Thermal propagation

- Korean proposal -

EVS-GTR TF#8 meeting in Washington

Jun 15, 2016

Introduction

❖ **DUT Level and criteria**

- As the target is to achieve safety performance of the vehicle, it is necessary to evaluate at vehicle level.
- However, it takes a lot of resources to test at vehicle level
- As an alternative, test can be conducted in module or system level to estimate the hazard level with real vehicle test.

→ The correlation of hazard level/safety performance between real vehicle level and module/system level should to be investigated

❖ Correlation test and case study

- Purpose: Test data for correlation between battery and vehicle hazard level
- Available data

<table>
<tr><th></th><th>Cell</th><th>Module</th><th>Pack</th><th>Vehicle</th></tr>
<tr><td rowspan="3"><u>Single cell abuse test</u>:
Nail penetration, Overcharge,
Short circuit, Crush</td><td colspan="3">▪ Certification data: QC/T, GB/T</td><td></td></tr>
<tr><td colspan="3">▪ Manufacturer’s internal test data</td><td></td></tr>
<tr><td colspan="3">▪ Manufacturer’s benchmarking test data ①</td><td></td></tr>
<tr><td rowspan="2"><u>Heat propagation test by heater</u></td><td colspan="4">▪ ③ Bus Test</td></tr>
<tr><td></td><td></td><td></td><td>▪ ② Passenger</td></tr>
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→ Based on the correlation test data ①,②,③, the correlation between battery and vehicle hazard level were investigated

Case study : ② Passenger car thermal propagation test

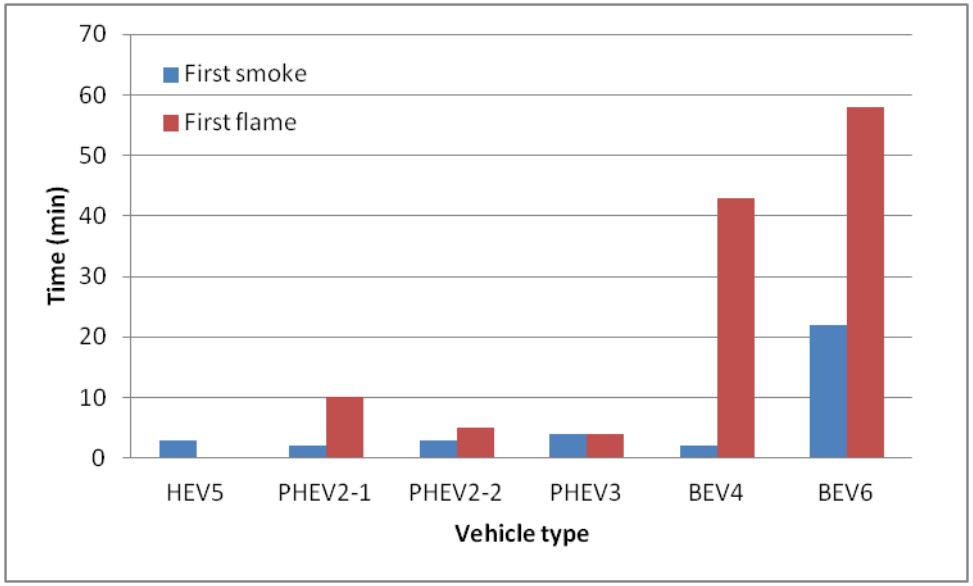
- **Internal fire test (**Presented at AABC Symposium – 2015 June)
  - DOT/NHTSA/SAE Cooperative research project
  - Test executed by TUV-SUD
  - Purpose : Support xEV vehicle safety standard by providing practical test method and results database

	Test condition
Initiation method	Partial heating: replacing one cell in module with heater or install heaters at cell top/bottom ※ heating method is dependent on battery cell/module design & type. 
Test method	1. DUT: module, pack, vehicle including heater 2. Preheating : Operating condition(5pt over 40℃) 3. Initiation : continue heating until single cell thermal runaway. 4. Real time based cabin temp, evolving gas measurement. 
Heater power	Power : 2~12kW ※ Calculated based on MATLAB model Targeted temp control range: 550~630℃(< Al melting point) 
Instrumentation	Vehicle : in/outside temp, toxic gas(CH4, CO) concentration Pack : Voltage, Temp in/outside Cell : Voltage, Temp 

