Lithium Ion Battery Introduction

Trend Power Technology 陳威成

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- **Cell Type and Structure**
- **Lithium Ion Battery Characteristic**
- **Lithium Ion Battery Safety**
- **BMS Design Requirement**

Where Use ?

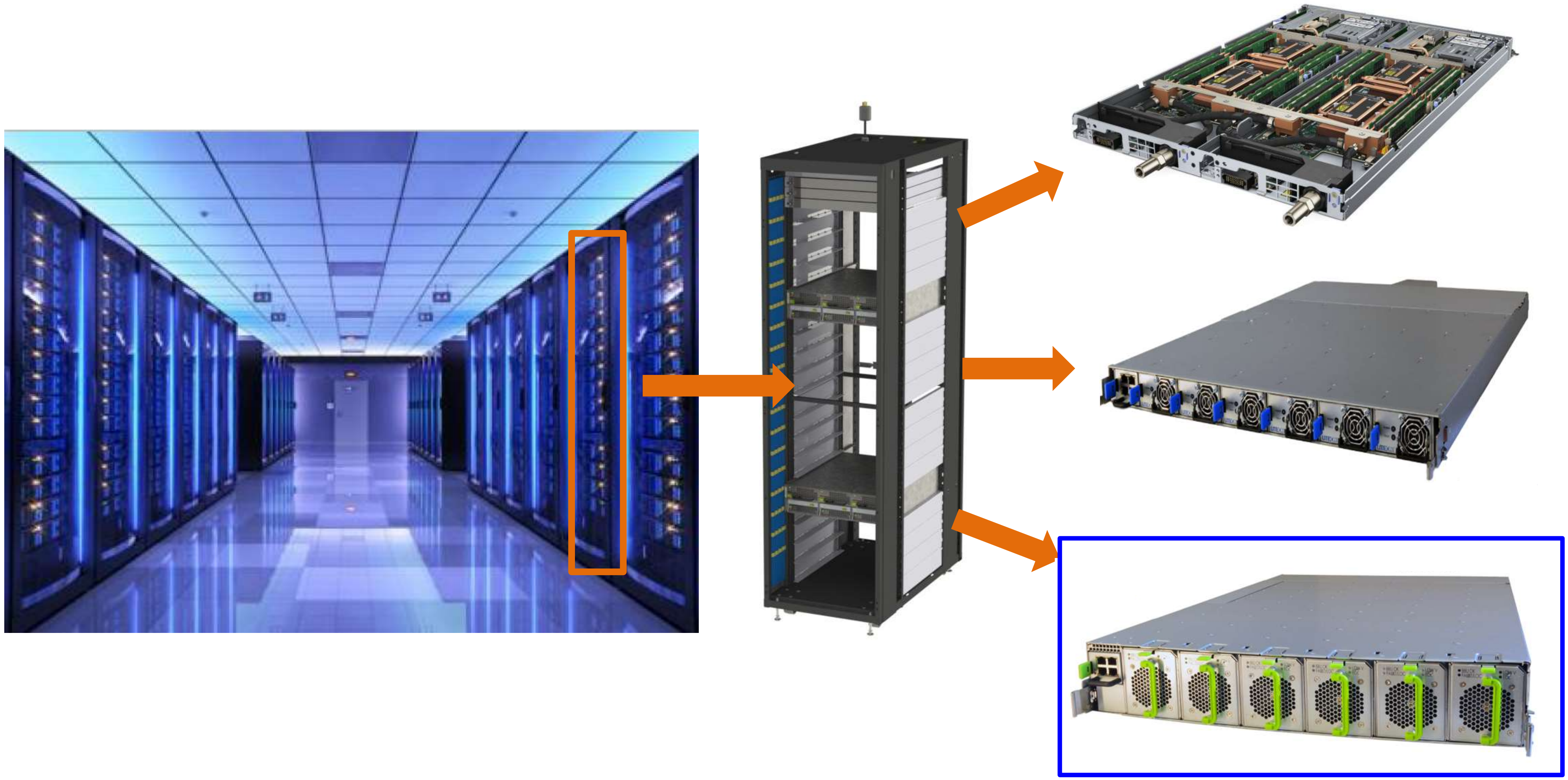
Consumer Application

Where Use ?

