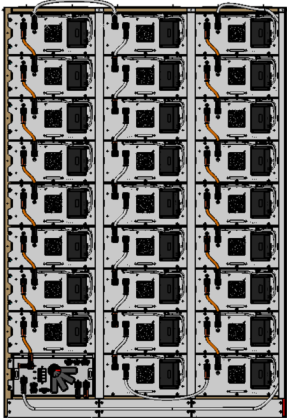


Prüfbericht-Nr.: <i>Test report no.:</i>	CN25KUMH 001	Auftrags-Nr.: <i>Order no.:</i>	326105734	Seite 1 von 47 Page 1 of 47
Kunden-Referenz-Nr.: <i>Client reference no.:</i>	2116531	Auftragsdatum: <i>Order date:</i>	2025-04-21	
Auftraggeber: <i>Client:</i>	Shanghai PYTES Energy Co., Ltd. No.3492 Jinqian Road, Fengxian District, 201400 Shanghai P.R. China			
Prüfgegenstand: <i>Test item:</i>	Battery Rack			
Bezeichnung / Typ-Nr.: <i>Identification / Type no.:</i>	HV-ES-1000EB3, HV-ES -1000EB4, HV-ES-1000EB5, HV-ES-1000EB6 HV-ES-1500EB3, HV-ES-1500EB4, HV-ES-1500EB5, HV-ES-1500EB1			
Auftrags-Inhalt: <i>Order content:</i>	Test report			
Prüfgrundlage: <i>Test specification:</i>	UL 9540A: 2019 (Fourth Edition) Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems			
Wareneingangsdatum: <i>Date of sample receipt:</i>	2023-09-11			
Prüfmuster-Nr.: <i>Test sample no.:</i>	#2023091101			
Prüfzeitraum: <i>Testing period:</i>	2023-09-12 - 2023-09-25			
Ort der Prüfung: <i>Place of testing:</i>	See clause 1.1 of main report			
Prüflaboratorium: <i>Testing laboratory:</i>	TÜV Rheinland (Shanghai) Co., Ltd.			
Prüfergebnis*: <i>Test result*:</i>	See main report			
geprüft von: <i>tested by:</i>		genehmigt von: <i>authorized by:</i>		
Datum: <i>Date:</i>	2025.05.12	Ausstellungsdatum: <i>Issue date:</i>	2025.05.12	
Stellung / Position:	Project Engineer	Stellung / Position:	Reviewer	
Sonstiges / Other:	The mentioned models listed on above are identical to the original model in the previous section report CN23T322 001 except for model name, trademark and/or license holder etc. The test data refer to previous section report CN23T322 001. See following pages for details.			
Zustand des Prüfgegenstandes bei Anlieferung: <i>Condition of the test item at delivery:</i>	Prüfmuster vollständig und unbeschädigt <i>Test item complete and undamaged</i>			
* Legende:	P(ass) = entspricht o.g. Prüfgrundlage(n)	F(ail) = entspricht nicht o.g. Prüfgrundlage(n)	N/A = nicht anwendbar	N/T = nicht getestet
* Legend:	P(ass) = passed a.m. test specification(s)	F(ail) = failed a.m. test specification(s)	N/A = not applicable	N/T = not tested
Dieser Prüfbericht bezieht sich nur auf das o.g. Prüfmuster und darf ohne Genehmigung der Prüfstelle nicht auszugsweise vervielfältigt werden. Dieser Bericht berechtigt nicht zur Verwendung eines Prüfzeichens. <i>This test report only relates to the above mentioned test sample as. Without permission of the test center this test report is not permitted to be duplicated in extracts. This test report does not entitle to carry any test mark.</i>				

V05

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 don't 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.

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

Testing period: Sep 12, 2023 ~ Sep 25, 2023

All tests were under supervision of TÜV Rheinland's engineer.

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 Revision information

New report, not applicable

1.4 Summary of the test

One external heater was placed in the module to initiate the thermal runaway inside the module. The initiating cells were heated at a rate of 4°C~7°C per minute until the cell thermal runaway.

White smoke was observed during test.

Cell thermal runaway was observed.

Cell to cell thermal runaway propagation was observed.

No module-to-module thermal runaway propagation.

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

No electrical arcs, or other electrical events during test.

No external flaming was observed.

The battery pack weight measured was 115.86 kg (before test) and 113.44 kg (after test).

Measured peak chemical heat release rate HRR was 28.04 kW;

Measured peak smoke release rate SRR was 1.9936 m²/s;

Total smoke release TSR was 3242.94 m²;

Total hydrocarbons was 49.98 L (equivalent to C₃H₈, measured by FID);

Detail information see relevant clause of this report.

1.5 List of attachments

Video records of the test from 3 directions were provided in .mp4 format.

Complete records were provided in the following documents, file numbers listed as below:

20230912 Batterio unit UL9540A video ch01 (01-02).mp4

20230912 Batterio unit UL9540A video ch02 (01-02).mp4

20230912 Batterio unit UL9540A video ch03 (01-03).mp4

1.6 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

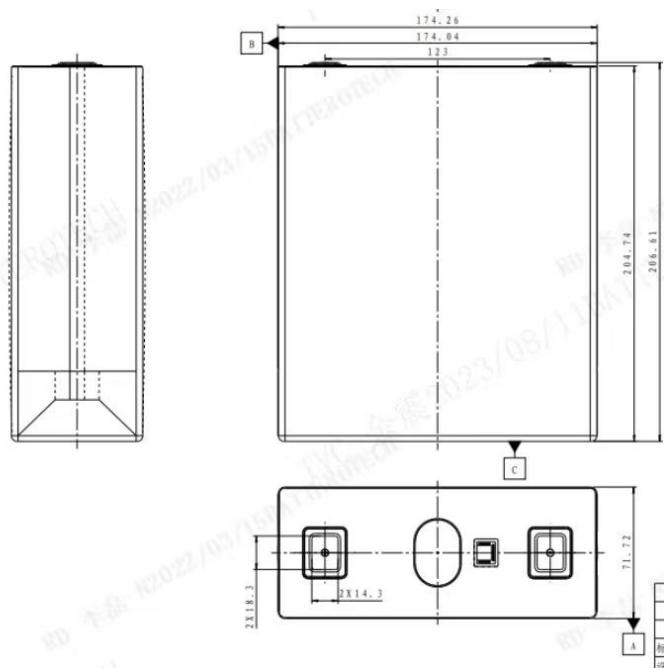
2.1 Cell

2.1.1 Product information and parameters

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

Manufacturer	BatteroTech Corporation Limited	
Model number.....	PC-0B1-72174L4-AH	
Chemistry	LiFePO ₄	
Physical configuration.....	Prismatic	
	Weight:	5.50±0.15 kg
Electrical rating	Rated capacity:	280 Ah
	Nominal voltage:	3.2 V
Standard charge method	Charge current:	140 A
	End of charge voltage:	3.65 V
Standard discharge method.....	Discharge current:	140 A
	End of discharge voltage:	2.5 V

Diagram with overall dimension



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2.1.2 Cell level test information

Cell level thermal runaway test information is from UL cell level test report 4789764706 provided by the client.

Thermal Runaway Methodology	Two heaters 152.4 mm by 203.2 mm in size for each sample.
Average Cell Surface Temperature at Gas Venting	152°C
Average Cell Surface Temperature at Thermal Runaway.....	228°C

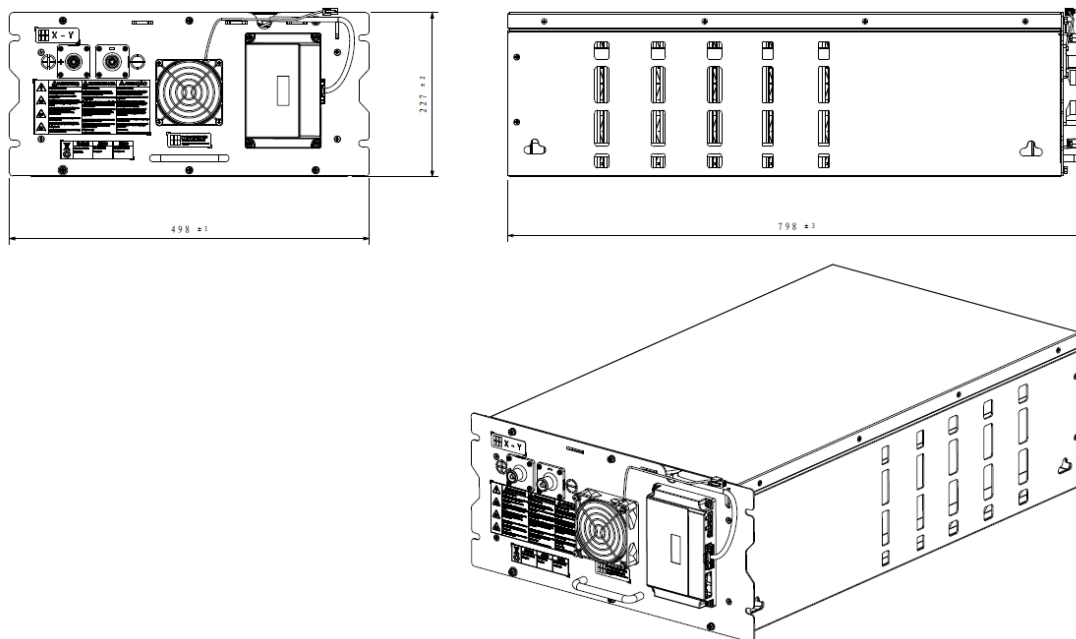
2.2 Module

2.2.1 Product information and parameters

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

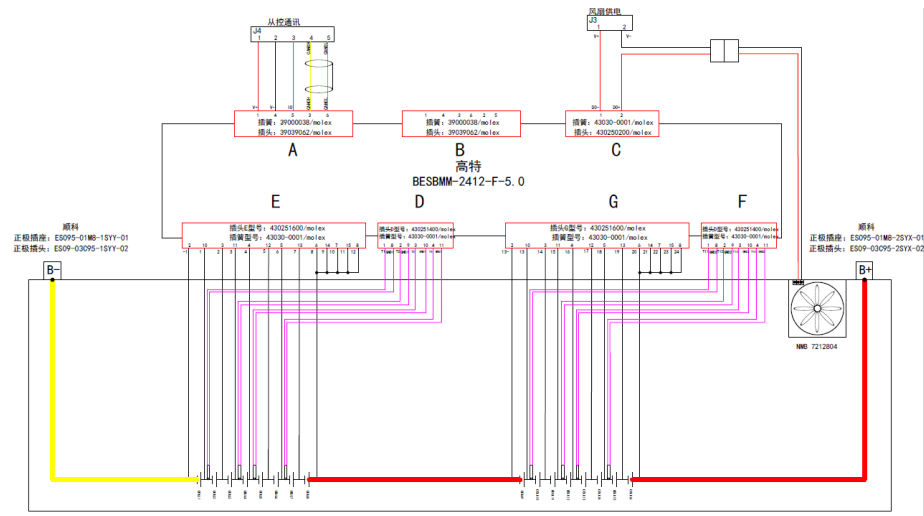
Manufacturer name.....		Shanghai PYTES Energy Co., Ltd.
Model number.....		HV-BEH-280P1
Physical configuration.....		Metal enclosure
		Weight: 114 kg
		Cells in series/parallel: 1P16S
Cooling method.....		Natural cooling with electric fan
Separation between cells.....		Metal frame
Electrical rating		Rated capacity: 280 Ah
		Nominal voltage: 51.2V
Standard charge method.....	Charge current:	140 A
	End of charge voltage:	57.6 V
Standard discharge method.....	Discharge current:	140 A
	End of discharge voltage:	40.0 V
Compliance with UL 1973.....		Yes