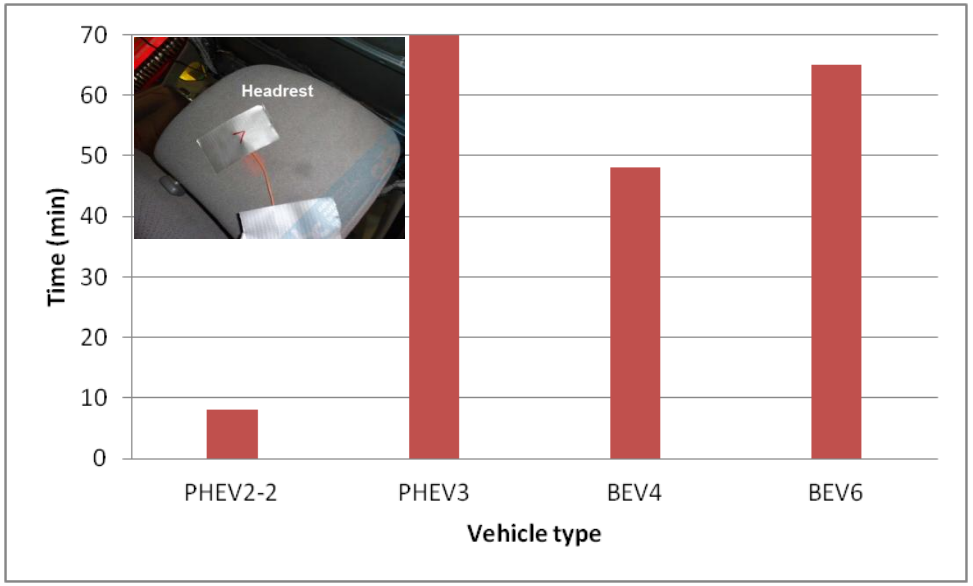
Case study : ② Passenger car thermal propagation test

▪ Test result

<Time to first smoke/flame>



<T50:time to 50℃ at driver headrest>



▪ Summary

• Time to first smoke and flame:

① BEV : all safety event were after 20 min

→ enough time for occupant to escape

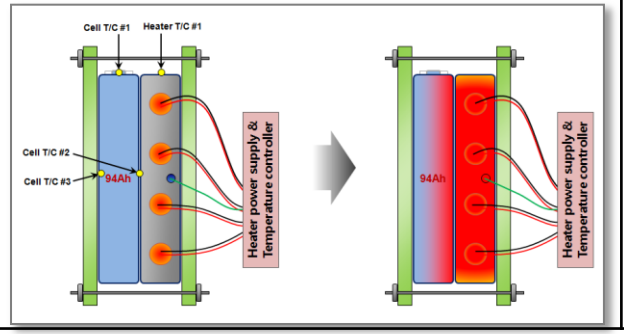
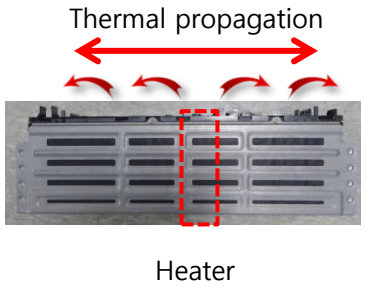
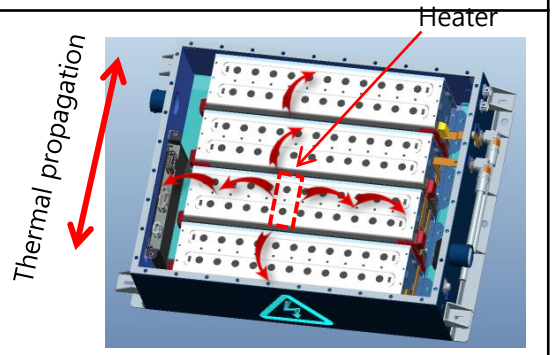
② The hazard occurrence speed of BEV is slower than that of HEV/PHEV