Industrial Application

Where Use ?

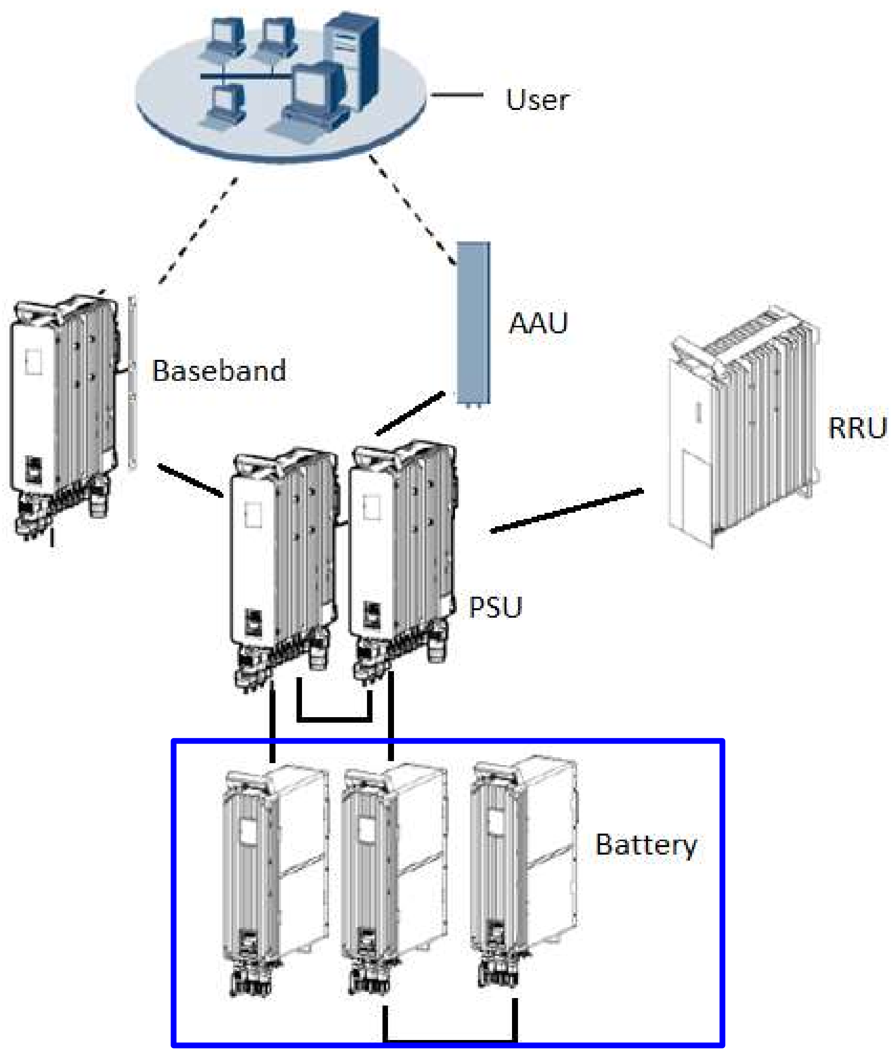
Data Center Application



Where Use ?

Telecom Application

Outdoor



Indoor / UPS

Where Use ?

Energy Storage Application

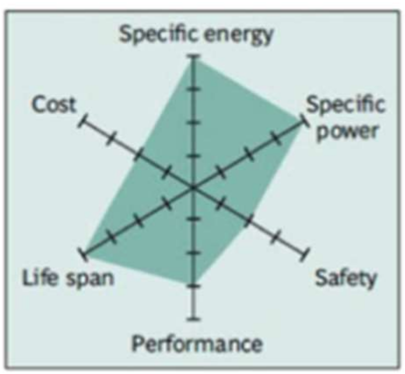
Where Use ?

