

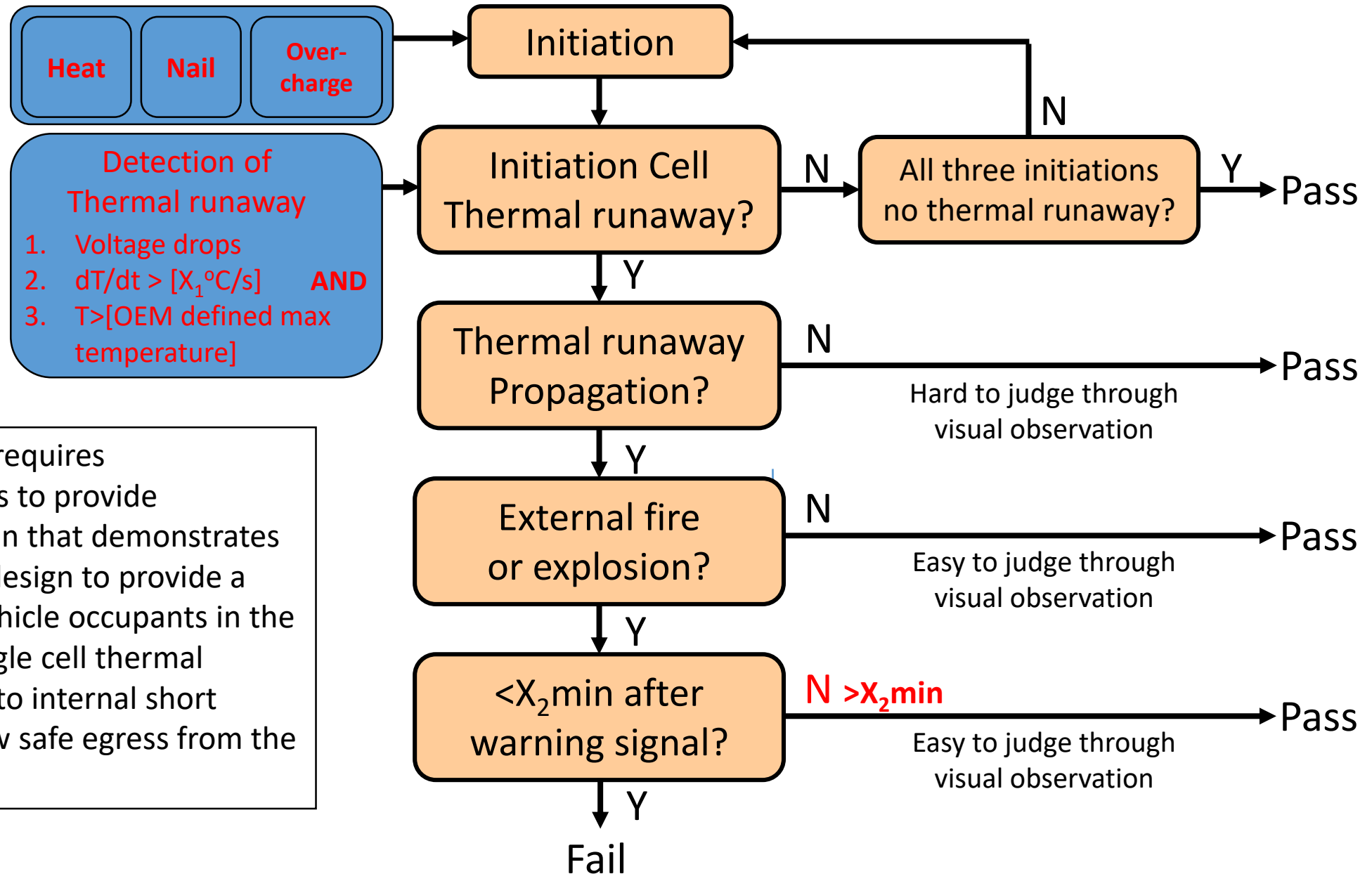
Thermal propagation

2018.03

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Work achievements in the first stage



The EVS-GTR requires manufacturers to provide documentation that demonstrates their system design to provide a warning to vehicle occupants in the event of a single cell thermal runaway due to internal short circuit to allow safe egress from the vehicle.

Problems

The EVS Working group agreed that further research was needed on the topic of thermal runaway propagation to:

- Evaluate **initiation methods** and their **feasibility, repeatability,**
- Investigate the **effect of manipulation of the test device** on test results,
- Investigate **potential new methods** for initiation,
- Evaluate appropriateness of pass/fail **criteria.**

Test scheme

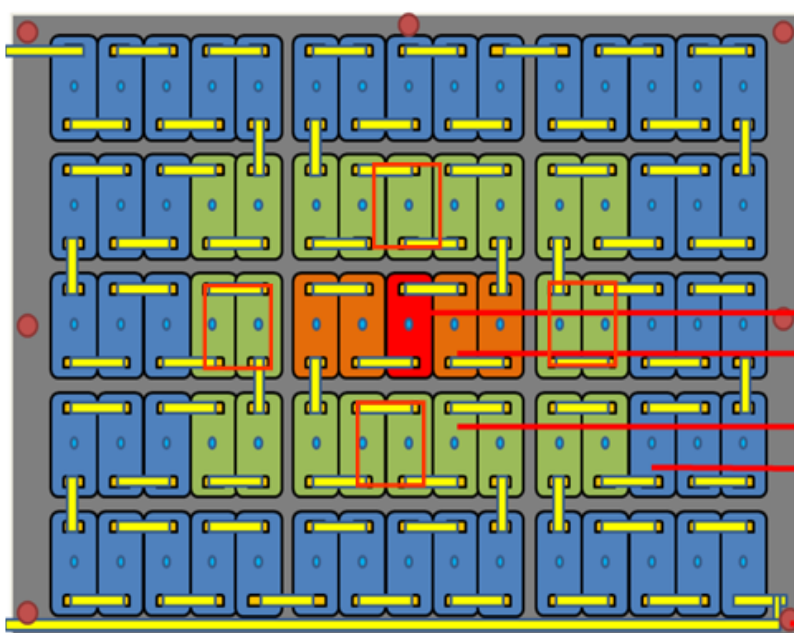
The trigger method are

- Penetration
- Heat
- Overcharge

The focuses of thermal propagation are

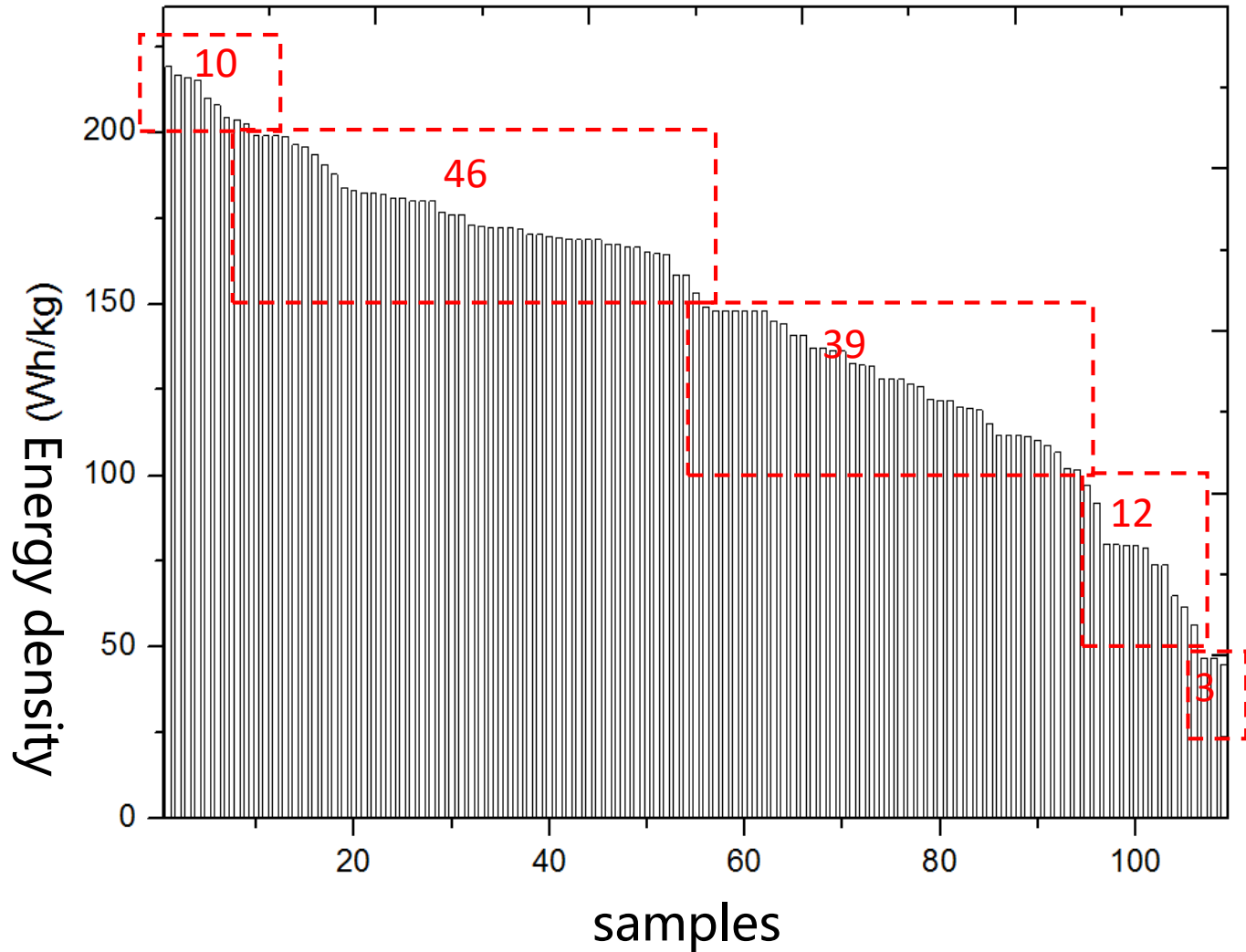
- the state of the trigger target cell
- the thermal propagation way

Type	thermal sensors position	Claps	Illustration
Prismatic	<ol style="list-style-type: none"> 1. valve (1#) 2. positive (2#) 3. negative (3#) 4. Both sides of nail position (4#, 5#) <p>As for over charge and heat, the central of the big plane</p> <ol style="list-style-type: none"> 5. Positive side (6#) 6. Negative side (7#) 7. Middle of bottom (8#) 	YES	
Pouch	<ol style="list-style-type: none"> 1. positive (1#) 2. negative (2#) 3. nail position; (3#, 4#, 5#, 6#) <p>As for over charge and heat, the positions are middle of front and back, and the point farthest from the center (3#, 4#, 5#, 6#)</p>	YES	
Cylindrical	<ol style="list-style-type: none"> 1. positive (1#) 2. negative (2#) 3. nail position (3#) <p>As for overcharge, the middle of side (3#)</p>	NO	



Trigger method	Nail	Over charge	Heat
	voltage	voltage	voltage
Parameters	——	current	power
	——	test time	test time
	——	energy introduced	energy introduced
	temperature	temperature	temperature
	video	video	video
requirement	data sampling rate of 100Hz	data sampling rate of 10Hz	data sampling rate of 10Hz
Other cells	<ol style="list-style-type: none"> 1) cell voltages and temperature in the same module 2) 2 series cells' voltages, temperature, and the module voltage in the adjacent modules 3) other modules' voltage 4) at least 4 temperatures which is farthest from the trigger target 		

Test results



➤ 0~50 Wh/kg (3%)

- Ni-H

➤ 50~100 Wh/kg (11%)

- Ni-H=1、 NCM/LTO=4、 NCM/C=7

➤ 100~150 Wh/kg (35%)

- NCM=14

- LFP=25

➤ 150~200 Wh/kg (42%)

