Prüfbericht-Nr.: *Test report no.:*	**CN24X4U9 001**	**Auftrags-Nr.:** *Order no.:*	**244570016**	
Kunden-Referenz-Nr.: *Client reference no.:*	**2003666**	**Auftragsdatum:** *Order date:*	2024-04-01	
Auftraggeber: *Client:*	Sungrow Power Supply Co., Ltd. No.1699 Xiyou Rd.,New & High Technology Industrial Development Zone, Hefei, 230088 Anhui, P.R. China			
Prüfgegenstand: *Test item:*	Outdoor Liquid Cooling Energy Storage Cabinet			
Bezeichnung / Typ-Nr.: *Identification / Type no.:*	R0229BL-AHAA, R0215BL-AHAA			
Auftrags-Inhalt: *Order content:*	Test report			
Prüfgrundlage: *Test specification:*	UL 9540A: 2019 (Fourth Edition) Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems			

Wareneingangsdatum: *Date of sample receipt:*	2024-03-26	
Prüfmuster-Nr.: *Test sample no:*	#2024032601	
Prüfzeitraum: *Testing period:*	2024-03-27 - 2024-04-12	
Ort der Prüfung: *Place of testing:*	See clause 1.1 of main report	
Prüflaboratorium: *Testing laboratory:*	TÜV Rheinland (Shanghai) Co., Ltd.	
Prüfergebnis*: *Test result*:*	See main report	

geprüft von: *tested by:*	[redacted]	**genehmigt von:** *authorized by:*	
Datum: *Date:* 2024.06.21		**Ausstellungsdatum:** *Issue date:* 2024.06.21	Bowen Dong
Stellung / *Position:*	**Project Engineer/Trainee**	**Stellung** / *Position:*	**Expert**

Sonstiges / *Other:*

Zustand des Prüfgegenstandes bei Anlieferung: *Condition of the test item at delivery:*	Prüfmuster vollständig und unbeschädigt *Test item complete and undamaged*

* 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.
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.

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.

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: 2024.03.27 ~ 2024.04.12

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 place in the module to initiating the thermal runaway inside 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 397.5 kg (before test) and 392.5 kg (after test).

Peak Chemical HRR(kW): No flaming observed;

Peak Convective HRR(kW): No flaming observed;

Total Heat Release: No flaming observed;

Measured peak smoke release rate SRR was 0.25 m^2/s;

Total smoke release TSR was 166.58 m^2;

Total hydrocarbons was 169.47 L (equivalent to C_3H_8, measured by FID);

Detail information see relevant clause of this report.

1.5 List of attachments

Video records of the test from 2 direction was provided in .mp4 format.

Complete records were provided in document, file number listed as below:

20240327 Sungrow unit UL9540A video ch01.mp4

20240327 Sungrow unit UL9540A video ch02.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

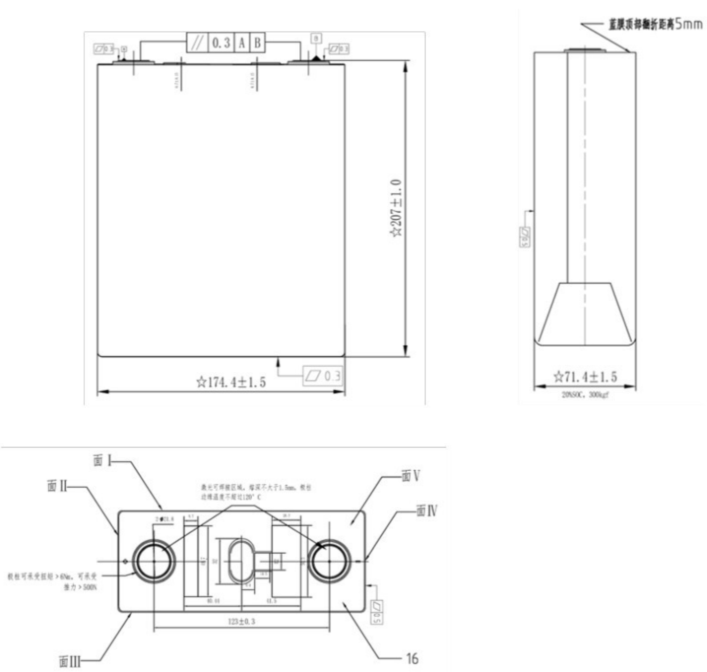
2.1 Cell

2.1.1 Product information and parameters

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

Manufacturer ....:	CALB Co., Ltd.	
Model number............................:	L173F280A	
Chemistry ....:	$LiFePO_4$	
Physical configuration................:	Prismatic	
	Weight:	5.350±160 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
Standard discharge method.......:	Discharge current:	280 A
	End of discharge voltage:	2.5 V

Diagram with overall dimension



2.1.2 Cell level test information

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

Thermal Runaway Methodology .... :	Two pieces 203.0 mm by 152.4 mm film heater for each sample
Average Cell Surface Temperature at Gas Venting .... :	172°C
Average Cell Surface Temperature at Thermal Runaway....................................... :	245°C

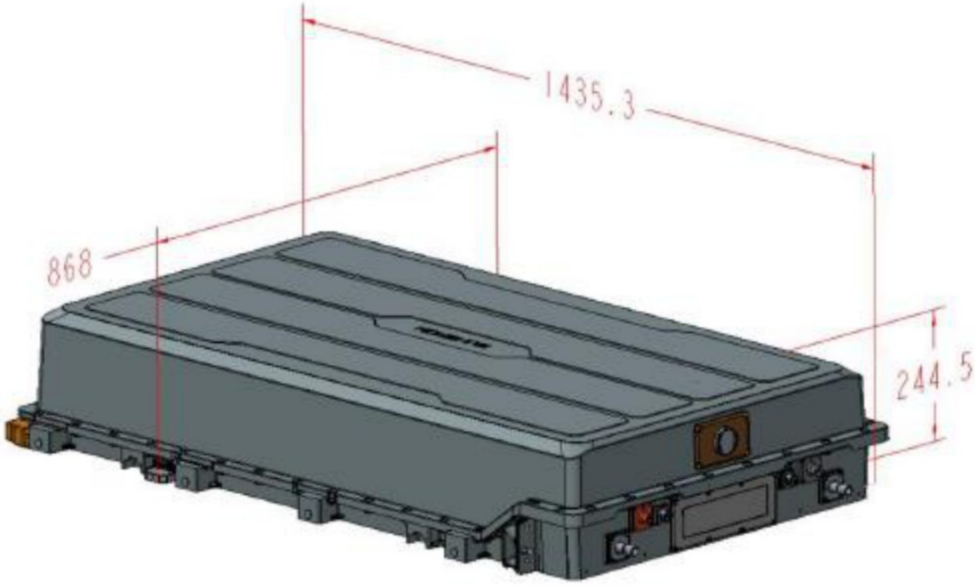
2.2 Module

2.2.1 Product information and parameters

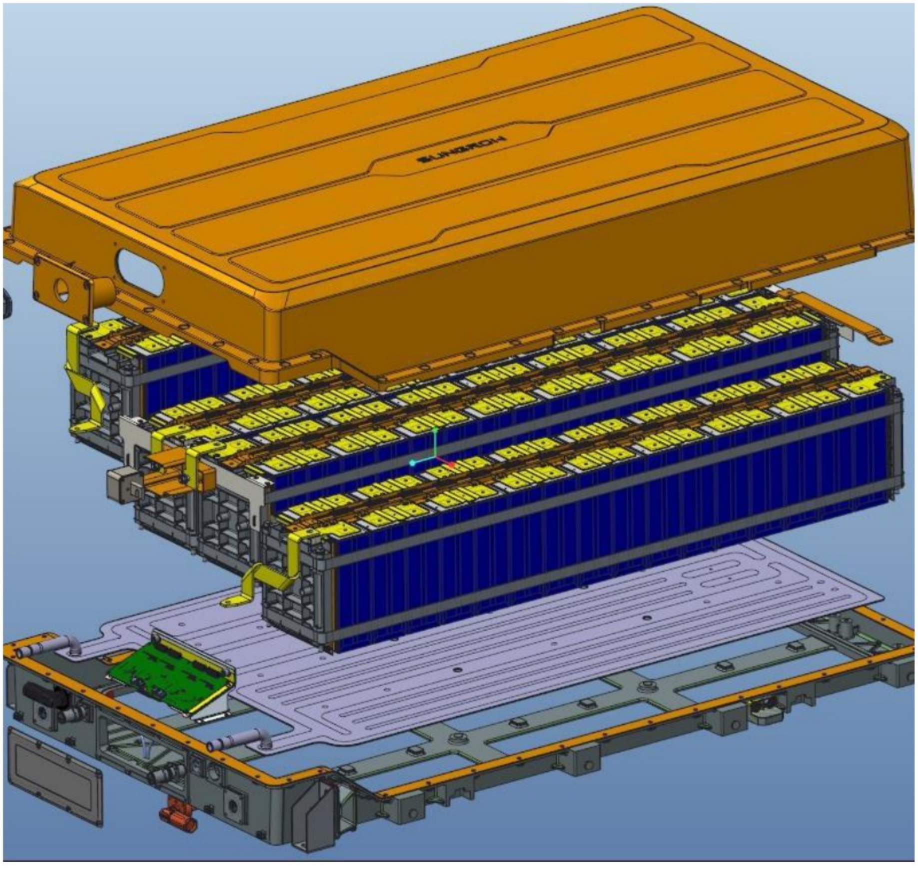
The product information and parameters are provided by the client as below.

Manufacturer name...........................:		SUNGROW ENERGY STORAGE TECHNOLOGY CO., LTD.
Model number...................................:		P573AL-181, P573BL-181
Physical configuration.......................:		Metal enclosure with plastic cover
		Weight: 400±12 kg
		Cells in series/parallel: 64 in series
Cooling method.................................:		Liquid cooling
Separation between cells..................:		0.45 mm separation between cells by air
Electrical rating ....:		Rated capacity: 280 Ah
		Nominal voltage: 204.8 V
Standard charge method.........:	Charge current:	140 A
	End of charge voltage:	233.6 V
Standard discharge method.........:	Discharge current:	140 A
	End of discharge voltage:	172.8 V
Compliance with UL 1973.................:		Yes, certification No. CU 72239863 01

2.2.2 Diagram with overall dimension

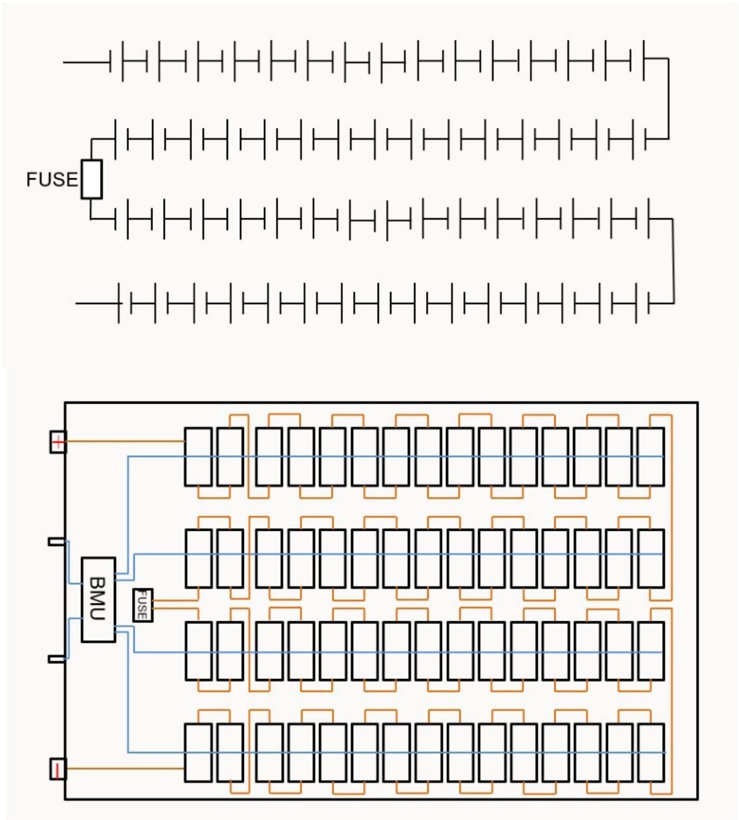


2.2.3 Layout of the module contents

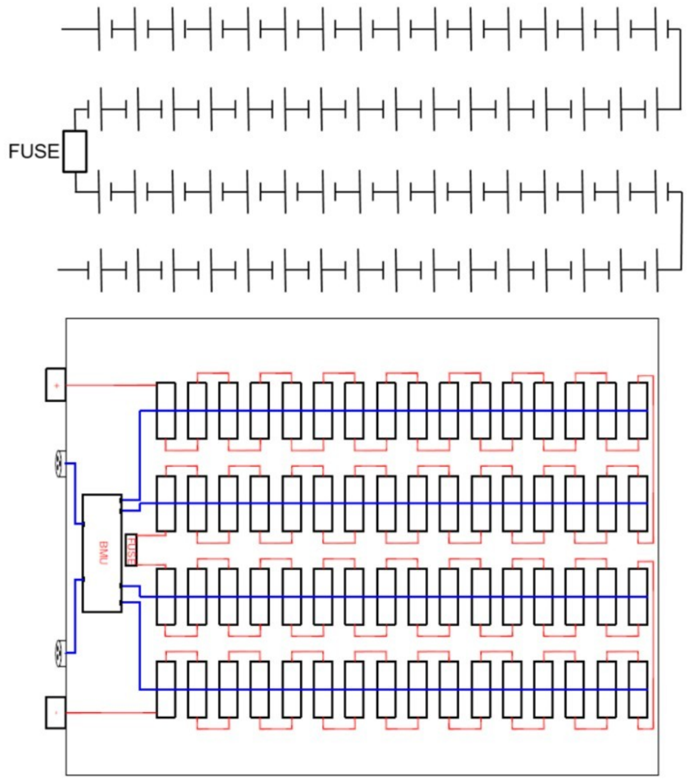


2.2.4 Configuration diagram of the module

1P60S



1P64S



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.