Traffic Application

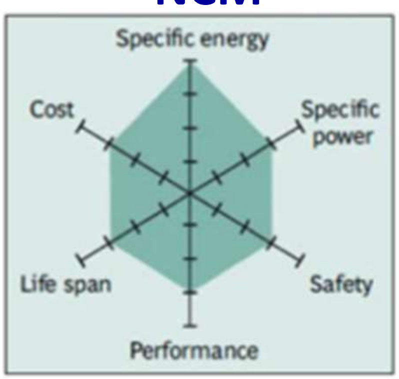
Lithium Ion Batteries by Material

Cell Type	鋰三元		錳酸鋰	磷酸鋰鐵	鈦酸鋰
	NCA	NCM	LMO	LFP	LTO
Positive (Cathode) Material	**$LiNiCoAlO_2$**	**$LiNiCoMnO_2$**	**$LiMn_2O_4$**	**$LiFePO_4$**	**$LiMn_2O_4$ or Others**
Negative (Anode) Material	**Graphite 石墨**	**Graphite 石墨**	**Graphite 石墨**	**Graphite 石墨**	**$Li_4Ti_5O_{12}$**
Operating Voltage	**2.5V~4.2V**	**2.5V~4.2V**	**2.5V~4.2V**	**2.0V~3.6V**	**1.5 ~ 2.7V**