- NCM=46

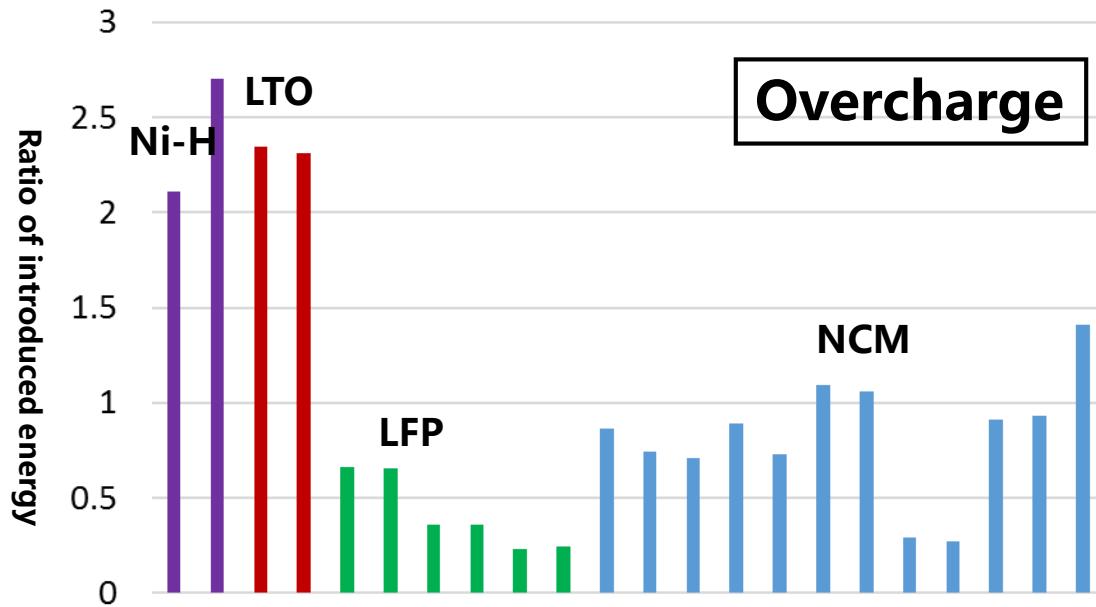
➤ 200+ Wh/kg (9%)

- NCM=14

Test results

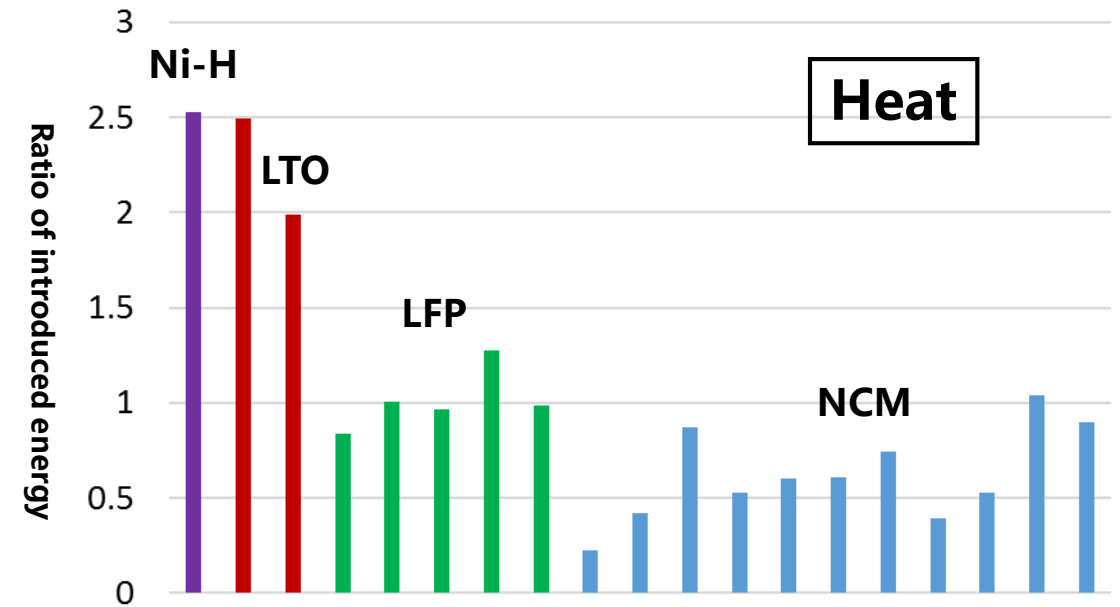
Samples				Method			
				Heat	Overcharge		penetration
Energy density	Material	Type	No.		2C		
>200	NCM	Prismatic	1	✓	✓	✓	
		Pouch	2	✓	✓	✓	✓
150~200	NCM	Pouch	3	✓	✓	✓	✓
		Cylindrical	4	✓	✓	✓	✓
100~150	NCM	Prismatic	5	✓	✓	✓	✓
		Cylindrical	6	✓	✓	✓	✓
		Pouch	7	✓	✓	✓	✓
	LFP	Prismatic	8	✓	✓	✓	✓
		Cylindrical	9	✓	✓	✓	✓
		Pouch	10	✓	✓	✓	✓
50~100	NCM	Prismatic	11	✓	✓	✓	
	LTO	Pouch	12	✓	smoke	✓	✓
<50	Ni-H	Cylindrical	13	✓	smoke	✓	✓

Test results



Ratio of introduced energy :

- Ni-H (1) : 2.11~2.70
- LTO (1) : 2.35~2.31
- LFP (3) : 0.23~0.66
- NCM (6) : 0.26~1.41

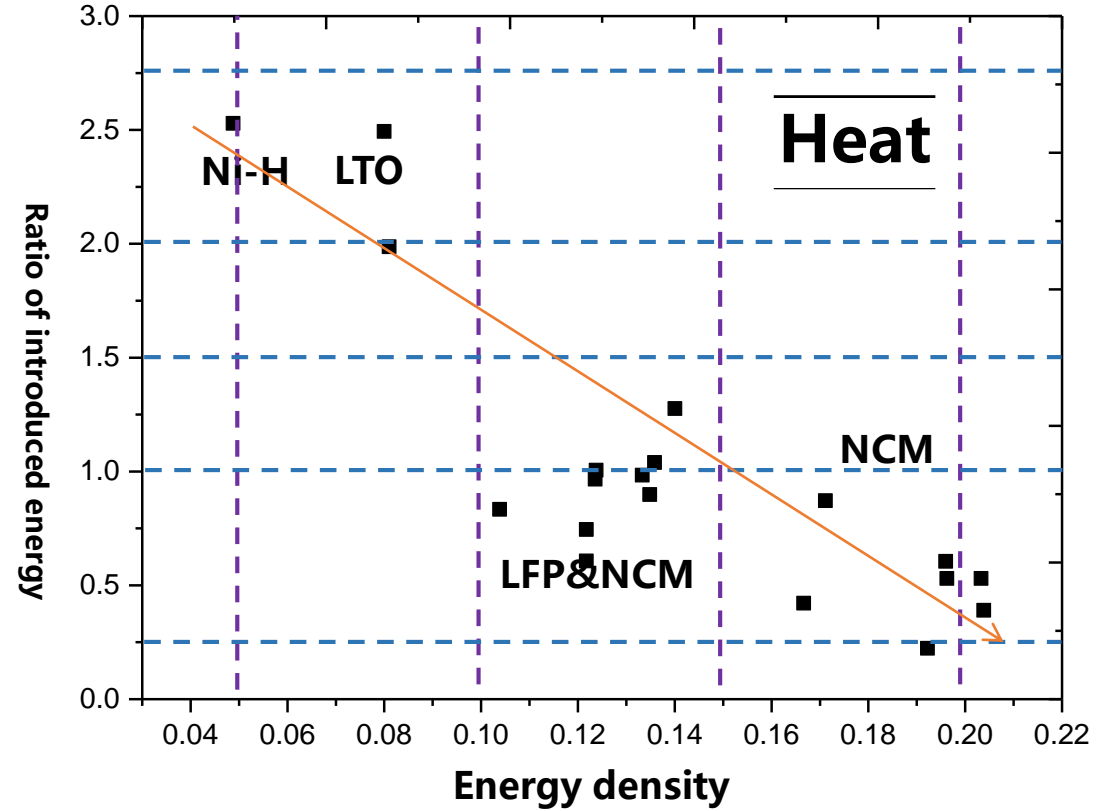
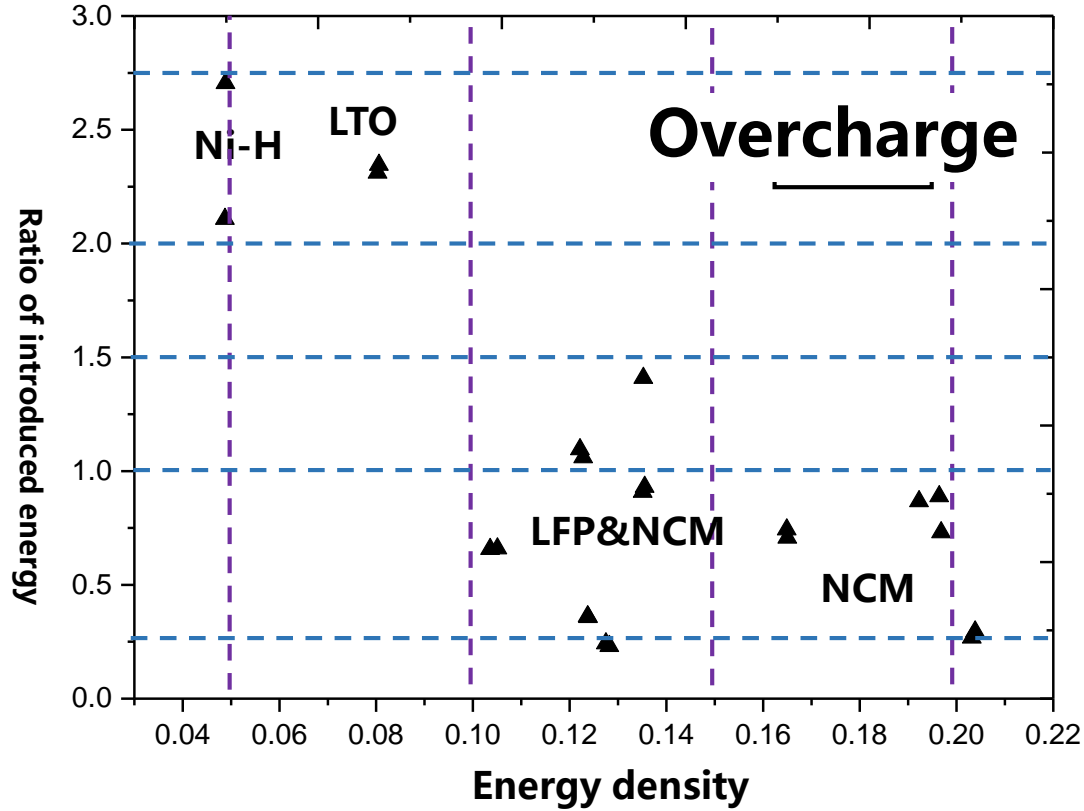


Ratio of introduced energy :

- Ni-H (1) : 2.53
- LTO (1) : 1.99~2.49
- LFP (3) : 0.83~1.28
- CNM (6) : 0.22~1.04

➤ The energy introduced is influenced by both the battery type and the triggering method

Test results



- The higher the energy density, the lower the energy required to trigger thermal runaway

