Investigate the Relationship between Cell Safety Devices' Activation Pressure and LIB Cell Safety with a Cell Failure Mechanism

Jaesik Chung Ph.D., Kwang Jung, Giovani Flores: PCTEST Engineering Lab.

Eric C. Darcy Ph.D., Samuel. P. Russell Ph.D.: NASA-Johnson Space Center

Gunho Kwak Ph.D. : Ford Motor Company

Email: jaesik.chung@pctest.com

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   - Measurement Method
   - Test System Design
   - Cell Specification and sample information
   - Abnormal test item description & test condition

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   - CID and Vent Activation Pressure measurement & requirement
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   - Mechanical Impact - Nail Penetration, Impact, Crush
   - Evaluation the test results by the EUCAR Hazard Level

4) Summary and conclusion

1) Cell safety consideration

Battery Safety Mechanism and measures

✓ Cell Design :
- Electrode material selection
- Separator shutdown
- Capacity valance : A capacity/C capacity
- Electrode design: consider the thermal management
- Alignment and Overhang :separator-anode-cathode
- Protection Mechanism: PTC, **CID, Vent Mechanism**
- Fire retardant or non-flammable

✓ Manufacturing process consideration
- process contamination
- identify impurity and contaminants
- identify defect & deform, anomalies, outlier
- screening and filtering out

✓ Quality control:
- Filtering out defect/contaminant/anomaly
- Maker internal approval test

Battery module/pack Design

Pack & Protection Circuit Design

❖ Cell Grading and Matching

❖ Battery Protection function

: Over/under voltage protection
High/Low temperature protection
Over current protection
Short circuit Protection

❖ Cell balancing to minimize the Cell Mismatch

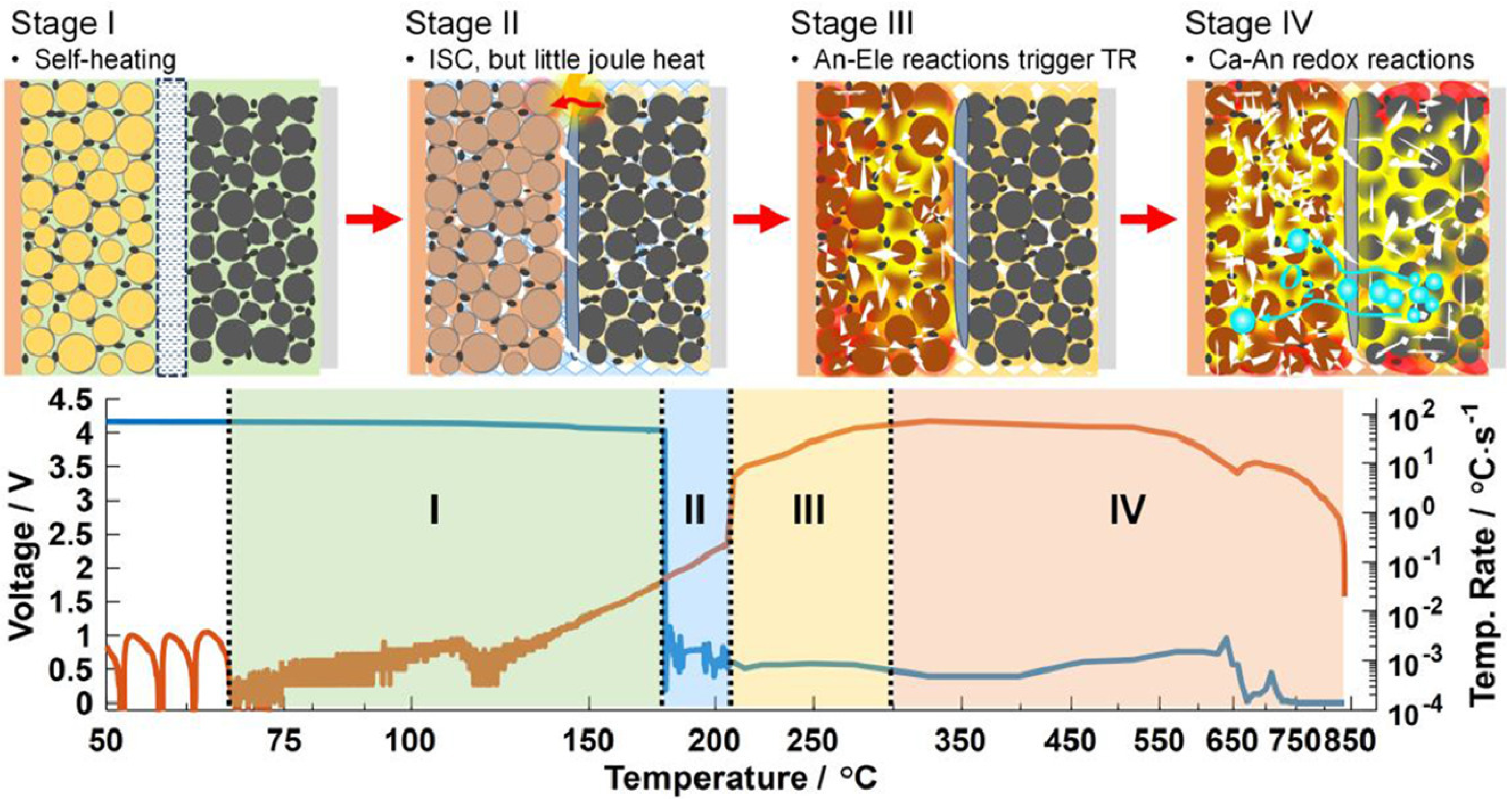
Host System Design

➢ System Integration consideration

➢ Communication among host -pack-module to manage and control the function and safety of Battery system.

2) LiB Cell failure/Thermal runaway mechanism – ARC test

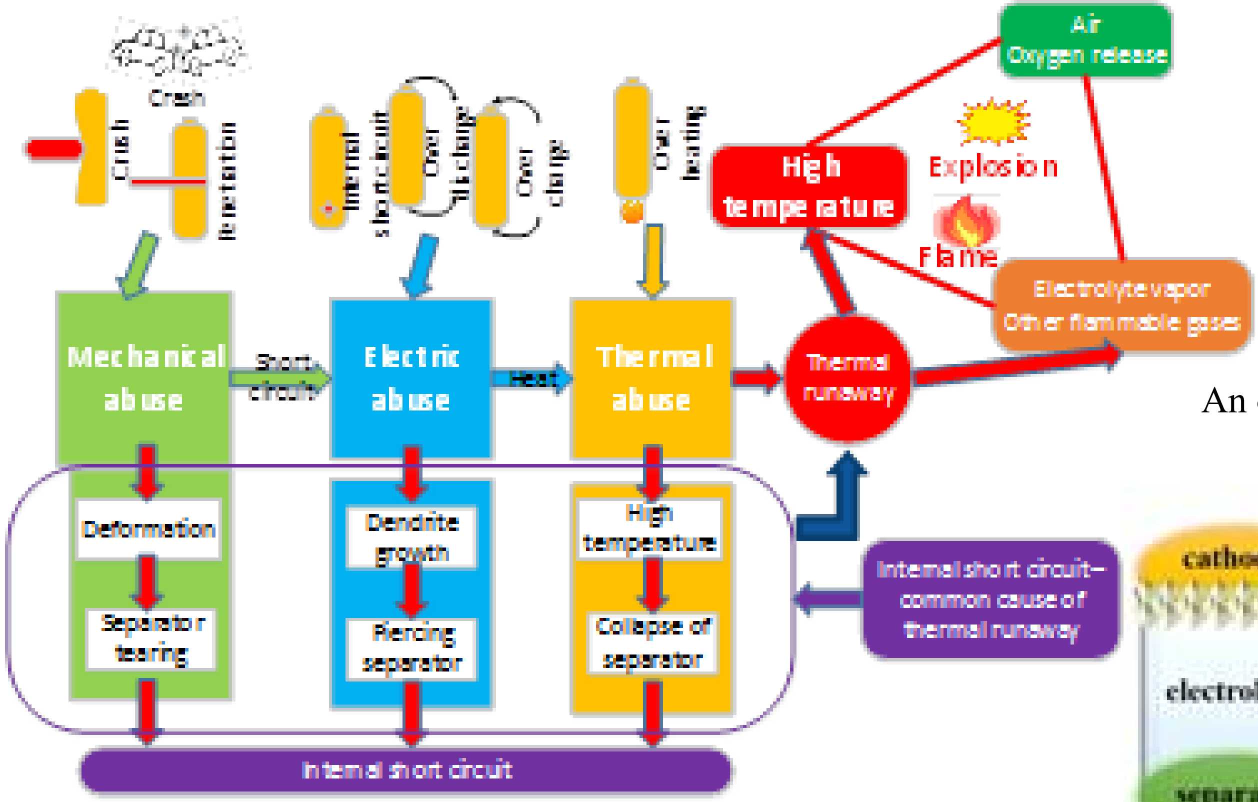
* ARC : Accelerating Rate Calorimeter



Dongsheng Ren, Xuning Feng, Lishuo Liu, Hungjen Hsu, Languang Lu, Li Wang, Xiangming He, Minggao Ouyang Investigating the relationship between internal short circuit and thermal runaway of lithium-ion batteries under thermal abuse condition, Energy Storage Materials V.34, January 2021, Pages 563-573

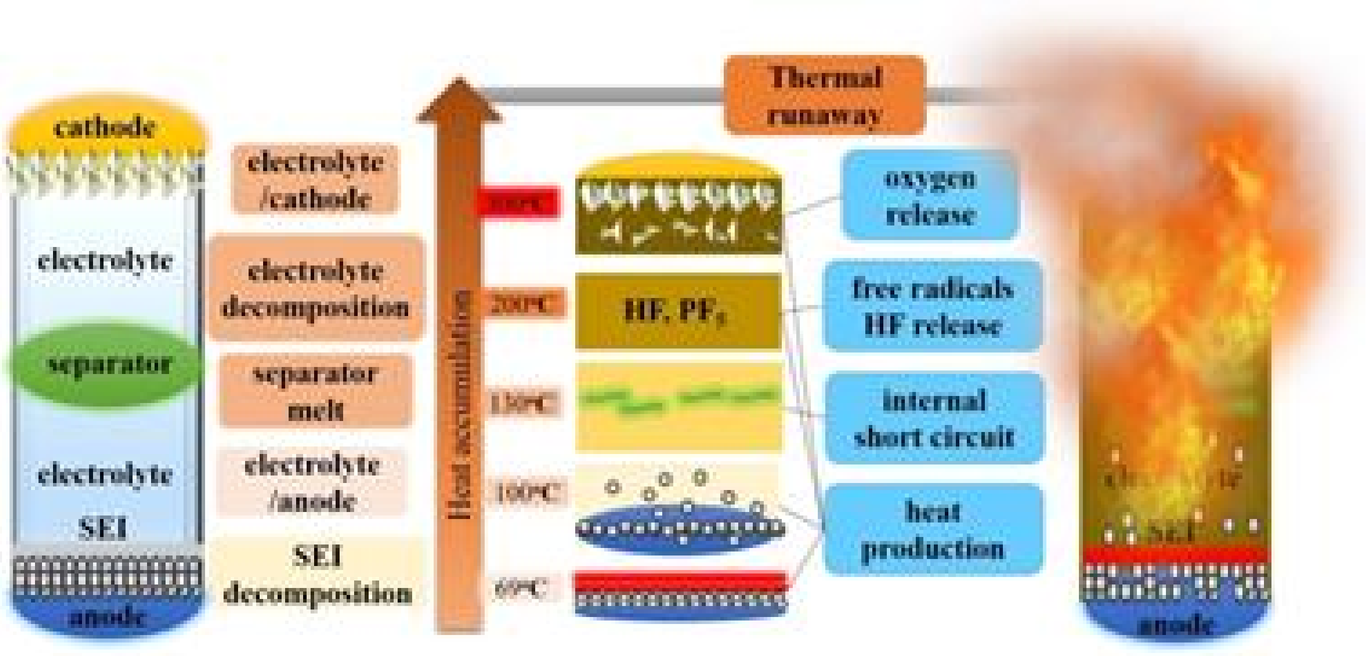
2-1) LiB Cell failure/Thermal runaway mechanism

- Mechanical, Electrical and Thermal abnormal and abuse trigger



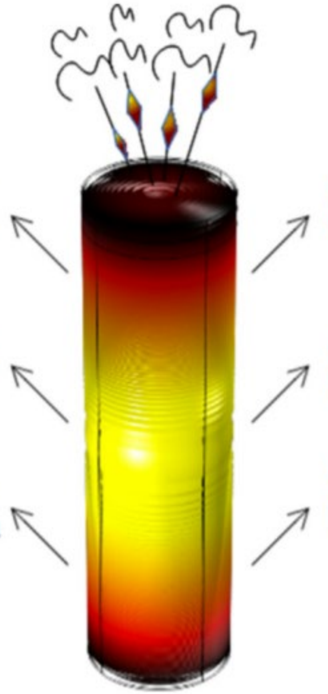
Schematic of the cause of LIB fire accidents

An overview of the thermal runaway process of $LiCoO_2$/graphite cell.