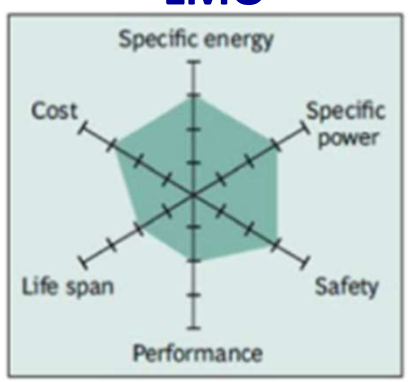
NCA



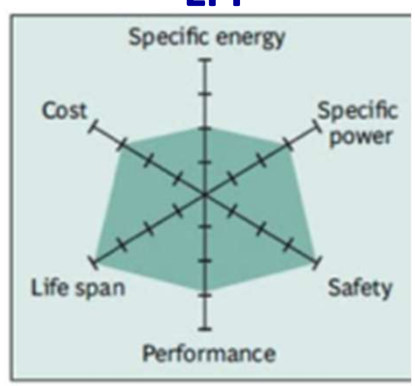
NCM



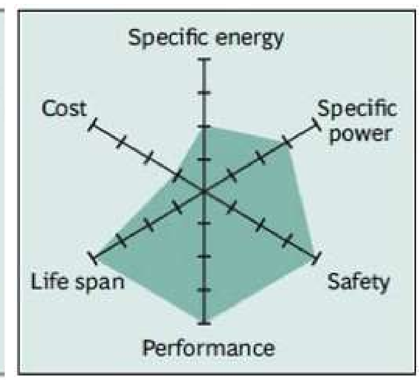
LMO



LFP



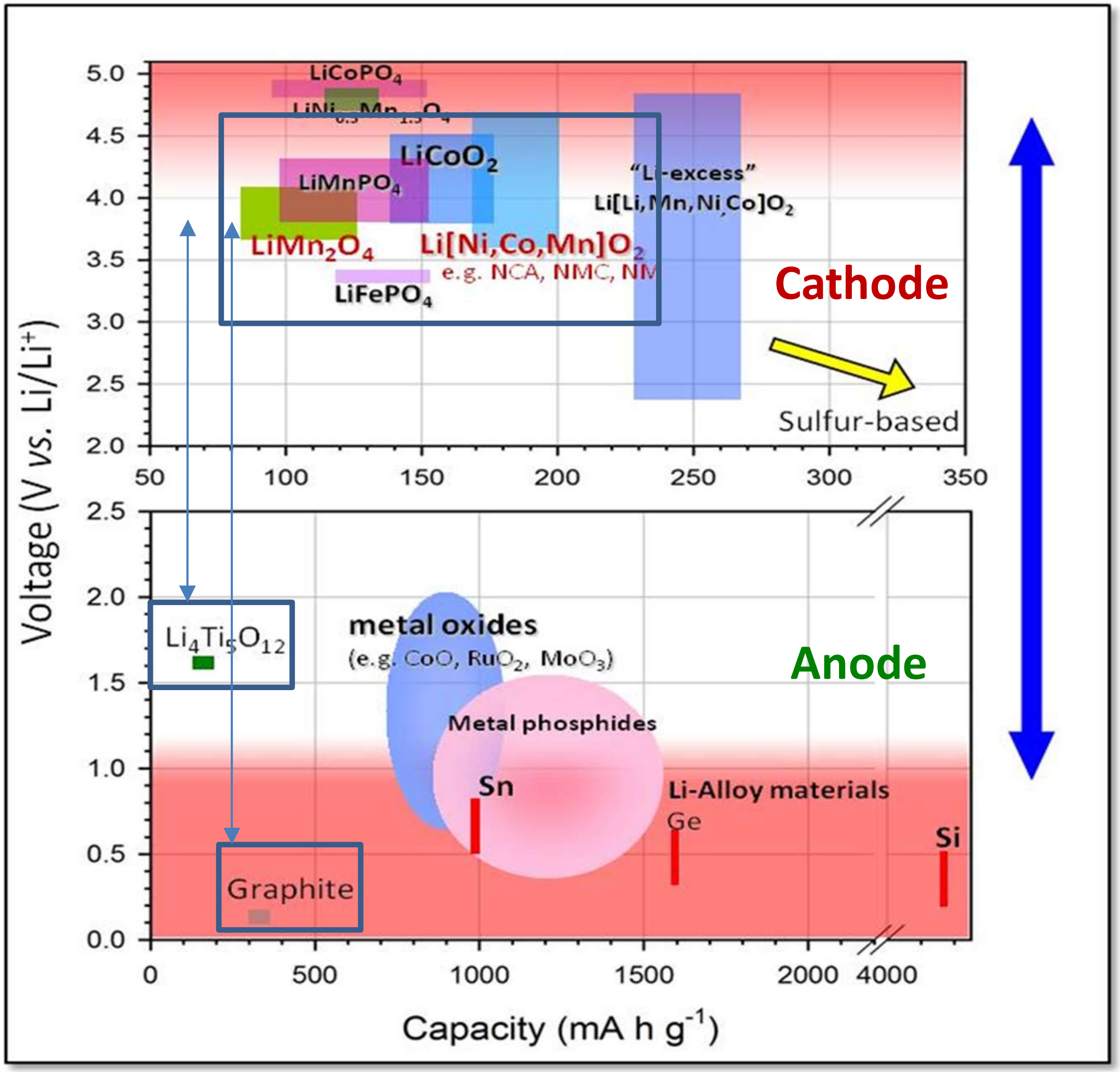
NCM

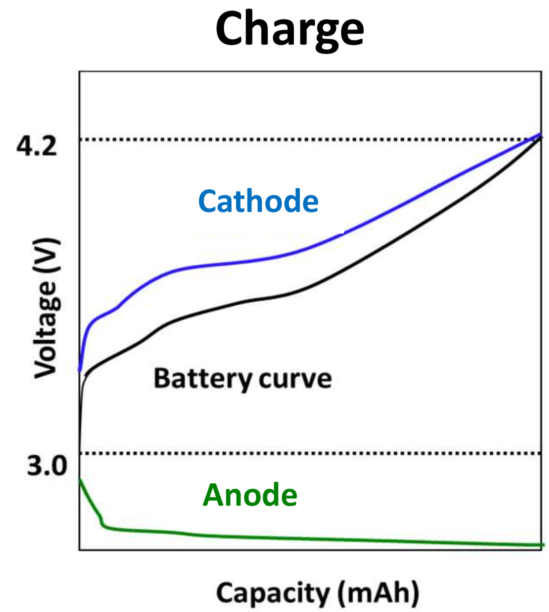


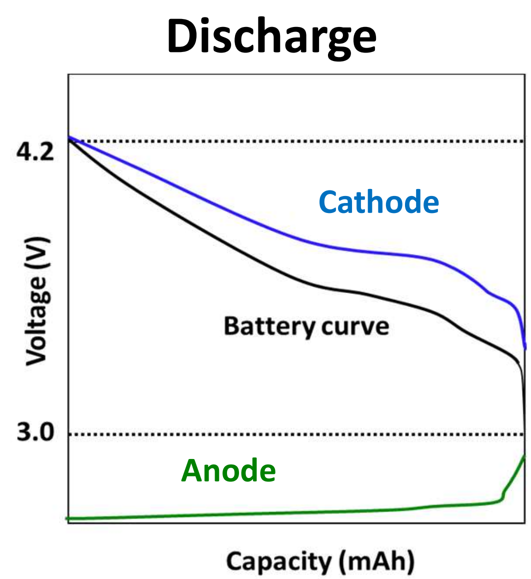
Courtesy of BCG research

The advantages of anode LTO are quick charge, long life, safe