	Battery system	Battery system
Product	LFP Lithium Ion Energy Storage System	LFP Lithium Ion Energy Storage System
Type/model	R0229BL-AHAA	R0215BL-AHAA
Cell Capacity [Ah]	280	280
Cell Quantity	256	240
Battery structure	(64S)4S	(60S)4S
Nominal voltage [V]	819.2	768
Rated capacity [Wh]	229,376	215,040
Upper limit charging voltage [V]	934.4	876
Recommend charging/ discharging current [A]	140	140
Maximum charging/ discharging current [A]	140	140
Maximum charging/ discharging power [kW]	114.5	107.5
Discharge cut-off voltage [V]	691.2	648
Temperature range for charging [°C]	0 to 50*	0 to 50*
Temperature range for discharging [°C]	-20 to 50*	-20 to 50*
Temperature threshold for protection	58	58
Overcharge protected voltage supply by battery system	≥3.65V /Cell	≥3.65V /Cell
Recommend charging method by manufacturer	Charge at constant current 140A until reach the voltage 819.2V then change to constant power 114.5 kW until the voltage reaches 934.4V or any one cell reaches 3.65V	Charge at constant current 140A until reach the voltage 768V then change to constant power 107.5 kW until the voltage reaches 876V or any one cell reaches 3.65V
Dimension [mm]	Rack: 868±10mm(W)×1415±10mm(D) ×1015±10mm(H) PCS (BMS inside PCS): 820mm*310mm*1019mm	Rack: 868±10mm(W)×1415±10mm(D) ×1015±10mm(H) PCS (BMS inside PCS): 820mm*310mm*1019mm
Weight [kg]	Rack: ≤1600 PCS: 100	Rack: ≤1600 PCS: 100

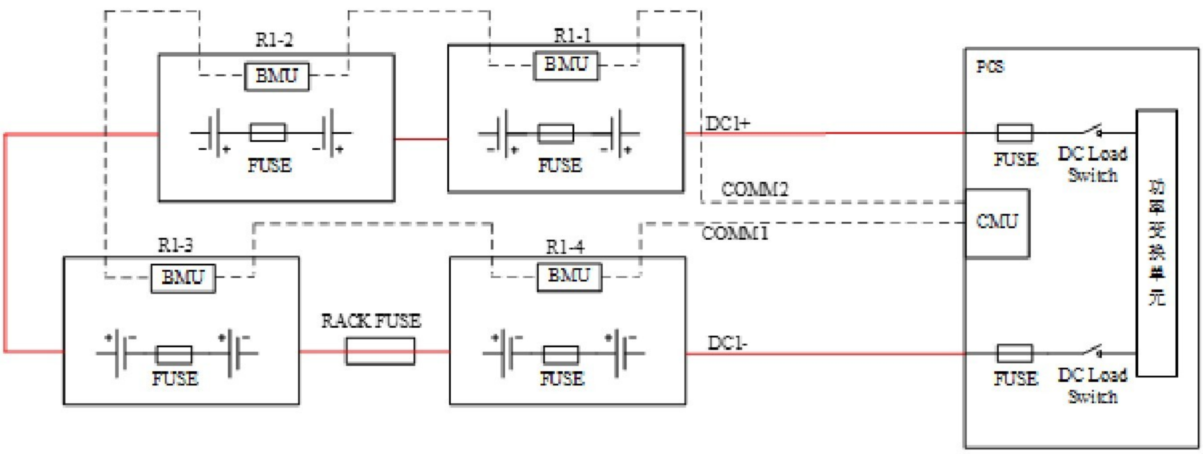
	Battery system	Battery system
Ingress Protection (IP)	IP65	IP65
Protective Class	I	I
Cooling type	Liquid cooling	Liquid cooling
Altitude	4000m	4000m
*: it will start derating when ambient temperature is more than 45°C.		

2.3.2 Product information

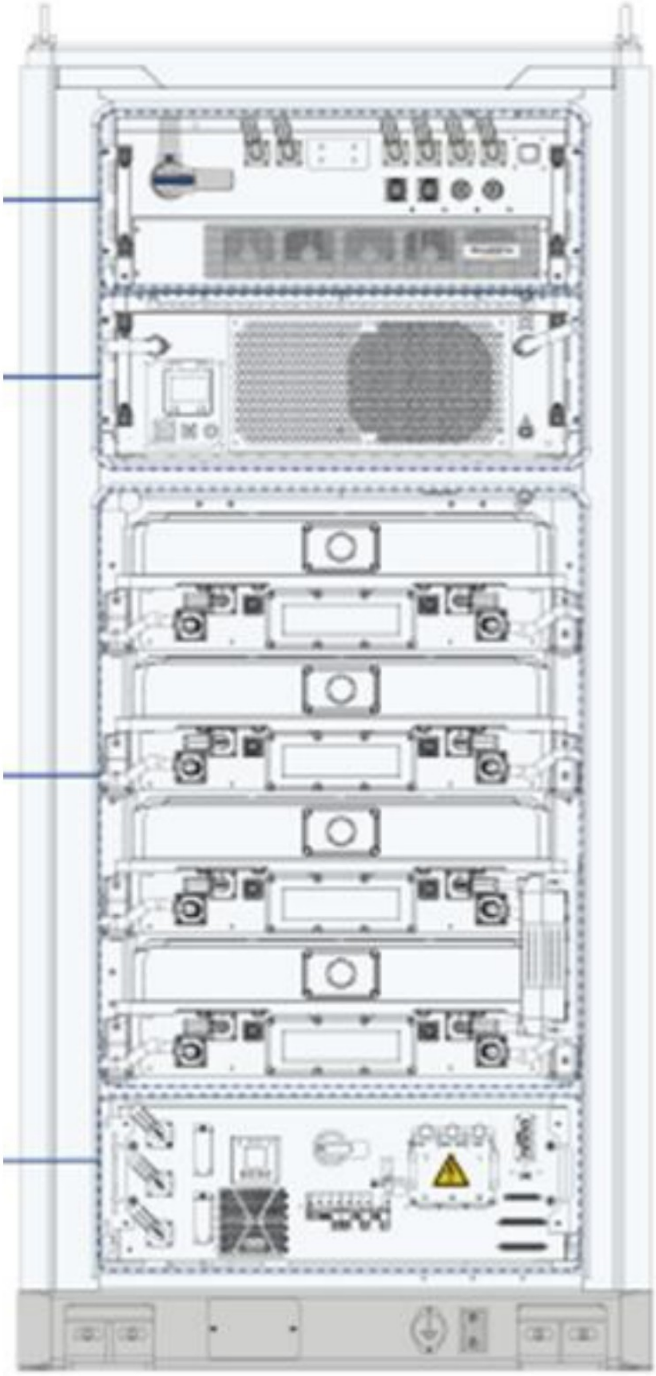
Product Description:

1. The system described in this report are one series of Energy Storage System which include one battery rack, one PCS cabinet, one power distribution cabinet, auxiliary distribution system, Air-condition system and fire suppression system.
   a) The auxiliary distribution box is for providing the auxiliary power for whole BMS control system, air-condition system.
   b) battery cabinet connects to PCS through the busbar convergence, and the PCS converts the DC power generated by the energy storage batteries into AC power which required for connecting to the grid through transformers and other components or required by client(off grid).
   c) The ESS is equipped with the local controller (EMS300CP) in Power distribution cabinet, it collects running information of the PCS, battery, and other devices in the system. And it uploads the information to the energy management system via the background and facilitate the management of energy storage system.
   d) The master control function integrated in PCS. The BMS master control board placed in PCS.
   e) Difference between Models ST225CS-2H, ST215CS-2H and ST225CS-2H-AU, ST215CS-2H-AU:
      1) internal components 2) 24V power supply system of fire suppression system
   f) A single distribution cabinet was included in off-grid models.
2. 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. OVC II considered for the battery rack, it shall be isolated from an OVC III supply source (such as from an OVC III PCS) through an isolated transformer or protected in a manner that prevents transient overvoltage conditions in end use.
3. The IP rating of the EUT is IP55, PD 2 inside and PD 3 outside evaluated.
4. The BMS functional safety was evaluated according to IEC 60730-1 Annex H.
5. The PCS (SC110CX) was certified individually by TÜV Rheinland Co., Ltd.

The system diagram block is outlined as below:



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

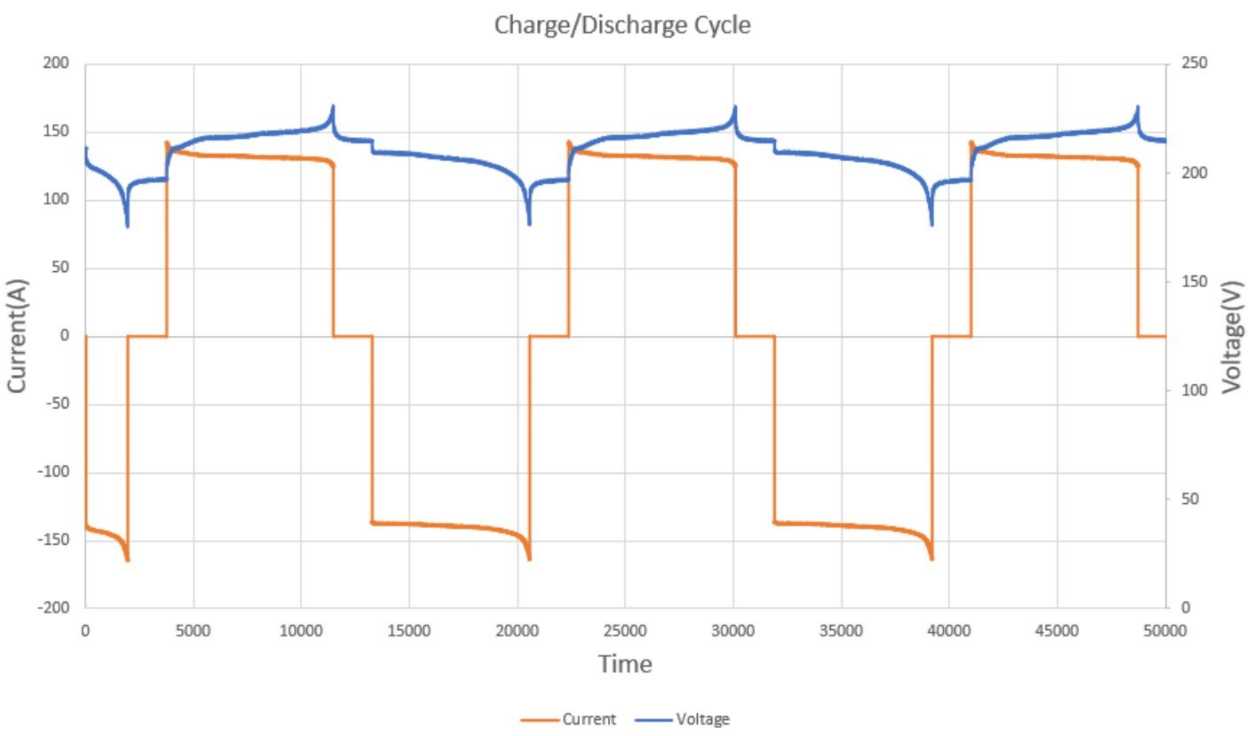
The battery system is constructed with open rack without enclosure. Four columns of the pack were considered as a unit for purposes of the test.

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°C±2°C and 50%± 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

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.

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 46.