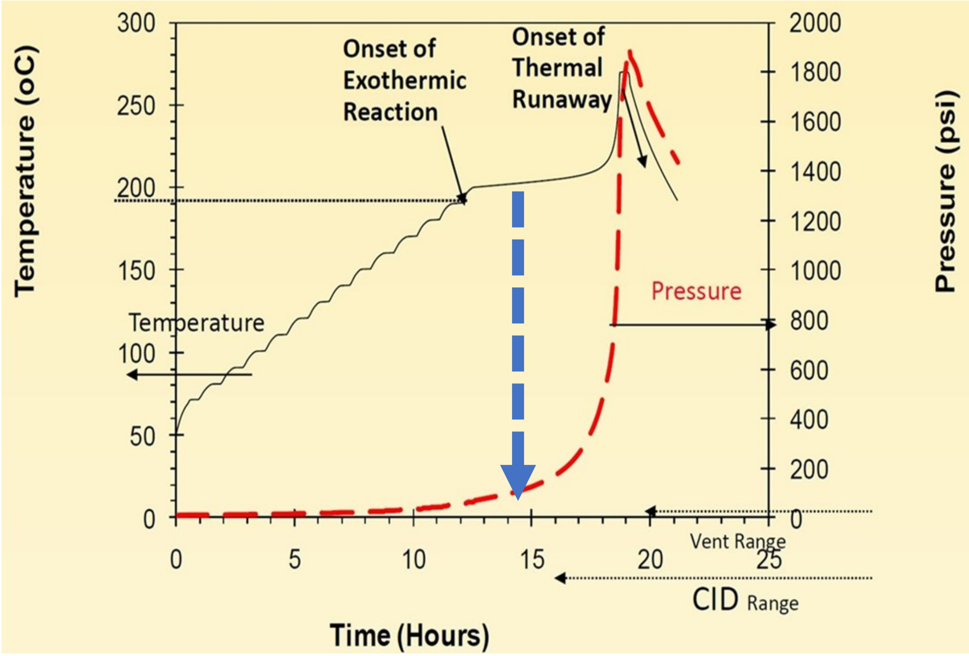
3) Effects of LiB Cell Pressure buildup and thermal runaway

1) LiB Cell thermal runaway contributions factors



Ref. : Paul T. Coman, Sean Rayman, Ralph E. White, Journal of Power Sources Volume 307, 1 March 2016, Pages 56-62

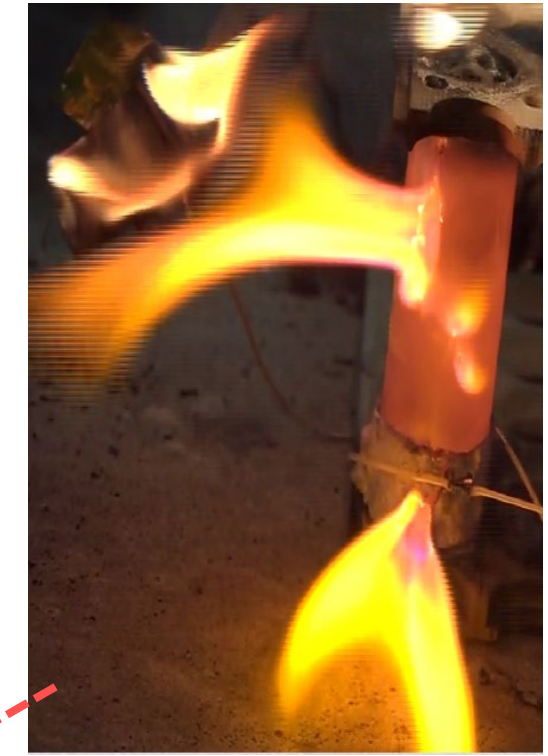
2 Pressure build up during LiB Cell thermal runaway.



Ref.: Battery Power 2009 Denver, NETZSCH, Peter Ralbovsky, October 21-22, 2009

Can side wall rupture happened before the CID and Vent activation occurred.

3) Side wall rupture during LiB 18650 cell Thermal runaway



*Ref.: 2016 NASA Aerospace Battery WS. P:resented by Dr. Eric Darcy.
-18650 Cell Bottom Vent Preliminary Evaluation into its Merits for Preventing Side Wall Rupture.

4) Safety Devices function and Structure in LiB cylindrical Cell

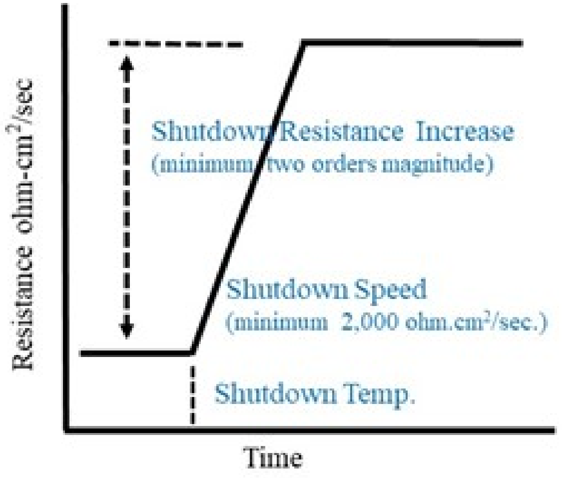
As a protective measure to prevent the appearance of excessive current, temperature and/or pressure

Vent Mechanism: response to the continuous increase of pressure inside cell, allowing the escape of excessive pressure gases.

CID: Current interrupt device: Activate at overheating, overcharging and short-circuiting, and high temperature/vapor pressure conditions.

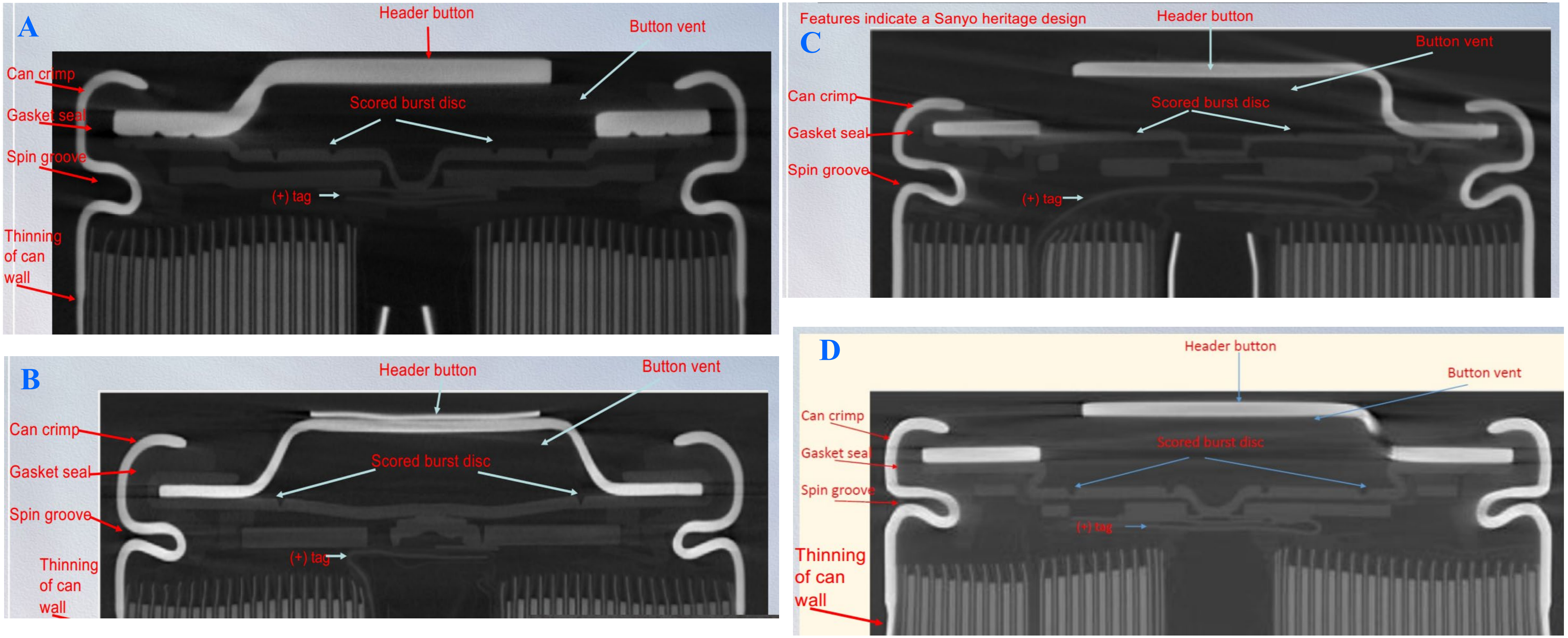
PTC: Positive temperature coefficient- Its's resistance increases dramatically in response to the rapid rise of temperature by current.

Shutdown Separator: Temperature, when the pore of a separator is closed and then it lose the function of the io



*Reference: IEEE1725 Battery safety standard

Structure of safety devices in a 18650 cell



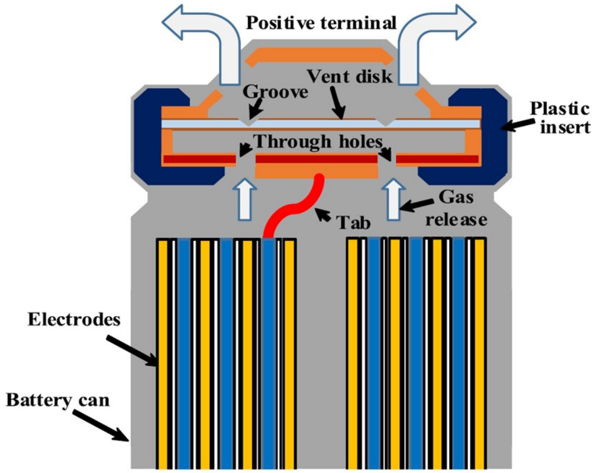
*Reference: 2016 NASA Aerospace Battery WS. Presented by Dr. Eric Darcy.

-18650 Cell Bottom Vent Preliminary Evaluation into its Merits for Preventing Side Wall Rupture.

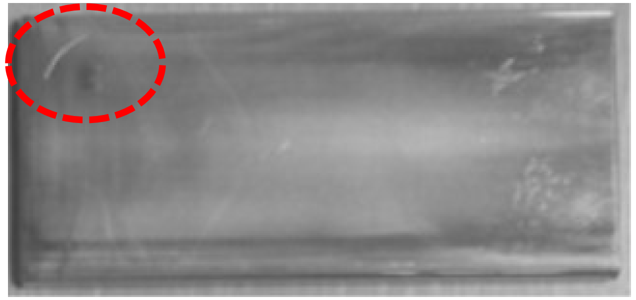
5) Safety Vent Mechanism by Cell Type

Battery Safety Vent Mechanism

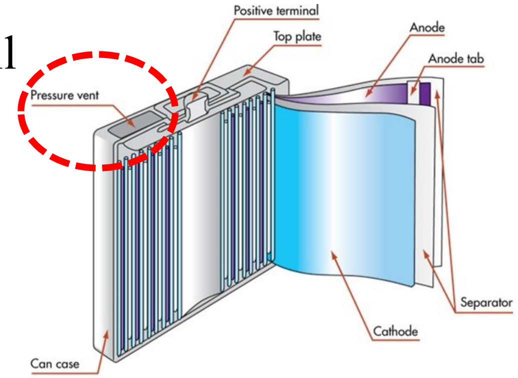
1. 18650 Cylindrical Cell:
   1) Top Cap: CID + Safety Vent + PTC
   2) Bottom Vent

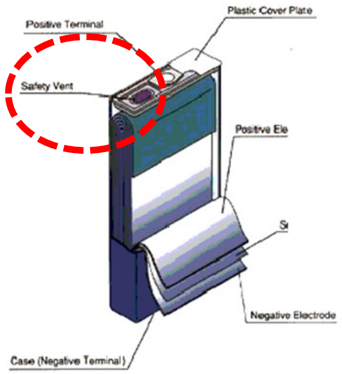


L. Kong, C. Li, J. Jiang, and M. G. Pecht, ``Li-ion battery fire hazards & safety strategies," *Energies*, vol. 11, no. 9, pp. 111, 2018.
X.-Y. Yao *et al.*: Reliability of Cylindrical Li-ion Battery Safety Vents, IEEEAccess, VOLUME 8, 2020, 101859 ~101866