2.2.2 Diagram with overall dimension



2.2.3 Layout of the module contents

2.2.4 Configuration diagram of the module



2.3 Battery system (unit)

2.3.1 Manufacture information and model list

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

Item	Battery system	Battery system	Battery system	Battery system
Product	Air Cooling LFP Battery Rack	Air Cooling LFP Battery Rack	Air Cooling LFP Battery Rack	Air Cooling LFP Battery Rack
Type/model	HV-ES-1000EB3	HV-ES-1000EB4	HV-ES-1000EB5	HV-ES-1000EB6
Cell Capacity [Ah]	280	280	280	280
Cell Quantity	112	208	224	240
Battery structure	112S	208S	224S	240S
Nominal voltage [V]	358.4	665.6	716.8	768
Rated capacity [Wh]	100352	186368	200704	215040
Upper limit charging voltage [V]	408.8	759.2	817.6	876
Recommend charging current [A]	140	140	140	140
Maximum charging current [A]	170	170	170	170
Recommend discharging current [A]	140	140	140	140
Maximum discharging current [A]	170	170	170	170
Discharge cut-off voltage [V]	280	520	560	600
Temperature range for charging [°C]	2 to 55	2 to 55	2 to 55	2 to 55
Temperature range for discharging [°C]	-25 to 55	-25 to 55	-25 to 55	-25 to 55
Overcharge protected voltage supply by battery system	3.7V /Cell	3.7V /Cell	3.7V /Cell	3.7V /Cell
Dimension [mm]	Rack: W570±5mm*D831±3mm*H2032±5mm	Rack: W1048±5mm*D831±3mm*H2032±5mm	Rack: W1048±5mm*D831±3mm*H2032±5mm	Rack: W1048±5mm*D831±3mm*H2032±5mm
Weight [kg]	Rack: ≤980kg	Rack: ≤1720kg	Rack: ≤1836kg	Rack: ≤1950kg
Protective Class	I	I	I	I
Cooling type	Air cooling	Air cooling	Air cooling	Air cooling
Altitude	2000m	2000m	2000m	2000m

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Item	Battery system	Battery system	Battery system	Battery system
Product	Air Cooling LFP Battery Rack	Air Cooling LFP Battery Rack	Air Cooling LFP Battery Rack	Air Cooling LFP Battery Rack
Type/model	HV-ES-1500EB3	HV-ES-1500EB4	HV-ES-1500EB5	HV-ES-1500EB1
Cell Capacity [Ah]	280	280	280	280
Cell Quantity	368	384	400	416
Battery structure	368S	384S	400S	416S
Nominal voltage [V]	1177.6	1228.8	1280	1331.2
Rated capacity [Wh]	329728	344064	358400	372736
Upper limit charging voltage [V]	1343.2	1401.6	1460	1497.6
Recommend charging current [A]	140	140	140	140
Maximum charging current [A]	170	170	170	170
Recommend discharging current [A]	140	140	140	140
Maximum discharging current [A]	170	170	170	170
Discharge cut-off voltage [V]	920	960	1000	1040
Temperature range for charging [°C]	2 to 55	2 to 55	2 to 55	2 to 55
Temperature range for discharging [°C]	-25 to 55	-25 to 55	-25 to 55	-25 to 55
Overcharge protected voltage supply by battery system	3.7V /Cell	3.7V /Cell	3.7V /Cell	3.7V /Cell
Dimension [mm]	Rack: W1550±5mm*D831±3mm*H2256±5mm	Rack: W1550±5mm*D831±3mm*H2256±5mm	Rack: W1550±5mm*D831±3mm*H2256±5mm	Rack: W1550±5mm*D831±3mm*H2256±5mm
Weight [kg]	Rack: ≤3000kg	Rack: ≤3118kg	Rack: ≤3234kg	Rack: ≤3350kg
Protective Class	I	I	I	I
Cooling type	Air cooling	Air cooling	Air cooling	Air cooling
Altitude	2000m	2000m	2000m	2000m

2.3.2 Product information

This product is used for Energy Storage System.
The EUT covered by this report is one LFP lithium ion battery energy storage system, Each unit consists of a Switch Gear and the following series of battery cells in series:

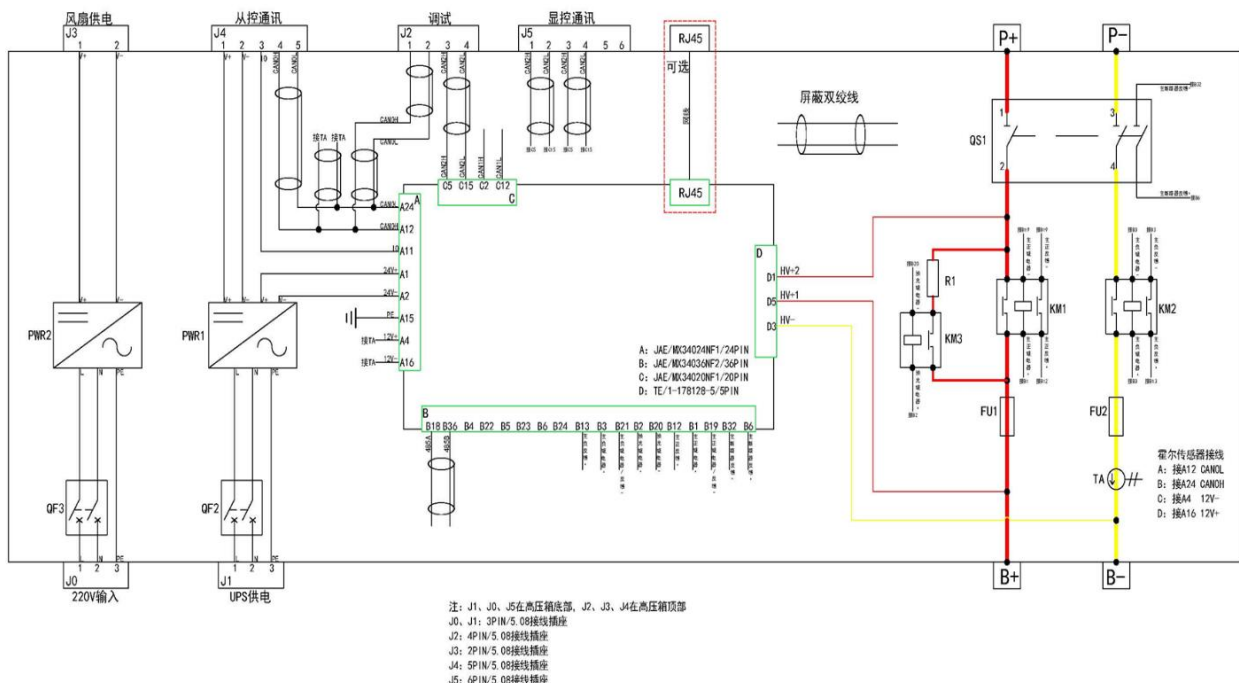
Type/model	Battery structure
HV-ES-1000EB3	112S
HV-ES-1000EB4	208S
HV-ES-1000EB5	224S
HV-ES-1000EB6	240S
HV-ES-1500EB3	368S
HV-ES-1500EB4	384S
HV-ES-1500EB5	400S
HV-ES-1500EB1	416S

The frame diagram is as follows:

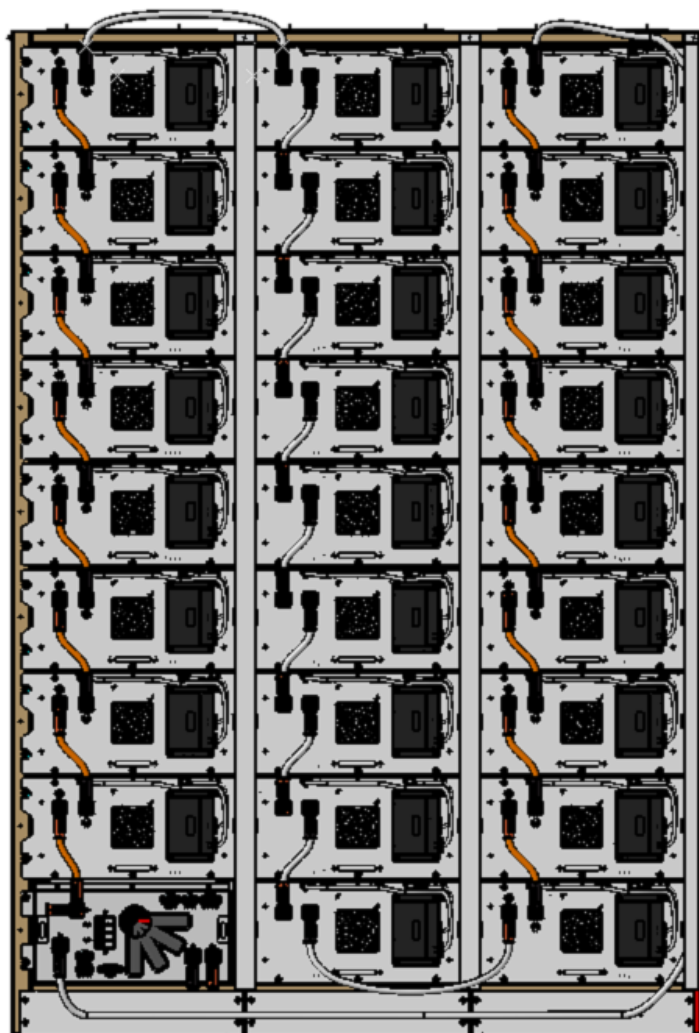
Each battery rack (Unit) has four hundred and sixteen battery cells. Each battery module contains two small modules, each consisting of 16 cells, connected in series by one CCS. Each battery module contains a BMU board. The BMU is used to measure and collect battery parameters and upload the battery voltage and temperature information to the SBCU in the Switch Gear.

The EUT is 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 UL 60730-1 Annex H by TÜV Rheinland.