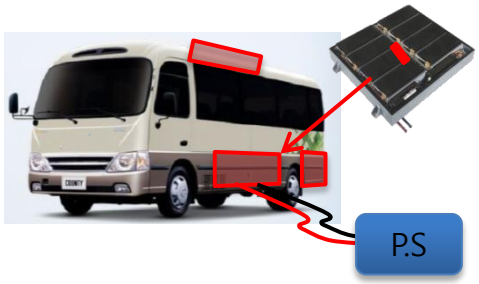
→ Other vehicle design parameters are more important than the amount of battery energy

※ HEV/PHEV battery pack is generally located behind rear seat, while EV battery is located underneath the underbody.

Time to	HEV	PHEV	BEV
Smoke	3min	2~4min	2~22min
CO gas	~10min	~10min	Not measured
Flame	-	4~10min	43~58min
T50	-	8~145min	48~65min

Correlation test : ③ Bus thermal propagation test

Cell	Module	Pack
- Validity of initiation method - Safety event severity by heater power	- Thermal propagation speed and pattern in module structure	- Propagation speed and pattern between adjacent modules
		

Vehicle
- Propagation speed to cabin area in real vehicle condition


- Observe propagation speed and pattern by step test for each cell-module-pack-vehicle level.
- Define relationship between vehicle and sub-component thermal propagation test result and develop module pack heat propagation test condition/criteria

Correlation test : ③ Bus thermal propagation test

BUS test

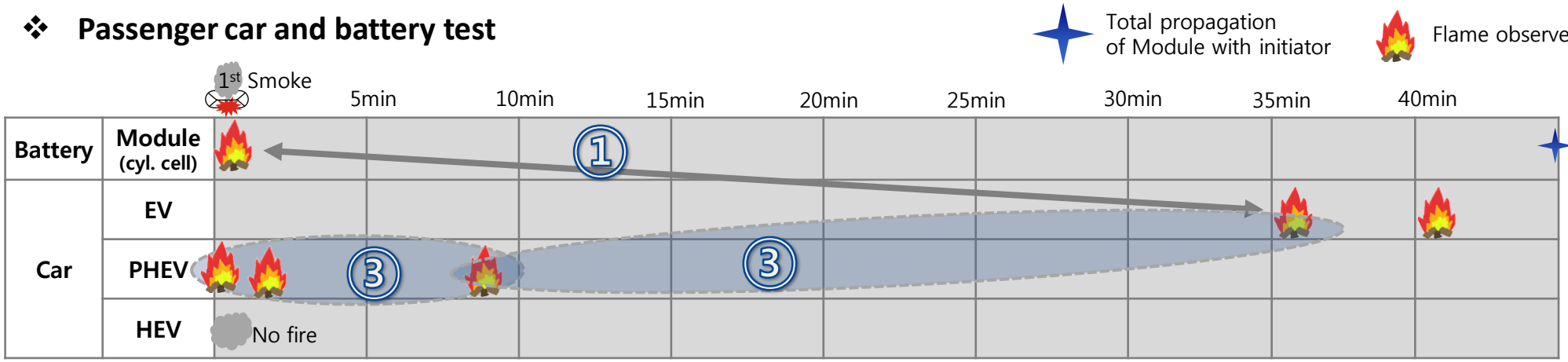
◆ Each DUT level, cell, module/pack and vehicle, were tested

- ✓ Cells/batteries did not result in explosive safety event.
- ✓ Forced thermal runaway on cell was propagated into total system and resulted in total vehicle burning.
- ✓ Enough time for occupants to escape was secured.
  - • Hazard indicator; fire in cabin and 50℃ in cabin observed at 30~40min. after initiation
  - • It was not resulted in catastrophic thermal event like explosion even though it was propagated.