2. Prismatic Cell : Portable Application Cell
   :Top or Side Vent Mechanism

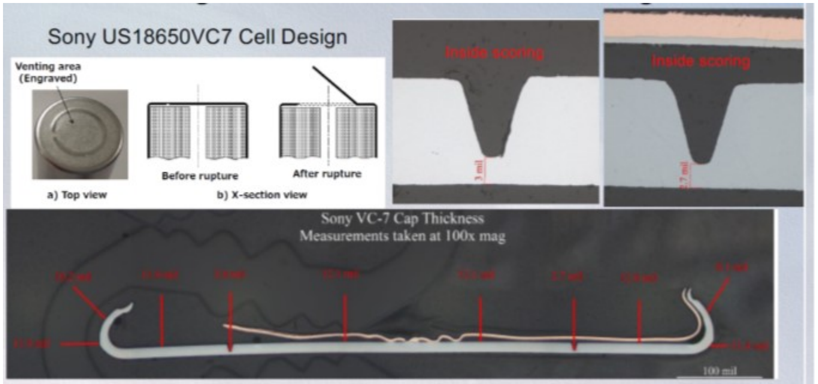


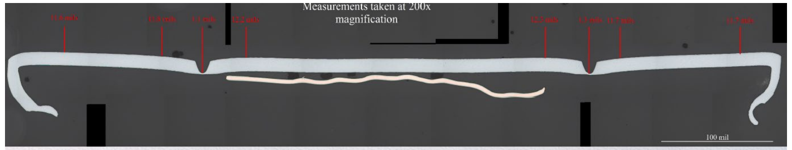


3. Pouch Cell:
   :Regards "thermal sealing area" as the Vent Mechanism

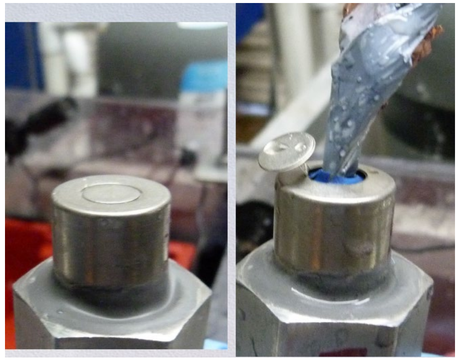
6) Additional safety: Bottom Vent Mechanism

To reduce the risk of side wall rupture during Thermal runaway

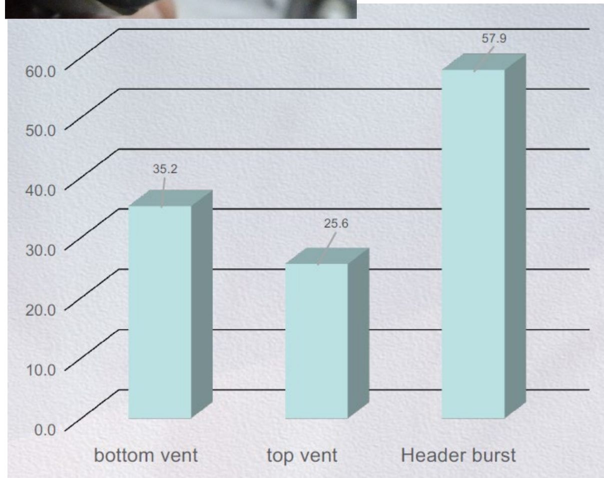


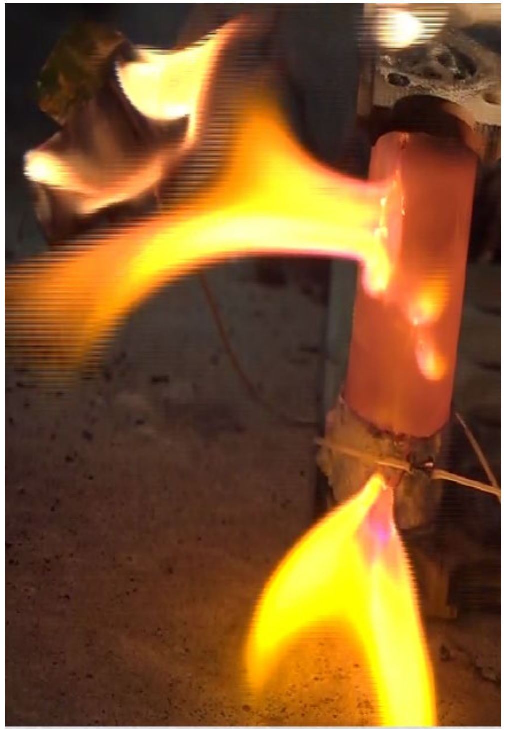


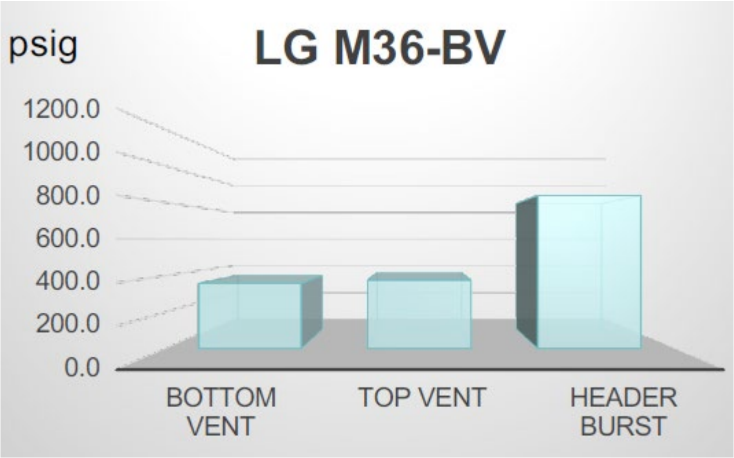
***Side wall rupture during Cell Thermal runaway**



25.6 kgf/cm2 = 364 psi
35.2 kgf/cm2 = 500 psi
57.9 kgf/cm2 = 824 psi







*Reference: 2016 NASA Aerospace Battery WS. P:resented by Dr. Eric Darcy.
18650 Cell Bottom Vent Preliminary Evaluation into its Merits for Preventing Side Wall Rupture.

Experimental

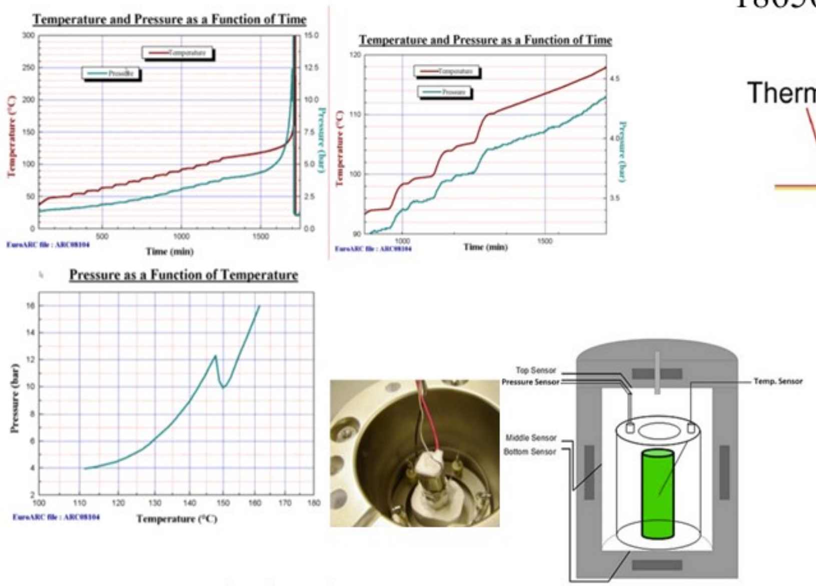
- ✓ Measurement Method
- ✓ Test System Design
- ✓ Cell Specification and sample information
- ✓ Abnormal test item description & test condition

I E R&D C

1) Measurement Method for the activation pressure of the safety vent mechanism

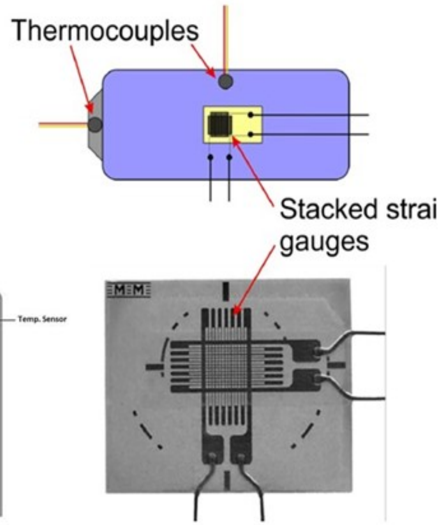
1. Cell base test

1) ARC with pressure chamber

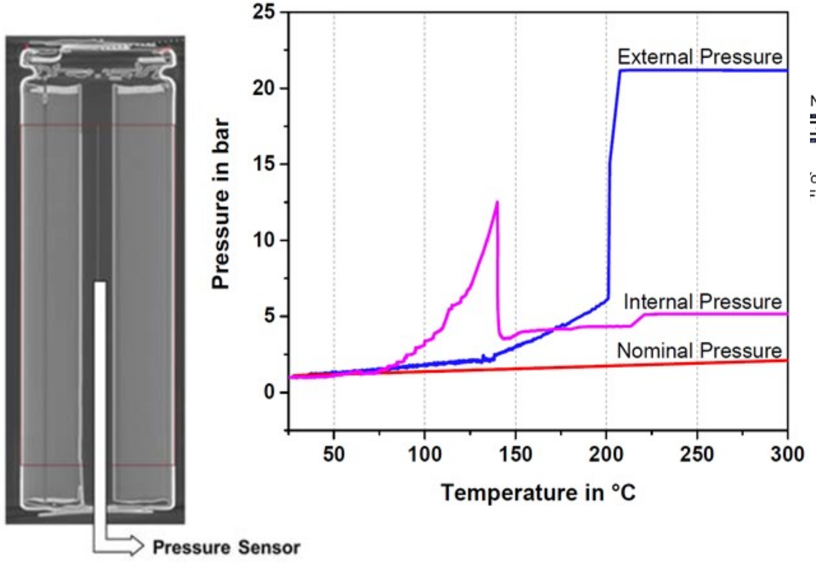


pressure reached 12 bar.

2) Strain Gauge of the 18650 cell surface

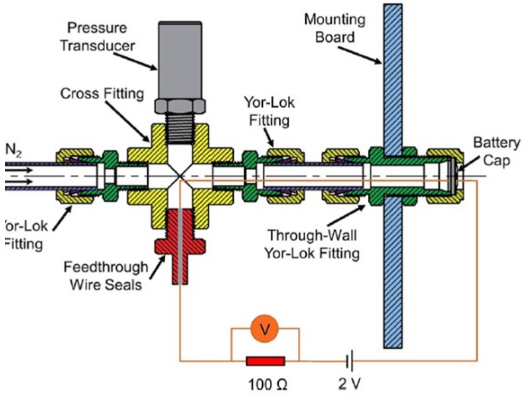


3) Pressure sensor in the cell within pressure chamber



Pressure in the cylinder was 8.31 bar (8.31 $\times 10^5$ Pa)

2. Component base test



Top Cap
- CID
- Vent mechanism

Ref. M. R. Ottaway, ARC Technical Application Note: Stability of Li-Ion Batteries; Internal Pressure Measurement, Thermal Hazard Technology, 2008.

Ref. EESAT, October 12, 2017
Frank Austin Miera, New Mexico Tech and Sandia National Laboratories

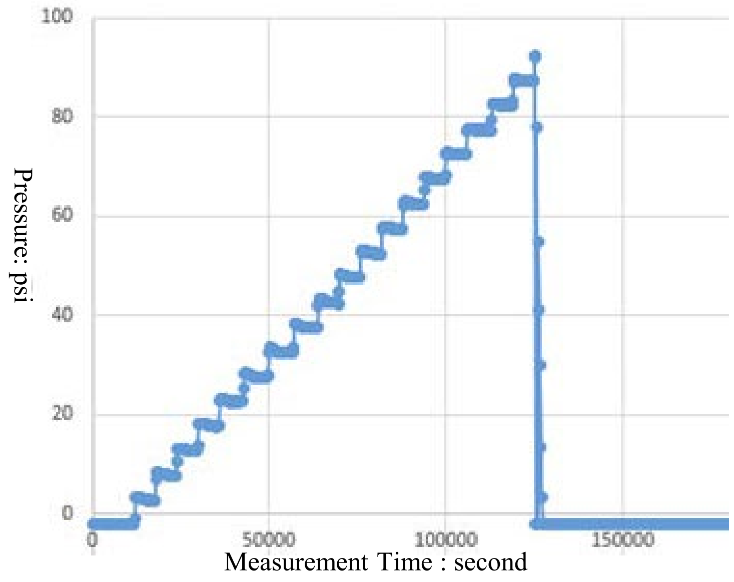
Experimental Analysis of Thermal Runaway in 18650 Cylindrical Li-Ion Cells Using an Accelerating Rate Calorimeter **Boxia Lei etal** Batteries **2017**, 3, 14

Ref. Comparison of Current Interrupt Device and Vent Design for 18650 Format Lithium-ion Battery Caps . Weisi Li etal Journal of Energy Storage 32 (2020) 101890

2) Cell Vent Mechanism Pressure measurement procedure - IEEE 1725/ CTIA Certification

Reference: IEEE 1725- Cells shall be designed to include a consistent vent design or mechanism, for example, foil, edge, seam, or score., -Retention of cell contents: The vent mechanism shall be designed to minimize projectiles and maximize retention of cell contents.