and good low temperature charging performance without Li metal plating, but low energy density and high cost are its drawback.

Cathode/Anode materials





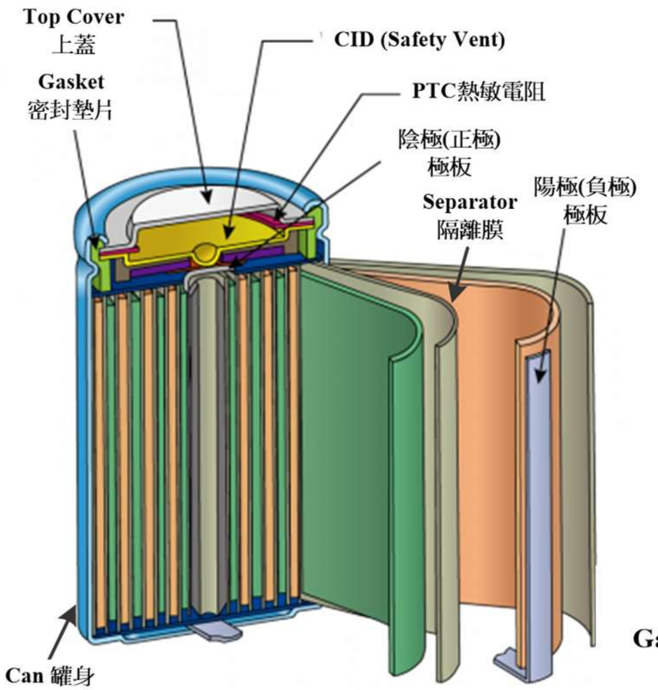


Battery operating voltage = Cathode voltage – Anode voltage

>99% anode material is graphite in commercial cells due to higher operating voltage (↑Energy density).