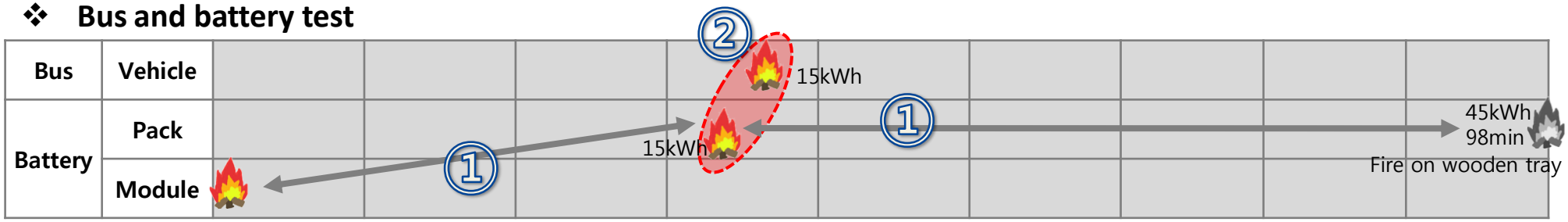
Hazard indicator		TFV	TLV	TFF	TFE	TE	TGD	T50℃
		Time to First Vent	Time to Last Vent	Time to First Flame	Time to Flame End	Time to Explosion	Time to Gas Detect(~50ppm)	Time to 50℃ at cabin
Module	A	7min	36min	8min	55min	NA	NA	NA
	B	7min	21min	10min	-	NA	NA	NA
Pack	15kWh	6min	26min(HT module) 55min(Pack)	23min	65min	NA	NA	NA
	45kWh	7min	36min(HT module) 150min(Pack)	(105min) Wooden tray	160min	NA	NA	NA
Vehicle (Initiation on 15kWh pack)		7min	21min(HT module) 27min(HT pack) 60min ↑ (Packs) 100min ↑ (Veh)	25min (Outside low) 32min(cabin)	125min	NA*	7min 12min(smoke)	35min

Correlation of test results

❖ Passenger car and battery test



❖ Bus and battery test



➢ Time to flame

① Module test: Fire observed right after thermal propagation.
Pack test: Time to first flame delayed. Depending on system design and energy contents inside the system, the fire can be prevented

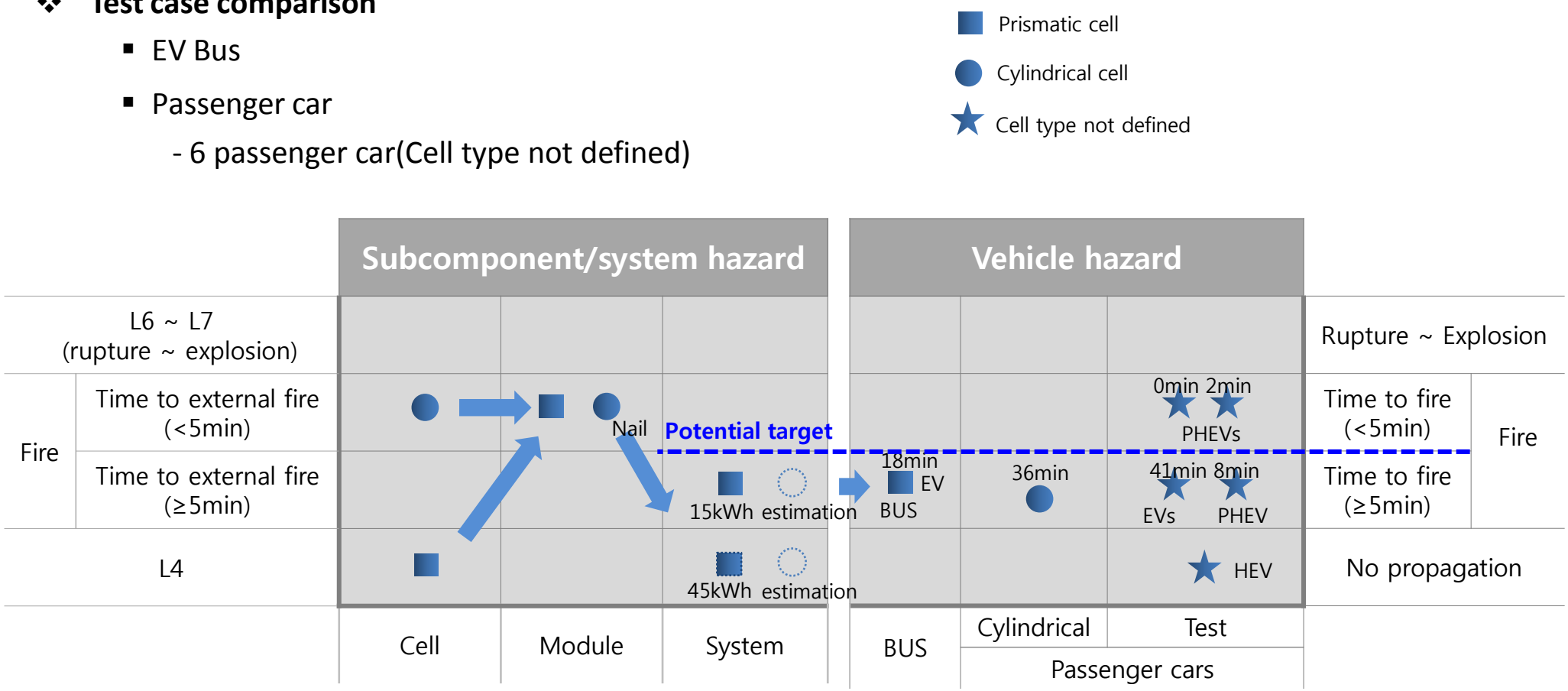
② Time to first flame in pack and vehicle level match each other.