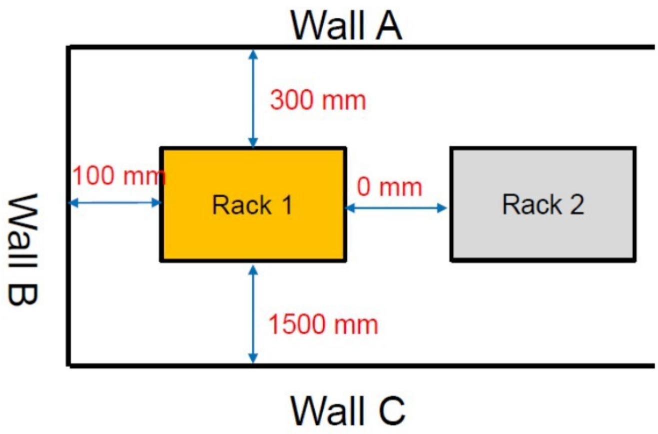
The initiating unit (Rack 1) was positioned at the corner, adjacent to the two instrumented wall sections.

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)

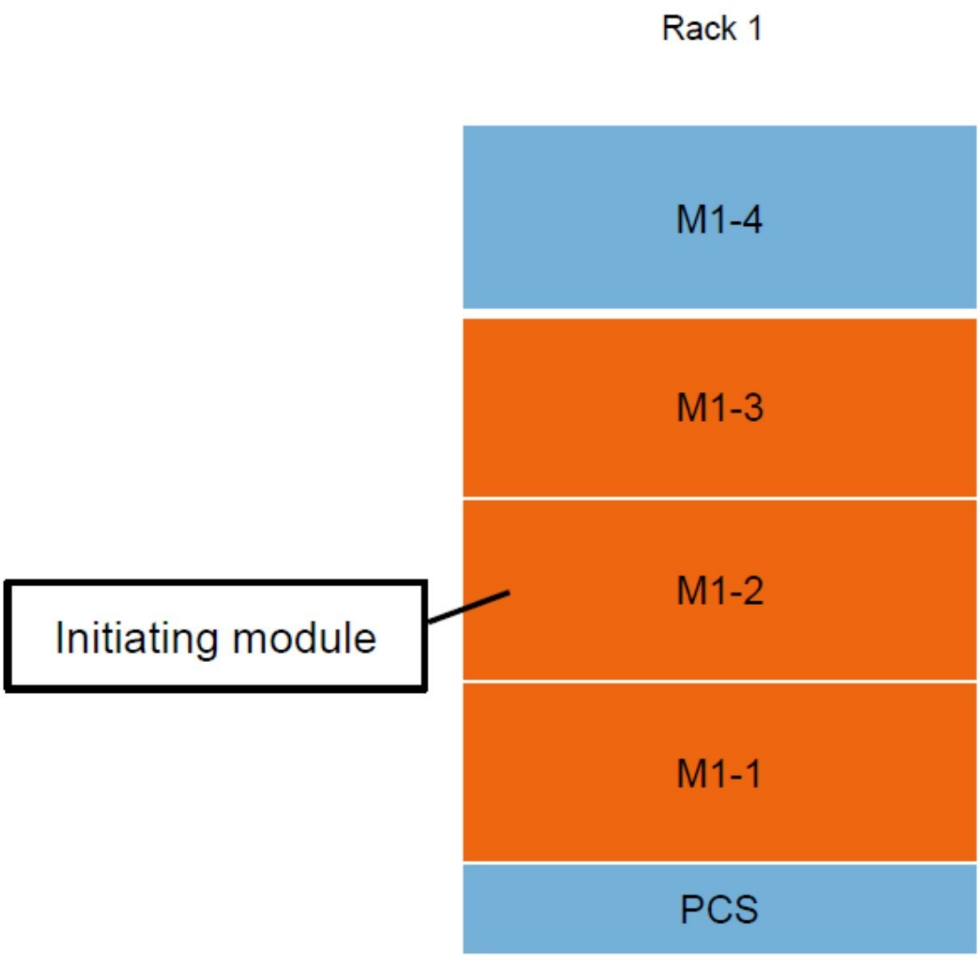


For this test, the modules were numbered according to the electrical continuity.

In initial unit, modules numbers from M1 to M4.

In target units, modules numbers from M1 to M4 which was the target unit setting next to the initial module. See Figure 3.

Figure 3. Module numbering in unit



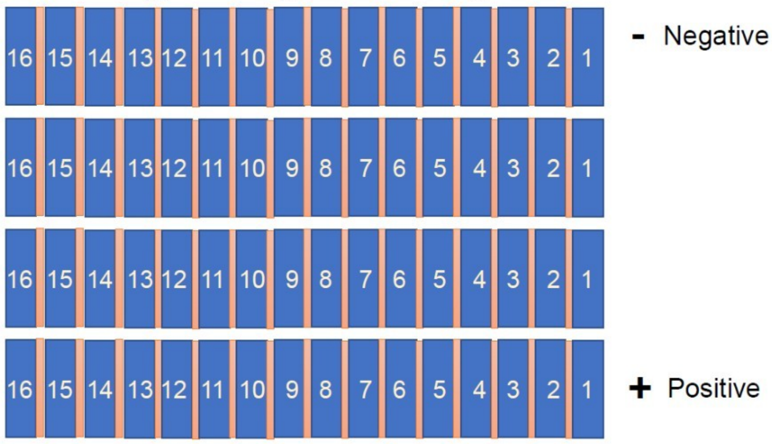
3.3.3 Thermal runaway setup

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

The external heating method used for initiating thermal runaway in cell level test was used to initiate thermal runaway within the module.

Consider the unit level installation in the module. #12~ #14 cells located in the middle of the module was chose as target cell to be forced into thermal runaway.

Figure 4. Cell numbering, initiating cell selecting.



Consider the unit level installation in the module. #12 ~ #14 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).

6 glass fiber thermocouples Type K, 24 AWG were attached on the center of each wide surface of #12~ #14 cells, used for record cell surface temperature. (See 3.3.2 figure 5)

4 glass fiber thermocouples Type K, 24 AWG were attached on the center of each wide surface of 9~#10 and #15 to #16 cells, used for record cell surface temperature. (See 3.3.2 figure 6)

14 glass fiber thermocouples Type K, 24 AWG were attached on the center of each narrow surface of 9~#10 and #15 to #16 cells, used for record cell surface temperature. (See 3.3.2 figure 6)

9 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)

Manual 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 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

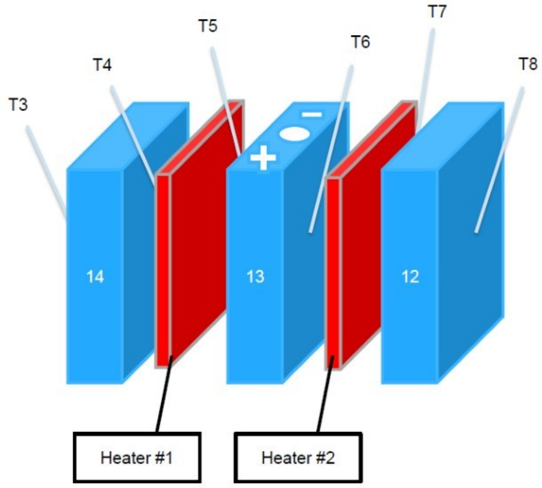


Figure 6. Cell numbering, heater location and thermocouples (no. xx) locations inside the sub-module

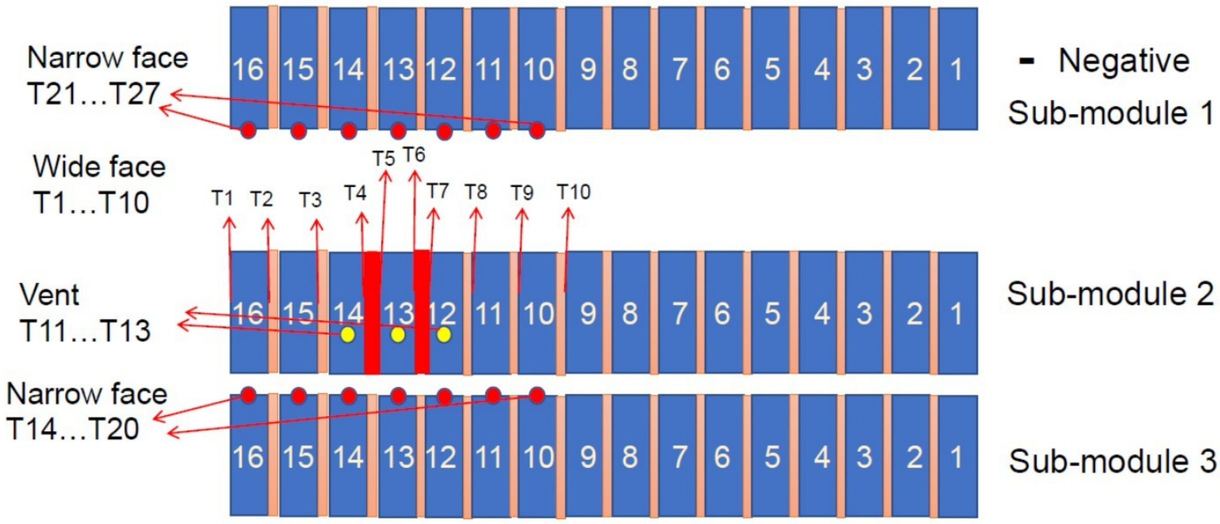
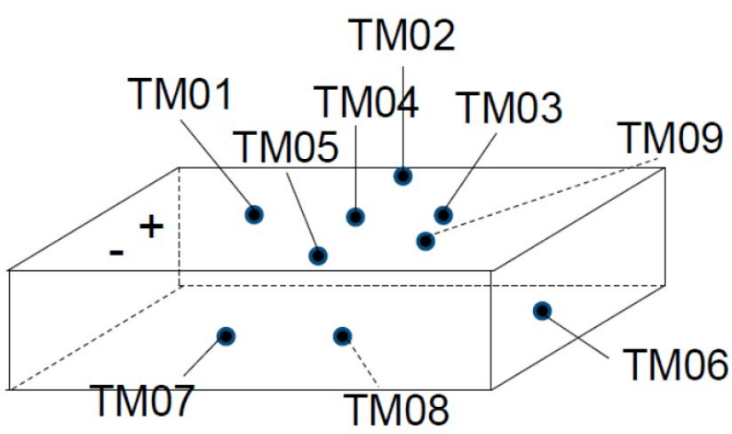


Figure 7. Thermocouple's locations outside module



3.4 Observations and records

Ambient conditions at the initiation of the test... :	15.7°C, 55.2% R.H.
Sample number .... :	#2024032601
Open circuit voltage before test (V) .... :	216.3
Weight before test (kg) .... :	397.5 (with thermocouples)
Time initiating the test........................ :	12:43 start to heat the cells
Observations during test.................... :	Audible pops were heard at 13:43 (the pressure relief valve burst). Large amount of white smoke was observed on 14:06. Large amount of white smoke was observed on 14:09, 14:09, 14:17 and 14:21 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 5 cells were damage after test. 3 of them were initiating cells and another 2 was cell-to-cell thermal propagation. Photos “sample after test” in page 48 show the damage of the module enclosure, electrolyte outside and damage of the components inside enclosure. 195.4 V was measured on the module output terminal.
Weight after test (kg) .... :	392.5 (with thermocouples)
Weight loss (kg)................................ :	5.0

3.5 Temperature measurements

3.5.1 Temperature measurement of initiating cells

Surface temperature of #9~#16, #10~#16 of Sub-module 1 and #10~#16 of Sub-module 3 cells in initial module were recorded during test.

Cell first thermal runaway occurred on 13:29. Maximum temperature 596.9°C (T5), 576.2°C (T4) and 680.1°C (T7) were measured on the #12 ~ #14 cells wide surface. See figure 8 for the temperature vs time curve. Maximum temperature please see table 1 for detail.

Cell to cell propagation was observed on #11 and #15~#16 cells in initial submodule in turn during the test. See figure 9 for the temperature vs time curve. Maximum temperature please see table 2 for detail.