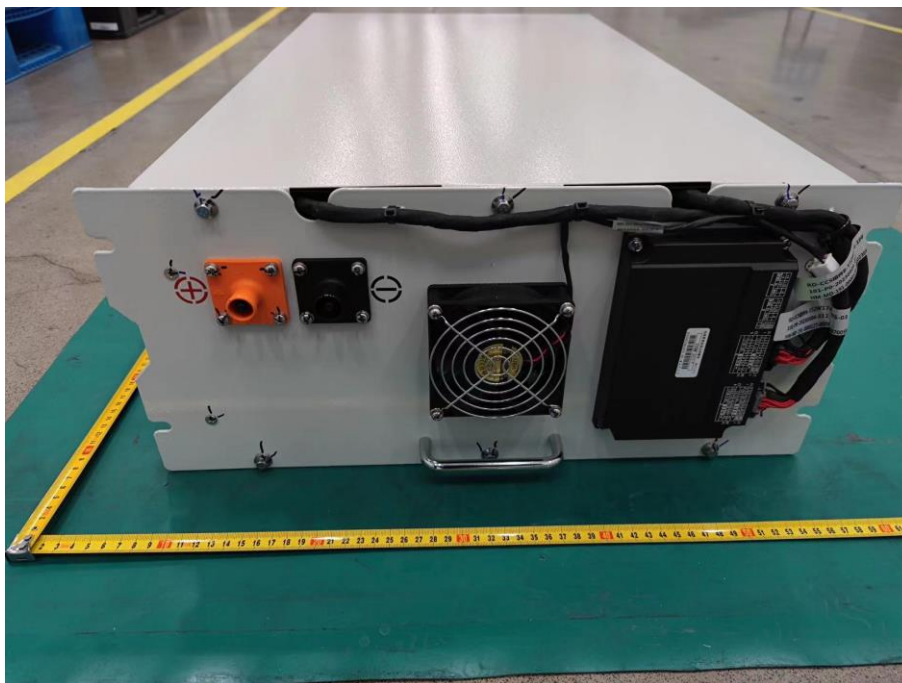


Diagram

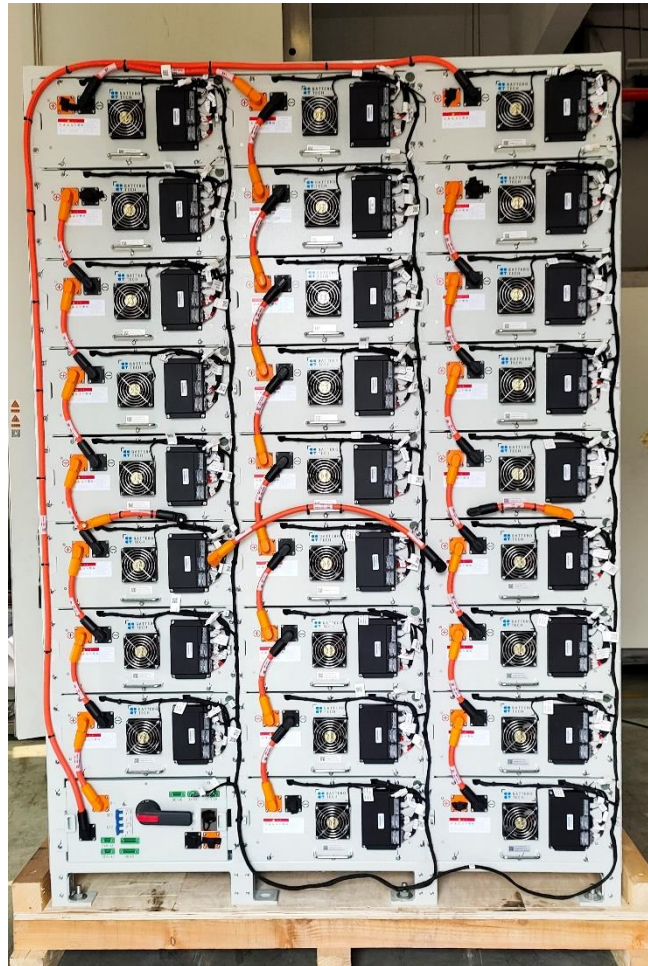


2.4 Photo

Module



Battery Rack



3 Unit level test (section 9 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

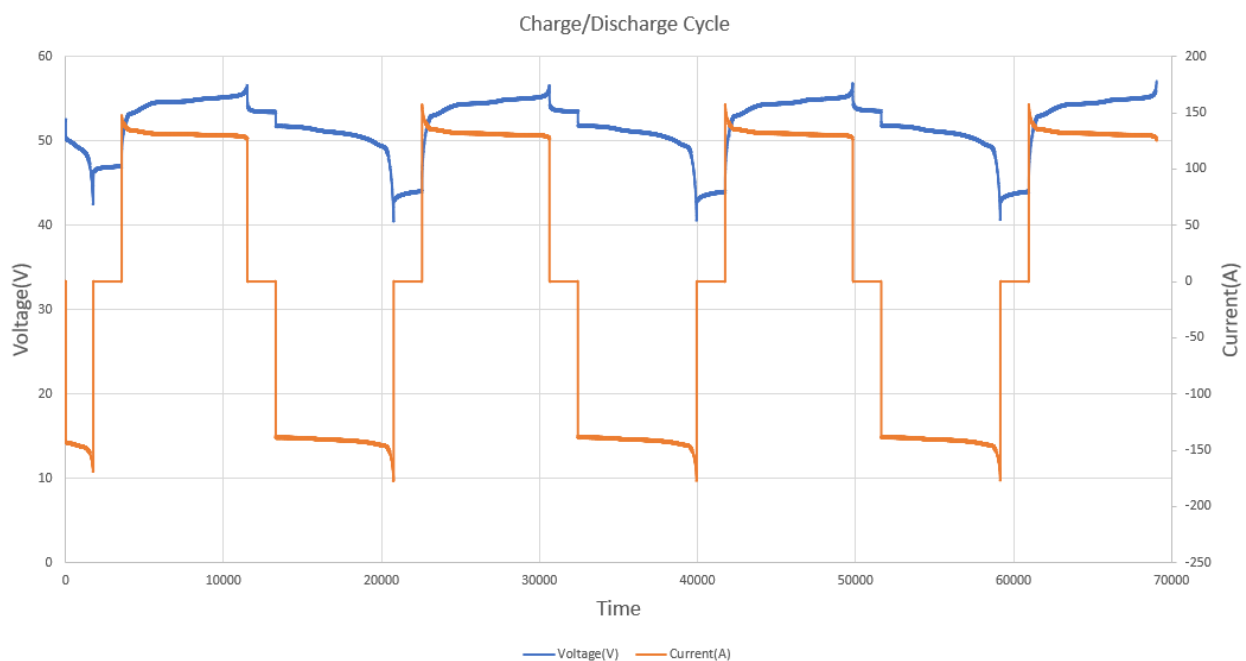
The battery system is constructed with open rack without enclosure. Three columns of the pack were considered as a unit for purposes of the test.

Module sample was conditioned, prior to testing, through charge and discharge cycles of 2 cycles to verify that the module was functional.

Each cycle was defined as a charge to 100% SOC and allowed to rest several minutes and then discharged to an end of discharge voltage (EODV) determined by the manufacturer. Refer to 2.1 for charge and discharge profile.

The module sample was put in a climate chamber during charge and discharge. The ambient is kept at $25^{\circ}\text{C} \pm 2^{\circ}\text{C}$ and $50\% \pm 5\%$ R.H.

Figure 1. Module charge and discharge voltage/current profiles



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

Three 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.

Two racks were used for the purpose of the test. As specified the manufacture, the target racks will be installed beside the initial unit. All racks were positioned facing instrumented wall C. See Figure 2 and photos in page 41.

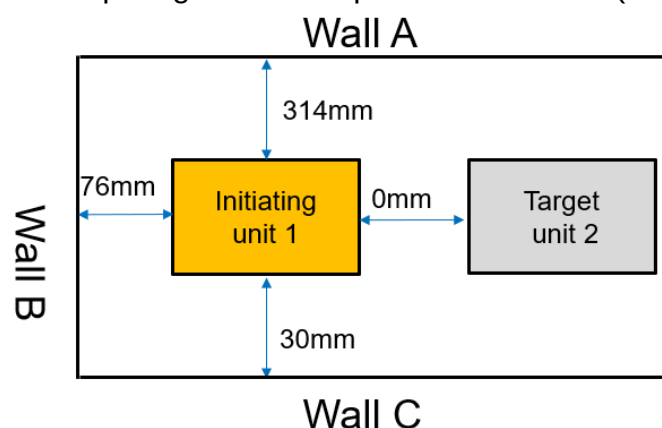
The initiating unit (unit 1) was positioned at the corner, adjacent to the two instrumented wall sections.

Minimum separation distance from the rack to wall and between racks were defined by the client. It is difficult to move the heavy rack to the position just conform to the separation distance provided by the client. There were 1 cm tolerance in actual setup.

Figure 2 was the test site setup diagram with separation distance.

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

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



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

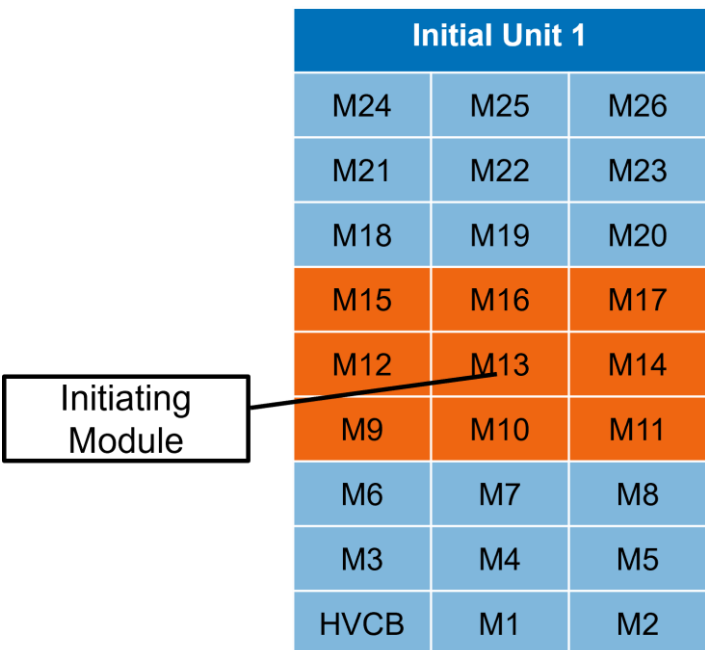
In initial unit, modules numbers from M1 to M26.

In target units, modules numbers from M1 to M26 which was the target unit setting next to the initial module. See Figure 3.

Figure 3. Module numbering in unit

Initial Unit 1		
M24	M25	M26
M21	M22	M23
M18	M19	M20
M15	M16	M17
M12	M13	M14
M9	M10	M11
M6	M7	M8
M3	M4	M5
HVCB	M1	M2

Initiating
Module



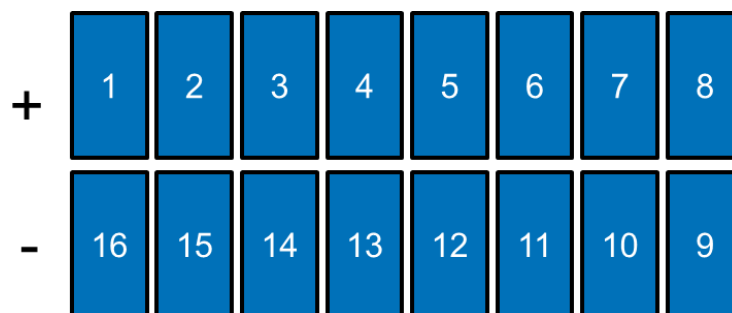
3.3.3 Thermal runaway setup

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

Module M6 was prepared with heater inside. Same as the method in module level test.

Cells inside the module was numbered from 1 to 16 as Figure 4.

Figure 4. Cell numbering, initiating cell selecting.



Consider the unit level installation in the module. #6 ~ #7 cells were chosen as target cell to be forced into thermal runaway.

The cells were heated by one external heater 220V/900 W (size 200*150*1mm).

17 glass fiber thermocouples Type K, 24 AWG were attached on the center of each wide surface of #1-#8 cell, one thermocouple used for heater rise feedback, other thermocouples used for record cell surface temperature. (See 3.3.2 figure 3)

8 glass fiber thermocouples Type K, 24 AWG were attached on the center of each narrow surface of #9 to #16 cells, used for record cell surface temperature. (See 3.3.2 figure 4)

10 glass fiber thermocouples Type K, 24 AWG were attached on the surface of module used for record module external temperature. (See 3.3.2 figure 5)

Auto control the voltage supply to the heater and maintain a 4°C/min to 7°C/min heating rate. Once thermal runaway was observed, the heaters were immediately de-energized.

Voltage of the modules are monitored during test.

The module was placed on top of a lift with the module orientation representative of its intended final installation.

The module was located under the smoke collection hood of the calorimeter measurement system.

Ambient conditions were within 25±5 °C and 50±25% RH at the initiation of the test.