③ Time to first flame is different depending on system/vehicle design.
← The system/vehicle design is important

Correlation of test results

❖ **Test case comparison**

- EV Bus
- Passenger car
  - 6 passenger car(Cell type not defined)



➔ Potential target is “no fire within 5min after initiation of thermal runaway” in system/vehicle test.
(initiation of thermal runaway should be detected by alarm system).
And no rupture and no explosion.

※ Test result of PHEVs may be related with the location of battery system.

I. Correlation test and case study

- Introduction
- Case study : Passenger car thermal propagation test
- Correlation test: Bus thermal propagation test
- Correlation of test results

II. Proposal

- Thermal runaway
- Initiation method
- Summary

Thermal runaway

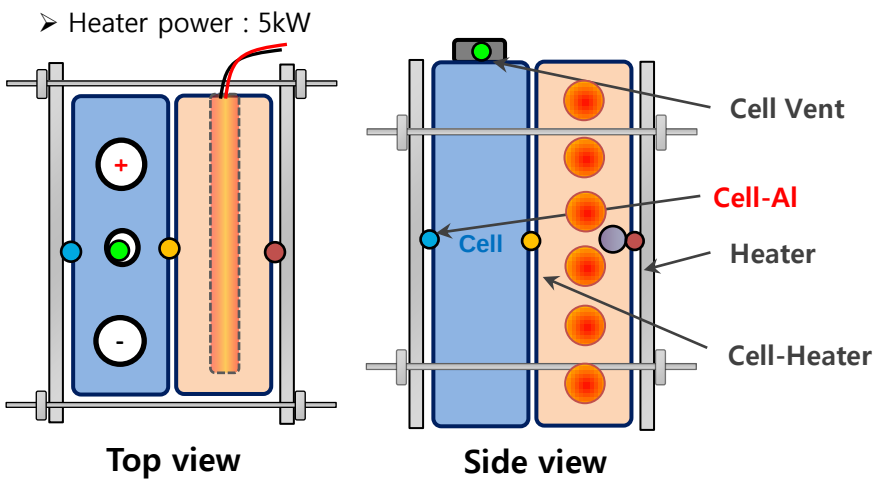
❖ Definitions

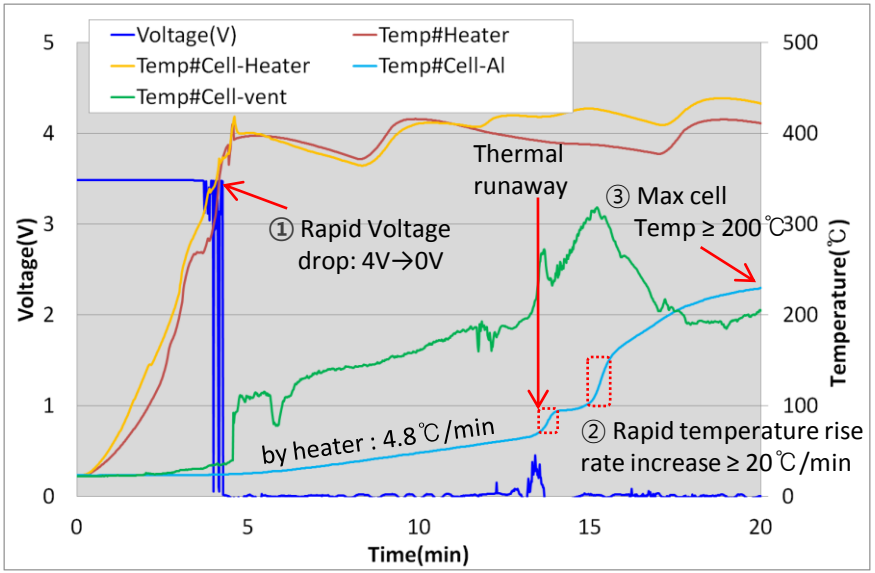
- Thermal runaway is uncontrolled increase of cell temperature rise rate caused by exothermic chain reactions inside the cell.

→ Phenomena: ① Voltage drop ② Rapid temperature rise rate increase
③ Thermal event(smoke/fire/explosion)

❖ Judgment criteria for existence of thermal runaway

① Voltage drop &
② Rapid temperature rise rate increase : 20℃/min &
③ Max cell temperature ≥ 200℃

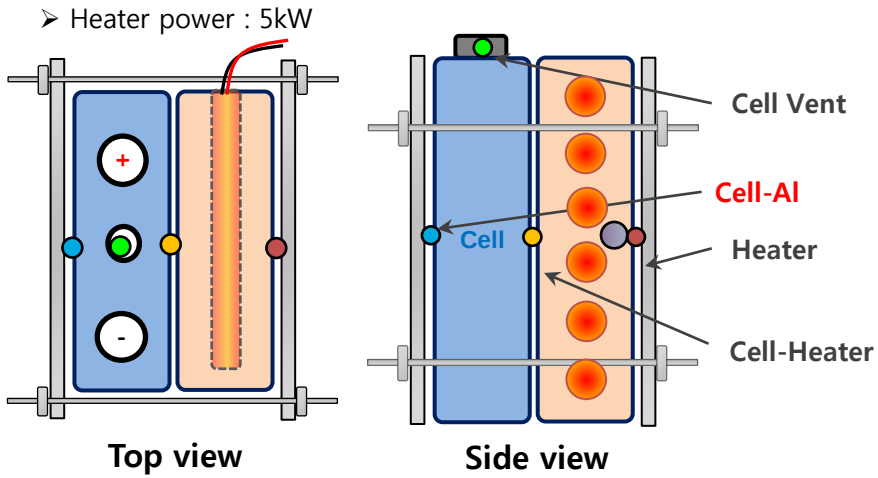




Thermal runaway

❖ **Cell test data : Initiation of thermal runaway**

- Test condition
  - Heater : Block heater 3~5kW
  - DUT temp : RT
  - Heating condition
    - .400℃ in 5min
    - .Heater off after thermal event