Figure 8. Temperatures of cell #12~#14

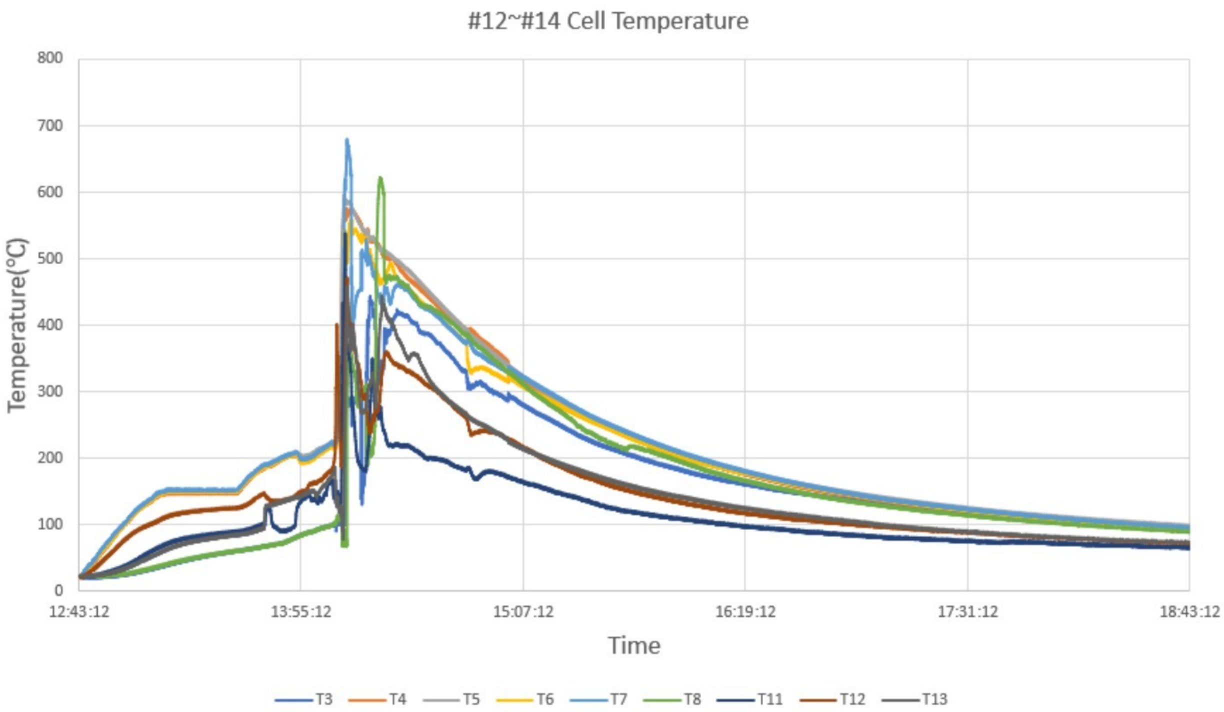


Table 1. Maximum temperature of cell #12~#14

Thermocouple no.	Location	Maximum temp.(℃)
T3	Surface of cell_14(left)	443.4
T4	Surface of cell_14(right)	576.2
T5	Surface of cell_13(left)	596.9
T6	Surface of cell_13(right)	558.0
T7	Surface of cell_12(left)	680.1
T8	Surface of cell_12(right)	622.1
T11	Vent of cell_12	538.1

T12	Vent of cell_13	471.7
T13	Vent of cell_14	458.3

Figure 9. Temperatures of cell #10~#11 and #15~#16

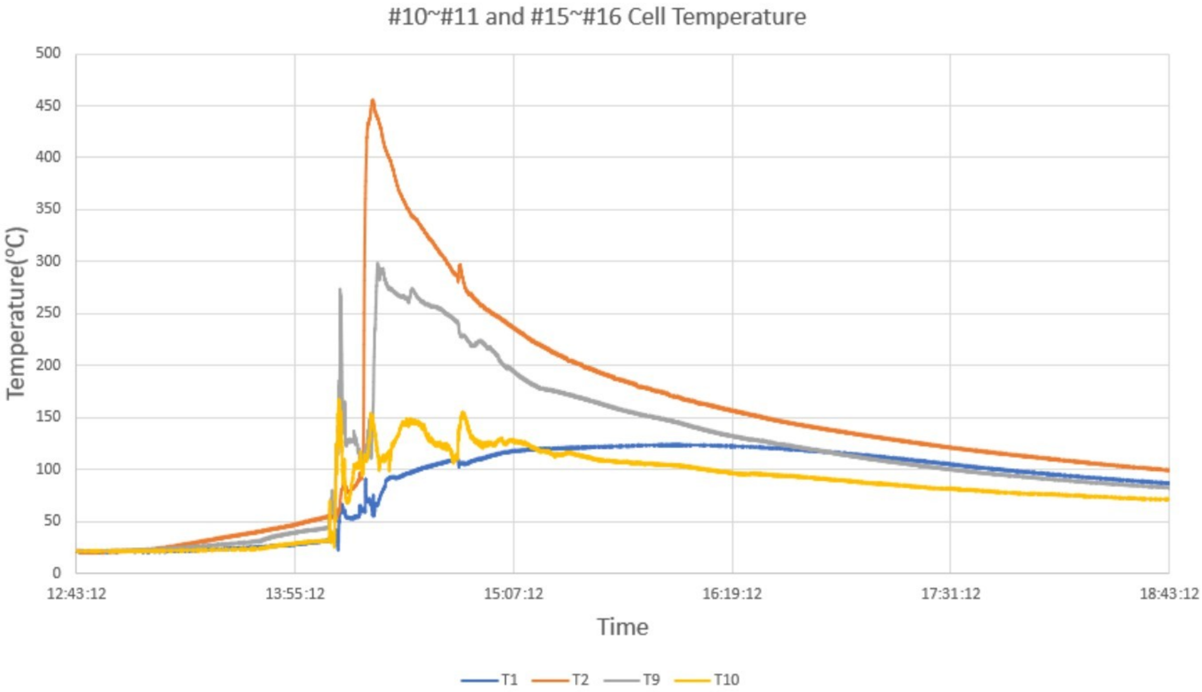


Table 2. Maximum temperature of cell #10~#11 and #15~#16

Thermocouple no.	Location	Maximum temp.(℃)
T1	Surface of cell_16	123.9
T2	Surface of cell_15	455.4
T9	Surface of cell_11	298.4
T10	Surface of cell_10	167.3

Figure 10. Temperatures of cell #10~#16 (Sub-module 3)

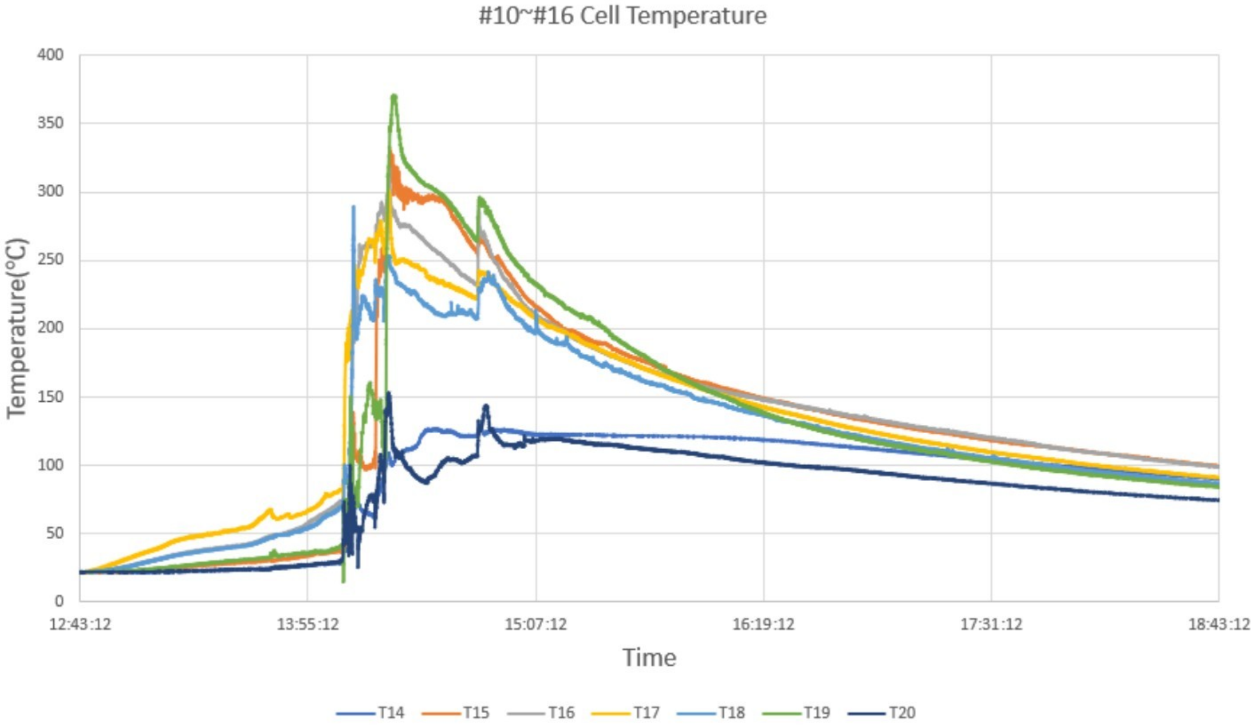


Table 3. Maximum temperature of cell #10~#16 (Sub-module 3)

Thermocouple no.	Location	Maximum temp.(°C)
T14	Surface of cell_16	127.7
T15	Surface of cell_15	333.4
T16	Surface of cell_14	317.9
T17	Surface of cell_13	301.8
T18	Surface of cell_12	289.8
T19	Surface of cell_11	371.0
T20	Surface of cell_10	153.5

Figure 11. Temperatures of cell #10~#16 (Sub-module 1)

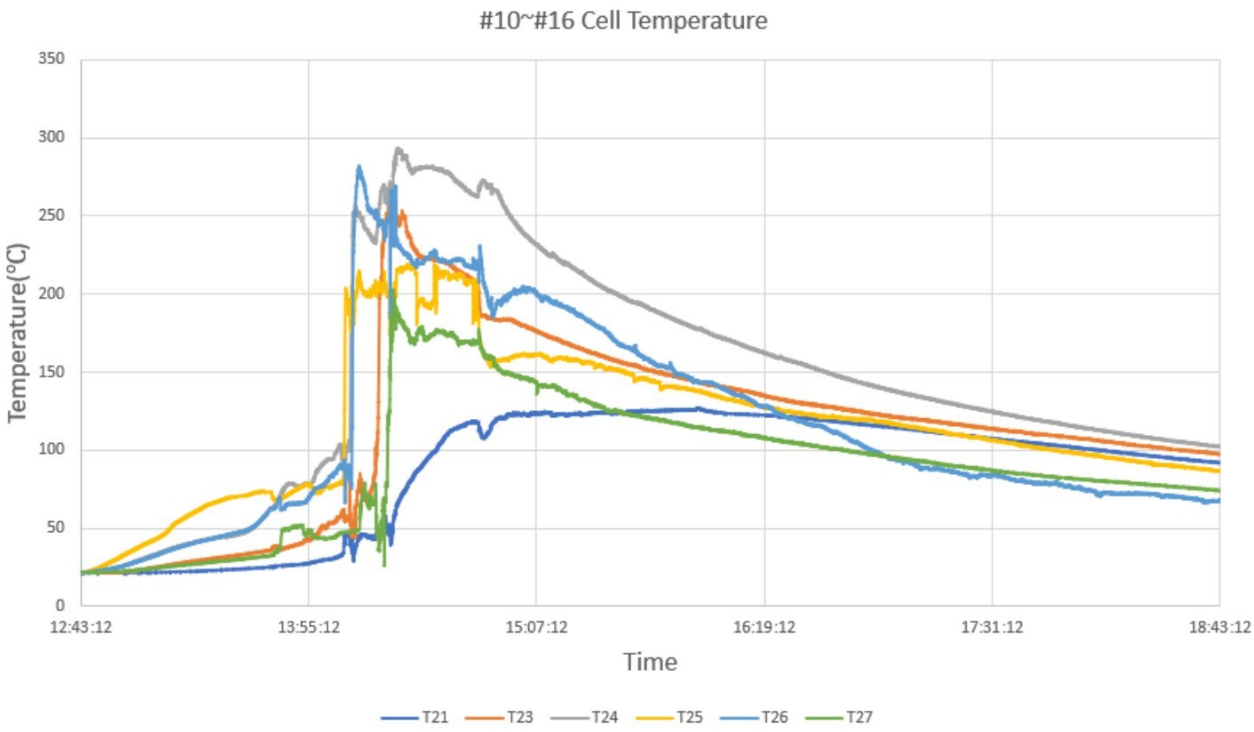


Table 4. Maximum temperature of cell #10~#16 (Sub-module 1)

Thermocouple no.	Location	Maximum temp.(°C)
T21	Surface of cell_16	127.0
T23	Surface of cell_14	267.6
T24	Surface of cell_13	293.8
T25	Surface of cell_12	219.0
T26	Surface of cell_11	282.1
T27	Surface of cell_10	203.0

Note: Thermocouples T22 was damaged during the test.