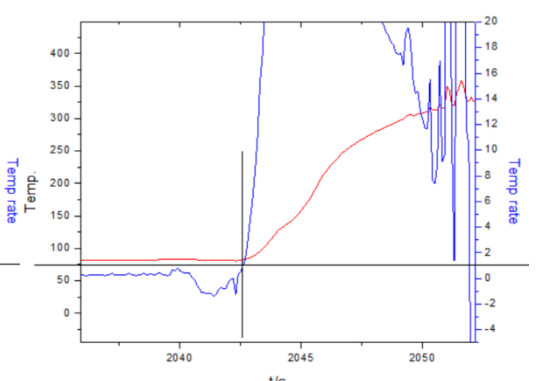
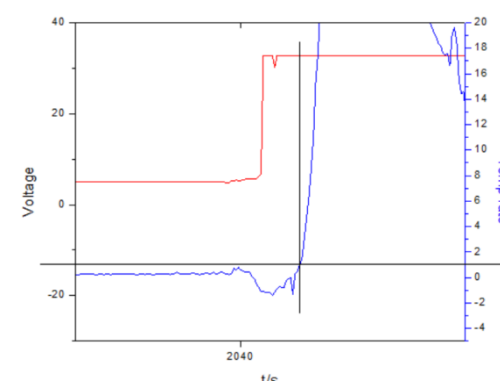
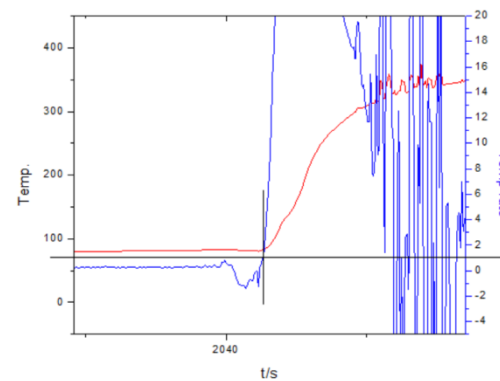
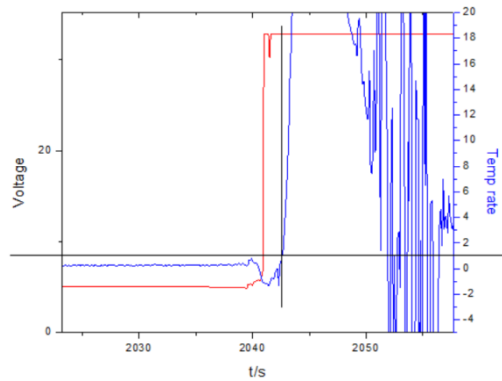
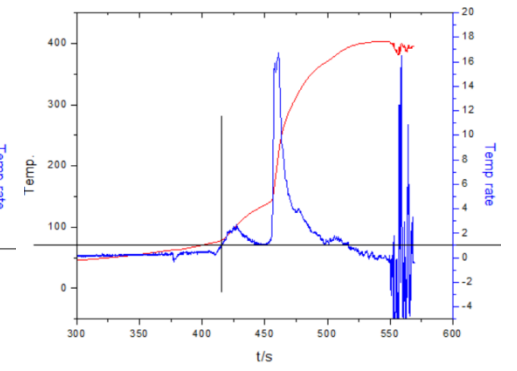
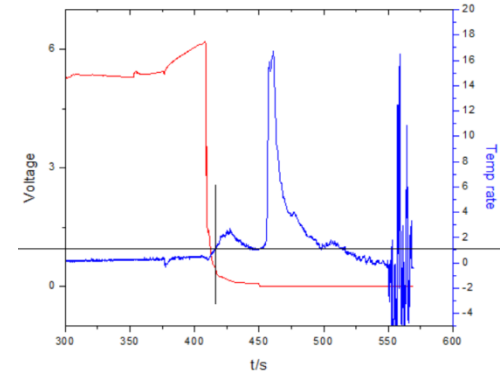
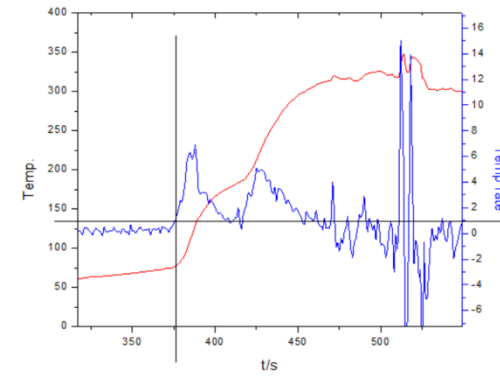
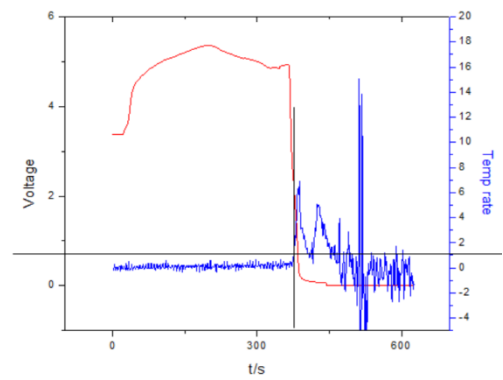
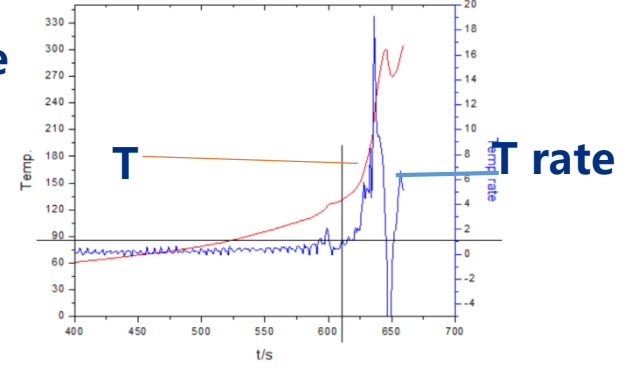
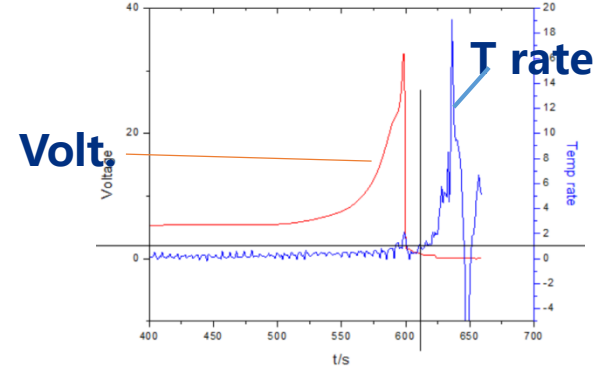
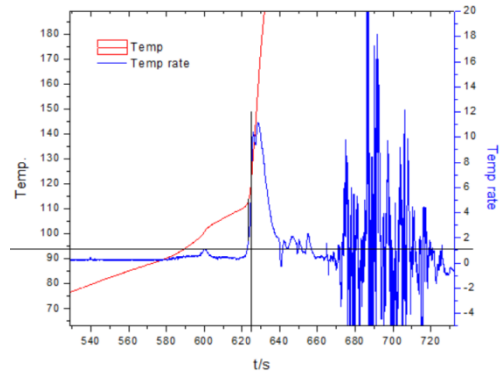
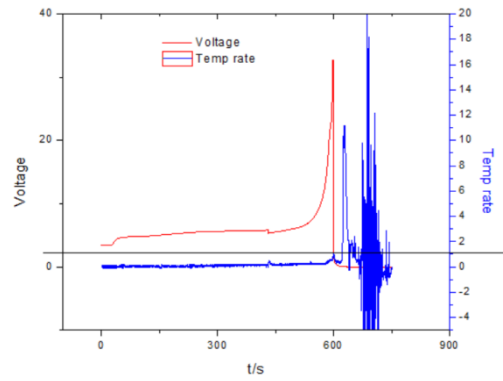
Test results

➤ Parameters of overcharge **No regularity**

Method	TR Temperature	Temp. rate	Voltage
Overcharge	113	2	0
	125	4	2.5
	90	2.5	2.5
	79	2	0
	75	1.5	1.5
	80	1.8	32 (MAX)
	85	1.9	32 (MAX)
	75	1.9	1
	105	2	30
	90	1.7	30 (MAX)
	95	4.1	0
	100	2	MAX

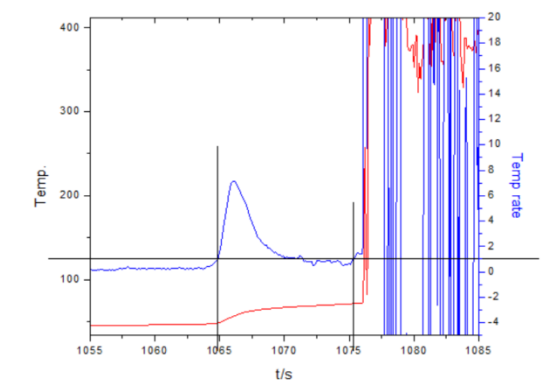
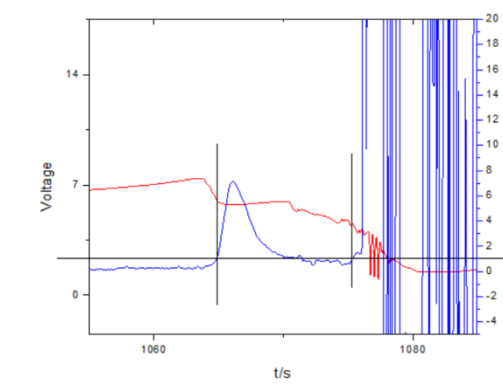
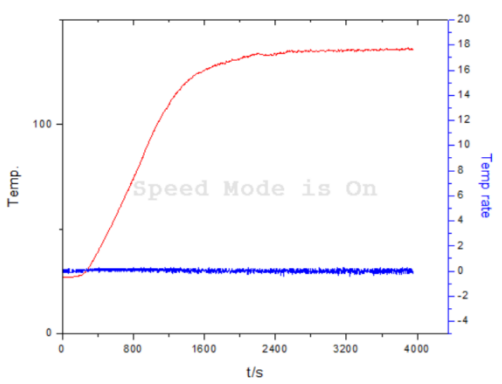
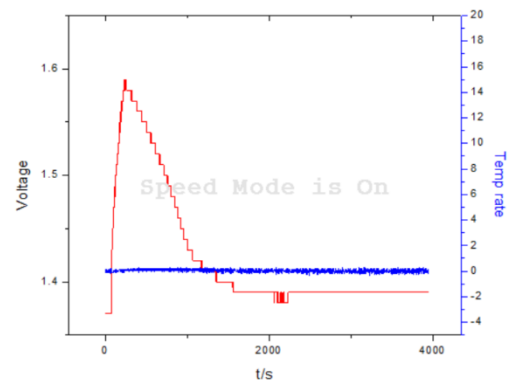
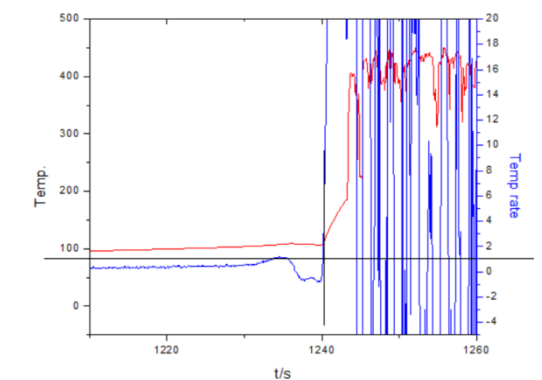
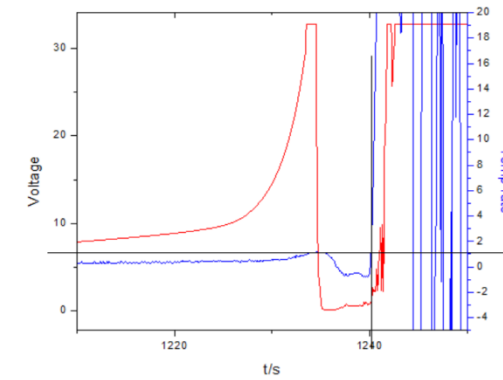
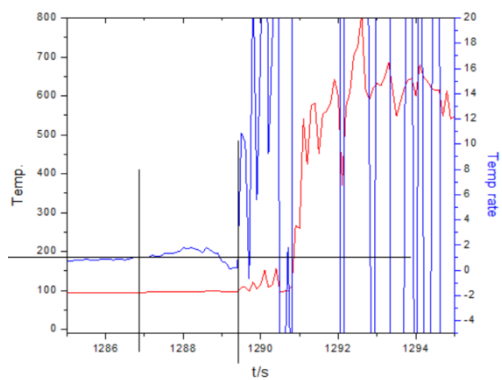
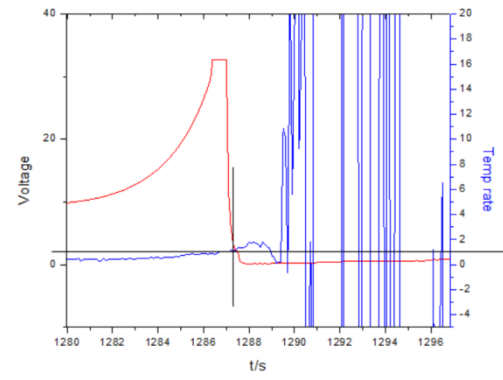
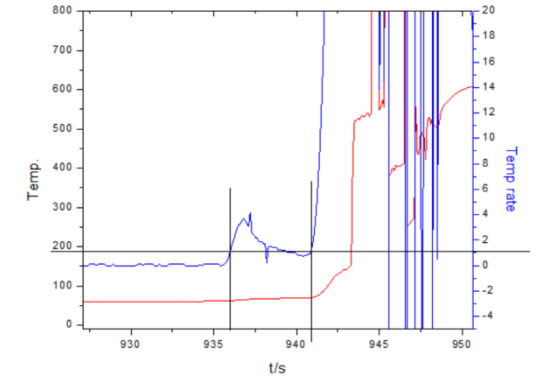
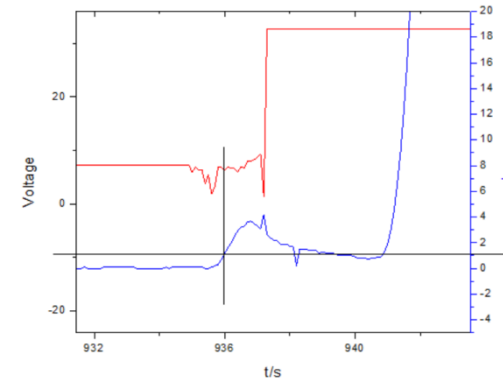
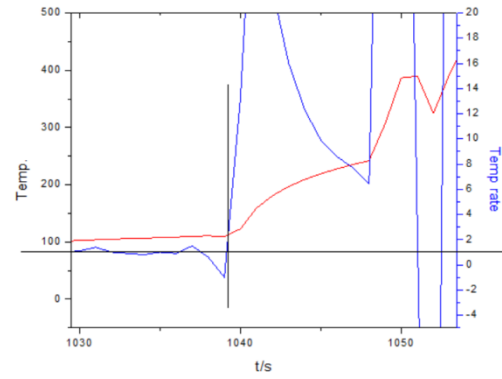
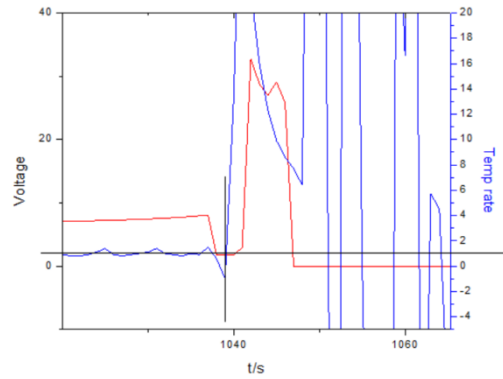
Test results