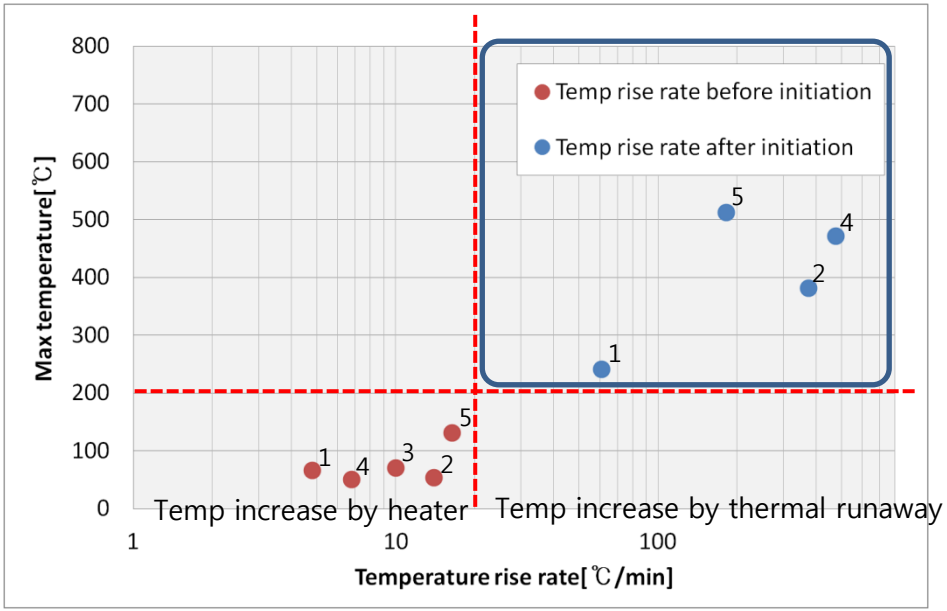


- Test results

Cell	Test method	Temp rise rate[℃/min]		Max temp[℃]	
		Before initiation	After initiation	Before initiation	After initiation
1	Heating	4.8	61	66.1	241.1
2	Heating	16.4	374	131	381.5
3	Heating	10.0	> 400	70.2	706
4	Heating	6.8	475.9	50.6	471.6
5	Heating	14.0	182.4	53.3	512.6

Thermal runaway

❖ Judgment criteria for thermal runaway



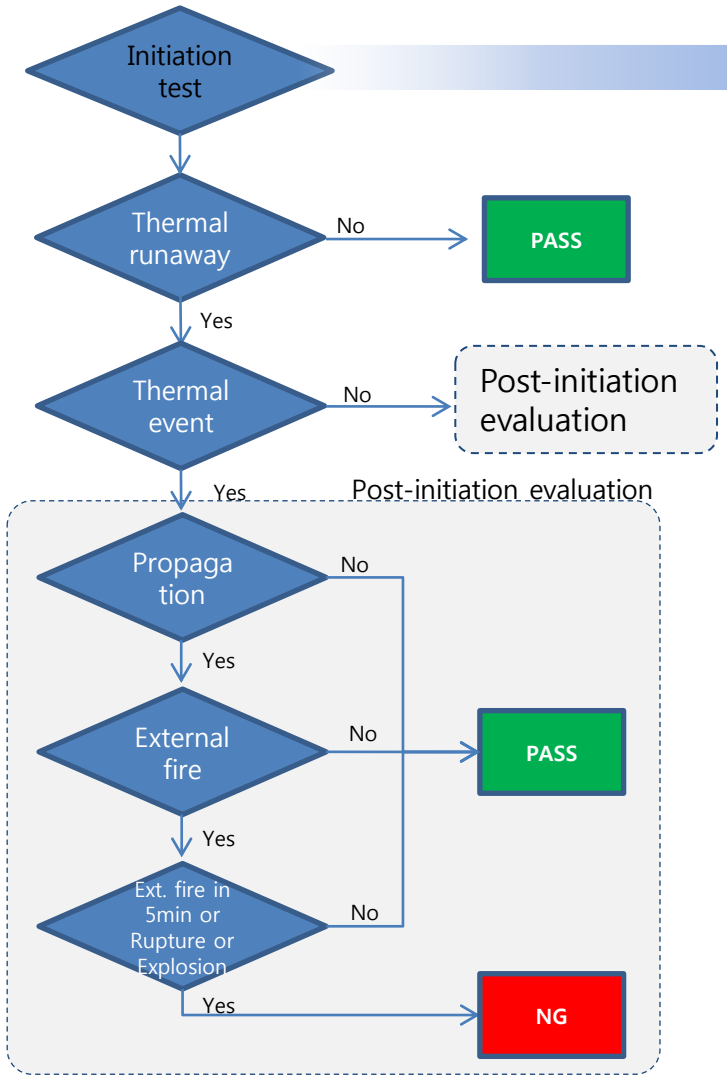
Temperature rise rate vs Cell max temperature