Purpose: To ensure cell designs include a consistent vent mechanism.
Procedure: Test lab to verify vent design and operation on 5 cells per their internal procedure.
1) Take 5 samples at ambient temperature (SOC is not critical; HOWEVER, to reduce hazards discharged cells are recommended).
2) Penetrate the cell : a) Canister type cell: Penetrate the can on opposite end of the cell canister. Not the same side as the vent.
b) Pouch type cell: Use a needle to penetrate the pouch as far away from the seam.
3) Connect cell to an inflow mechanism without disturbing the cell internals. 4) Seal using appropriate sealing method (e.g. epoxy, O-ring).
5) Use compressed inert gas (e.g. Air or inert gas (e.g. N2, Ar etc.)) and pressurize at a rate of 5 +/-1 psi (35 kPa +/- 7 kPa) intervals.
6) Hold pressure for a minimum of 5 sec per interval. 7) Note the activation pressure of the vent.
Compliance: Vent operates per the vendor specification. Visual inspection confirms that the vent operated at its intended location.



Average Vent activation pressure by cell type

Cell Type	Average Vent activation pressure	
	Kgf/cm^2	psi
18650	18 ~ 35	256 ~ 498
Prismatic	7 ~ 20	99.6 ~ 285
Pouch	3 ~ 9	42.7 ~ 128

* The trend is cell design gets lower the Vent activation pressure.

3) Test System Design - Activation Pressure Measurement

CID/Vent Activation Pressure test Equipment

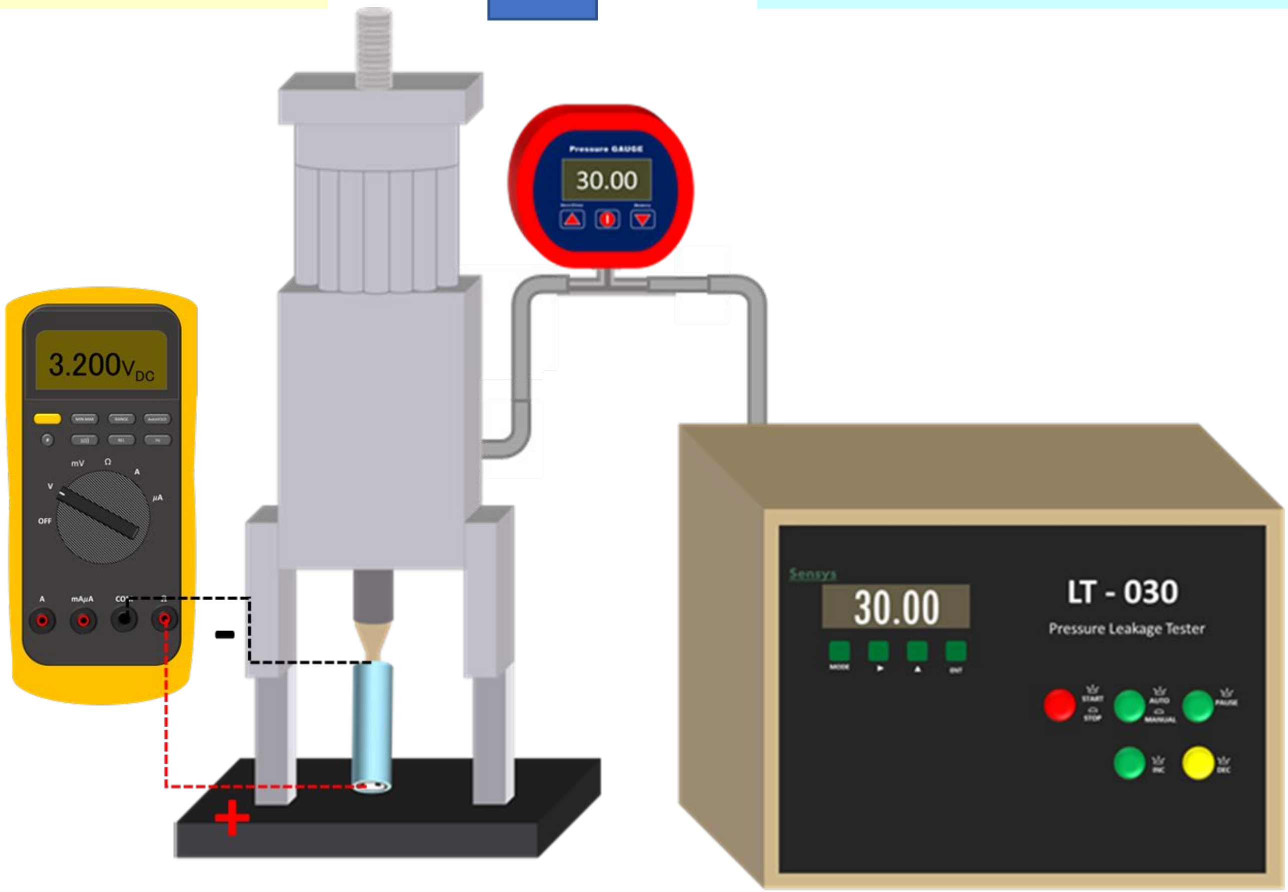
IEEE 1725 and CTIA Certification :

Vent activation Pressure measure

Additional Measurement :

Cell voltage during testing

CID activation pressure check by cell voltage drop : CID open.



Vent Mechanism activation pressure check by pressure drop : Vent open.

* Cell SOC : < 3.0 %

4) Cell Specification and sample information

Select the similar cell design, structure, capacity, and passed certifications to minimize experimental variable.

- ❖ Select four 18650 cell models form four cell vendors.
- ❖ 4 cell models have similar design and performance, and **no PTC**
- ❖ Cell capacity: around 3,500 mAh (3,350 ~ 3,500)
- ❖ Pass UN/DOT 38.3/UL1642/IEC62133/IEEE1625& 1725 Certification testing.

Cell	Voltage		Nominal Capacity : **mAh**	PTC in a Cell	Cell IQC characteristic data Average from total 60 cells/ model					
	Nominal	Operation			Mass: g	OCV: V	Dia.:mm	Length	AC-imp.	Capacity@ 1 C
A	3.6 V	4.2~2.65	3,400	No	48.04 g	3.50 V	18.35	65.16	22.66 mΩ	3,345 mAh
B	3.6 V	4.2~2.5	3,500	No	46.62 g	3.63 V	18.36	65.09	29.84 mΩ	3,415 mAh
C	3.6 V	4.2~2.5	3,350	No	47.52 g	3.67 V	18.31	65.13	23.61 mΩ	3,410 mAh
D	3.6 V	4.2~2.5	3,500	No	47.44 g	3.50 V	18.35	64.89	25.23 mΩ	3,432 mAh

5) Abnormal test item description & test condition

- Abnormal test conditions are referenced from the IEEE1625/1725, UL1624,IEC62133, UN 38.3 battery safety standards.
- Test Result present one cell of the average from the three cells tested.

Test item		Test Description & test condition	Sample
CID-Vent Activation Pressure		Used designed Test Equipment with discharged cell (< 3% SOC). Measure pressure & cell voltage drop	Fresh : 5
Thermal Impact	1)Thermal Test	Maintain fully charged cell in 130 ±2°C chamber for 1.0 Hr. after the cell temperature reach to 130 ±2°C and then cooldown the temperature to RT. Ramping speed: 5 ±2°C/min. IEEE 1725 Test condition	Fresh : 3 Aged :3
	2)Isolation Property	Maintain 80% SOC cell in 150 ±2°C chamber for 10 Min. after the cell temperature reach to 150 ±2°C and then cooldown the temperature to RT. Ramping speed: 5 ±2°C/min. IEEE 1725 Test condition	Fresh : 3 Cycled : 3
Electrical Impact	1)External Short Test	Externally short circuit fully charged cells independently with a load of < 80 +/- 5 m ohm, 57 ± 4 °C,. Maintained it until a discharged state of less than 0.1V has been reached. Test is performed for 0.5~1.0 hours after current is no longer drawn or cell temperature is within 10°C +/- 5 of the ambient temperature.	Fresh : 3 Cycled : 3
	2)Overcharging	Charge cells to >12.0 V with CC of 3 times the max. charge condition for 7.0 hours. Overcharge test shall be performed with the UL1642 standard.	Fresh : 3 Cycled : 3
Mechanical Impact	1)Nail Penetration	Penetrate center of fully charged cell with 1/8" nail and perform at 0.01mm/sec. speed at room temperature. Maintained until the cell voltage falls by about lower than 100 mV. at 100% SOC	Fresh :3 Cycled :3
	2)Impact Test	Drop 9.1kg weight from 610mm height onto a hard flat surface with 15.8mm diameter steel bar placed across the center of the cell. The cell is placed with its longitudinal axis parallel to the flat surface. Cell to be conditioned in a circulating air oven for 1.0 + 0.25 hours at specified temperature (45 ±5°C) prior to Impact test. The test performed within 1 minute of removal from the oven. at 100% SOC	Fresh : 3 Cycled : 3
	3)Crush Test	Apply a 13kN force onto the cell with a longitudinal axis of the cell parallel to the flat surfaces of the Fresh. Cell to be conditioned in a circulating air oven for 1.0 + 0.25 hours at specified temperature (45 ±5°C) prior to crush test. The test performed within 1 minute of removal from the oven. at 100% SOC	Fresh : 3 Cycled : 3

Result and Discussion

- ✓ Pre-test : 100 Cycle Test result
- ✓ CID and Vent Activation Pressure measurement & requirement
- ✓ Thermal Impact - Thermal Test, Isolation prosperity test
- ✓ Electrical Impact- External short circuit Test, Overcharging Tet
- ✓ Mechanical Impact - Nail Penetration, Impact, Crush
- ✓ Evaluation the test results by the EUCAR Hazard Level

Summary and Conclusion

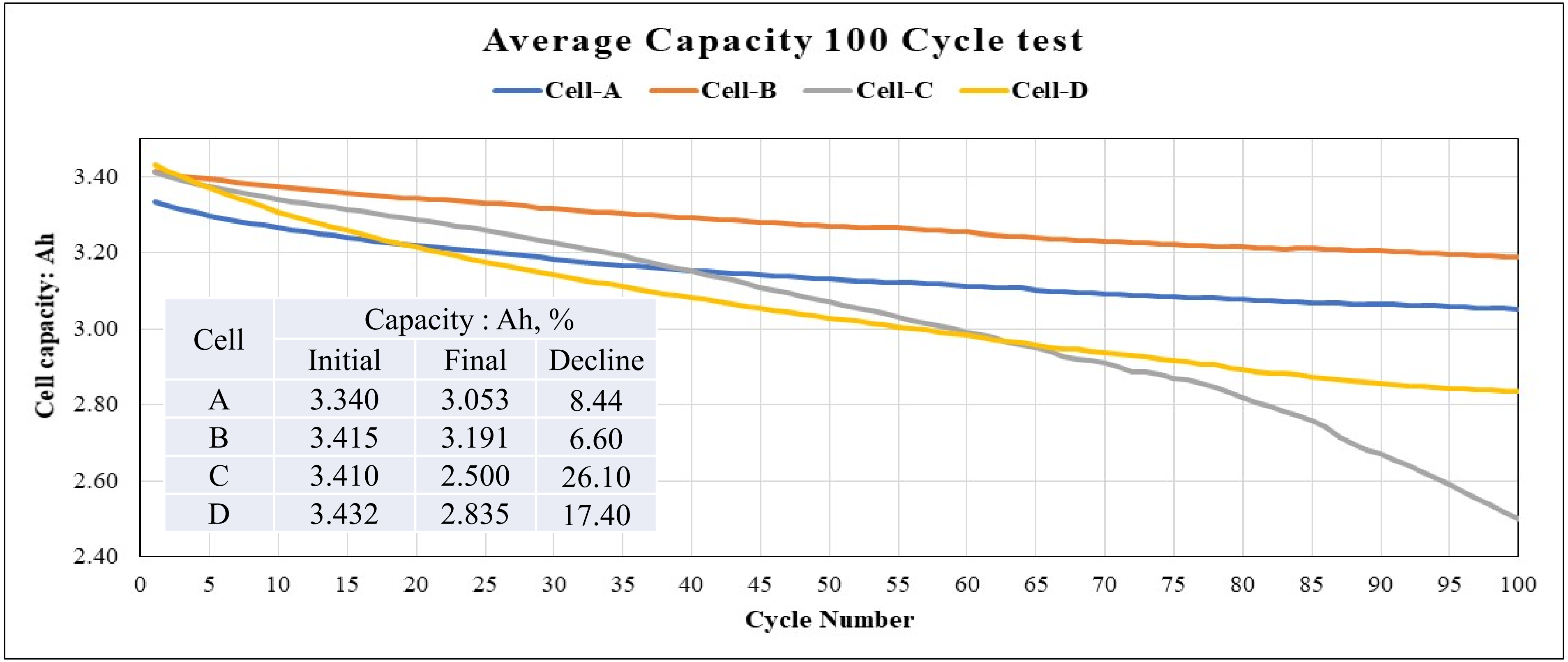
1) Aged cell : 100 Cycle Test result

To compare between fresh-cell and aged-cell, 100 cycle test was performed for cell aging.

a) Cycle test condition : cycled cells consider as an aged cell.