Figure 5. Thermocouples (no. xx) locations of initiating cell

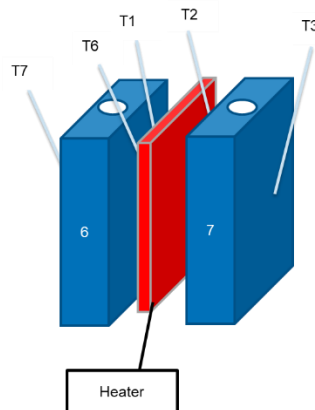


Figure 6. Cell numbering, heater location and thermocouples (no. xx) locations inside the sub-module

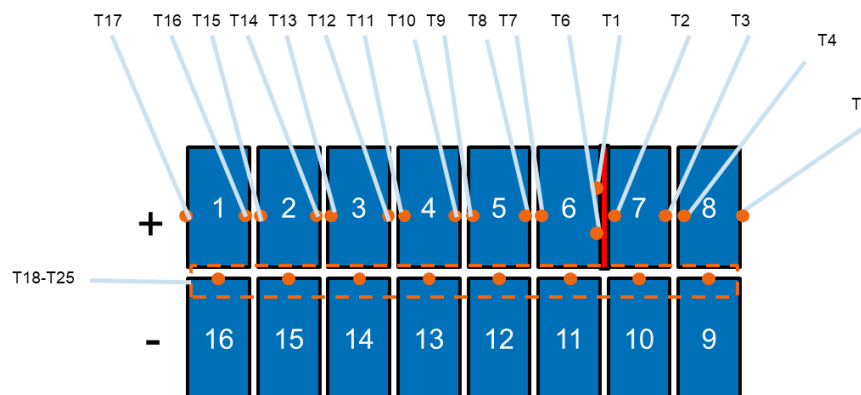
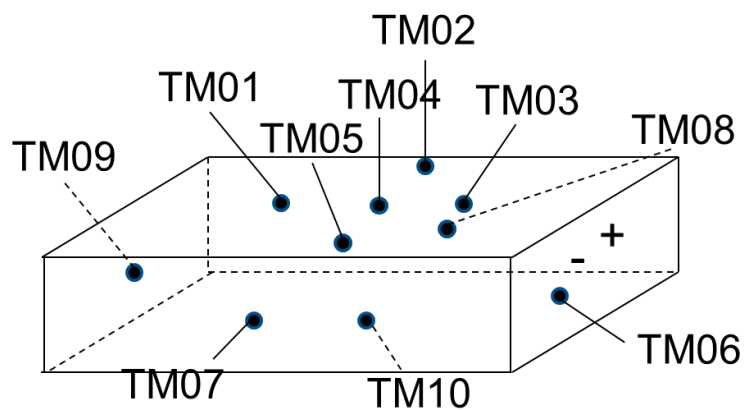


Figure 7. Thermocouple's locations outside module



3.4 Observations and records

Ambient conditions at the initiation of the test..... :	27.9°C, 61.3% R.H.
Sample number :	#2023091101
Open circuit voltage before test (V) :	53.8
Weight before test (kg) :	115.86 (with thermocouples)
Time initiating the test..... :	14:26 start to heat the cells
Observations during test..... :	Audible pops were heard at 15:14 (the pressure relief valve burst). Large amount of white smoke was observed on 15:28. After first audible pop, audible pops were heard on 15:21 and 15:50. Large amount of white smoke was observed on 15:35. No flying debris or explosive discharge of gases during test. No sparks, electrical arcs, or other electrical events during test. No flaming observed.
Posttest evaluation :	Posttest evaluations were performed after 12 hours of test. Total 2 cells were damage after test. Including 1 thermal runaway cell and another 1 was cell-to-cell thermal propagation. Photos "sample after test" in page 43 show the damage of the module enclosure, electrolyte outside and damage of the components inside enclosure. 46.9V was measured on the module output terminal.
Weight after test (kg) :	113.44 (with thermocouples)
Weight loss (kg)..... :	2.42

3.5 Temperature measurements

3.5.1 Temperature measurement of initiating cells

Cell to cell propagation was observed during the test.

Wide surface temperature of #1~#16 cells in initial module were recorded during test.

Cell thermal runaway occurred on #7 cell at around 15:28, Maximum temperature 493.4°C (T3) were measured on the #7 cell wide surface. See figure 6 for the temperature vs time curve. Maximum temperature please see table 1 for detail.

Cell to cell propagation was observed on #8 cell in initial module during the test.

Figure 8. Temperatures of cell #1~#8

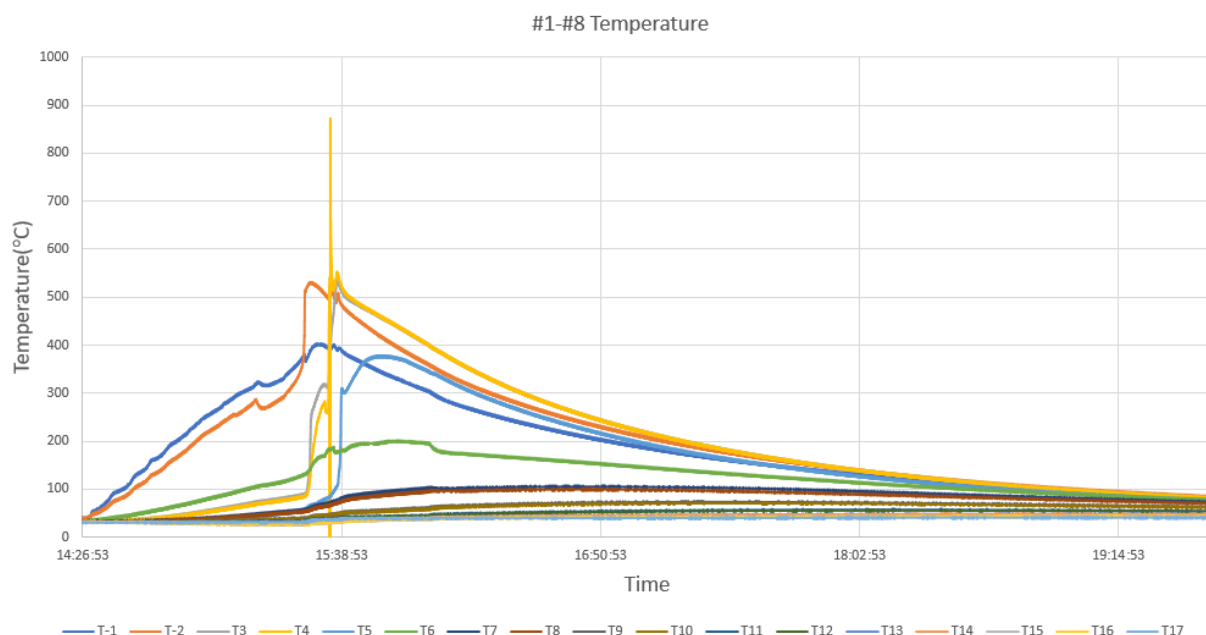


Table 1. Maximum temperature of cell #1~#8

Thermocouple no.	Location	Maximum temp.(°C)
T1	Surface of cell_6 under heater (right)	402
T2	Surface of cell_7 under heater (left)	529.8
T3	Surface of cell_7 (right)	537.9
T4	Surface of cell_8(left)	872.1
T5	Surface of cell_8(right)	376.8
T6	Surface of cell_6(right)	199.8
T7	Surface of cell_6(left)	105
T8	Surface of cell_5(right)	99.4
T9	Surface of cell_5(left)	73.2
T10	Surface of cell_4(right)	70.3
T11	Surface of cell_4(left)	56.9

T12	Surface of cell_3(right)	55.4
T13	Surface of cell_3(left)	48
T14	Surface of cell_2(right)	47.9
T15	Surface of cell_2(left)	43.6
T16	Surface of cell_1(right)	43.4
T17	Surface of cell_1(left)	40.6

Figure 9. Temperatures of cell #9~#16 cells

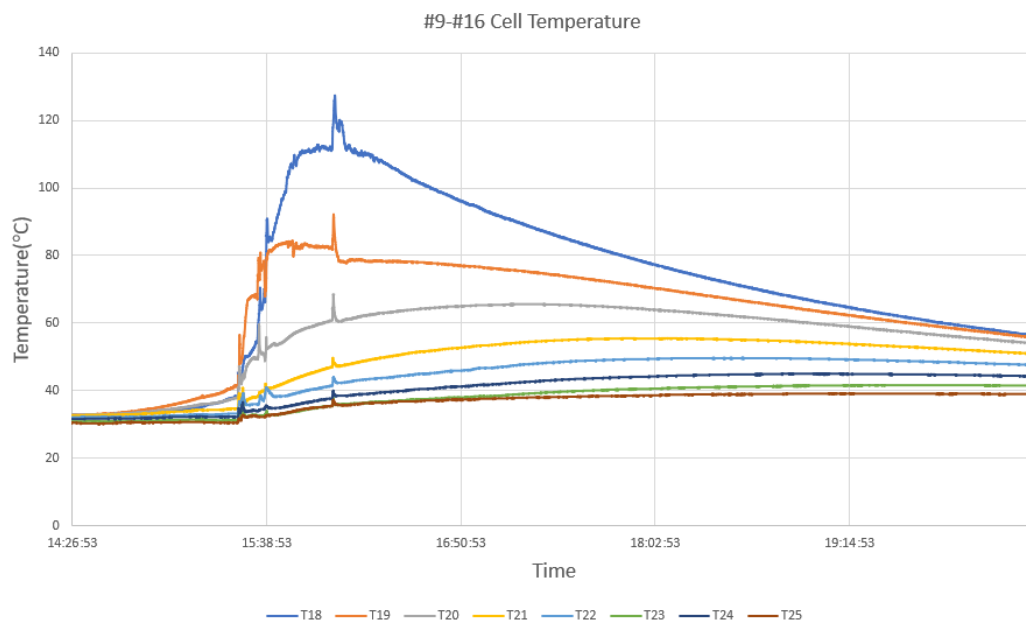


Table 2. Maximum temperature of cell #9~#16

Thermocouple no.	Location	Maximum temp.(°C)
T18	Surface of cell_9(side)	127.4
T19	Surface of cell_10(side)	92.2
T20	Surface of cell_11(side)	68.5
T21	Surface of cell_12(side)	55.5
T22	Surface of cell_13(side)	49.7
T23	Surface of cell_14(side)	41.6
T24	Surface of cell_15(side)	45
T25	Surface of cell_16(side)	39.2