Figure 12. Module voltage

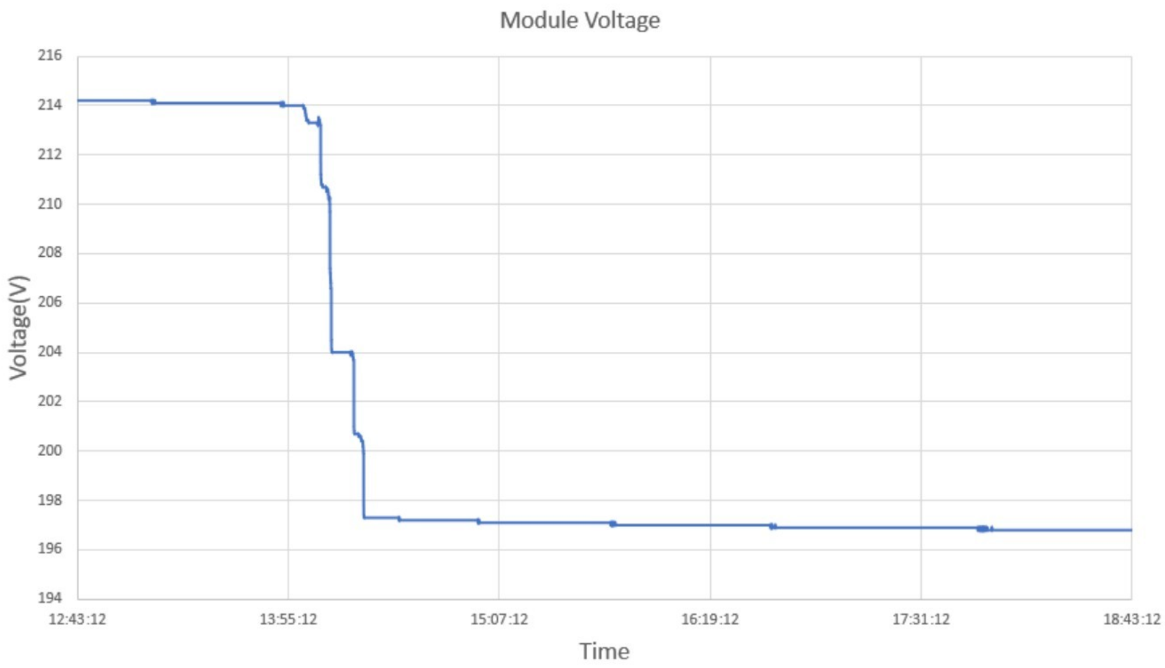
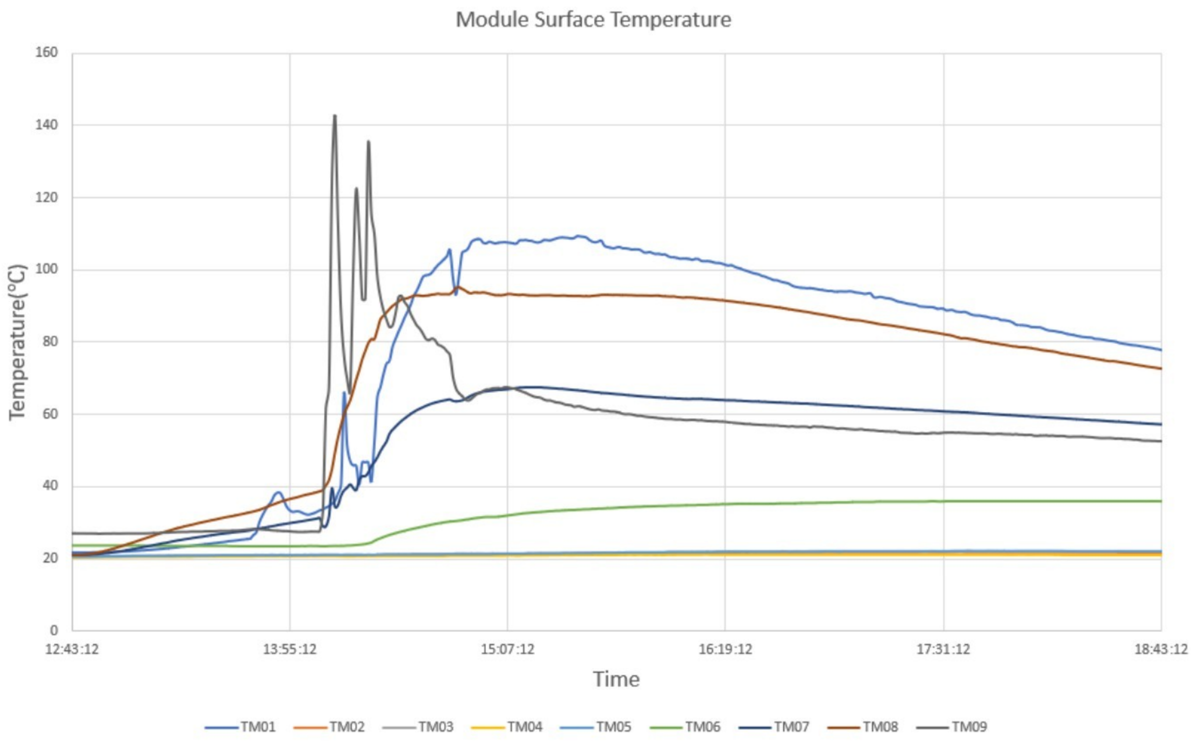


Figure 13. Temperatures of module surface



3.5.2 Temperature measurement of units

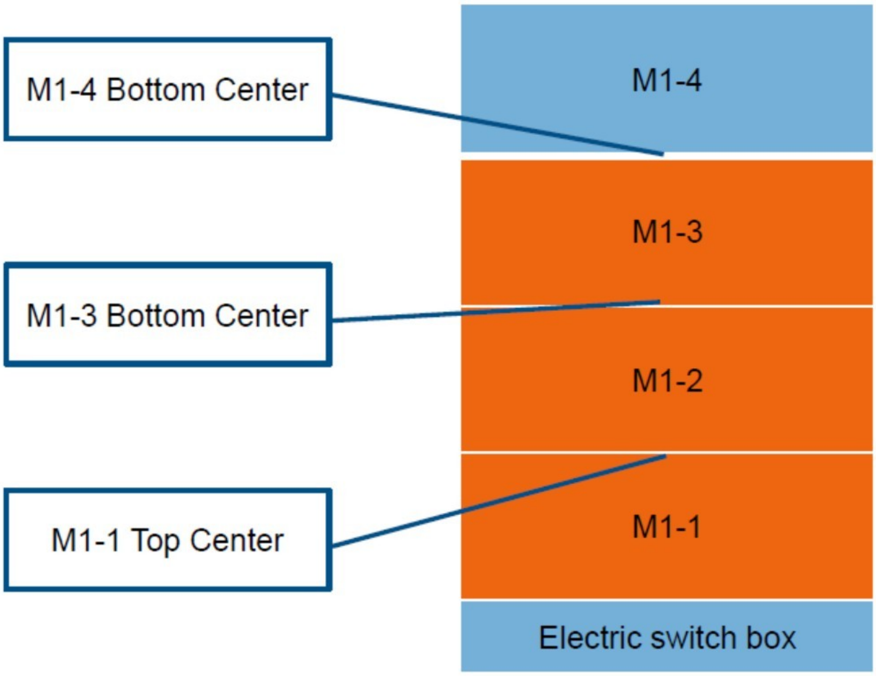
3 glass fiber insulated thermocouples, Type K, 24 AWG were attached on the center of the top, bottom, or side surface of modules M1-1 to M1-4 in initial unit 1.

4 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 161.1°C was measured on the bottom surface of the module M1-3.

In target unit 2, the maximum temperature 16.9°C was measured on the left surface of the module M2-4.

Figure 14. Thermocouple location on modules in initial unit 1



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

Figure 15. Surface temperatures of modules in initial unit 1

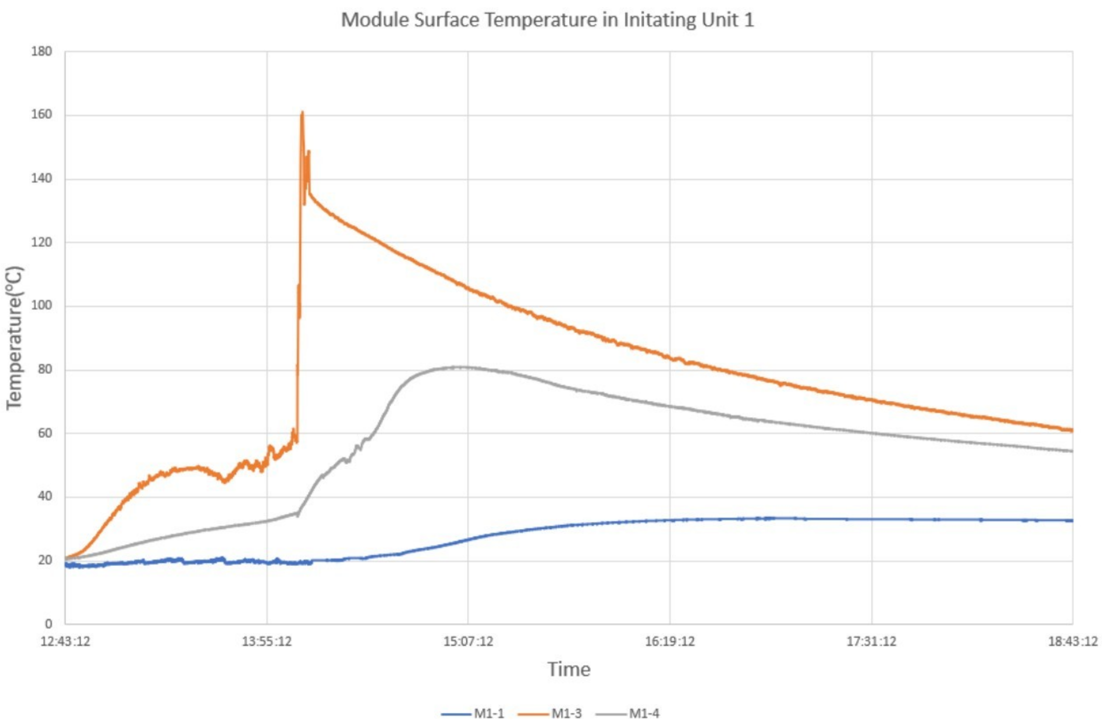
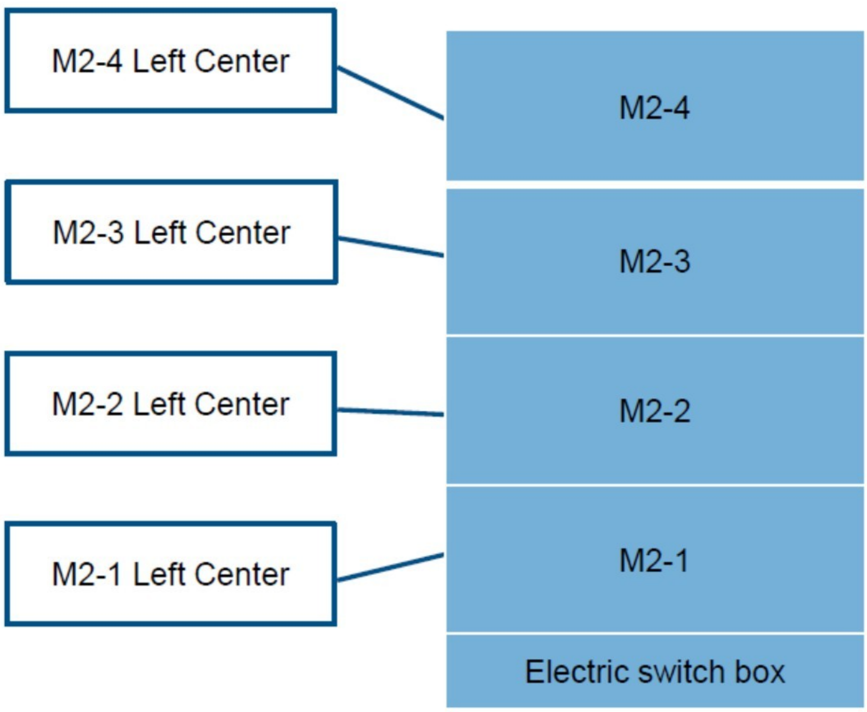
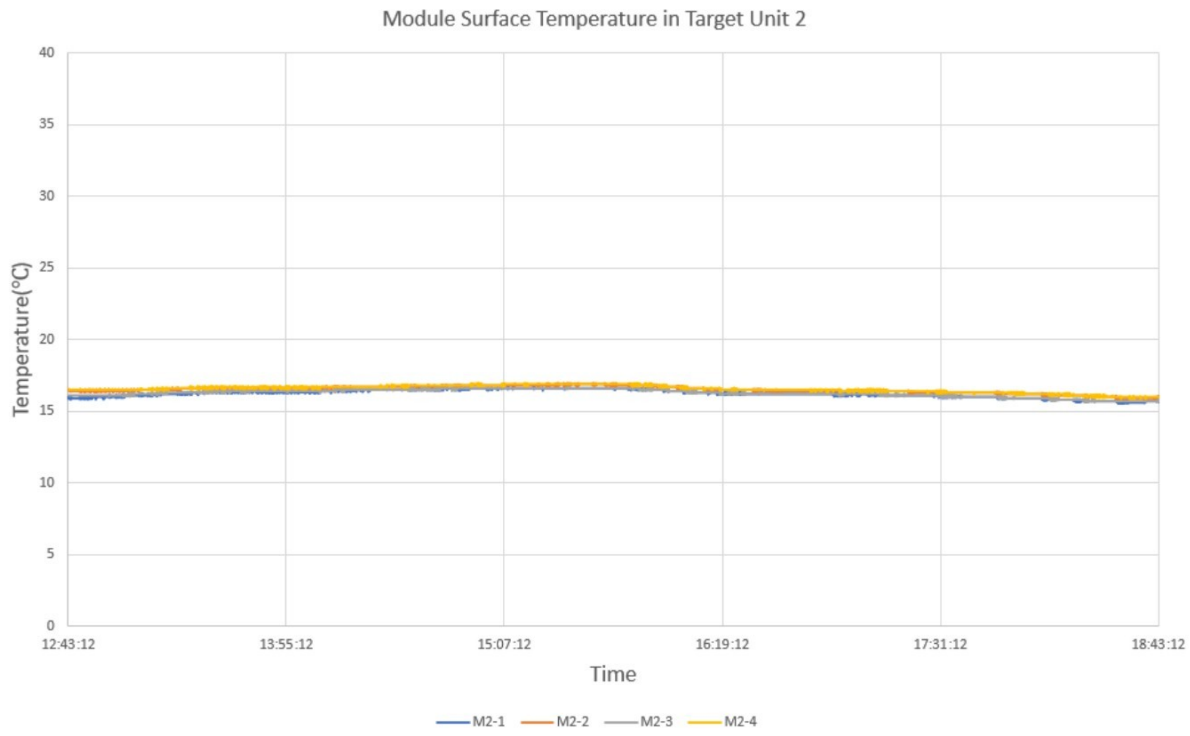