- Temperature : at 45 ± 5°C environnement chamber
- Cycle test condition: - Charge: CC- CV mode, Current: 3.3A to 4.2V, Cut-off current: 165 mA, rest: 20 min.
- Discharge: CC Mode, Current: 3.3A to 2.65V, rest: 20 min.

b) Test Result



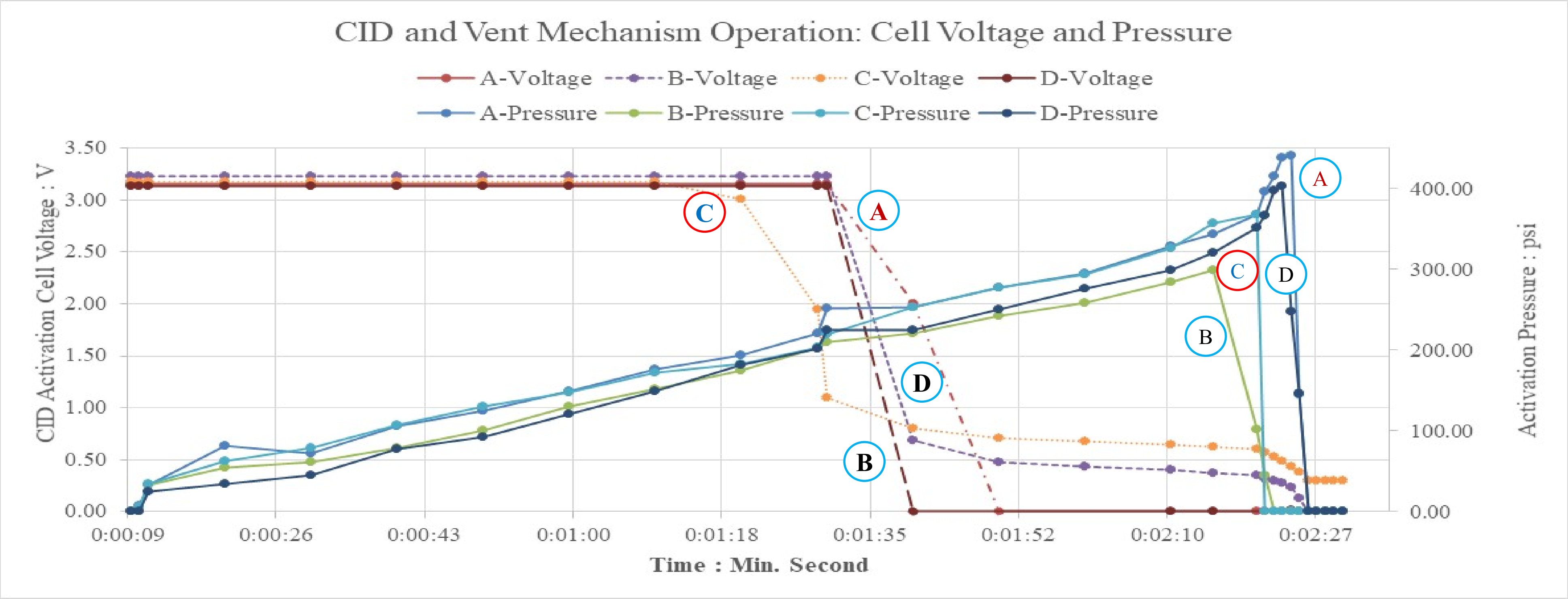
Cell	Capacity : Ah, %		
	Initial	Final	Decline
A	3.340	3.053	8.44
B	3.415	3.191	6.60
C	3.410	2.500	26.10
D	3.432	2.835	17.40

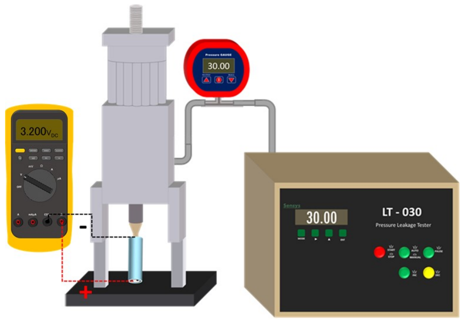
2) CID and Vent Activation Pressure measurement

Cell #	CID Activation Pressure		Vent Activation Pressure		Activation position
	psi	Kgf/cm²	psi	Kgf/cm²	
A	249.2	17.51	430.1	30.24	Cell vented from proper area
B	214.2	15.05	283.8	19.96	Cell vented from proper area
C	204.3	14.46	368.2	25.89	Cell vented from proper area
D	225.1	15.83	409.2	28.76	Cell vented from proper area

The C-cell has the lowest CID Activation pressure
➔ Earlier and lower pressure.

The B-cell has the lowest Vent Mechanism Activation Pressure
➔ lower pressure.



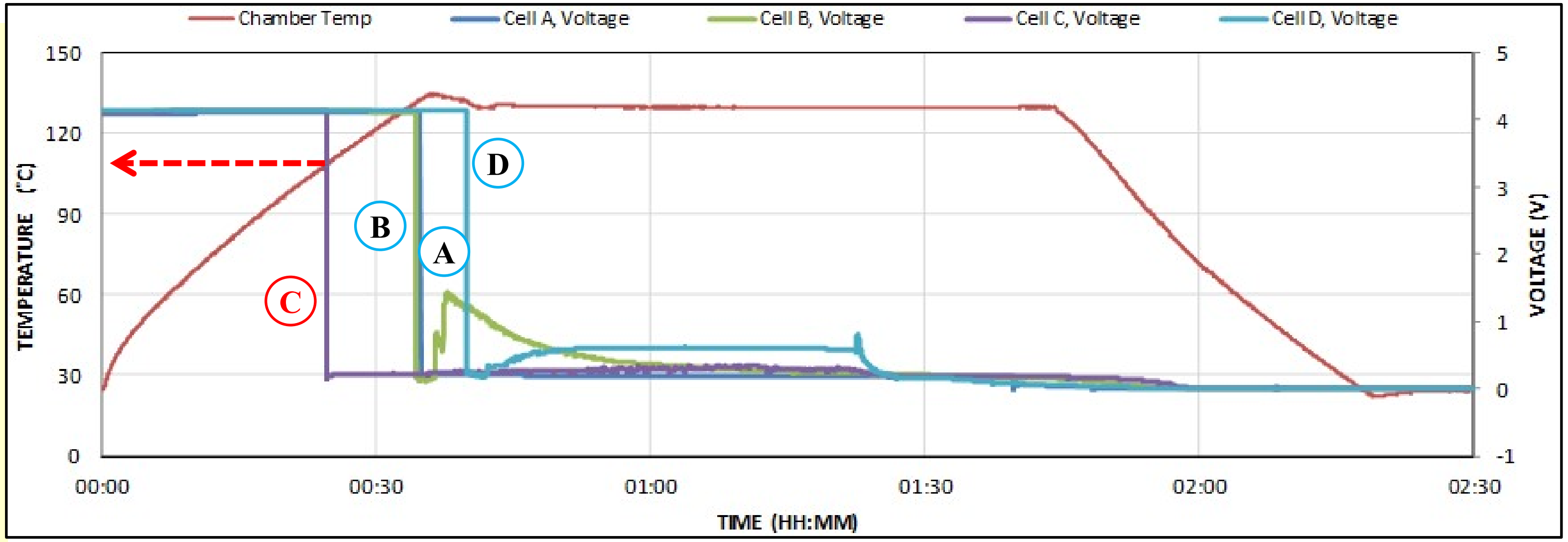


3) Thermal Impact - Thermal Test

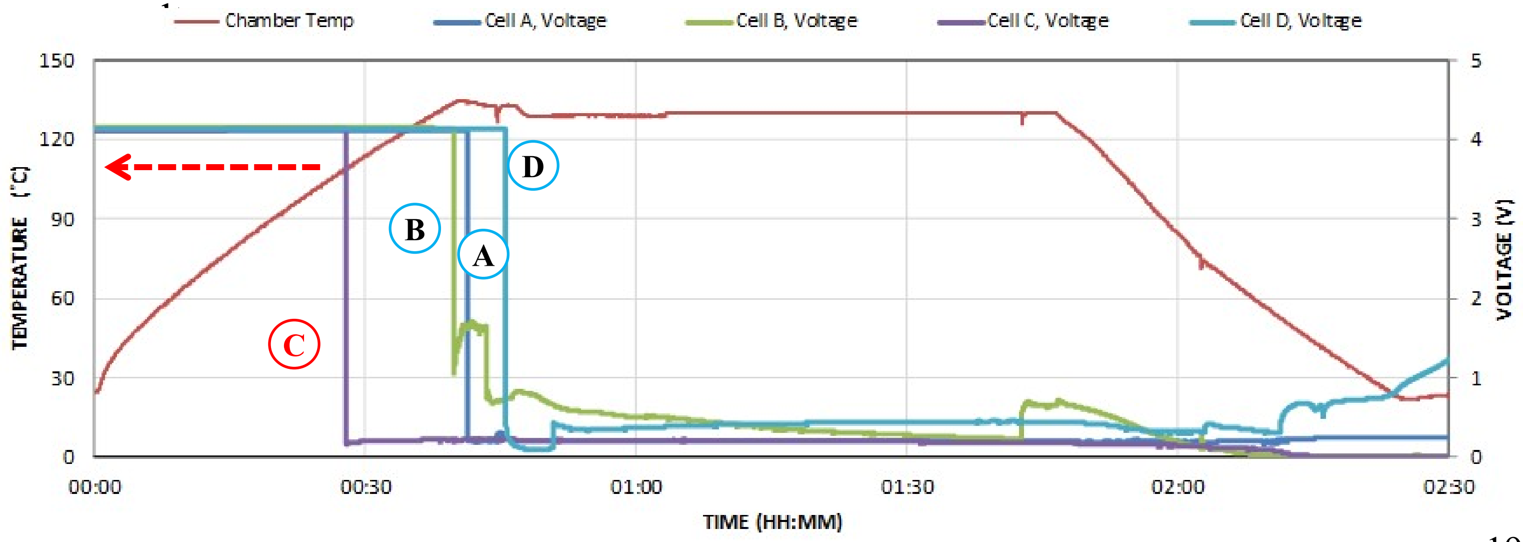
Result Review

- ✓ The lower activation pressure cells open the CID/Vent and discharge gases earlier than that of higher.
- ✓ C cell, the lowest CID activation pressure, response earlier at lowest temperature.
- ✓ The trend of activation is the same between fresh and aged cells.

Fresh cell Test result



100 Cycled aged cell Test

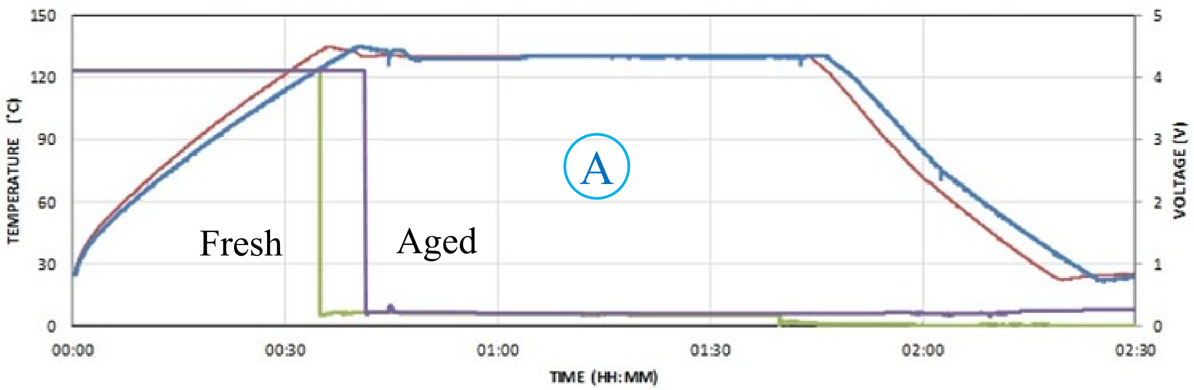


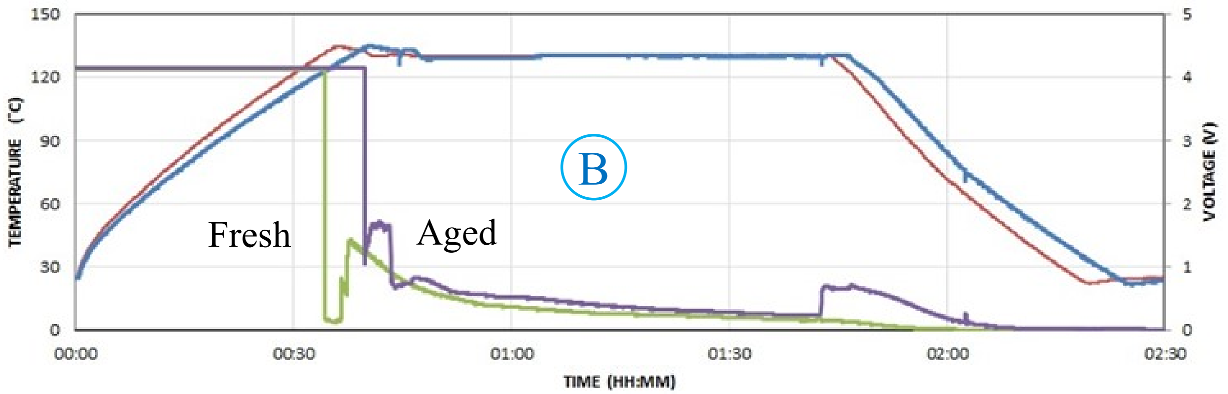
Test Condition

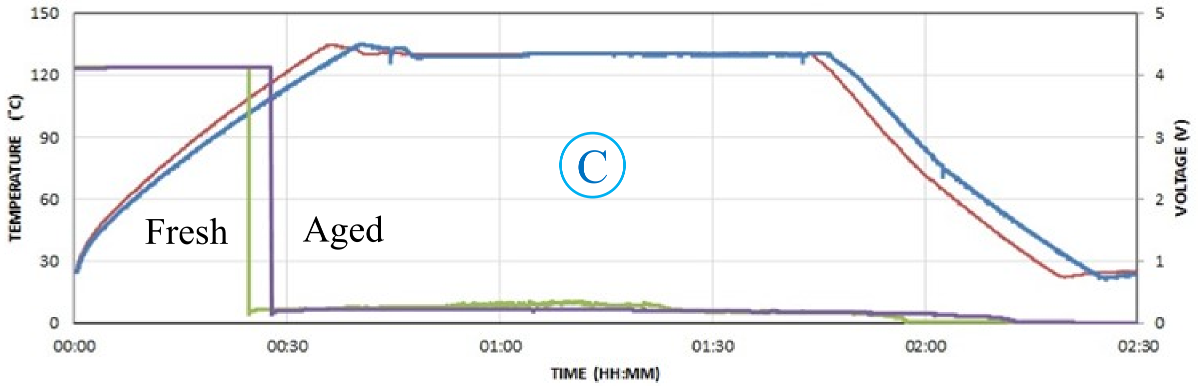
-Maintain fully charged cell in 130 ± 2°C chamber for 1.0 hour after the cell temperature reach to 130 ± 2°C,
and then cooldown the temp to RT.
Temperature Ramping speed: 5 ± 2°C/minute.