Curves of overcharge



Test results

Curves of overcharge



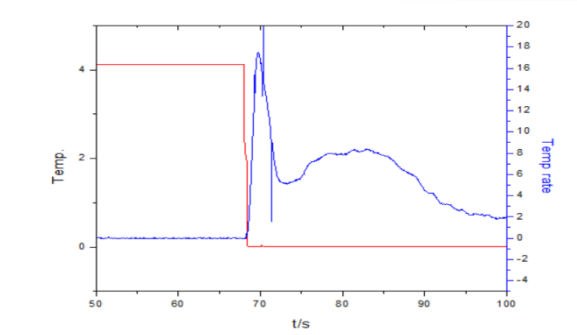
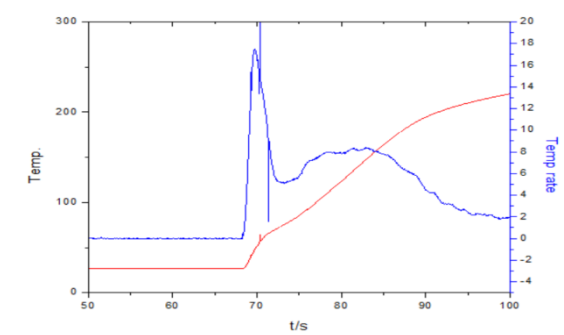
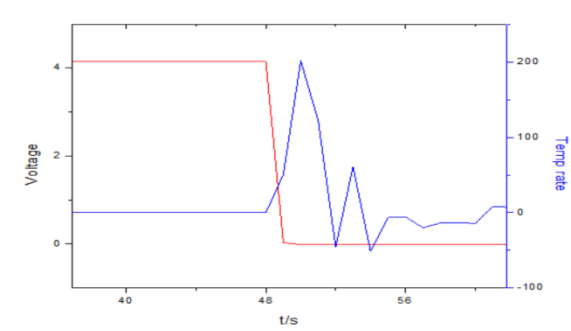
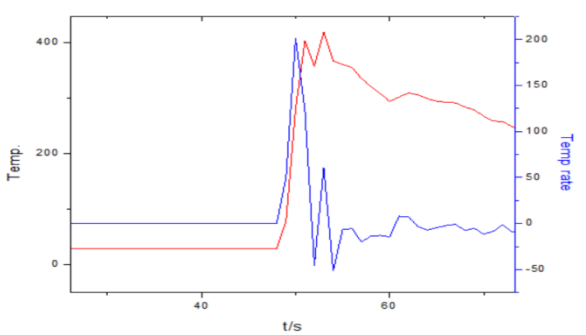
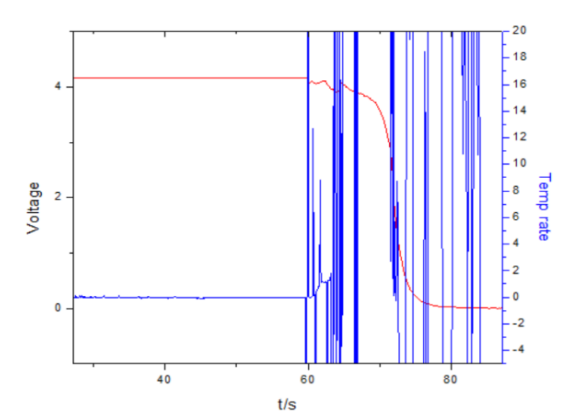
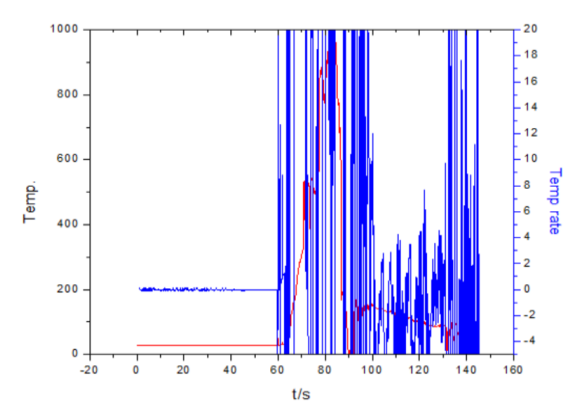
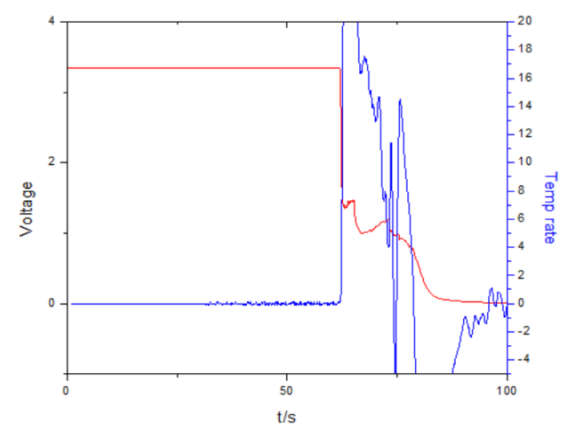
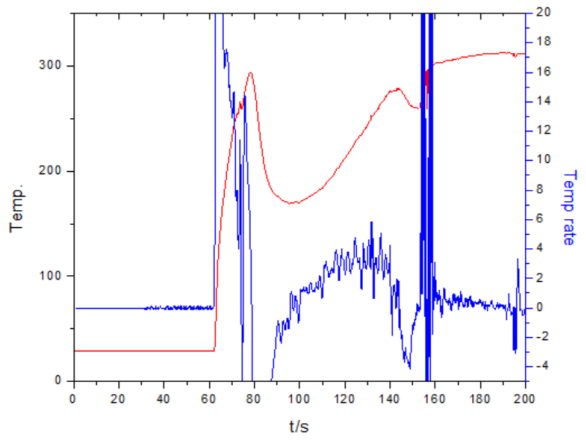
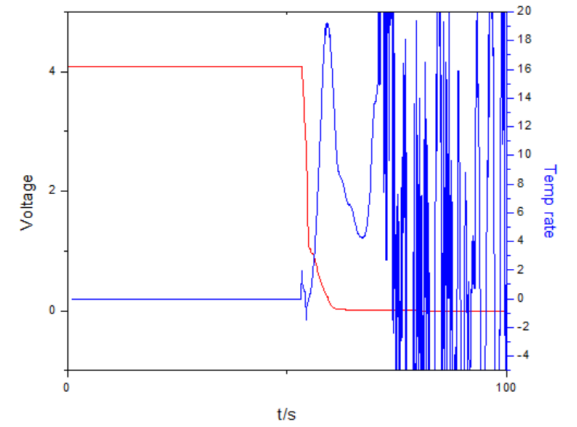
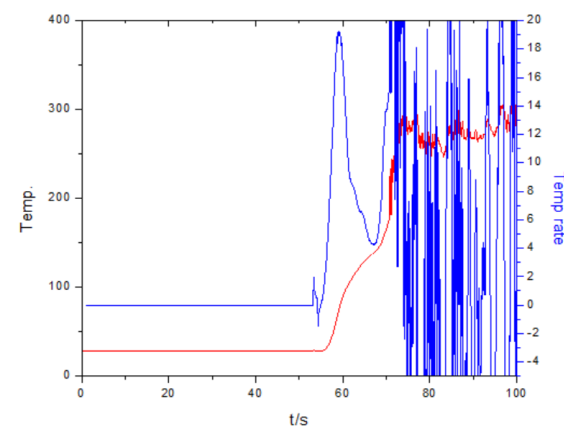
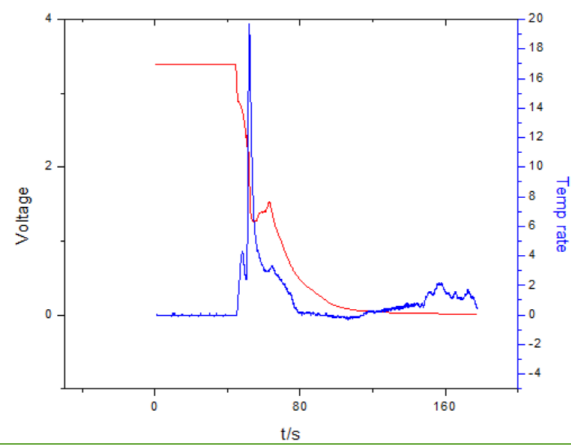
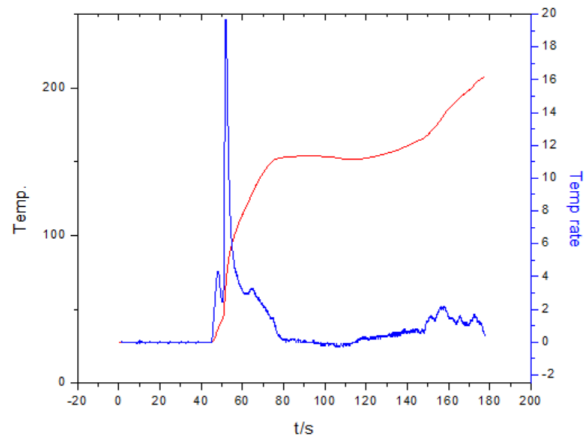
Test results