Figure 10. Module voltage

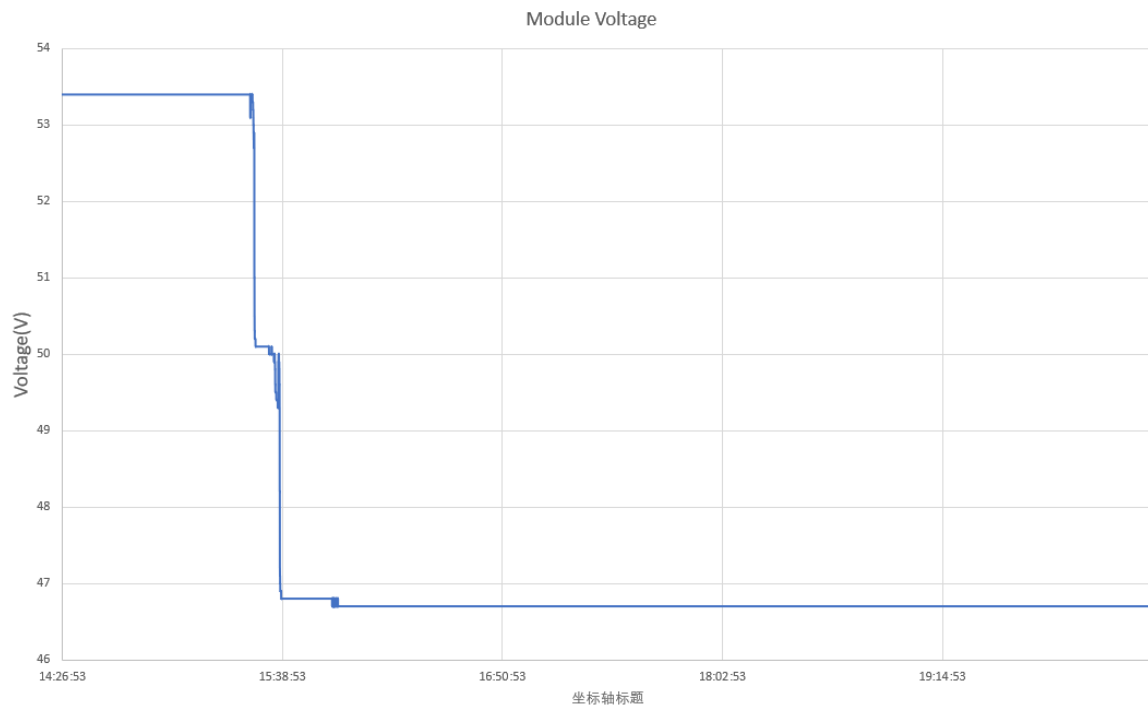
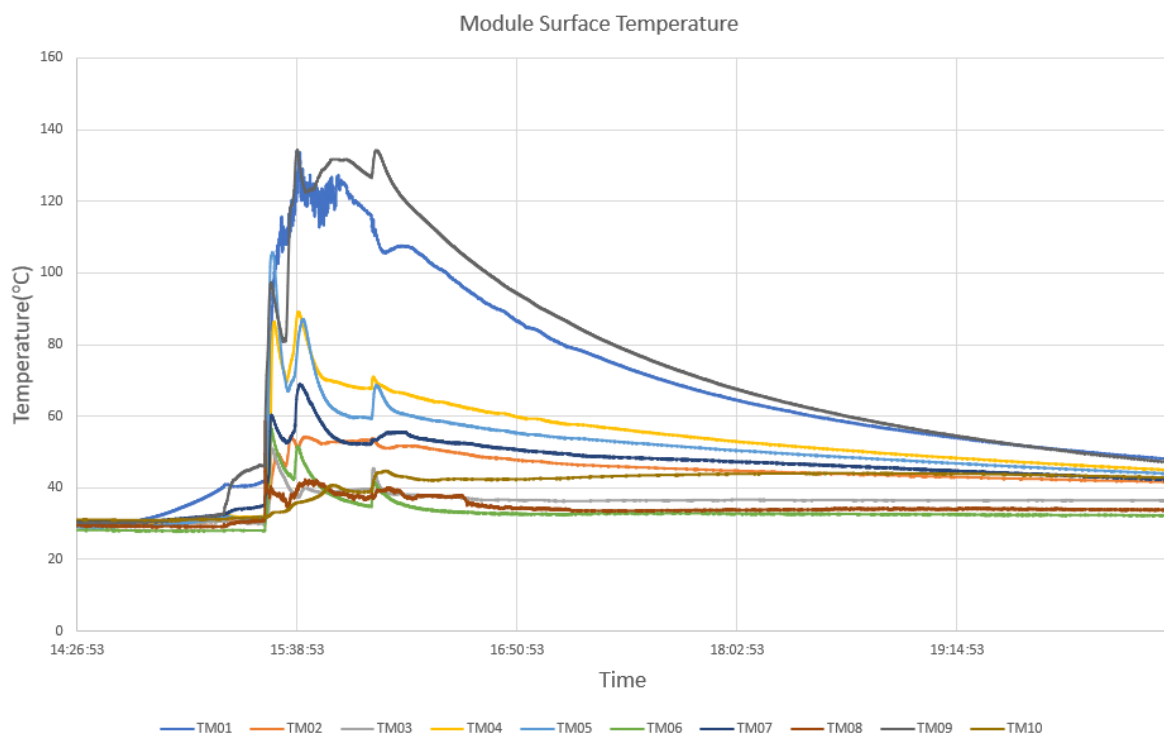


Figure 11. Temperatures of module surface



3.5.2 Temperature measurement of units

26 glass fiber insulated thermocouples, Type K, 24 AWG were attached on the center of the top, bottom, or side surface of modules M1 to M26 in initial unit.

9 glass fiber insulated thermocouples, Type K, 24 AWG were attached on the center of side or front surface of modules in target unit 2.

In initial unit 1, the maximum temperature 68.6°C was measured on the top surface of the module M13.

In target unit 2, the maximum temperature 31.2°C was measured on the right surface of the module M23.

Figure 12. Thermocouple location on modules in initial unit 1

Initial Unit 1		
M24	M25	M26
M21	M22	M23
M18	M19	M20
M15	M16	M17
M12	M13	M14
M9	M10	M11
M6	M7	M8
M3	M4	M5
HVCB	M1	M2

T1-1 ~ T1-26, center of modules surface facing M13

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

Figure 13. Surface temperatures of modules in initial unit 1 (refer to Figure12)

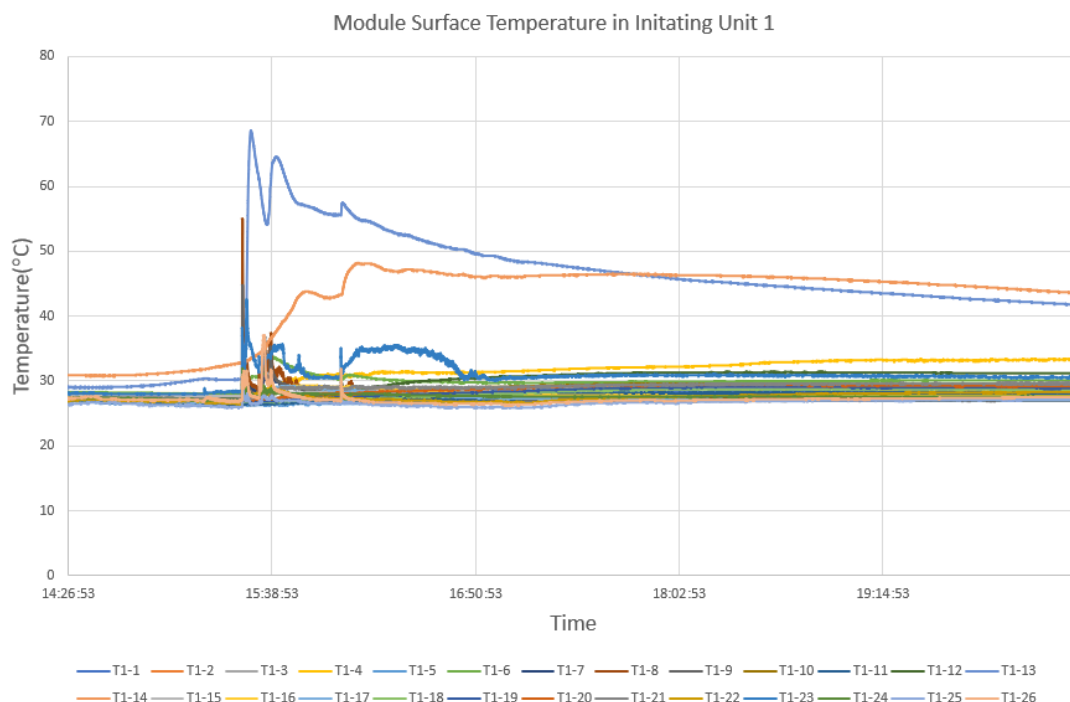


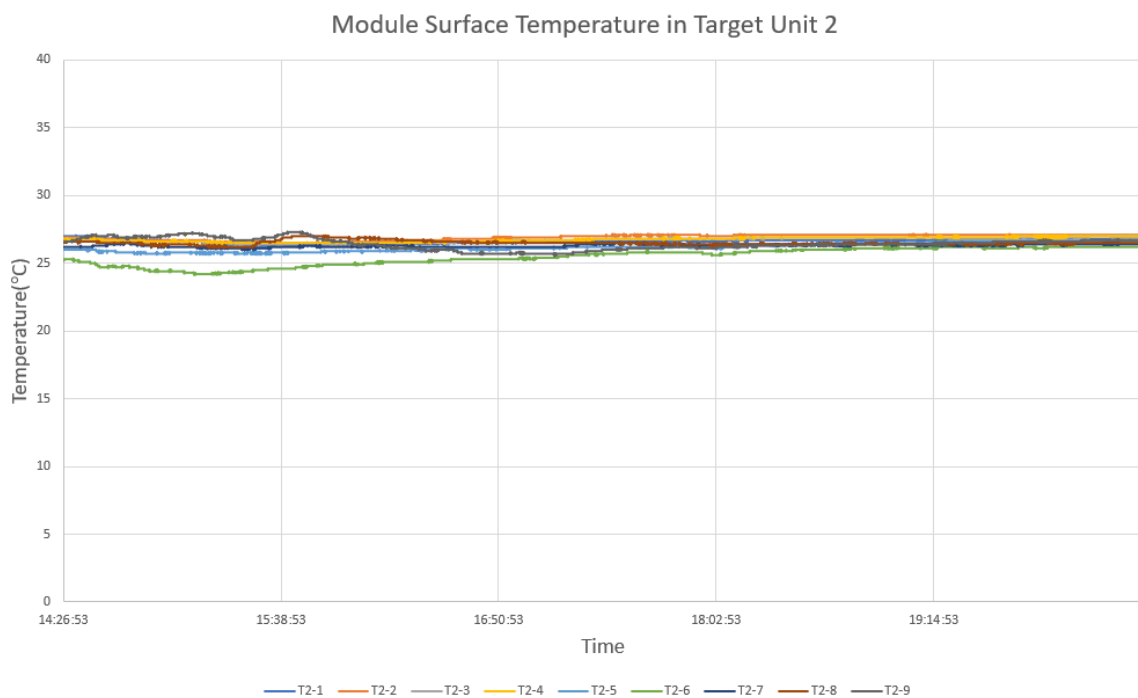
Figure 14. Thermocouple location on modules in target unit 2

Target Unit 2		
M24	M25	M26
M21	M22	M23
M18	M19	M20
M15	M16	M17
M12	M13	M14
M9	M10	M11
M6	M7	M8
M3	M4	M5
BMS	M1	M2

T2-1~T2-9, center of modules surface facing unit 1

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

Figure 15. Surface temperatures of modules in target unit 2 (refer to Figure 14)



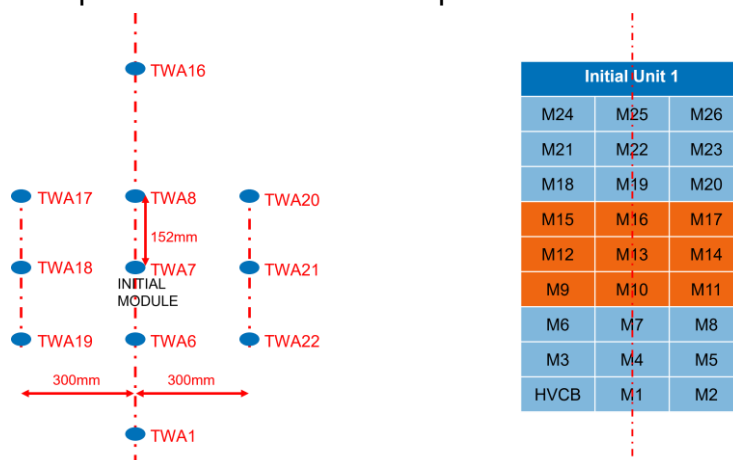
3.5.3 Temperature measurement of instrumented walls

Wall surface temperatures were measured in vertical array at 152 mm intervals for the full height of the instrumented wall sections. The thermocouples array was collinear with the centre line of unit 1. The red line shows the thermocouple array on the wall.

The first thermocouple starts from 152 mm from ground. Total 16 thermocouples were used for each array. The thermocouples were numbered from low to high as TWA1 to TWA16 for wall A, TWB1 to TWB16 for wall B and TWC1 to TWC16 for wall C.