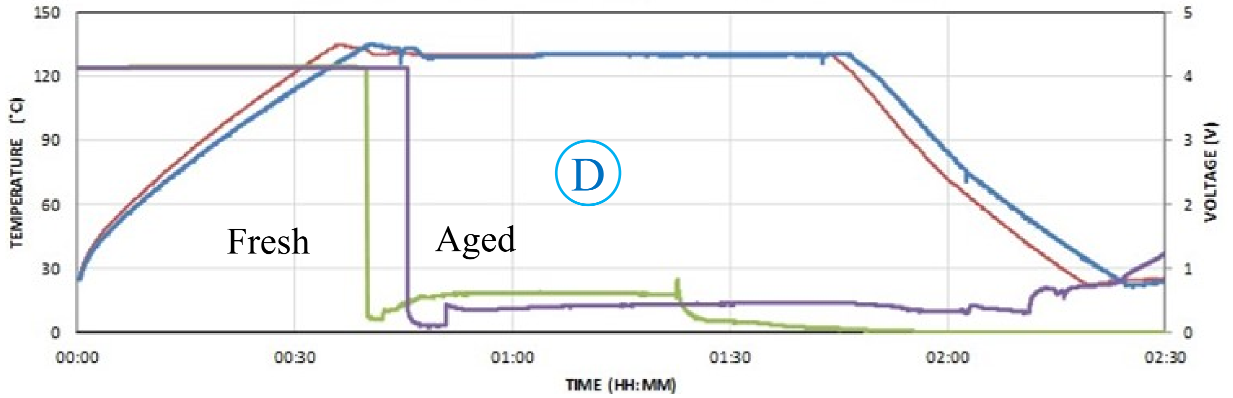
3-1) Thermal Test : comparison fresh and aged (100 cycled) cells

- ✓ Fresh and Aged(100 cycled) cells shown the similar activation behavior and trend among the four cells.
- ✓ C-cells activated much earlier than that of other three cell models both in fresh and aged cells.
- ✓ Fresh cells activated earlier than the Aged (100 cycled)cells for all the 4 cell models.









4) Thermal Impact -Isolation property

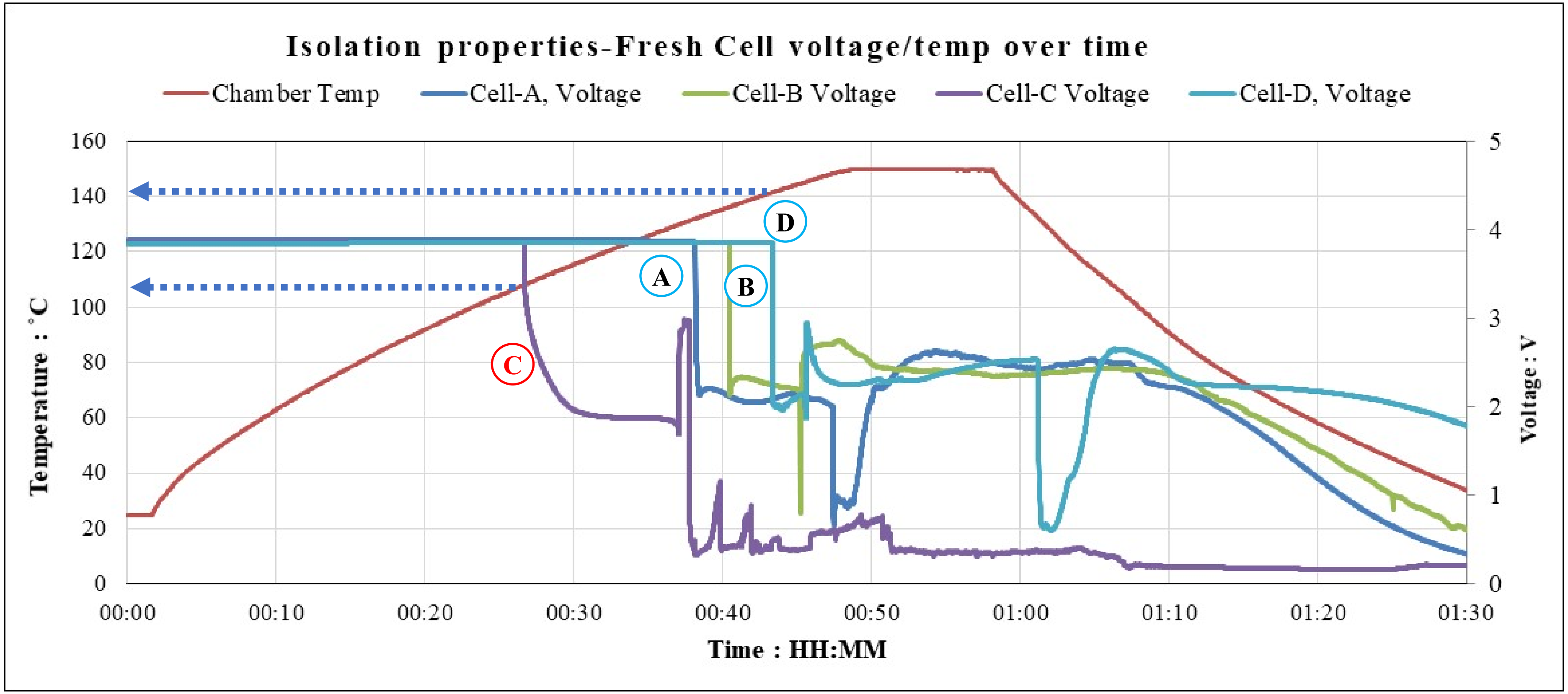
- ✓ The lower activation pressure cells open the CID/Vent and discharge gases earlier than that of higher.
- ✓ C-cells activated much earlier than that of other three cell models both in fresh and aged cells.
- ✓ Comparison : C-cell : at 106 °C vs D-cell : 143 °C

Result Review

Cell voltage drops are dependent on CID activation and Jelly roll micro short by temperature

Test Condition

-Maintain 80% SOC cell in 150 ±2°C chamber for 10 Min. after the cell temperature reach to 150 ±2°C, and then cooldown the temperature to RT. Ramping speed: 5 ±2°C/min.
: IEEE 1725 Test condition

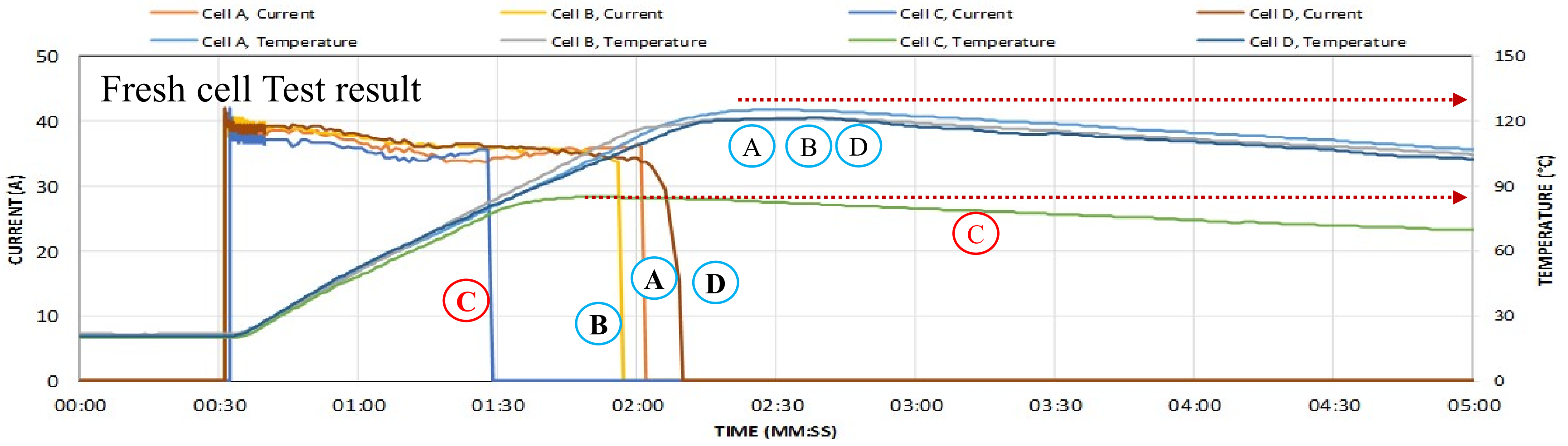


5) Electrical Impact - External short circuit Test

- ✓ External short circuit test directly depends on the CID activation pressure trend.
- ✓ C-cells activated much earlier than that of other three cell models both in fresh and aged cells.

Result Review

C-cell generate less heat compared to other cells due to the earlier CID activation both in fresh and aged .

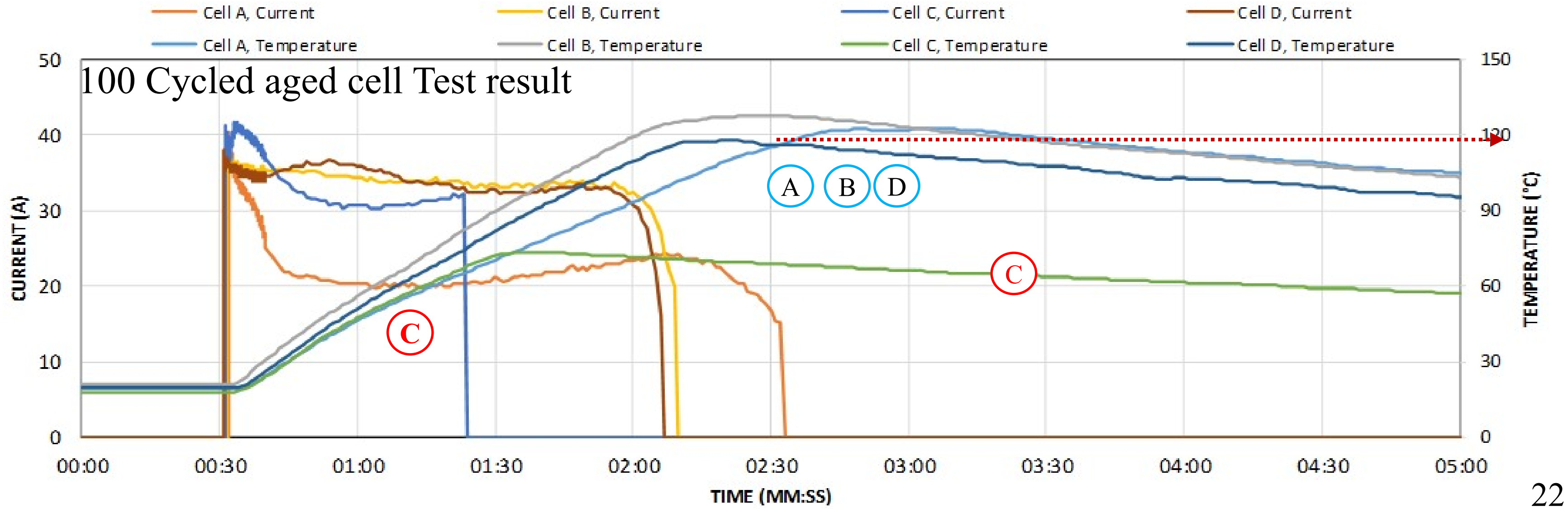


Test Condition

- Externally short circuit fully charged cells independently with a load of < 80 +/- 20 m ohm.