➤ Parameters of penetration

Sample	Method	Temp. rate 1°C/s	Temp. rate 2°C/s	Temp. rate 4°C/s
LFP-25	Penetration	28	30	48
LFP-25		29	30	35
NCM-26.5		25	30	32
NCM-26.5		28	29	30
LFP-22		28	31	34
LFP-22		28	28	31
LTO-30		---		
NCM-44		25	26	27
NCM-44		25	25	25
Ni-H-6		28	29	35
Ni-H-6		29	30	50
LFP-1.6		30	32	49
LFP-1.6		---		
NCM-2.0		28	29	31
NCM-2.0		30	30	33
NCM-33		25	28	34
NCM-33		30	30	37
LMO-35		27	29	35
LMO-35		28	30	33
NCM-2.5		25	25	30
NCM-2.5		25	25	25
NCM-26		29	29	30
NCM-26		29	29	30

Test results

Curves of penetration

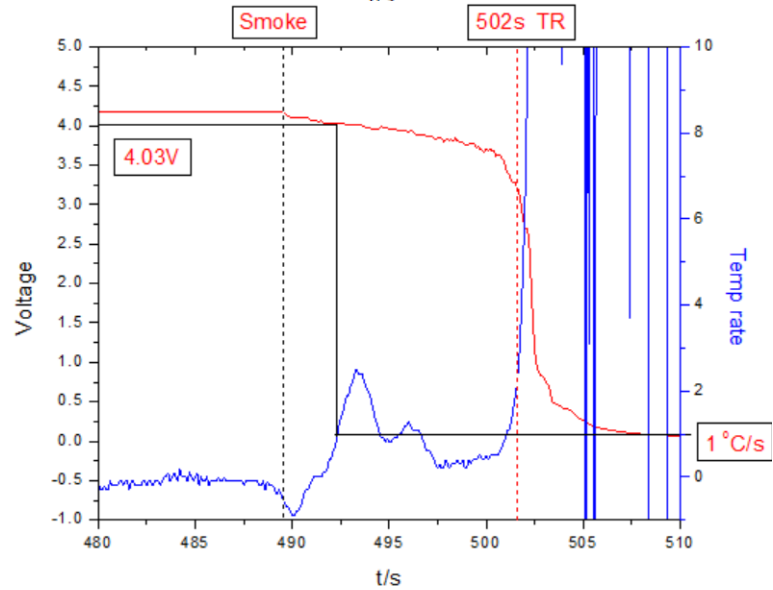
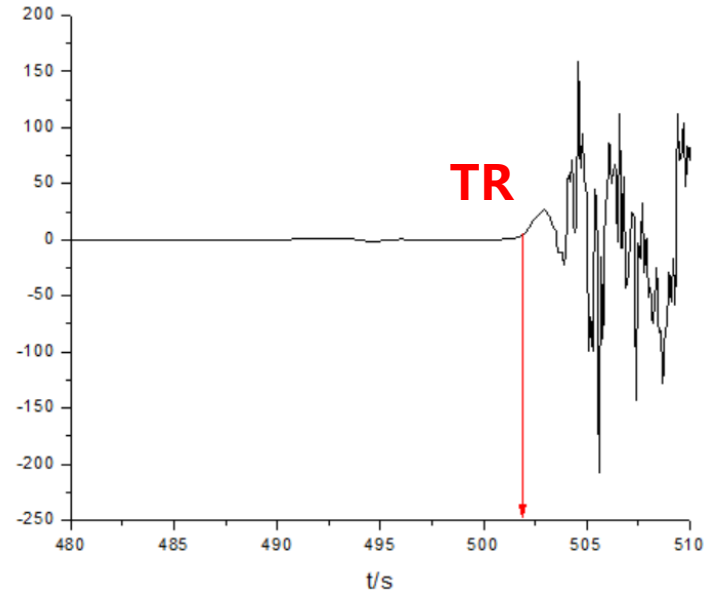
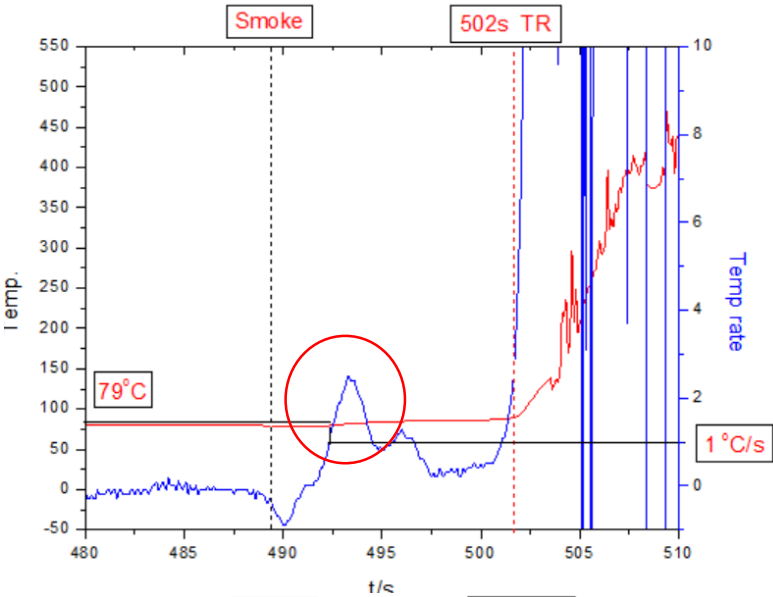


Test results

➤ Parameters of heat

Material	Energy density	Method	Time (s)	Ratio of introduced energy	T0	Tmax	Phenomenon	TR
NCM	203.83	Heat	790	39.03%	25	424.1	Fire	√
NCM	203.28		810	53.03%	25	565.1	Fire	√
NCM	196.21		1242	53.00%	25	562.9	Fire	√
NCM	195.98		1333	60.50%	25	503.7	Fire	√
NCM	192.23		497	22.35%	25	488	Fire	√
NCM	171.14		729	87.19%	25	744	Fire	√
NCM	166.63		518	42.13%	25	733.6	Fire	√
LFP	140.06		971	127.60%	25	353	Smoke	√
NCM	135.82		1440	103.95%	25	629.7	Fire	√
NCM	134.83		1245	89.87%	25	581.3	Fire	√
LFP	133.30		518	98.36%	25	318.2	Smoke	√
LFP	123.78		1790	100.53%	25	441.1	Smoke	√
LFP	123.58		1345	96.59%	25	402.8	Smoke	√
NCM	121.76		1240	60.67%	25	789	Fire	√
NCM	121.76		1465	74.54%	25	502.8	Smoke	√
LTO	81.01		1740	198.67%	25	115.8	—	×
LTO	80.00		2444	249.33%	25	172.2	—	×
Ni-H	48.77	284	252.85%	25	329.4	Smoke	×	

Test results



TR time/s	T / °C	T rate / °C/s	V drop/%
501	87.4	1.1	35.25 %

V drop	Time / s	T / °C	T rate / °C/s
0%	489.7	78.6	-0.7
25%	501.7	89.6	2.8
50%	502.3	102.7	14.9
75%	502.5	109.3	20.8
100%	555	378.7	-0.9
T / °C	Time / s	V	T rate / °C/s
60	191	4.17	0.2
100	502.2	2.59	11.6
150	504	0.41	20.2
200	505	0.26	62.7
T rate / °C/s	Time / s	T / °C	V
0.5	491.9	78.6	4.03
1	492.3	79.1	4.03
2	493	80.7	4.02
3	501.7	89.6	3.14
4	501.8	90.6	2.99
5	501.9	91.9	2.81

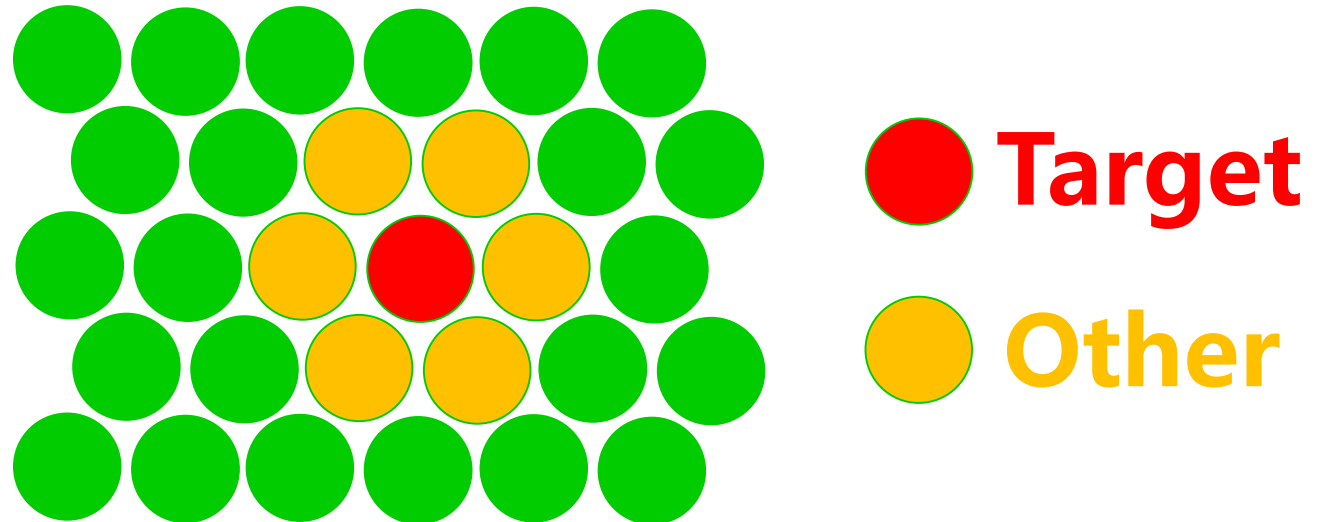
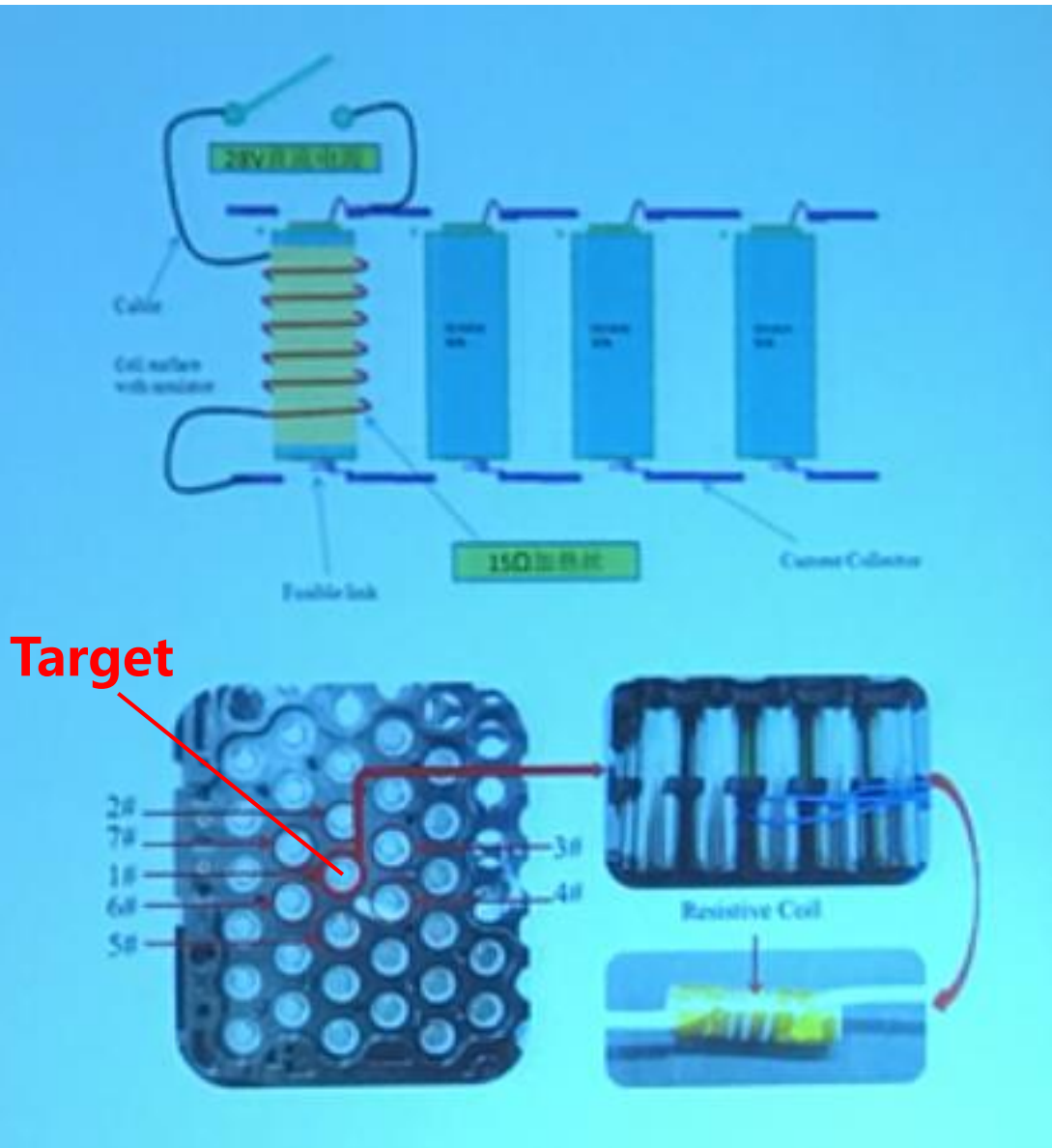
Test results