- Temp increase rate ≥ 20℃/min
  .It should be more than the one by heating device.
- Maximum temperature ≥ 200℃
  .Onset temp of thermal runaway should be higher than initiation temperature.

Initiation method

❖ Initiation method

▪ Scope



✓ According to current scope, initiation test method shall be described in detail.

Heating
Heat up to 400℃ within 5min
Continue heating until cell temp 400℃ in 30min

Penetration
Steel nail, Φ8, 1mm/sec

Overcharge
1C, 18V, until 200% SOC
Protection device to be altered

Summary

❖ Summary of Korean proposal

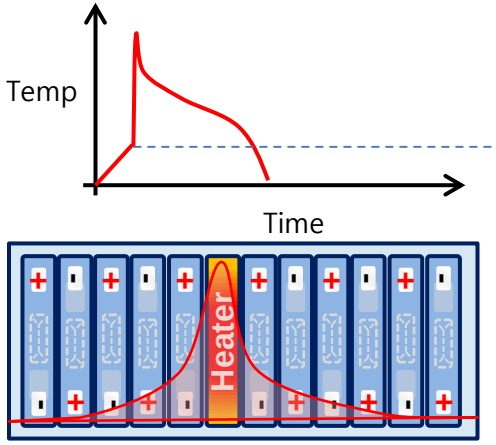
		Proposal	Remark
Initiation method		Based on OEM and manufacturer agreement	
	Heating	Heat up to 400℃ within 5min Until thermal runaway or cell temp > 400℃ in 30min	Detail test method used should be described in the test report.
	Penetration	Steel, Φ8, 1mm/sec	
	Overcharge	1C, 18V, until thermal runaway or 200% SOC Protection device altered	
Location of initiator		where propagation most likely occurs (center of DUT)	
Ambient condition		Room temperature Indoor facility or in a shelter	
Cooling system		Equipped but not operating	
Thermal runaway		Cell temperature rise rate ≥ 20℃/min & Max cell temp ≥ 200℃	
Requirement		No external fire in 5min after alarm system operating, no rupture and no explosion	

Appendix

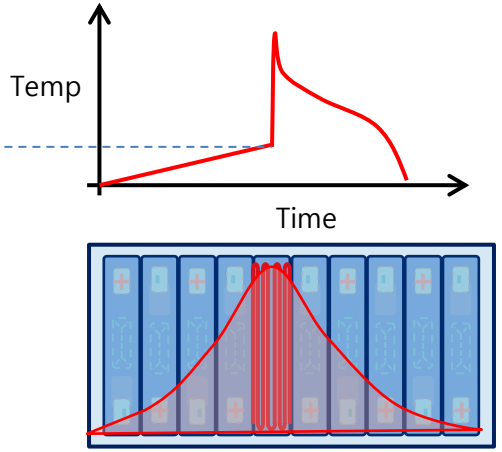
❖ Heating devices and heating speed

1. Block heater
- Purpose : Fast reaction and thermal runaway
- Remark
  - .High power (2~5kW)
  - .Fast/forced initiation, regardless of cell design
  - .Less preheating of adjacent cell before initiation
  - .Low conduction efficiency for cylindrical cell
  - .Replacement of a cell needed

2. Coil/film heater
- Purpose : Steady reaction and thermal runaway
- Remark
  - .Low power (<200W)
  - .Forced initiation, regardless of cell type
  - .More preheating of adjacent cell before initiation
  - .No replacement of a cell needed



Example of block heater on prismatic cell
- Heater and temp variation



Example of film heater on prismatic cell
- Heater and temp variation

Both of two phenomena, fast/steady reaction, are existing failure modes by an internal short circuit.