-Maintained it until a discharged state of less than 0.1V has been reached.

-Test is performed for 0.5~1.0 hours after current is no longer drawn or the case temperature is within 10°C +/- 5 °C of the ambient temperature.

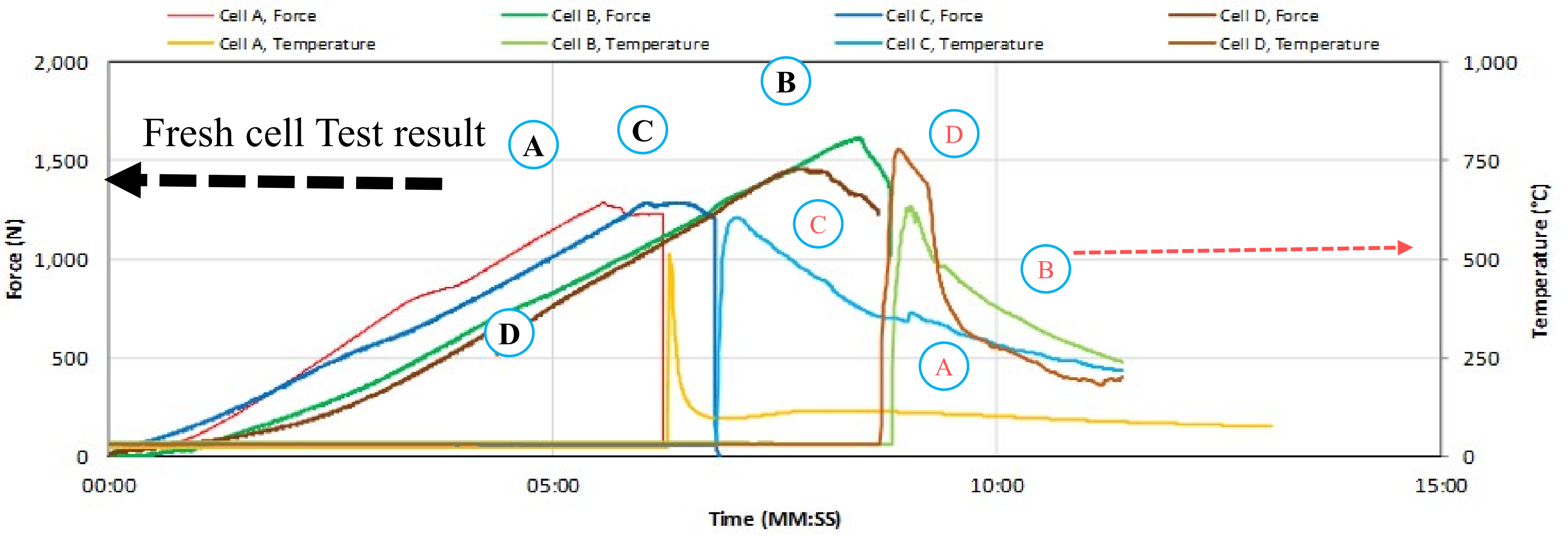


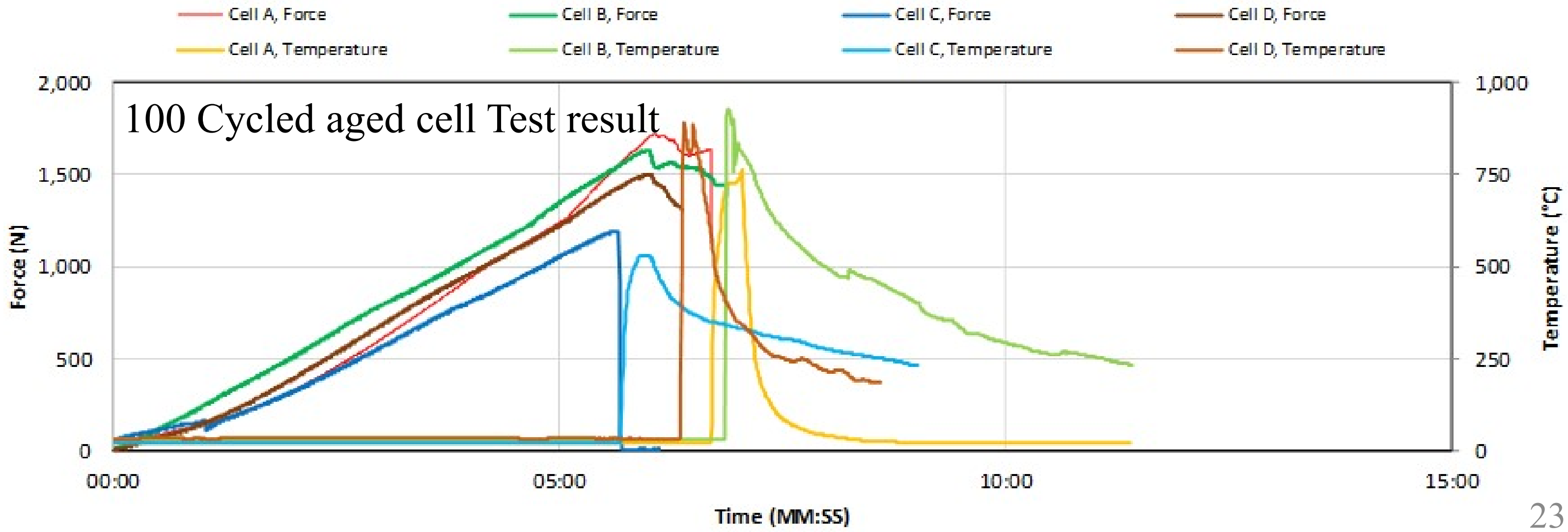
6) Mechanical Impact - Nail Penetration

✓ Cell Can was damaged opened before the CID and Vent reach its activation pressure.

Result Review

- ✓ Nail test results did not show any relation with the CID/Vent mechanism.
- ✓ Nail penetration made an open hole on the Can first and lead the Cell internal short-circuit.
- ✓ The heat and gas generated by ISC escape through the hole and that prevent the activation of the CID & Vent mechanism.





Test Condition

- Penetrate center of fully charged cell with 1/8" nail.
- Perform 0.01 mm/sec (specified by Ford) speed at room temperature (25 +/-5 °C).
- Nail penetration test is maintained until the cell voltage falls by about lower than 100 mV.
- When the cell voltage falls by about lower than 100 mV, stop the nail penetration process manually.

7) Mechanical Impact - Impact Test

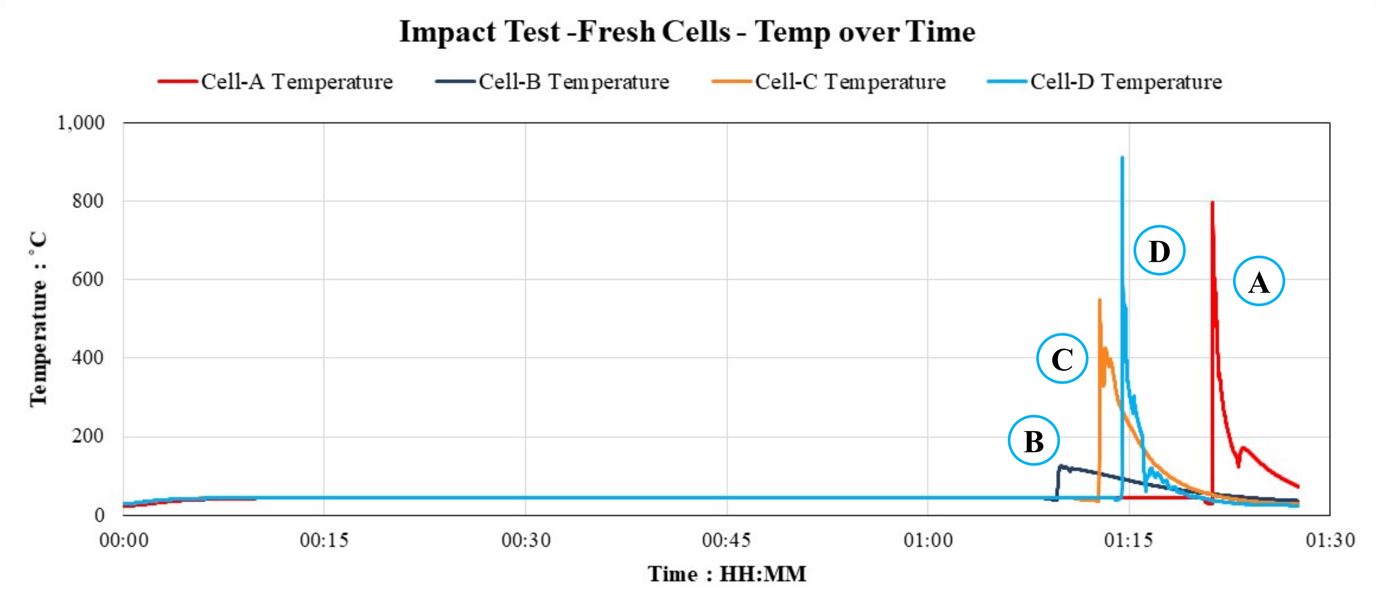
Cell Can was damaged before the CID and Vent reach its activation pressure.

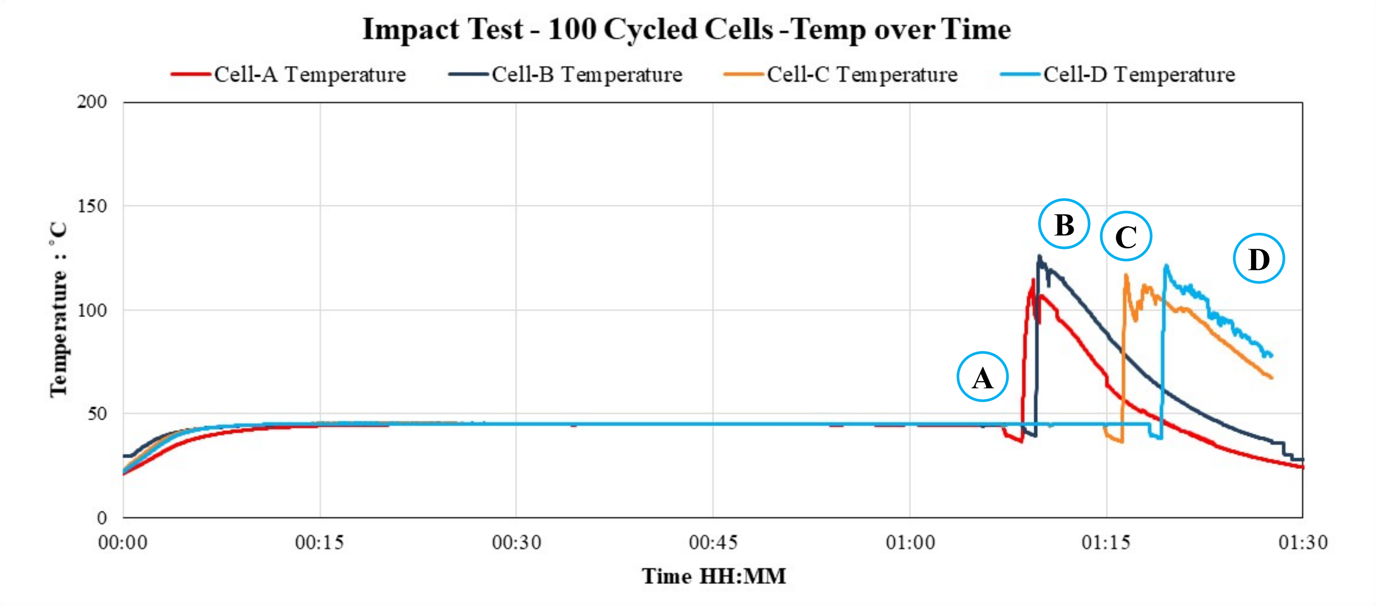
Result Review

- ✓ Impact test results did not show any relation with the CID/Vent mechanism.
- ✓ Impact demolished the Can structure and opened the cell before additional thermal reactions by cell ISC.
- ✓ The heat and gas generated by Impact escape through the opening and that prevent the activation of the CID & Vent mechanism.

Test Condition

-Drop 9.1 kg weight from 610 mm height onto a hard flat surface with 15.8 mm diameter steel bar placed across the center of the cell.
-The cell is placed with its longitudinal axis parallel to the flat surface.
-Cell to be conditioned in a circulating air oven for 1.0 + 0.25 hours at specified temperature (45 ±5 °C) prior to Impact test. The test performed within 1 minute of removal from the oven.





7-1) Impact Test – cell after testing

B

Cell structures were demolished by applied pressure.