Figure 16. Thermocouple location on modules in target unit 2



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

Figure 17. Surface temperatures of modules in target unit 2



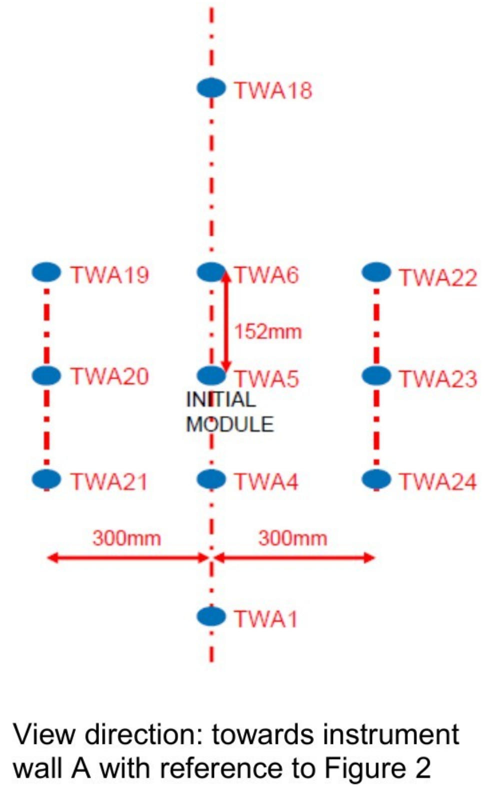
3.5.3 Temperature measurement of instrumented walls

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 18 thermocouples were used for each array. The thermocouples were numbered from low to high as TWA1 to TWA18 for wall A, TWB1 to TWB18 for wall B and TWC1 to TWC18 for wall C.

Additional 6 thermocouples were positioned horizontally near the initial module M1-2 300 mm away from the vertical array each side, on instrumented wall A, wall B and wall C.

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



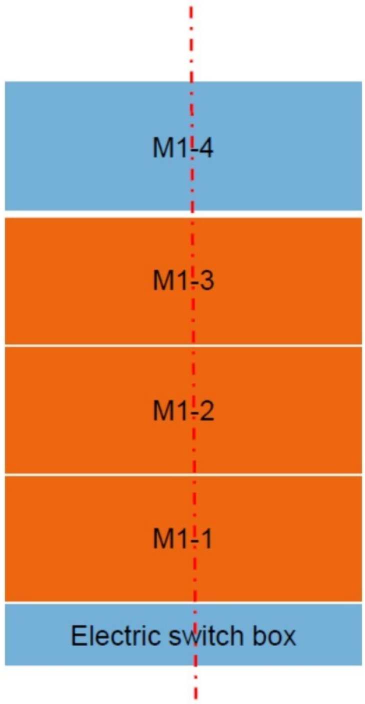
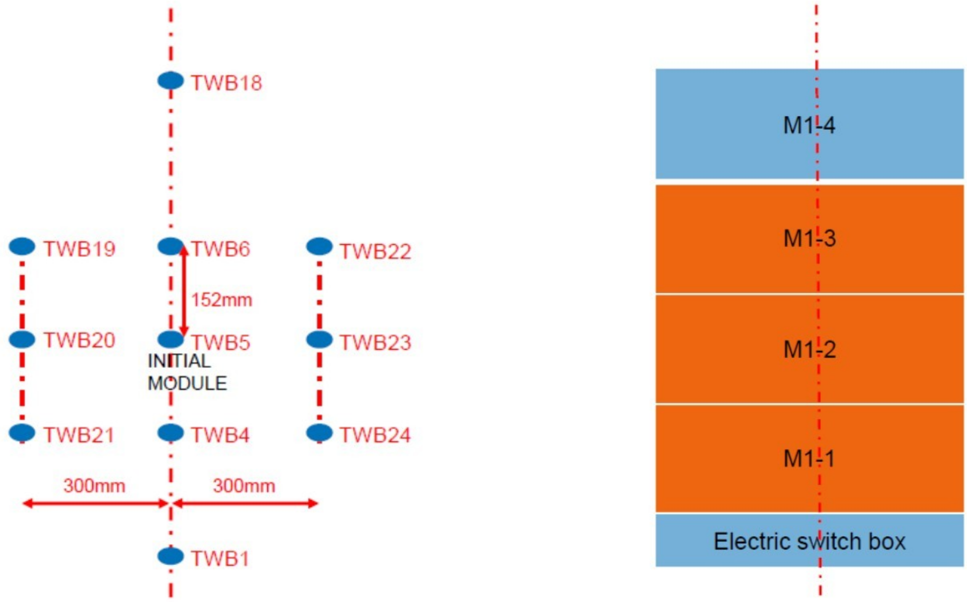
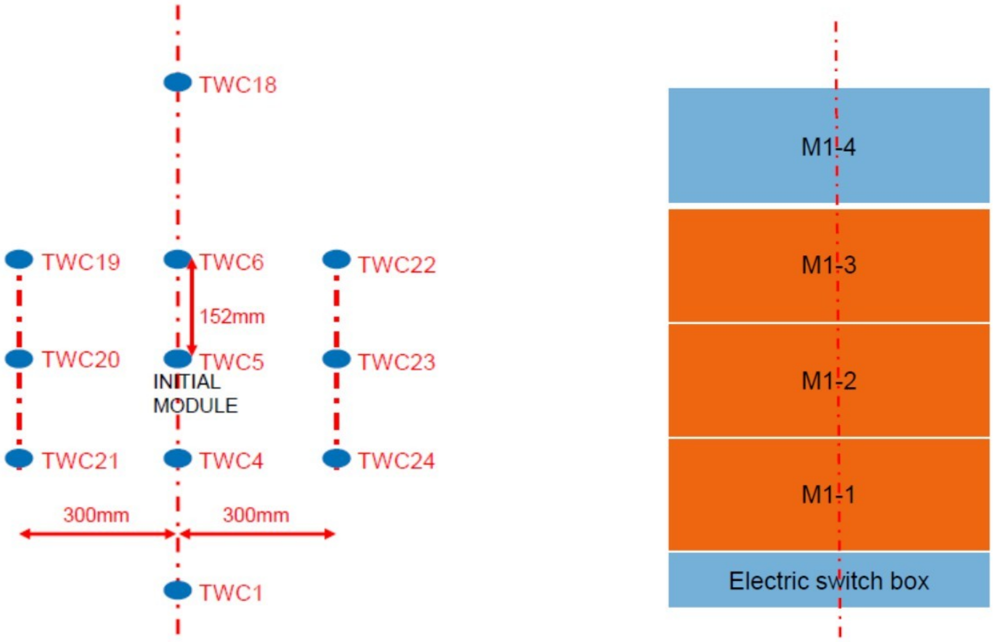


Figure 19. Vertical position of the thermocouples on the wall B



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

Figure 20. Vertical position of the thermocouples on the wall C



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

Maximum temperature measured on instrument wall A was 16.6°C at TWA18, temperature curve see figure 21 for detail.

Maximum temperature measured on instrument wall B was 16.5°C at TWB7, temperature curve see figure 22 for detail.

Maximum temperature measured on instrument wall C was 17.3°C at TWC18, temperature curve see figure 23 for detail.

Figure 21. Temperatures on instrument wall A.

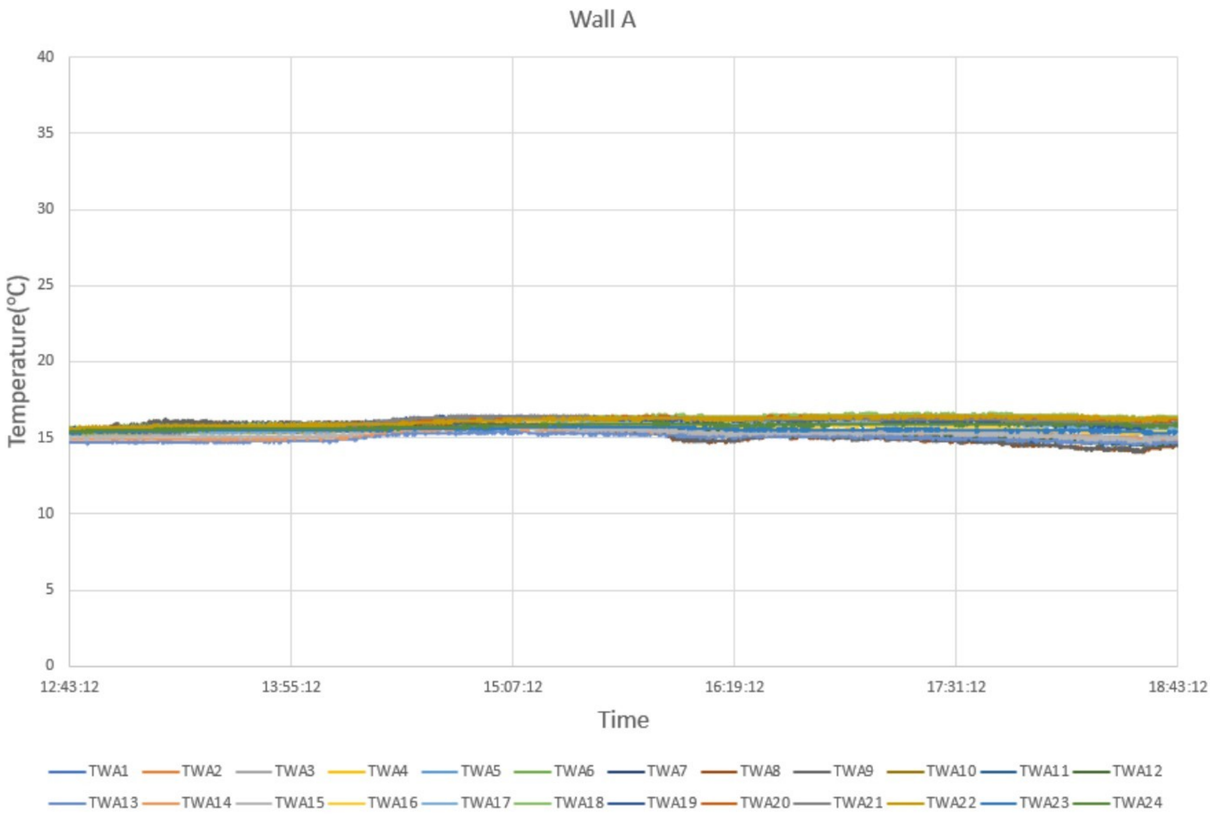


Figure 22. Temperatures on instrument wall B.