parameters		LFP-25Ah		LFP-22Ah		NCM-44Ah		LFP-1.6Ah-1		LFP-1.6Ah-2		NCM-2.0Ah-1		NCM-2.0Ah-2		NCM-33Ah-1		NCM-33Ah-2		LM0-35Ah-1		LM0-35Ah-2		NCM-2.5Ah-1		NCM-2.5Ah-2		NCM-26Ah-1		NCM-26Ah-2	
		Time	Judgment	Time	Judgment	Time	Judgment	Time	Judgment	Time	Judgment	Time	Judgment	Time	Judgment	Time	Judgment	Time	Judgment	Time	Judgment	Time	Judgment	Time	Judgment	Time	Judgment	Time	Judgment	Time	Judgment
TR Time		1019		1778		501		937		1224		495.5		719		1321.6		1246		1243		1473.5		816.7		790.5		1421.7		1249	
Voltage	0%	1006	×	1433.3	×	489.7	×	555.3	×	787.4	×	297.3	×	490	×	1317	×	1238	×	1234.4	×	1454.2	×	557.9	×	601.3	×	890.9	×	695.4	×
	25%	1020.5	✓	1493.9	×	501.7	✓	555.3	×	787.4	×	297.3	×	490.5	×	1317.1	×	1239.9	×	1237.1	×	1456	×	558.1	×	605.9	×	890.9	×	695.4	×
	50%	1022.5	✓	1496.5	×	502.3	✓	555.3	×	787.4	×	345.2	×	505.3	×	1317.4	×	1245.5	×	1238.4	×	1458.1	×	628.5	×	674.7	×	890.9	×	695.4	×
	75%	1026.3	✓	1500.6	×	502.5	✓	555.3	×	787.4	×	346.7	×	528.7	×	1317.8	×	1246.3	✓	1239.9	×	1460.7	×	672.9	×	674.9	×	890.9	×	695.4	×
	100%	1061.9	✓	1781.9	✓	555	✓	555.3	×	787.4	×	495.5	✓	719.8	✓	1329.5	✓	1255.5	✓	1251	✓	1474.1	✓	781.3	×	778.1	×	890.9	×	695.4	×
Temp.	60	499.9	×	95	×	191	×	38.5	×	177.8	×	21.6	×	111.2	×	264.3	×	566.7	×	823.1	×	937.9	×	153.4	×	39.3	×	339.4	×	254.4	×
	100	933.5	×	387.7	×	502.2	✓	205.9	×	402.3	×	44	×	286.5	×	801.6	×	1246.5	✓	1247	✓	1464.2	×	407.6	×	297.5	×	653.2	×	582.3	×
	150	1056.1	✓	781.5	×	504	✓	598	×	823.6	×	159.4	×	589.7	×	1237.4	×	1247.5	✓	1247.5	✓	1474.4	✓	808.8	×	658.6	×	1342.8	×	1199	×
	200	1074.6	✓	1242.8	×	505	✓	897.5	×	1193.8	×	363.1	×	717.3	×	1321.7	✓	1247.7	✓	1247.6	✓	1475.1	✓	817	✓	790.7	✓	1424.8	✓	1250.6	✓
Temp. rate	0.5	1017	×	1390.1	×	491.9	×	/	×	1149	×	438.9	×	669.1	×	1312.8	×	1238.1	×	1238	×	1453.2	×	1453.2	×	780.4	×	1419.1	×	1237.1	×
	1	1022	✓	1470.1	×	492.3	×	936.4	×	1202.4	×	488	×	710.2	×	/	✓	1238.3	×	1240.4	×	1459.6	×	799.8	×	783.1	×	1421.7	✓	/	×
	2	1065	✓	1780.5	✓	493	✓	947.5	✓	1234.5	✓	495.6	✓	719.4	✓	/	✓	1238.5	✓	/	✓	/	✓	/	✓	790.3	✓	1421.9	✓	/	✓
	3	1069	✓	1782	✓	501.7	✓	967.6	✓	1235.7	✓	495.8	✓	/	✓	/	✓	1238.7	✓	/	✓	/	✓	/	✓	790.5	✓	1422.6	✓	/	✓
	4	1071	✓	1783.8	✓	501.8	✓	968.2	✓	1236.6	✓	495.8	✓	/	✓	/	✓	1239	✓	/	✓	/	✓	/	✓	/	✓	1423	✓	/	✓
	5	1073	✓	1793	✓	501.9	✓	969.1	✓	1237.1	✓	496	✓	719.5	✓	1321.6	✓	1246.5	✓	1242	✓	1470	✓	816.9	✓	790.6	✓	1423.2	✓	1246	✓
V & T	V	25%	✓	100%	✓	25%	✓	100%	×	100%	×	75%	✓	75%	✓	75%	✓	50%	✓	75%	✓	75%	✓	100%	✓	100%	✓	100%	✓	100%	✓
	T	150		>200		100		>200	×	>200	×	>200		>200		200		100		100		150		200		200		200			
V & T rate	V	25%	✓	100%	✓	25%	✓	100%	✓	100%	✓	75%	✓	75%	✓	75%	✓	50%	✓	75%	✓	75%	✓	100%	✓	100%	✓	100%	✓	100%	✓
	T rate	1		2		2		2		2		2		2		2		1		2		2		2		2		2			
T & T rate	T	150	✓	>200	✓	100	✓	>200	✓	>200	✓	>200	✓	>200	✓	200	✓	100	✓	100	✓	150	✓	200	✓	200	✓	200	✓	200	✓
	T rate	1		2		2		2		2		2		2		1		2		2		2									

Test results

➤ Repeatability of heating

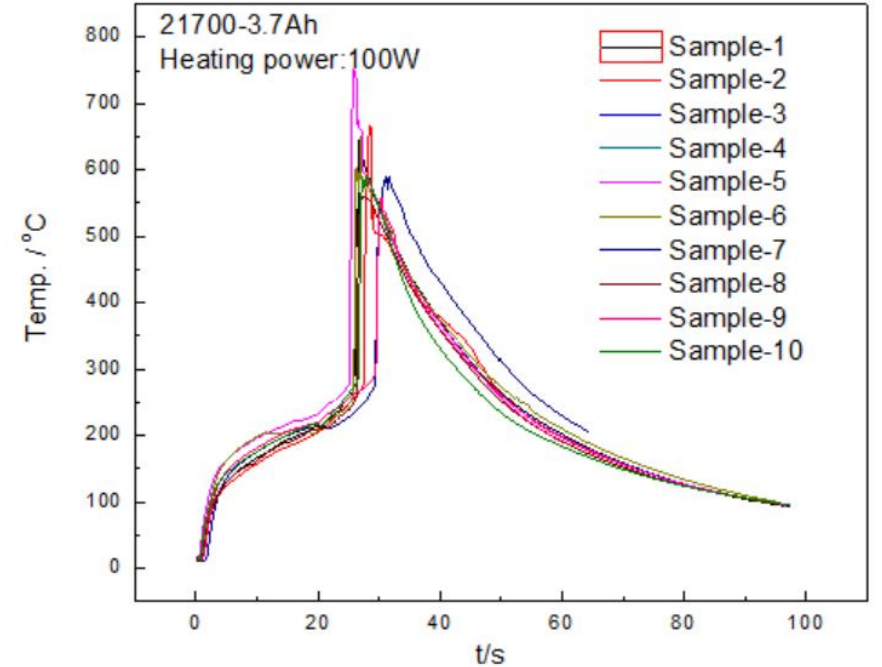
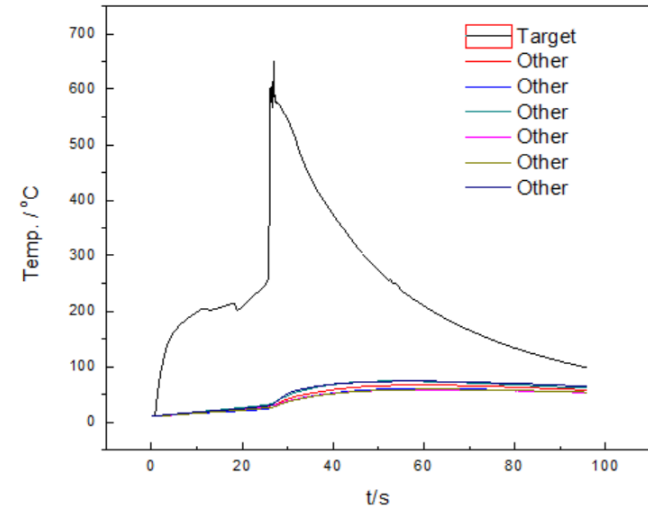
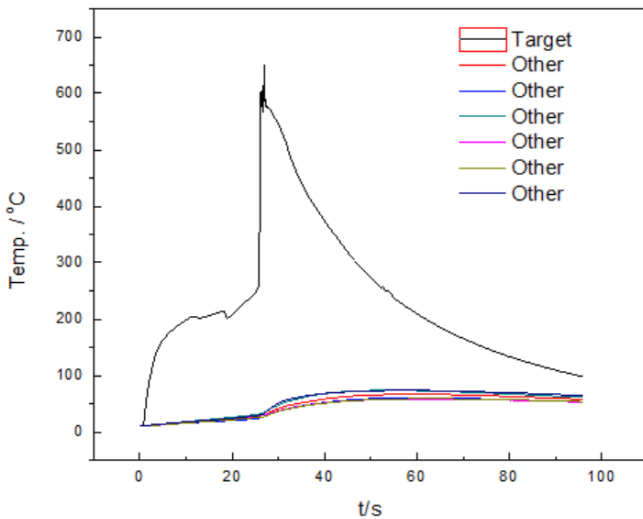
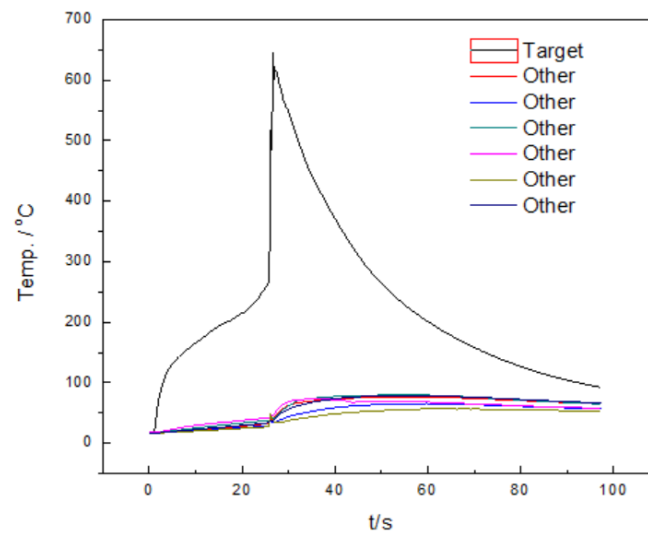
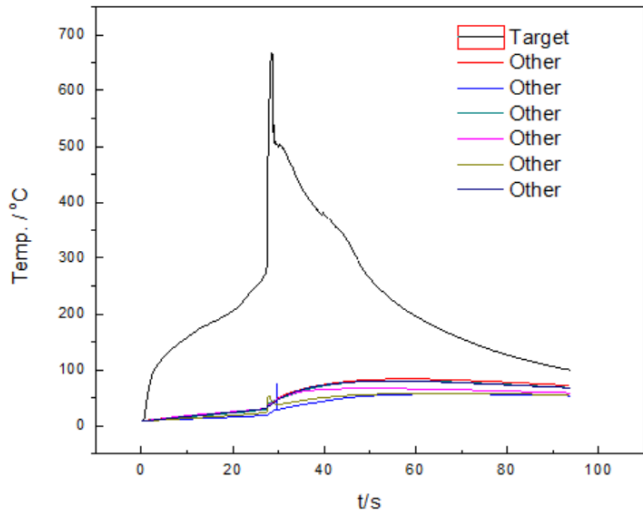
- ◆ Samples: 21700-3.7Ah-NCM
18650-3.0Ah-NCA
- ◆ SOC : 100%
- ◆ Heating Power: Fixed, 80W/100W
- ◆ Ambient temperature: 5°C~30°C



