-Golay filtered data



Raw original data



Savitzky-Golay filtered data

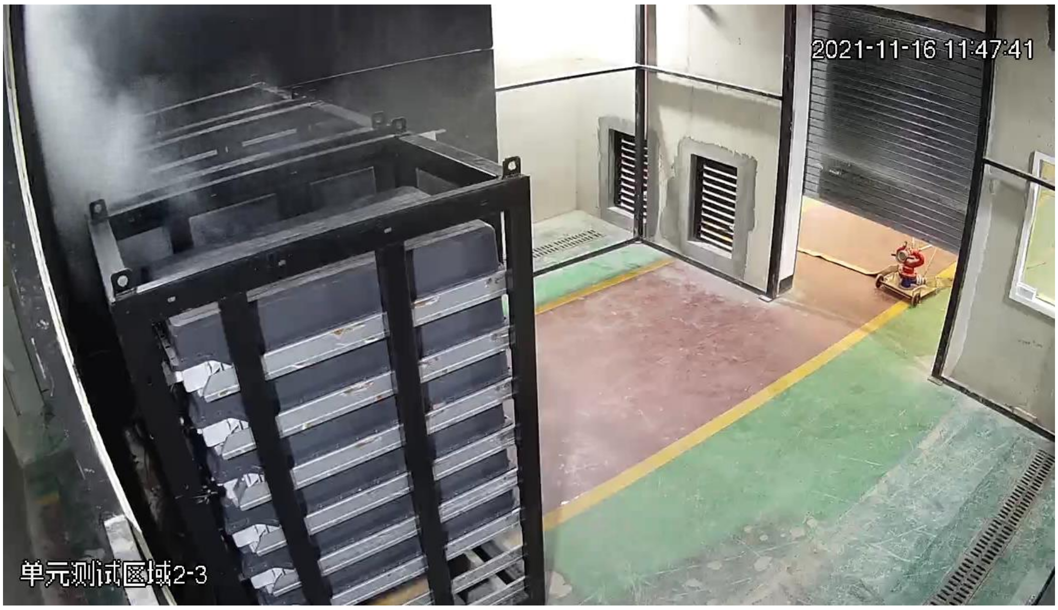
Note: Since raw original data is hard to interpret. Savitzky-Golay filtered data is also provided as this smooths the data and increases the precision of the data without distorting the signal tendency.