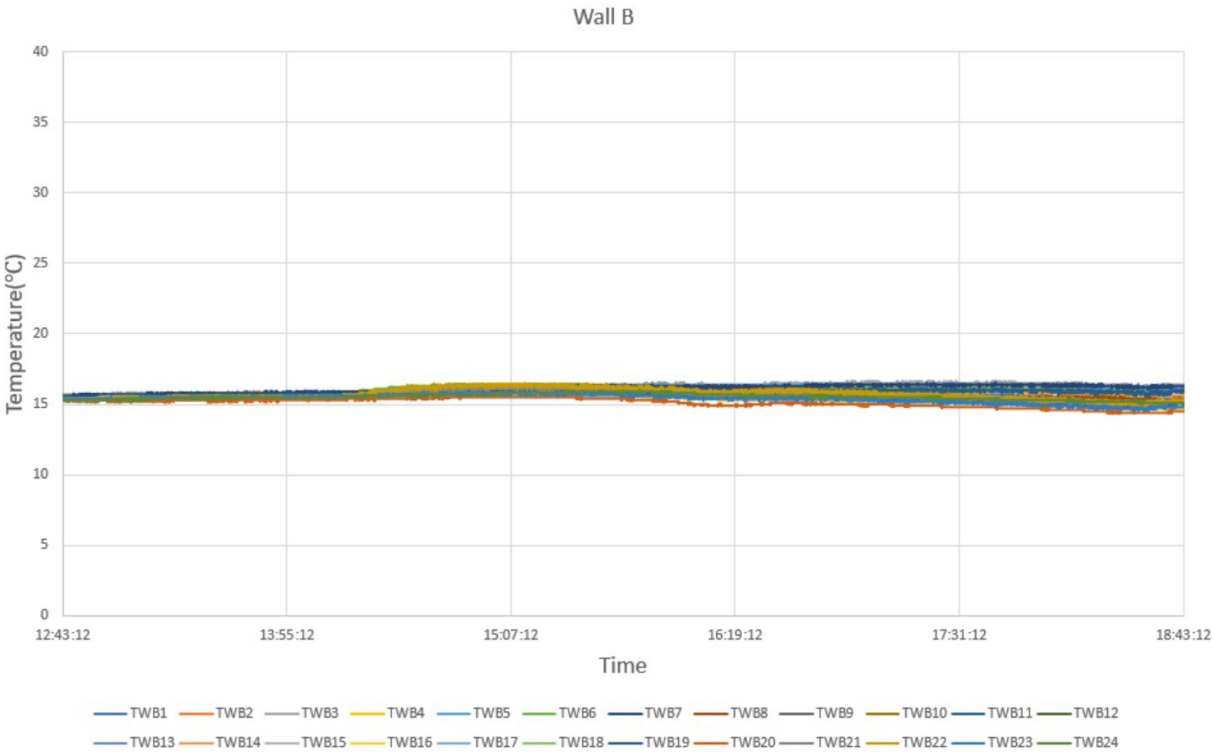
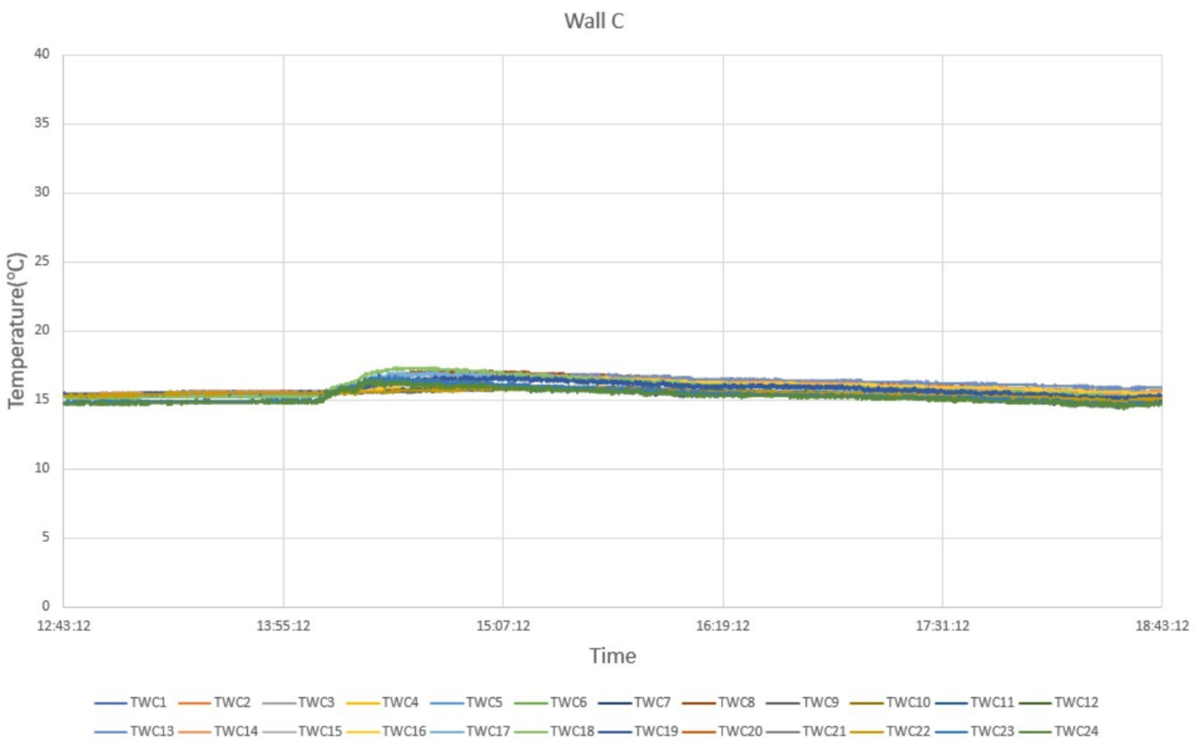


Figure 23. Temperatures on instrument wall C.



3.6 Heat flux measurement

9 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 M1-2 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 M1-3 top edge, which was estimated to receive the greatest surface heat flux due to the thermal runaway of the initiating unit.

One sensor was placed in the middle position between the initiating unit and wall C, which was positioned at the height equivalent to module M1-2 top edge.

Figure 24. Heat flux sensor locations on instrument wall

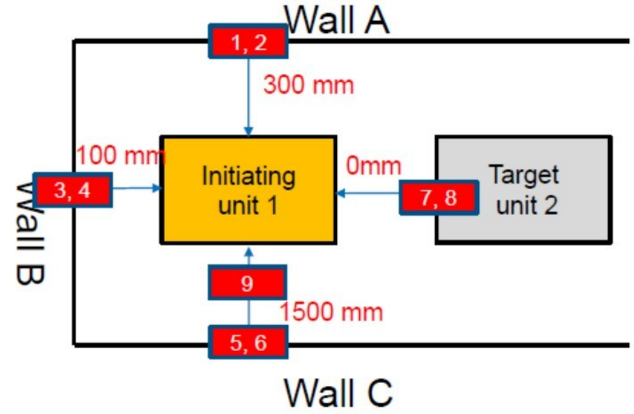
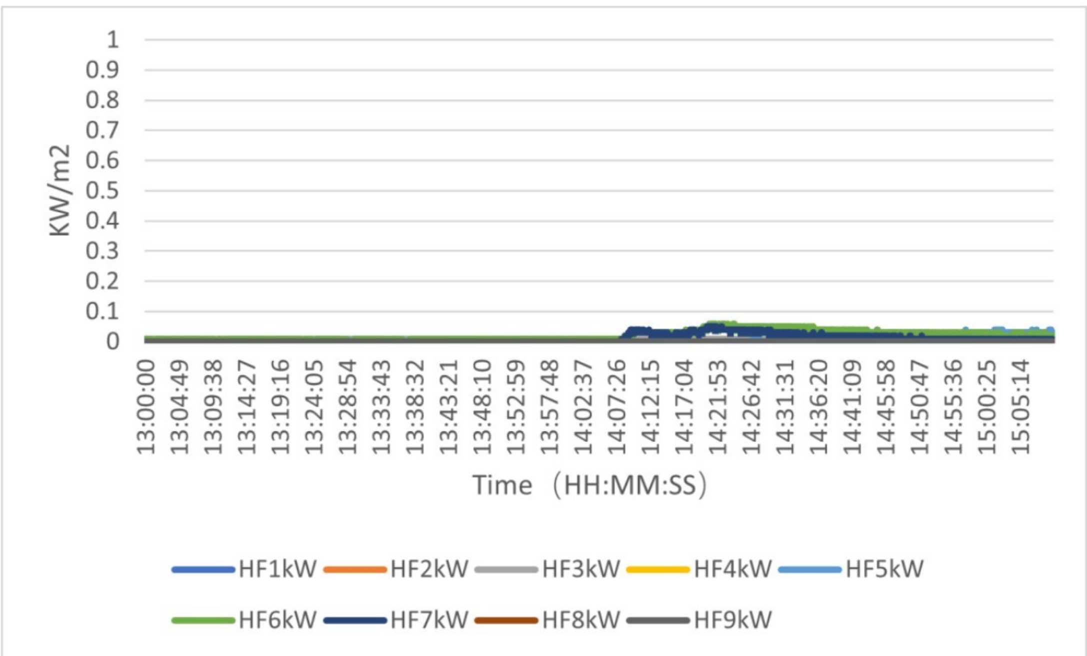


Figure 25. Measured heat flux of target wall and units



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:

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

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

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

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 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.

Peak Chemical HRR: No flaming observed

Total heat release THR: No flaming observed

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 (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

Peak Convective HRR(kW): No flaming observed

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 26. Peak smoke release rate SRR: 0.25 m^2/s

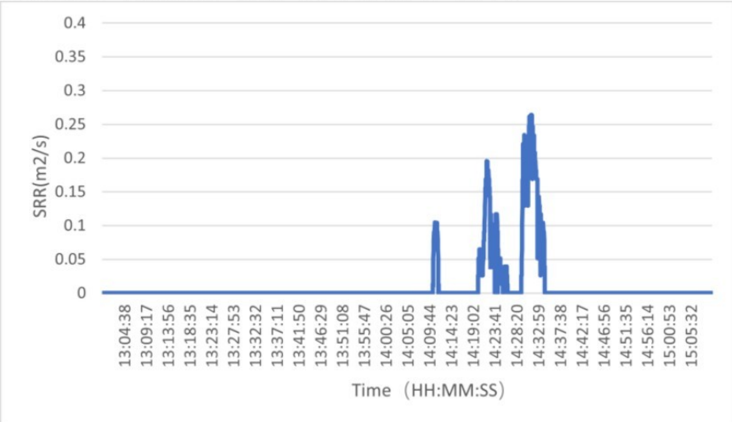
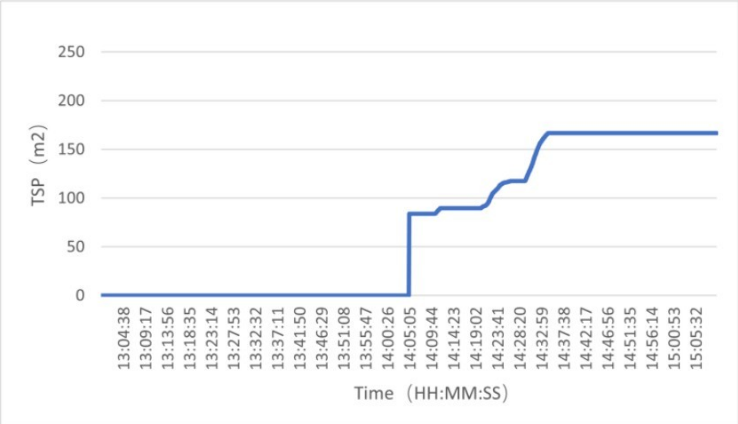


Figure 27. Total smoke release TSR: 166.58 m^2



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 (12:43 ~ 15:15) were presented in below table.

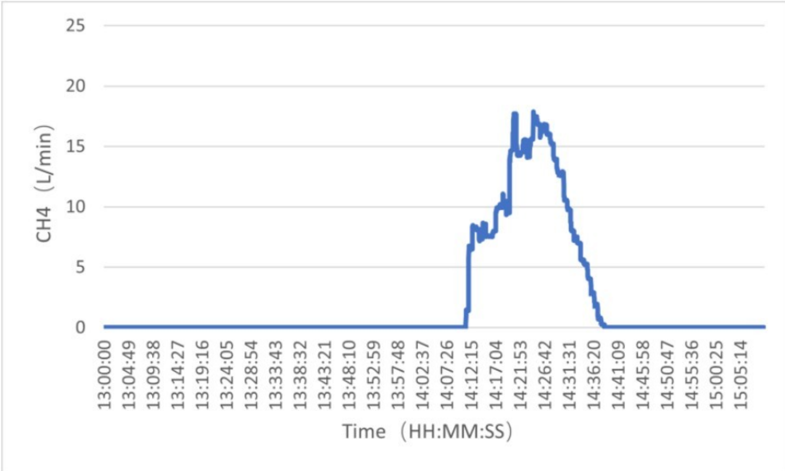
Total cumulative volume of gases before cell venting (12:43 ~ 13:43) were also presented in table for reference. Which may be considered as ambient gases background before test.

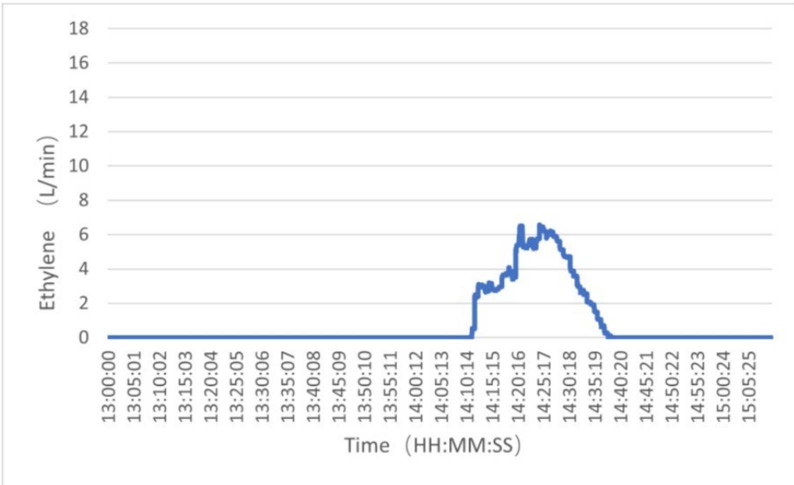
Gas type	Gas components		Total volume of gas (L)	
			Before cell venting	Throughout the test
Hydrocarbon species	Methane	CH_4	0.00	136.11
	Ethylene	C_2H_4	0.00	110.66
	Ethane	C_2H_6	0.00	14.19
	Propylene	C_3H_6	0.00	28.77
	Propane	C_3H_8	0.00	8.73
Others	Carbon Monoxide	CO	0.00	202.92
	Carbon Dioxide	CO_2	1.10	44.01
	Hydrogen[2)]	H_2	0.00	135.56
Total Hydrocarbons (equivalent to C_3H_8, measured by FID)				169.47
Note: 1) The collection time is from 12:43 to 15:15; 2) The Hydrogen was measured by palladium nickel thin film solid state sensor.				