Test results

➤ 21700-3.7Ah

➤ Heating power: 100W



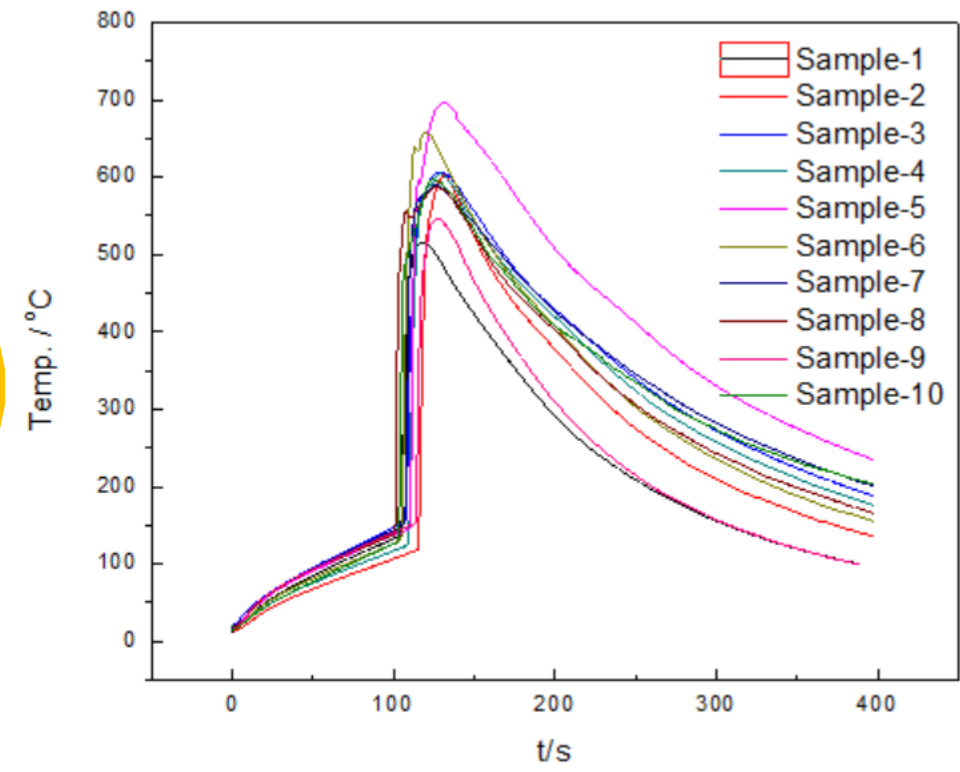
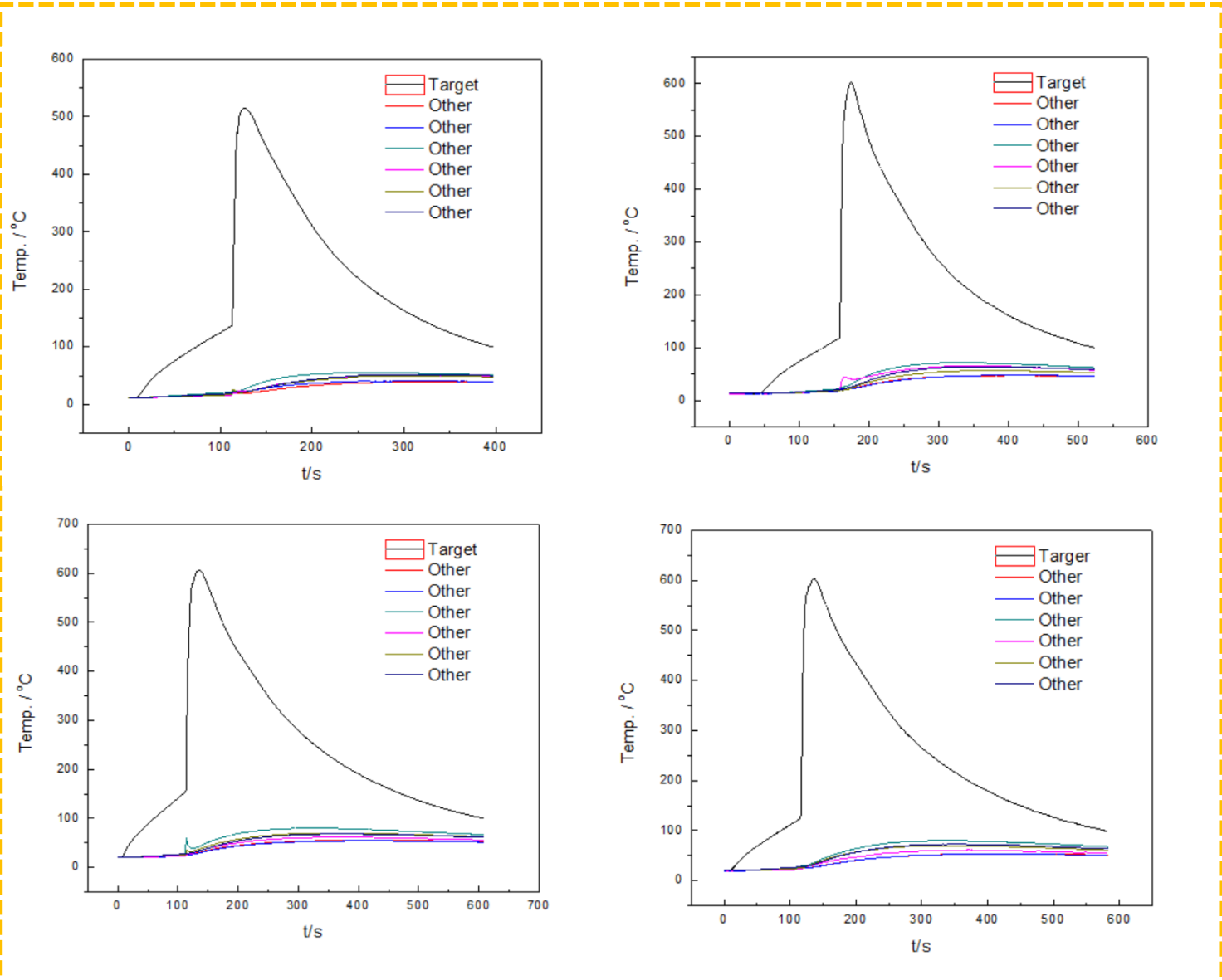
◆ More than 10 tests

◆ Show good repeatability

Test results

➤ 18650-3.0Ah-NCA

➤ Heating power: 80W



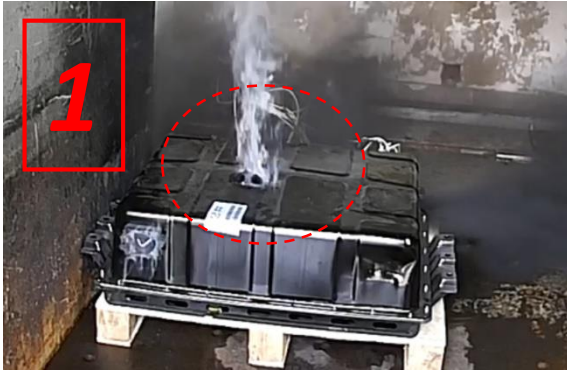
- ◆ More than 10 tests
- ◆ Show good repeatability

Test results

Samples	Application	Cell type	TR method	Fire Time after TR
1	PHEV	Prismatic-NCM	Heat	20min
2	EV	Prismatic-NCM	Heat	No fire after 15min
3	EV	Prismatic-NCM	Heat	36min
4	EV-bus	Pouch -NCM	Heat	5.6min
5	EV-bus	Cylindrical-LTO	Heat	No Fire
6	EV-bus	Cylindrical-LTO	Heat	No TR
.....more than 200	EV-buses	LFP	Heat or overcharge	No fire