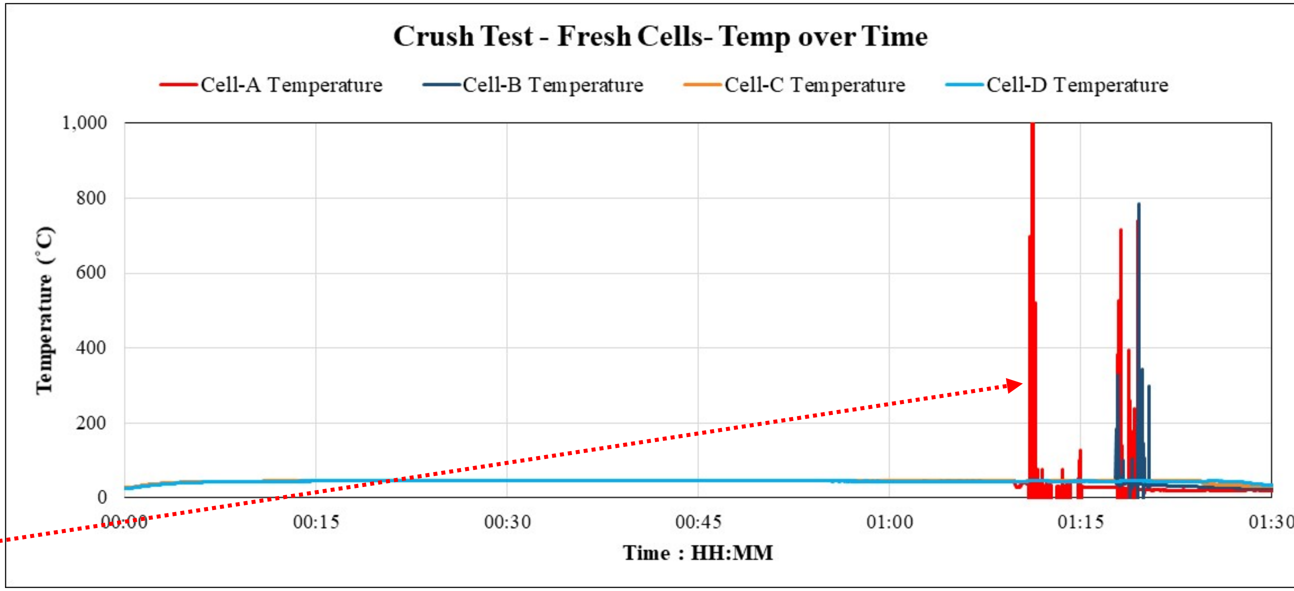
8) Mechanical Impact - Crush Test

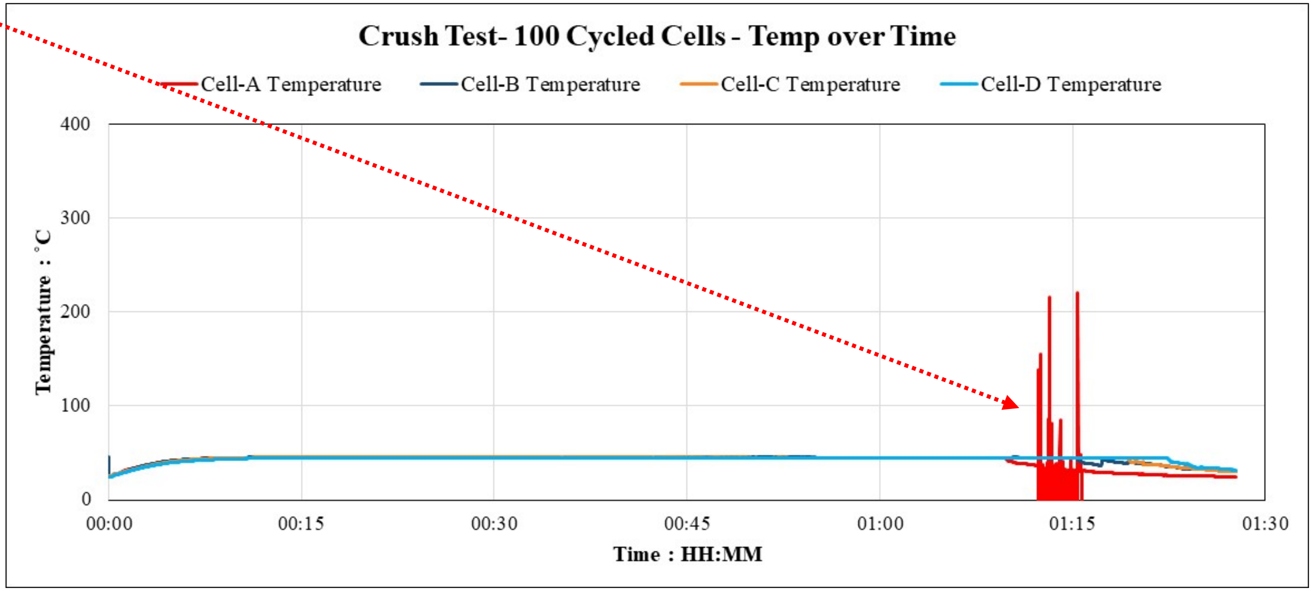
Cell Can structure damaged before the CID and Vent reach its activation pressure.

Result Review

- ✓ Crush test results did not show any relation with the CID/Vent mechanism.
- ✓ Crush test deformed the Can but couldn't lead the cell in the ISC to generate heat and gas.

*The cell temperature were not the real of the cells.
*The temperature values are caused by the thermistor deformation by applied impact.

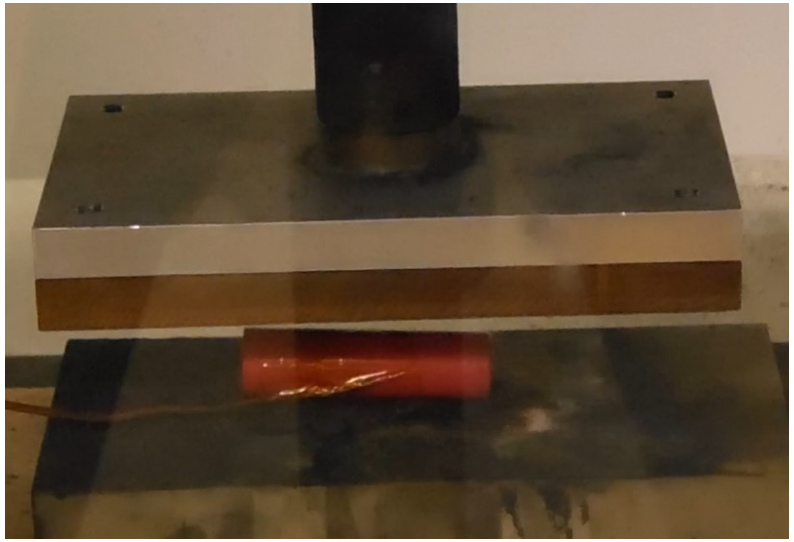


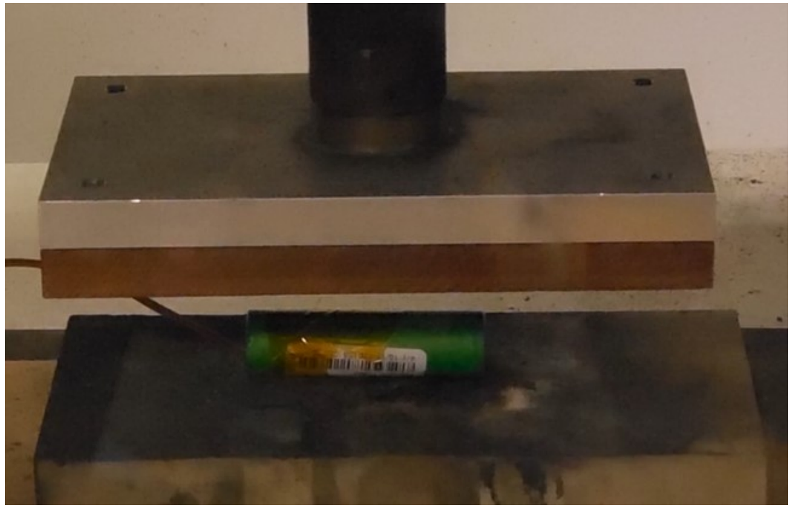


Test Condition

-Apply a 13kN force onto the cell with a longitudinal axis of the cell parallel to the flat surfaces of the Fresh.
- Cell to be conditioned in a circulating air oven for 1.0 + 0.25 hours at specified temperature (45 ±5°C) prior to crush test. The test performed within 1 minute of removal from the oven.

8-1) Crush Test – cell after testing





A

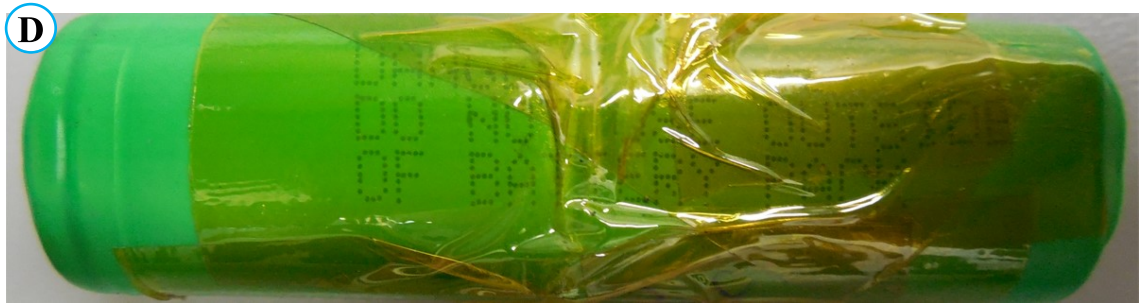
B

C

Cell structures were deformed by applied force, but that couldn't lead the cell to the ISC to generate heat and gas.

➔ No CID/Vent activation

D



9) Evaluation the test results by the EUCAR Hazard Level

Impact	Test Item	Test Description	Cell Model	EUCAR Hazard Level	CID/Vent activation	Hazard Description
Thermal Impact	Thermal Test	Maintain fully charged cell in 130 ±2°C chamber for 1.0 hour after the cell Temperature reach to 130 ±2°C and then cooldown the temp to RT. Ramping speed: 5 ±2°C/min.	Cell A	3 / 3	Activated	Leakage Change in Mass <= 50%
			Cell B	3 / 3	Activated	Leakage Change in Mass <= 50%
			Cell C	3 / 3	Activated	Leakage Change in Mass <= 50%
			Cell D	3 / 3	Activated	Leakage Change in Mass <= 50%
	Isolation propriety	Maintain 80% SOC cell in 150 ±2°C chamber for 10 min. after the cell temperature reach to 150 ±2°C and then cooldown the temperature to RT. Ramping speed: 5 ±2°C/min.	Cell A	3 / 3	Activated	Leakage Change in Mass <= 50%
			Cell B	3 / 3	Activated	Leakage Change in Mass <= 50%
			Cell C	3 / 3	Activated	Leakage Change in Mass <= 50%
			Cell D	3 / 3	Activated	Leakage Change in Mass <= 50%
Electric Impact	External Short Test	Externally short circuit fully charged cells independently with a load of < 80 +/- 20 m ohm.	Cell A	2 / 2	Activated	Defect / Damage
			Cell B	3 / 3	Activated	Leakage Change in Mass <= 50%
			Cell C	2 / 2	Activated	Defect / Damage
			Cell D	3 / 3	Activated	Leakage Change in Mass <= 50%
Mechanical Impact	Nail Penetration Test	Penetrate center of fully charged cell with 1/8" nail	Cell A	5 / 5	No	Fire or Flame
			Cell B	5 / 5	No	Fire or Flame
			Cell C	5 / 5	No	Fire or Flame
			Cell D	5 / 5	No	Fire or Flame
	Impact Test	Drop 9.1kg weight from 610mm height onto a hard flat surface with 15.8mm diameter steel bar placed across the center of the cell.	Cell A	**7 / 7**	**No**	Explosion
			Cell B	3 / 3	No	Leakage Change in Mass <= 50%
			Cell C	**5 / 5**	**No**	Fire or Flame
			Cell D	**5 / 5**	**No**	Fire or Flame
	Crush Test	Apply a 13kN force onto the cell with a longitudinal axis of the cell parallel to the flat surfaces of the Fresh.	Cell A	2 / 2	No	Defect / Damage
			Cell B	2 / 2	No	Defect / Damage
			Cell C	3 / 3	No	Leakage Change in Mass <= 50%
			Cell D	3 / 3	No	Leakage Change in Mass <= 50%

Summary and Conclusion

- ✓ Activation pressures of the CID & Vent mechanism measured by designed test equipment.
  - CID : measured by Voltage drop when the CID open.
  - Vent mechanism : measured by Pressure drop when the Vent open.
- ✓ To investigate the relationship between Activation pressures of the CID & Vent mechanism and the battery safety, three categories of battery abnormal tests (Thermal, Electric, and Mechanical Impacts) were performed.
- ✓ CID activation pressures are sensitive to the “Thermal” and “Electric” impact trigger test, and fresh cells are more sensitive compared to aged (100 cycled) cells to the triggers.
- ✓ Mechanical impact test (Impact, Crush, and Nail test) don’t show any relation with the activation pressure of the CID & Vent mechanism.

  ➔ Can structure damaged or demolished before CID & Vent reaches their activation conditions : Nail & Impact. Crush test can not lead the cell to reach thermal runaway to generate heat and gas.