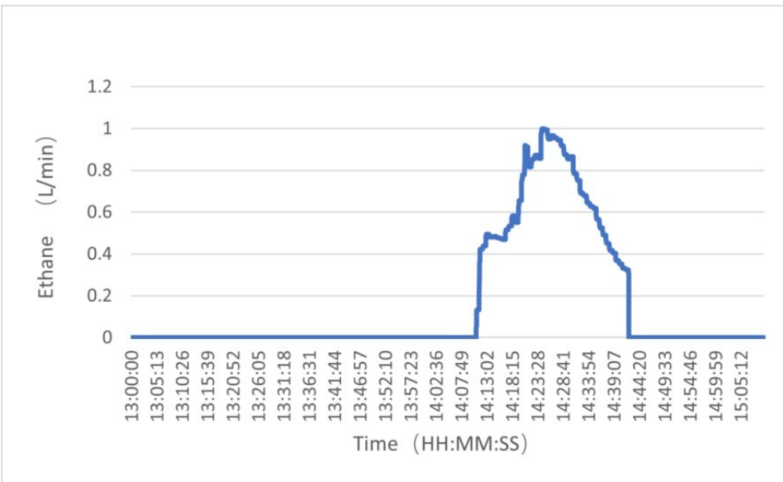
3.10.2 Gas components

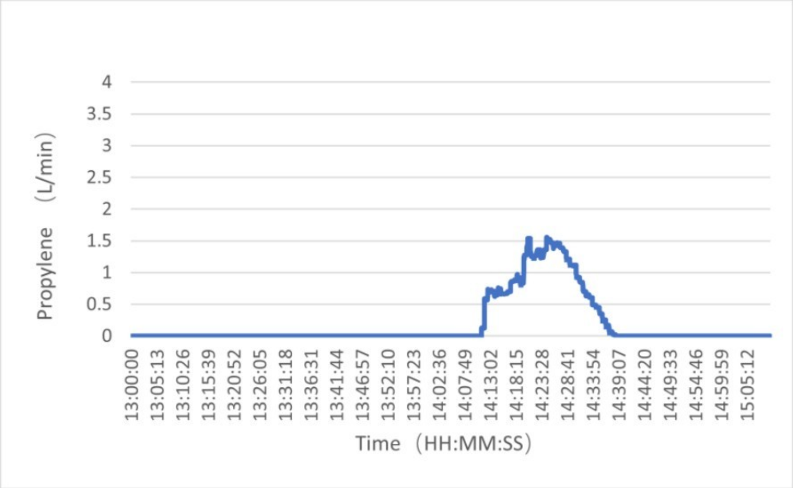
Concentrations of the gases were scaled based on the measured flow rate of the exhaust system and were presented in standard volume flow rate of gas ventilated in below figures.

Figure 28. Hydrocarbon species









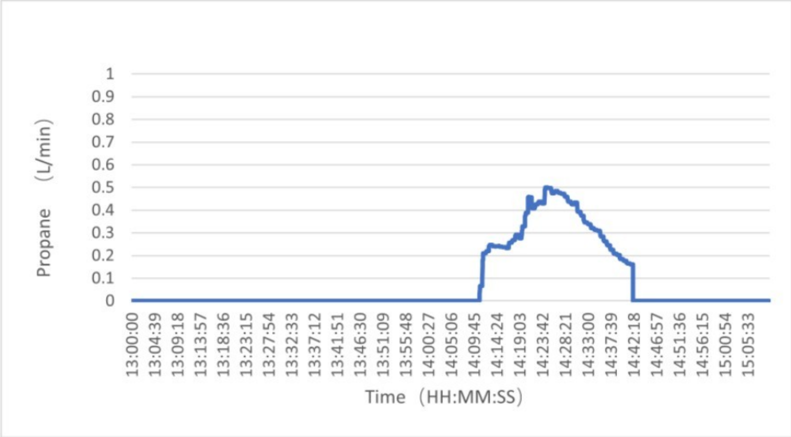
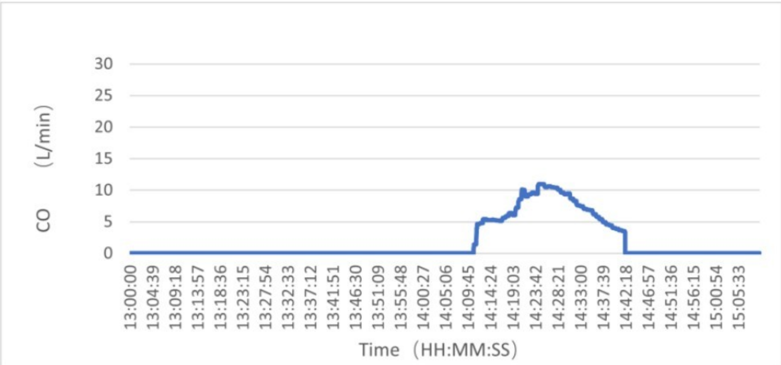


Figure 29. CO, CO_2 containing species



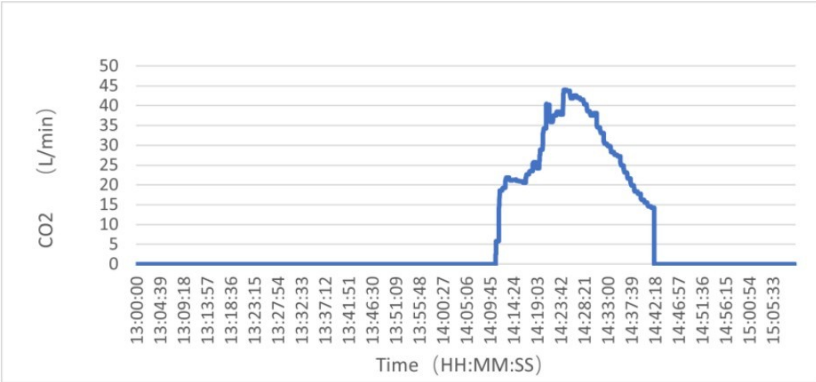
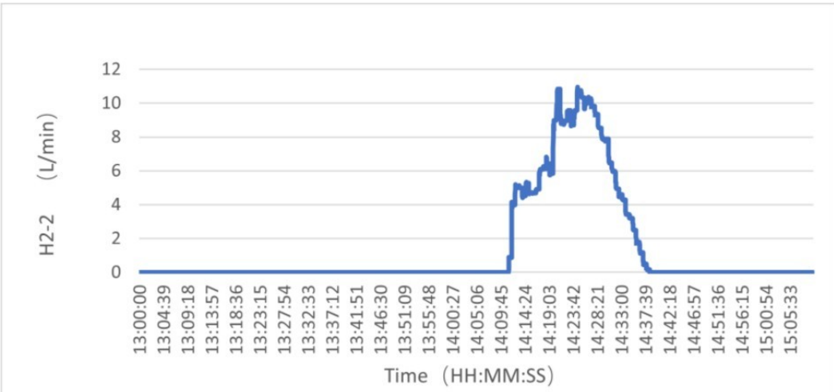
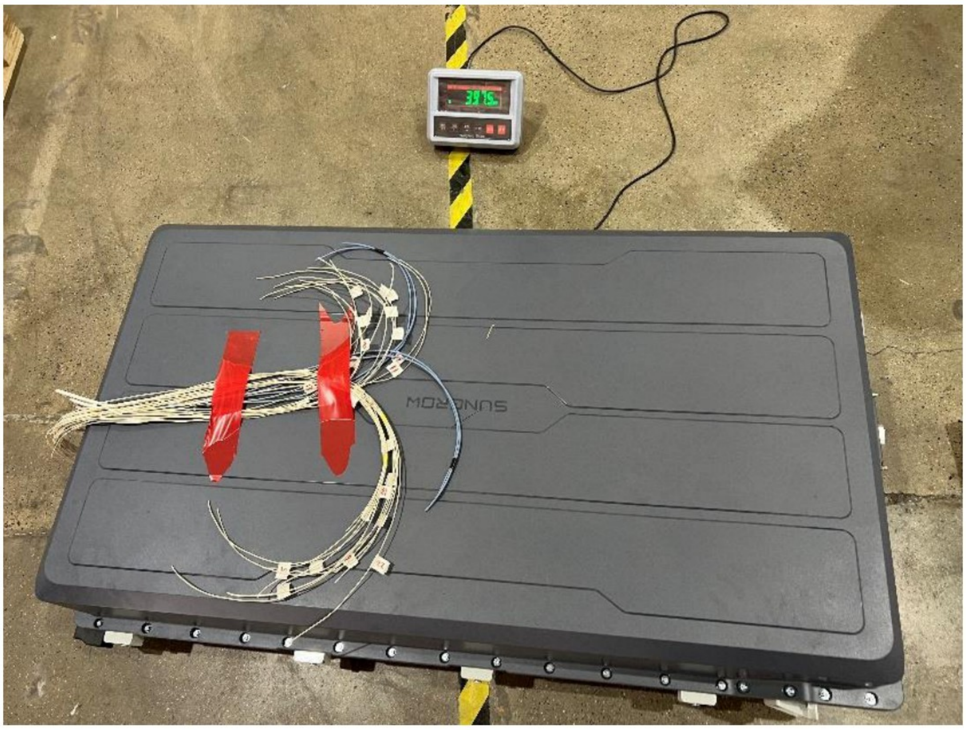


Figure 30. H_2 containing species



3.11 Photos

Initiating module



Test setup

Smoke release during test

Photos after test

Initiating module after test


FLUKE
0.000


FLUKE
0.000
HOLD
RANGE


FLUKE 15B+ DIGITAL MULTIMETER
-0.086
HOLD
RANGE
COM
OFF

4 List of Test and Measurement Instruments

No.	Equipment	Model	Rating	Inventory no.	Last Cal. date
1	Ambient temperature and humidity	HWP01-10S	-30℃~50℃, 20%RH~100%RH	12005577	2025.2.2
2	Data acquisition equipment	DAQ970A	3-slot cardcage with 6½ digit (22 bit) internal DMM 0.004%, accuracy 0.06% Vac	TY2020000138	2025.2.2
3	Data acquisition equipment	TP700	Measuring range-60 ℃ to 1372 ℃ Measurement accuracy ±(0.05% rdg.+0.5℃) Display resolution0.01℃	TY2211000716-2	2025.2.2
4	Data acquisition equipment	TP700	Measuring range-60 ℃ to 1372 ℃ Measurement accuracy ±(0.05% rdg.+0.5℃) Display resolution0.01℃	TY2020000217	2025.2.2
5	Electronic scale	CHAOOU C1	0-500KG	65960494169	2025.2.2
6	Paramagnetic oxygen analyser	SERVOMEX4100	O2: paramagnetic sensor, range 0-25%, accuracy 0.02%, response time T90 < 7S	ZY2020000018-1	2025.2.6
7	Velocity probe	2671-25L-D-11-G2-E-N	4-20mA output, range 0-250pa, accuracy ± 1% F.S	ZY2020000018-2	2025.2.6
8	Photo detector	PDA36A2	Thorlabs optical receiver, wavelength range (350-1000) mm, gain adjustable, voltage output (0-10) V, instability < 0.1%	ZY2020000018-3	2025.2.2
9	Fourier-Transform Infrared Spectrometer	atmosFIR	Spectral scanning range: 485 - 7500cm-1; Spectral repeatability: < 0.1cm-1	ZY2020000018-5	2025.3.9

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	2025.2.6
11	Palladium-nickel thin-film solid state sensor	MODEL 2000	Range: 0-2000ppm, temperature less than 100 C, -90~110kPa	ZY20210002 10	2025.2.2
12	Flame ionization detector	3010	Accuracy: 2.0%	19937	2025.3.9
13	Heat flux measurement equipment	MW88-JTC08C	0 ~ ± 99999 w / m2, - 250 ~ 980 ℃, accuracy 5%, response time less than 0.1s,	ZY20200000 10	2025.2.2
14	Thermopile	RS-WD-HW-1	0-200 ℃, 4-20mA, response speed < 0.15s	2834814194 2	2025.2.2

End of Test Report