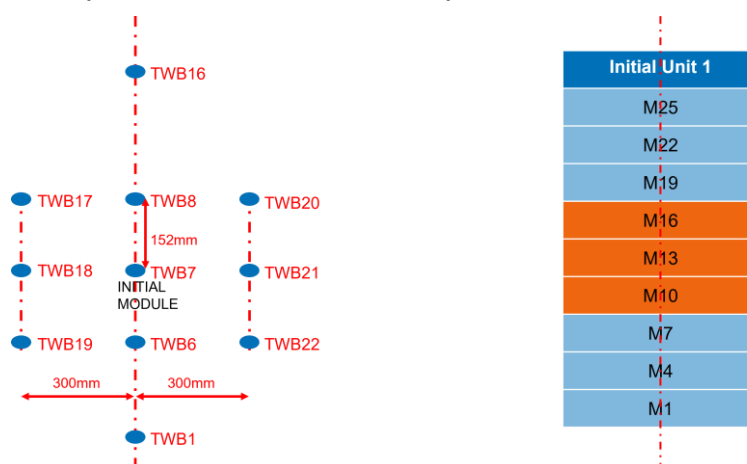
Additional 6 thermocouples were positioned horizontally near the initial module M6 300 mm away from the vertical array each side, on instrumented wall A, B and C.

Figure 16. Vertical position of the thermocouples on the wall A



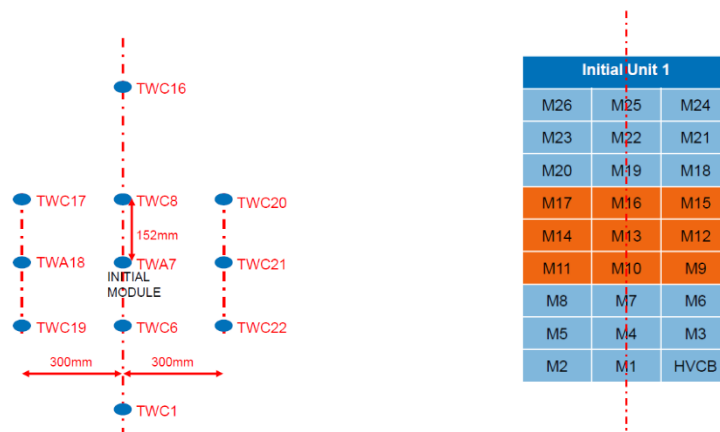
View direction: towards instrument wall A with reference to Figure 2

Figure 17. Vertical position of the thermocouples on the wall B



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

Figure 18. Vertical position of the thermocouples on the wall C



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

Maximum temperature measured on instrument wall A was 27.7°C at TWA9, temperature curve see figure 19 for detail.

Maximum temperature measured on instrument wall B was 27.4°C at TWB16, temperature curve see figure 20 for detail.

Maximum temperature measured on instrument wall C was 47.3°C at TWC7, temperature curve see figure 21 for detail.

Figure 19. Temperatures on instrument wall A.

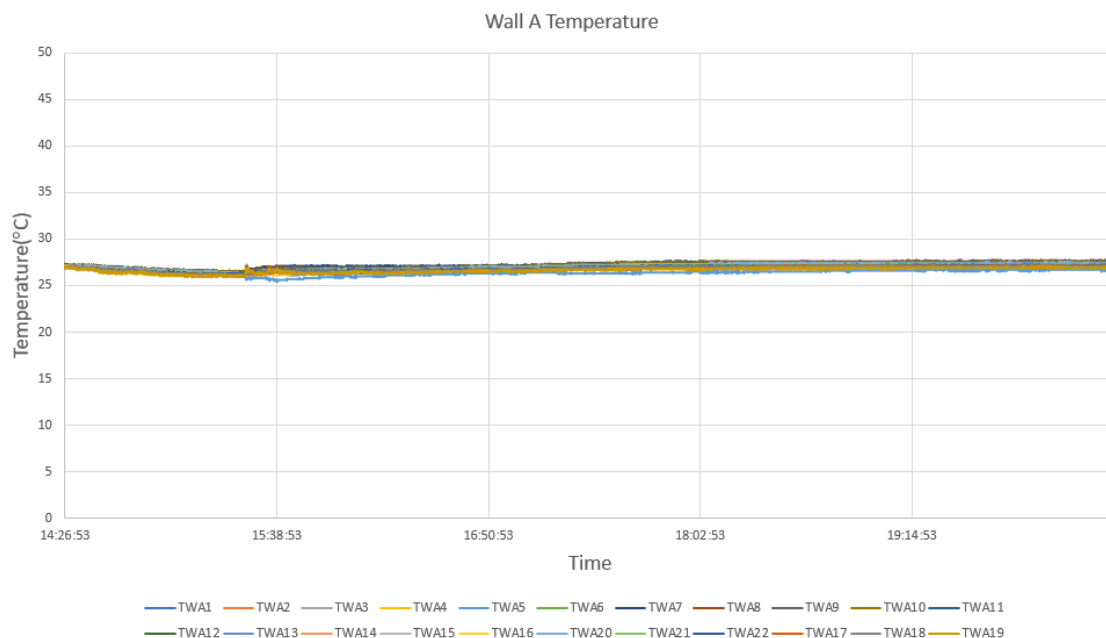


Figure 20. Temperatures on instrument wall B.

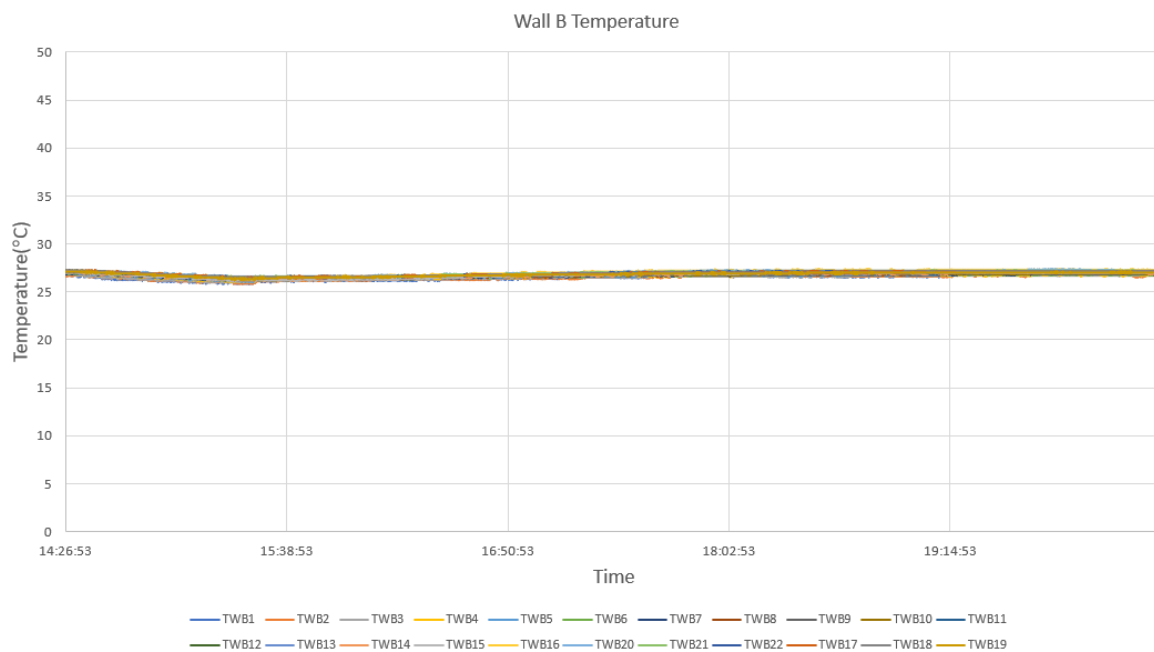
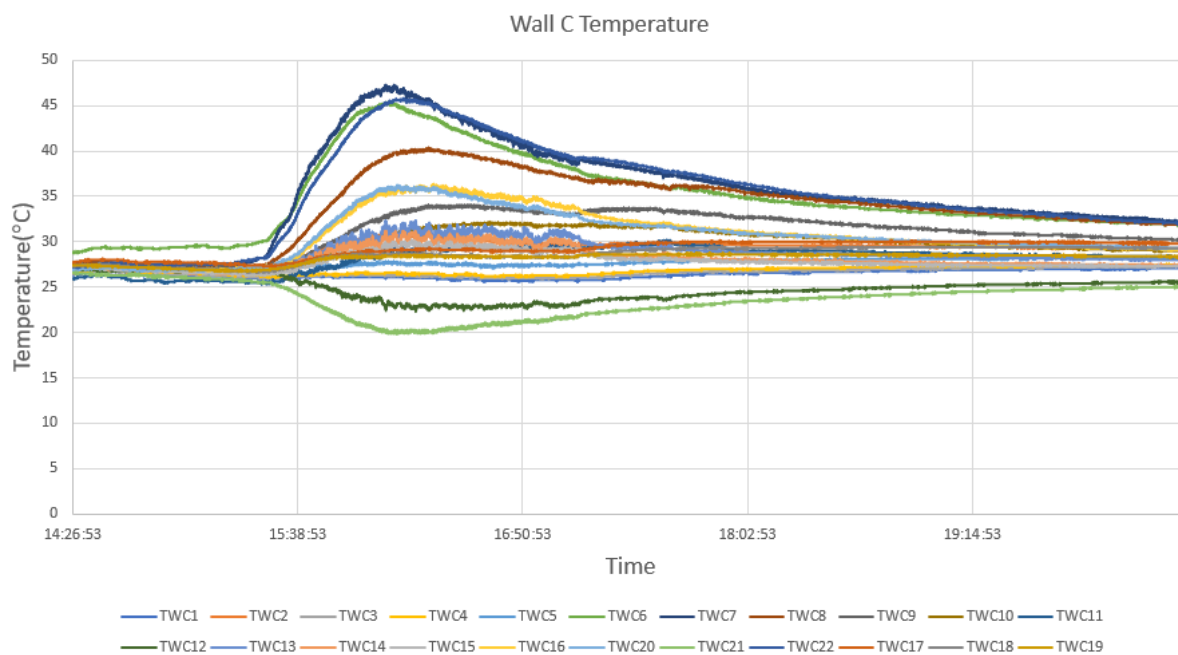


Figure 21. Temperatures on instrument wall C.



3.6 Heat flux measurement

8 sensors were placed on the surface of unit, instrumented wall A, wall B and wall C. Two sensors were placed on the surface of each instrumented wall and adjacent unit 2 that faces the initiating unit.

The sensors were collinear with the vertical thermocouple array. One was positioned at the height equivalent to module M13 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 M10 top edge, which was estimated to receive the greatest surface heat flux due to the thermal runaway of the initiating unit.