Test results

Prismatic-NCM



0 min smoke



10 min smoke



15 min smoke



0 min smoke



10 min smoke



15 min smoke



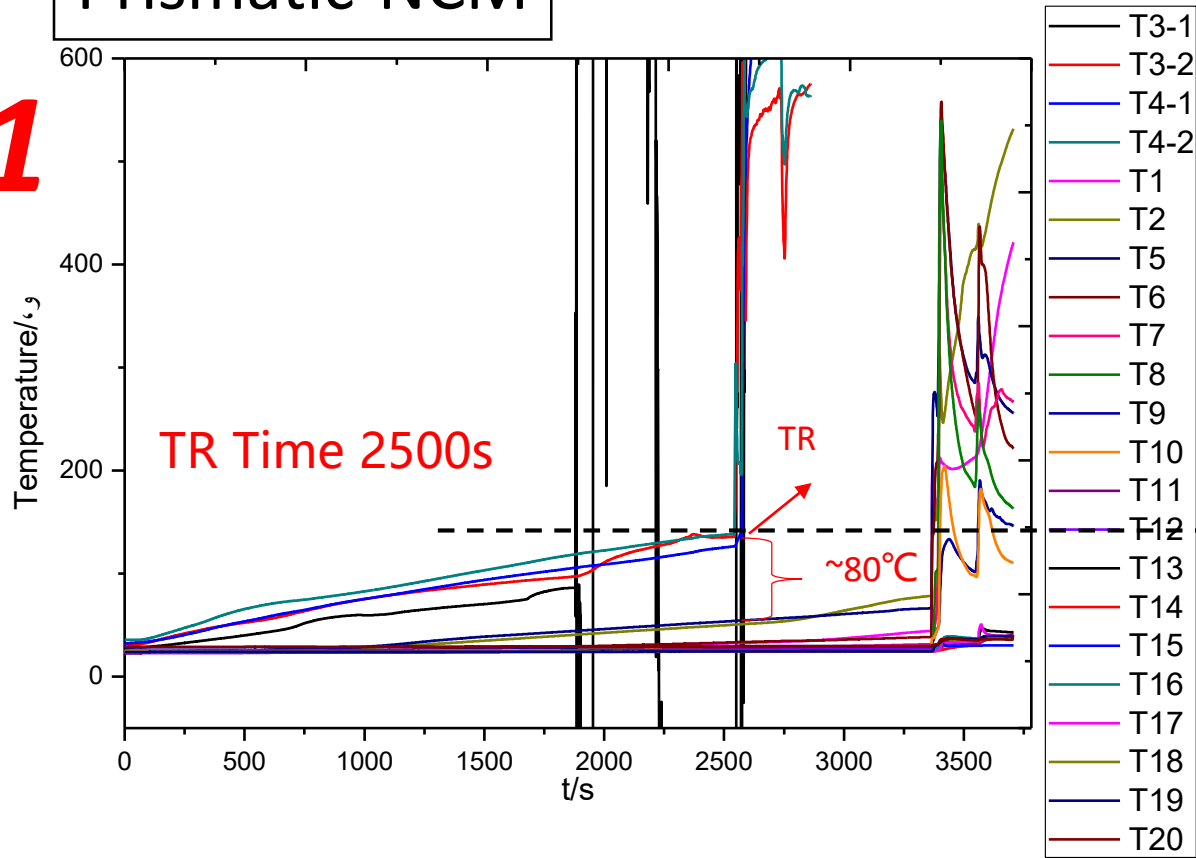
36.5 min fire

➤ Almost the same results

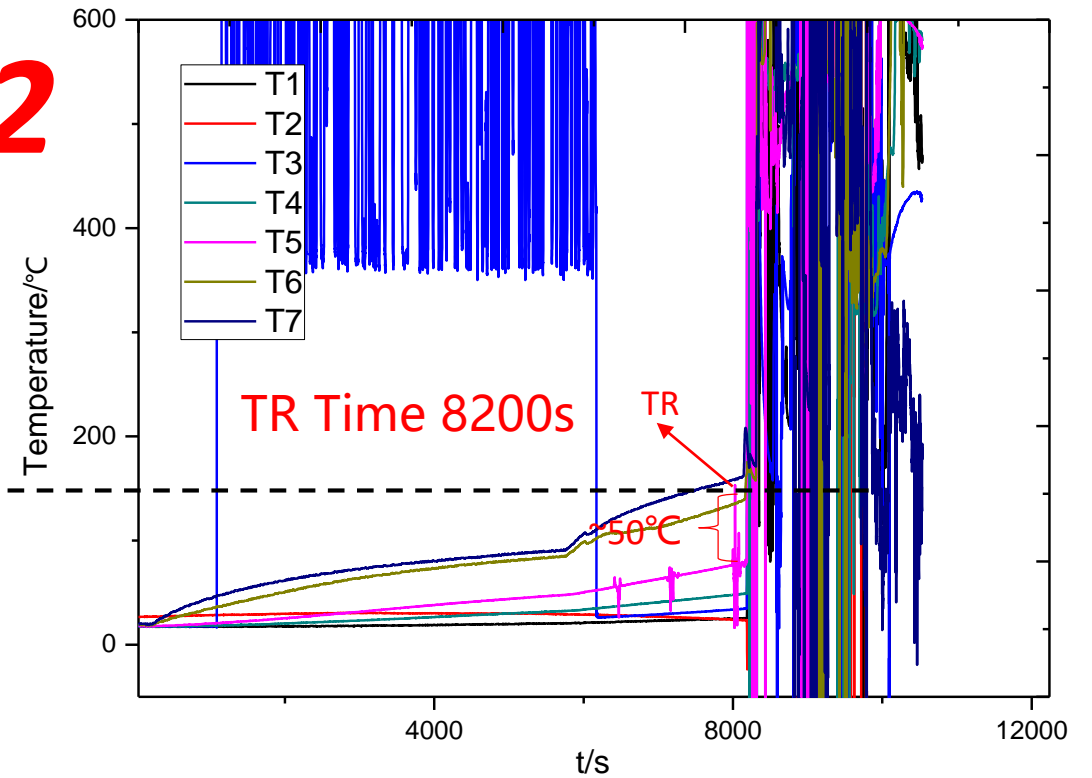
Test results

Prismatic-NCM

1



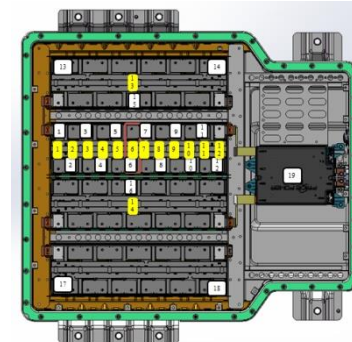
2



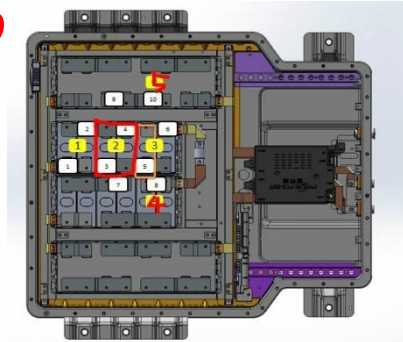
- The TR temperatures are both 150°C
- The temperature gradient between the cells is larger for sample 1, which has a shorter heating time
- The shorter heating time, the smaller the impact on other cells

➤ Different heating power

1



2



Test results

- ◆ Overcharge has low success rate to trigger thermal runaway
- ◆ Penetration can trigger thermal runaway, but still some batteries can not be triggered
- ◆ Heating can trigger most of the batteries thermal runaway.
- ◆ The energy and characteristic parameters (voltage, temperature, temperature change rate, etc.) vary greatly when using different trigger methods
- ◆ The phenomenon and characteristic parameters (voltage, temperature, temperature change rate, etc.) showed good repeatability with the same triggering method on the same battery

5.2.7 Lithium-ion battery packs or systems shall be tested for thermal stability in accordance with 8.2.7 and shall not explode in an external fire test

8.2.7.1 External fire

8.2.7.2 Thermal propagation

manufacturers have two options for thermal propagation analysis or verification of lithium-ion battery packs or systems:

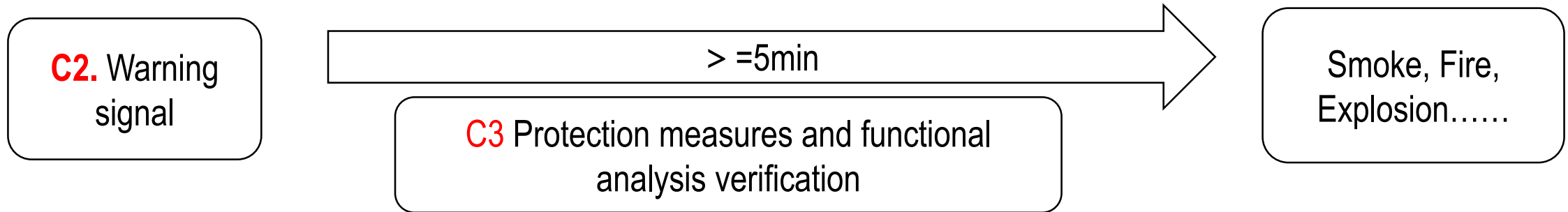
—Option 1: (Appendix C) Protection Analysis and Validation Report for thermal propagation

—Option 2: (Appendix D) Thermal propagation test report

Note : No requirement for Ni-H battery

GB draft

Option 1 (Appendix C) Protection Analysis and Validation Report for thermal propagation



C2.1 Parameters of trigger warning signal	C2.2 Introduction of warning signal
Threshold of temp. ,temp. rate, SOC, volt. Drop.....	Sensors, control instructions in the thermal event

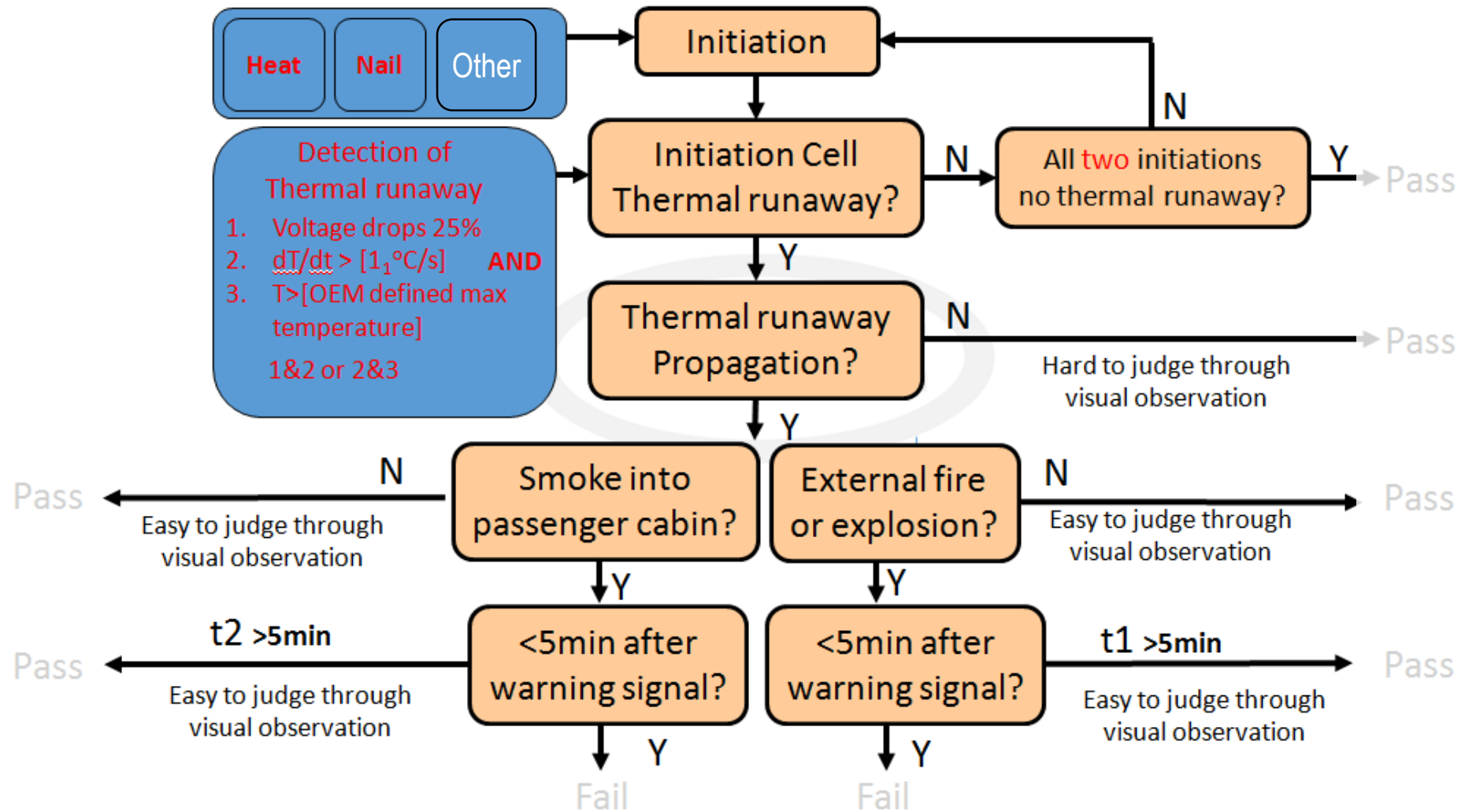
C3.1 Risk reduction analysis
C3.2 System diagrams of related physical systems and components
C3.3 Chart showing functional actions of related systems and components, confirming all risk mitigation features or characteristics
C3.4 A description of each identified risk mitigation feature or characteristic

C3.4.1 Operation strategy
C3.4.2 System identification
C3.4.3 Analysis and simulation report
C3.4.4 Test verification report

Time
Test procedure (Appendix D or other methods)
Test results

GB draft

Option 2 (Appendix D) Thermal propagation test report



Further research plan

- ◆ Thermal runaway triggering method reproducibility (different methods, different heating rate)
- ◆ Thermal propagation test results reproducibility verification (different methods, different heating rate)
- ◆ Investigate potential new methods for initiation

Thanks