3.10 Photos

Initial module

Test setup

Smoke release during the test

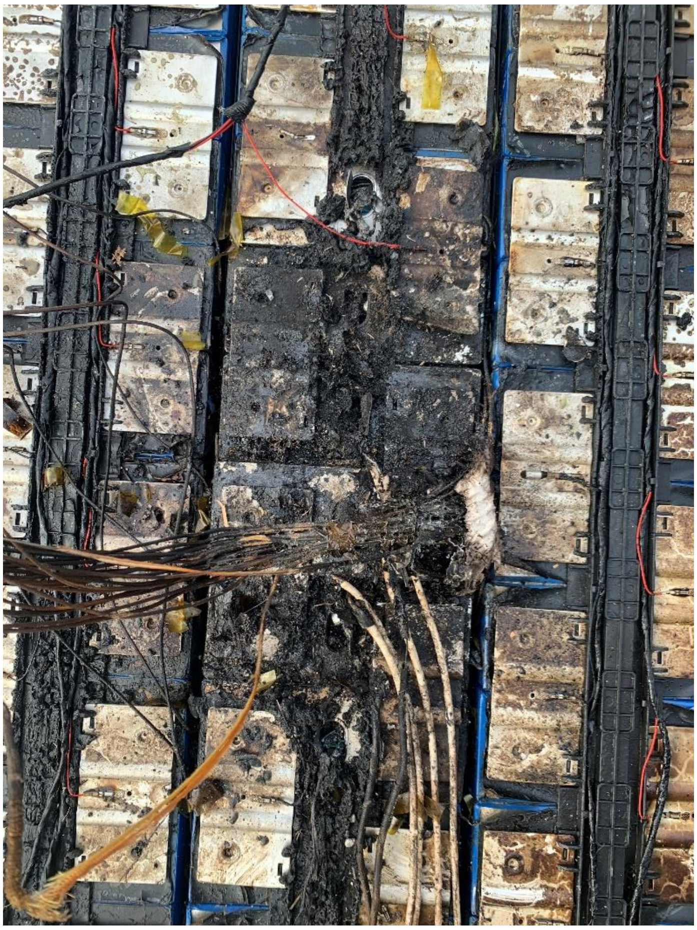


Photos after the test

399.8kg

Initial module after test

Initial cell after test



4 List of Test and Measurement Instruments

<table>
<tr><th>No.</th><th colspan="2">Equipment</th><th>Model</th><th>Rating</th><th>Inventory no.</th><th>Last Cal. date</th></tr>
<tr><td>1</td><td colspan="2">Ambient monitor</td><td>WSB-2-H1</td><td>0-40°C，10-90%RH</td><td>T-125</td><td>2021.07.24</td></tr>
<tr><td>2</td><td colspan="2">Ambient monitor</td><td>WSB-2-H1</td><td>0-40°C，10-90%RH</td><td>S-050</td><td>2021.05.31</td></tr>
<tr><td>3</td><td colspan="2">Data acquisition equipment</td><td>DTM</td><td>0-1000°C</td><td>S-029</td><td>2021.04.19</td></tr>
<tr><td>4</td><td colspan="2">Data acquisition equipment</td><td>ADAM-4117
ADAM-4118
MT4W
DTB4824</td><td>0-10V
0-1000°C
0-100V
0-1000°C</td><td>S-028-3
S-028-4
S-030-(5~8)
S-046-2</td><td>2021.04.19
2021.05.06
2021.07.19
2021.07.20</td></tr>
<tr><td>5</td><td colspan="2">Digital multi-meter</td><td>FLUKE101</td><td>0-600V</td><td>S-038</td><td>2021.04.22</td></tr>
<tr><td>6</td><td colspan="2">Tape</td><td>1000mm
5000mm</td><td>0-1000mm
0-5000mm</td><td>S-040
S-042</td><td>2021.04.22
2021.04.22</td></tr>
<tr><td>7</td><td colspan="2">Electronic scale</td><td>TCS-500</td><td>0-500kg</td><td>S-039</td><td>2021.04.19</td></tr>
<tr><td rowspan="6">8</td><td rowspan="6">Oxygen consumption calorimeter measurement system</td><td>Paramagnetic oxygen analyzer</td><td rowspan="2">SERVOMEX MultiExact 4100</td><td rowspan="2">O_2: 0-21%
CO_2: 0-10%
CO: 0-1%</td><td rowspan="2">S-024</td><td rowspan="2">2021.03.20</td></tr>
<tr><td>CO and CO2 sensor</td></tr>
<tr><td>Velocity probe</td><td>WIKA</td><td>0~0.4MPa</td><td>S-024-5</td><td>2021.03.08</td></tr>
<tr><td>Photo detector</td><td>DP101MD</td><td>-100~100Pa</td><td>S-024-4</td><td>2021.03.08</td></tr>
<tr><td>Light filter</td><td>——</td><td>25%、50、75%</td><td>S-024-6
S-024-7
S-024-8</td><td>2021.03.12</td></tr>
<tr></tr>
<tr><td>9</td><td colspan="2">Palladium-nickel thin-film solid state sensor</td><td>H2scan 740B
MODEL5000
OMD-650</td><td>500ppm-100%
0-4%
<20%</td><td>S-023-1
S-023-2
S-023-3</td><td>2021.03.20</td></tr>
<tr><td>10</td><td colspan="2">Fourier-Transform Infrared Spectrometer</td><td>MG6000</td><td>0.01ppm-100%</td><td>S-019</td><td>2021.03.20</td></tr>
<tr><td>11</td><td colspan="2">Flame Ionization Detector</td><td>ABB AO2000</td><td>0-3000ppm</td><td>S-025</td><td>2021.03.20</td></tr>
<tr><td>12</td><td colspan="2">Thermopile</td><td>OMEGA
TT-K-24</td><td>0-260℃</td><td>S-026</td><td>2021.04.01</td></tr>
</table>

13	Heat flux measurement equipment	Schmidt-Boelter, 64-5-20	0-50kW	S-031 S-032 S-033 S-034 S-035 S-036 S-037 S-065	2021.06.21

End of Test Report