Figure 22. Heat flux sensor locations on instrument wall

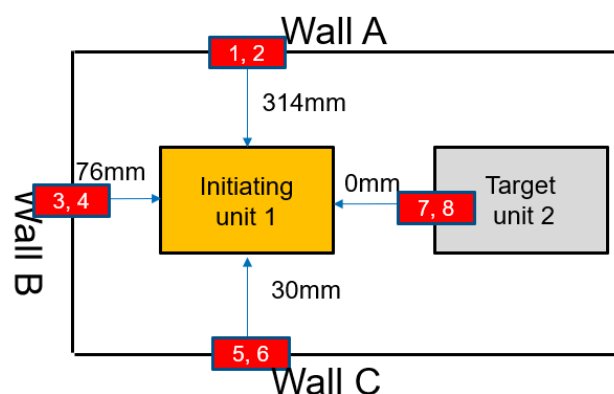
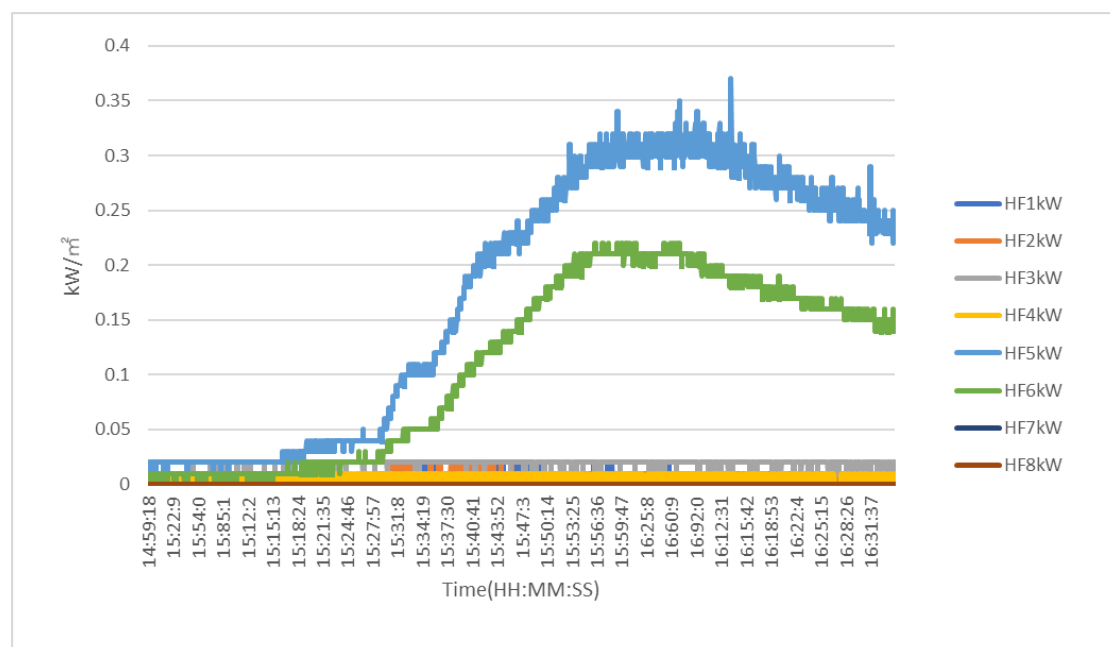


Figure 23. Measured heat flux of target wall and units



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:

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

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:

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

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

X_{CO_2} = Measured mole fraction of CO₂ in exhaust flow (non-dimensional)

$X_{CO_2}^o$ = Measured mole fraction of CO₂ in incoming air (non-dimensional)

$X_{H_2O}^o$ = Measured mole fraction of H₂O in incoming air (non-dimensional)

X_{O_2} = Measured mole fraction of O₂ in exhaust flow (non-dimensional)

$X_{O_2}^o$ = Measured mole fraction of O₂ 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

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

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

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)

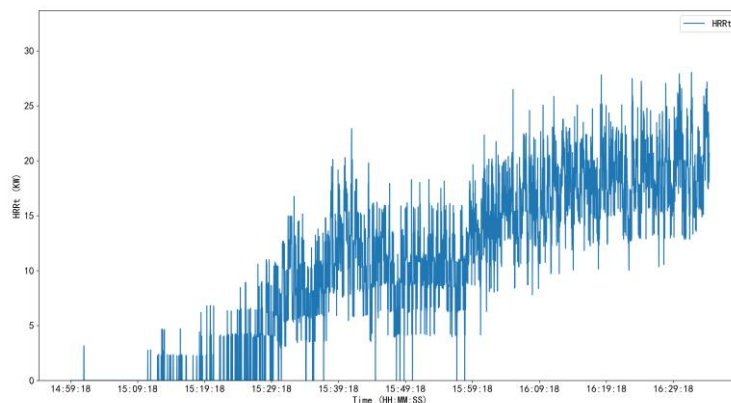
k_c = Velocity profile shape factor (non-dimensional)

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

The whole 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.

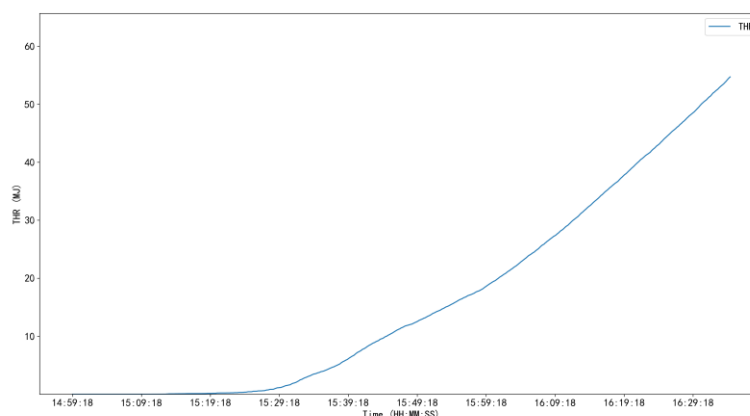
Measured peak chemical heat release rate HRR_t was 28.04 kW

Figure 24. HRR_t curve



Measured total heat release THR through the test was 54.712 MJ

Figure 25. THR curve



3.8 Convective heat release rate measurement

The convective heat release rate were 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 (m²)

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/m³)

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

T = The thermopile temperature (K)

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

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

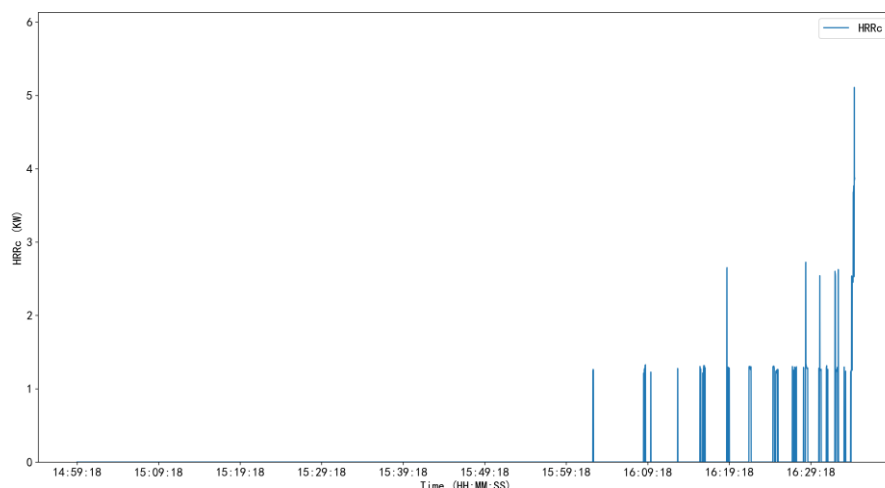
$$A_0 = 0.9950$$

$$A_1 = -5.29933E-05$$

$$A_2 = 3.21022E-07$$

$$A_3 = -1.22004E-10$$

Figure 26. HRRc curve



3.9 Smoke release rate measurement

The light transmission in the calorimeter's exhaust duct was measured using a white light source and photo detector for the duration of the test.

The smoke release rate was calculated as follows:

$$SRR = 2.303 \left(\frac{V}{D} \right) \log_{10} \left(\frac{I_o}{I} \right)$$

Where:

SRR = Smoke release rate (m^2/s)

V = Volumetric exhaust duct flow rate (m^3/s)

D = duct diameter (m)

I_o = Light transmission signal of clear (pre-test) beam (V)

I = Light transmission signal during test (V)

The whole smoke release rate measurement system was self-checked using calibrated light filter before the test. The self-check was performed at 100%, 79%, 50%, 32%, 16%, 10%, 1% and 0% light transmittance.

Figure 27. Peak smoke release rate SRR: 1.9936 m^2/s

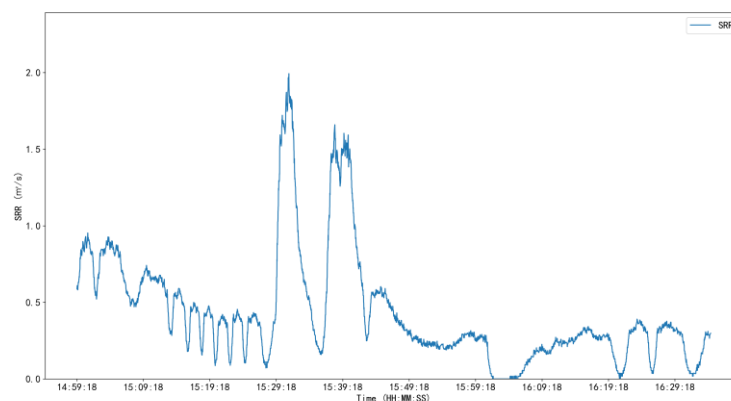
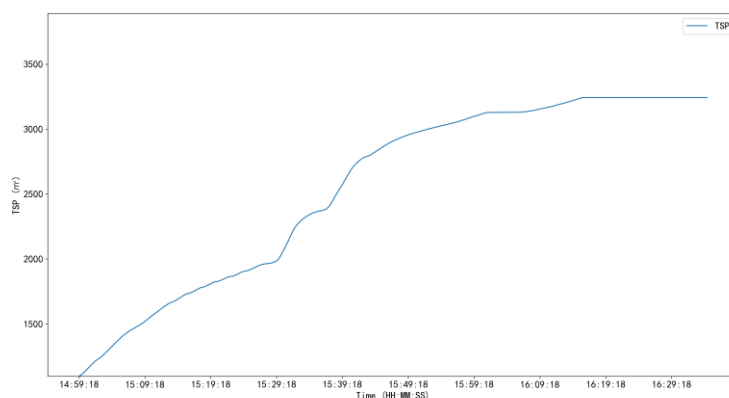


Figure 28. Total smoke release TSR: 3242.94 m^2



3.10 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 palladium nickel thin film solid state sensor.

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 (14:26 ~ 16:55) were presented in below table.

Total cumulative volume of gases before cell venting (14:26 ~ 15:14) were also presented in table for reference. Which may be considered as ambient gases background before test.

Gas type	Gas components		Total volume of gas (L)	
			Before cell venting	Throughout the test
Hydrocarbon species	Methane	CH ₄	0.00	67.2
	Ethylene	C ₂ H ₄	0.00	21.8
	Ethane	C ₂ H ₆	0.00	6.6
	Propylene	C ₃ H ₆	0.00	50.8
Others	Carbon Monoxide	CO	0.00	57.4
	Carbon Dioxide ²⁾	CO ₂	1.10	43.6
	Hydrogen ³⁾	H ₂	0.00	225.6
Total Hydrocarbons (equivalent to C ₃ H ₈ , measured by FID)				49.98

Note:

1) The collection time is from 14:26 to 16:55;

2) The carbon dioxide in the air during this period¹⁾ was not counted;

3) The Hydrogen was measured by palladium nickel thin film solid state 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 standard volume flow rate of gas ventilated in below figures.

Figure 29. Hydrocarbon species

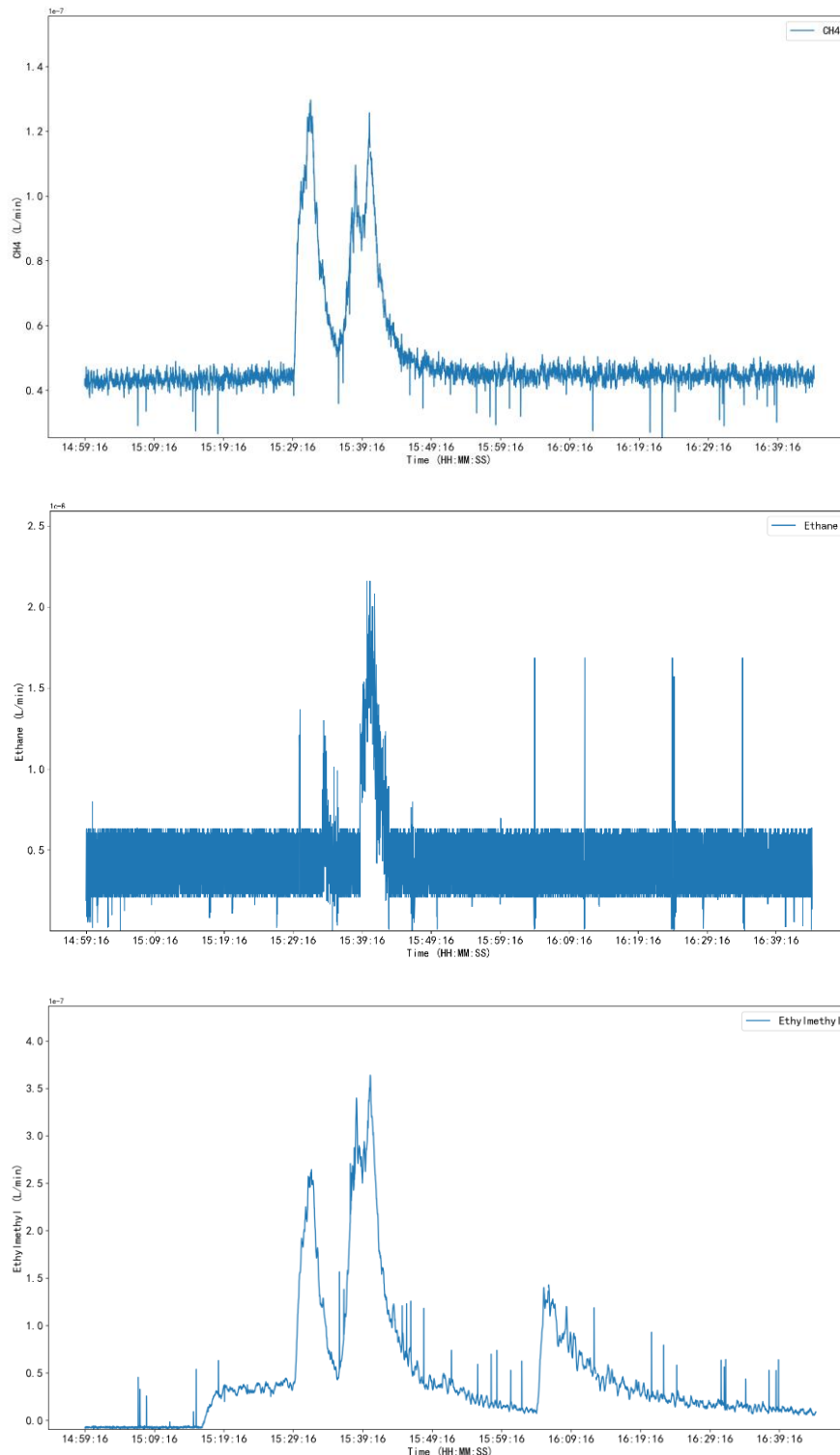


Figure 30. CO, CO₂ containing species

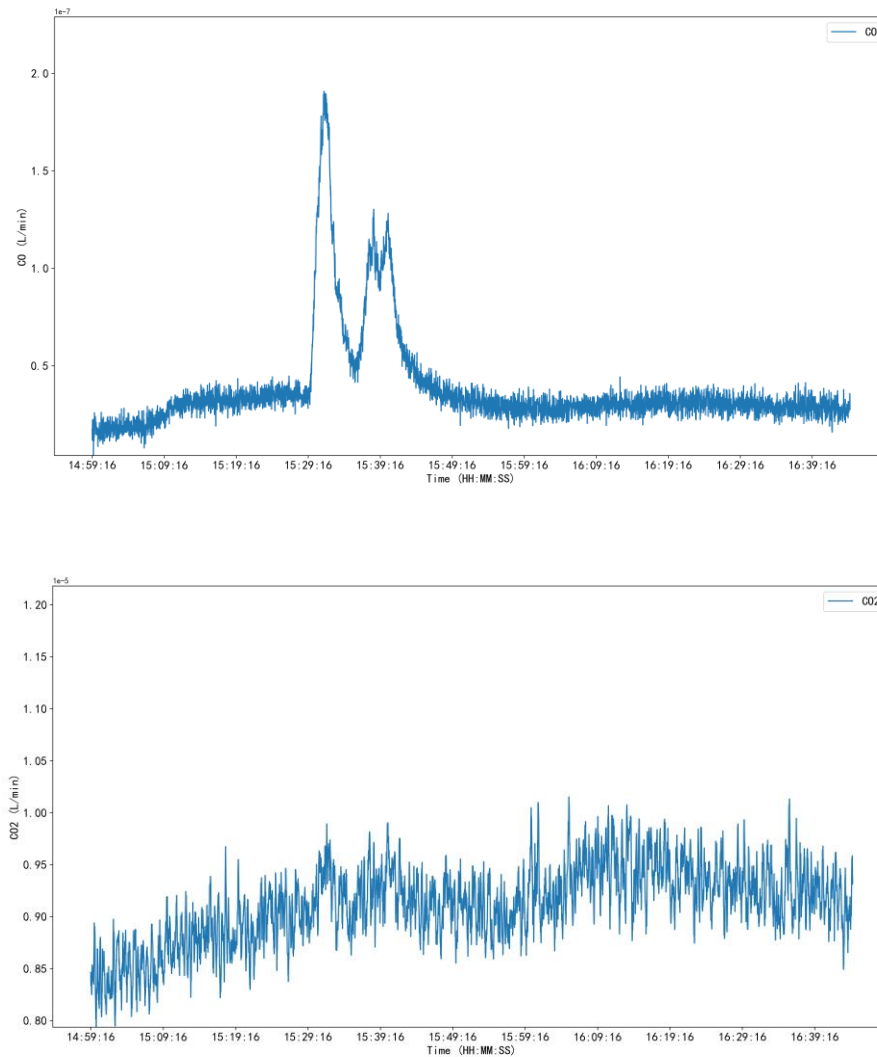
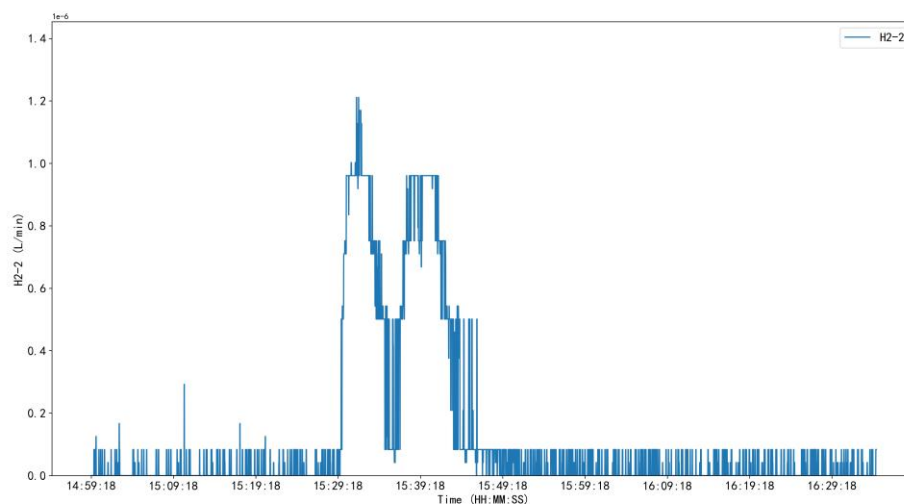


Figure 31. H₂ containing species



3.11 Photos

Initiating module



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Test setup



Smoke release during test



Photos after test

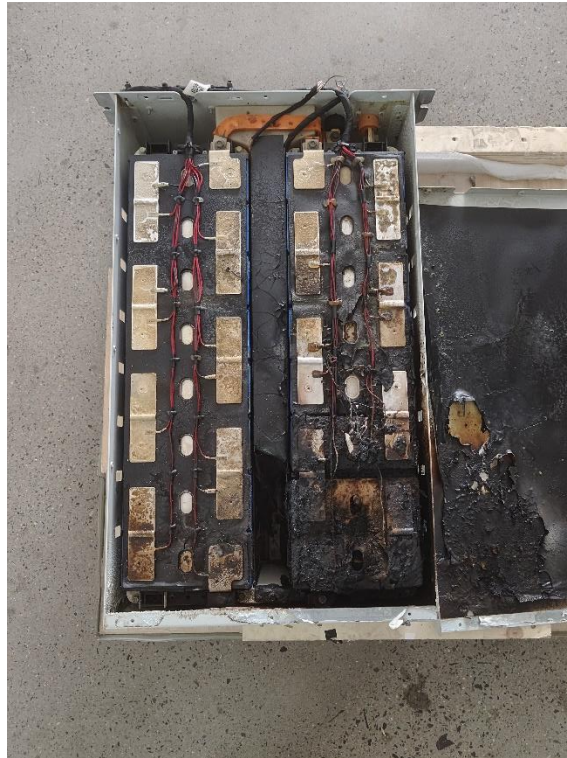


Initiating module after test



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4 List of Test and Measurement Instruments

No.	Equipment	Model	Rating	Inventory no.	Cal. expire date
1	Ambient temperature and humidity	HWP01-10S	-30°C~50°C, 20%RH~100%RH	12005577	2024.2.2
2	Data acquisition equipment	DAQ970A	3-slot cardcage with 6½ digit (22 bit) internal DMM 0.004%, accuracy 0.06% Vac	TY2020000138	2024.2.2
3	Data acquisition equipment	TP700	Measuring range-60 °C to 1372 °C Measurement accuracy ± (0.05% rdg.+0.5 °C) Display resolution0.01 °C	TY2211000716-2	2024.2.2
4	Data acquisition equipment	TP700	Measuring range-60 °C to 1372 °C Measurement accuracy ± (0.05% rdg.+0.5 °C) Display resolution0.01 °C	TY2020000217	2024.2.2
5	Electronic scale	CHAOOU C1	0-500KG	65960494169	2024.2.2
6	Paramagnetic oxygen analyser	SERVOME X4100	O2: paramagnetic sensor, range 0-25%, accuracy 0.02%, response time T90 < 7S	ZY2020000018-1	2024.2.6
7	Velocity probe	2671-25L-D-11-G2-E-N	4-20mA output, range 0-250pa, accuracy ± 1% F.S	ZY2020000018-2	2024.2.6
8	Photo detector	PDA36A2	Thorlabs optical receiver, wavelength range (350-1000) nm, gain adjustable, voltage output (0-10) V, instability < 0.1%	ZY2020000018-3	2024.2.2
9	Fourier-Transform Infrared Spectrometer	atmosFIR	Spectral scanning range: 485 - 7500cm ⁻¹ ; Spectral repeatability: < 0.1cm ⁻¹	ZY2020000018-5	2024.3.9

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10	Non-dispersive infrared carbon dioxide and carbon monoxide sensor	SERVOME X4100	CO2: infrared sensor, measuring range 0-10%, accuracy 1% F.S, response time T90 < 7S Co: infrared sensor, measuring range 0-1%, accuracy 1% F.S, response time T90 < 8s	ZY20200000 18-4	2024.2.6
11	Palladium-nickel thin-film solid state sensor	MODEL 2000	Range: 0-2000ppm, temperature less than 100 C, -90~110kPa	ZY20210002 10	2024.2.2
12	Flame ionization detector	3010	Accuracy: 2.0%	19937	2024.3.9
13	Heat flux measurement equipment	MW88-JTC08C	0 ~ ± 99999 w / m2, - 250 ~ 980 °C, accuracy 5%, response time less than 0.1s,	ZY20200000 10	2024.2.2
14	Thermopile	RS-WD-HW-1	0-200 °C, 4-20mA, response speed < 0.15s	2834814194 2	2024.2.2

End of Test Report