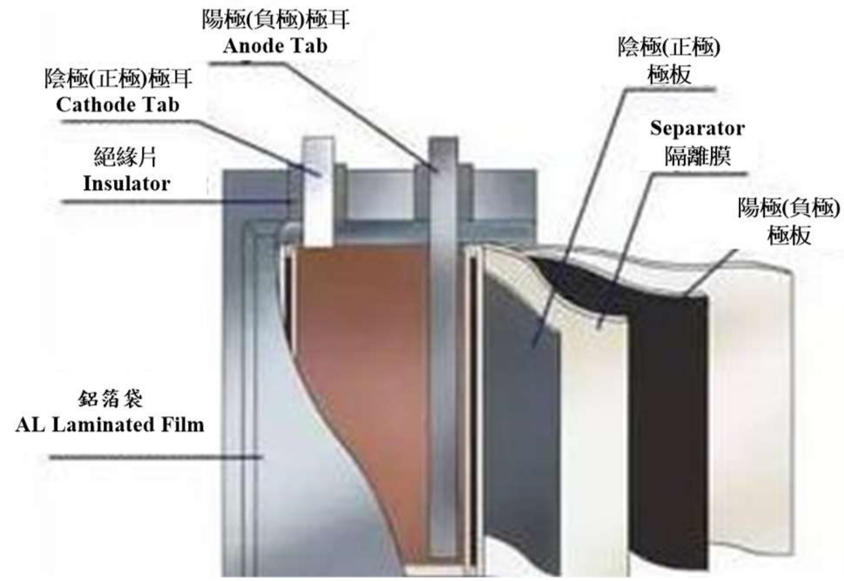
Lithium ion Batteries Types

Cylindrical Cell(圓柱電池)



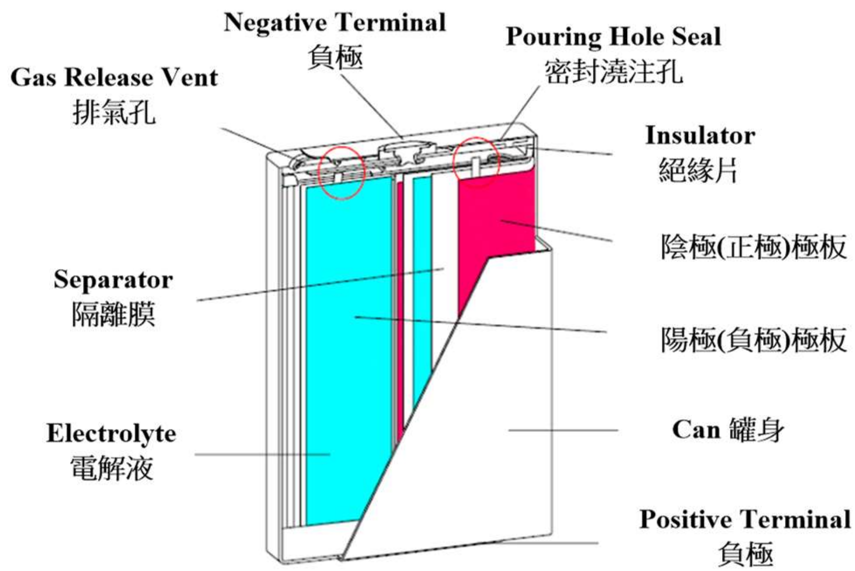
Stainless can(鐵鍍鎳金屬殼)

Punch Cell(軟包裝電池)



Al lamination film(鋁箔袋)

Prismatic Cell (方形電池)



Al or Stainless can(鋁金屬殼)

Cell Disassemble - Cylindrical

Cell -

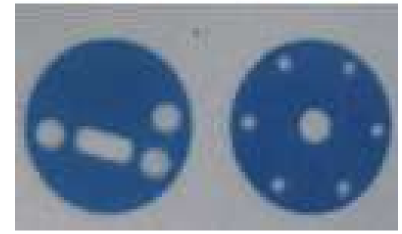
Jelly Roll -

Center pin

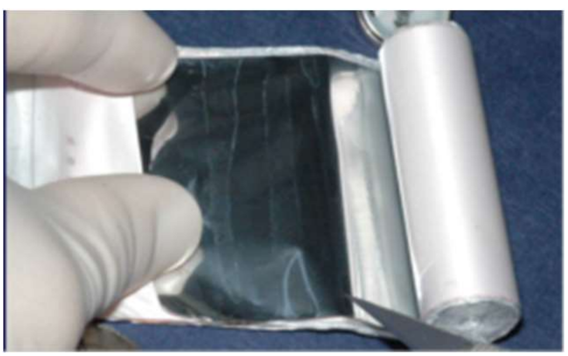
Cap

Bottom

Top Insulator | Bottom Insulator



Gasket | CID / Vent | PTC | Cap-up

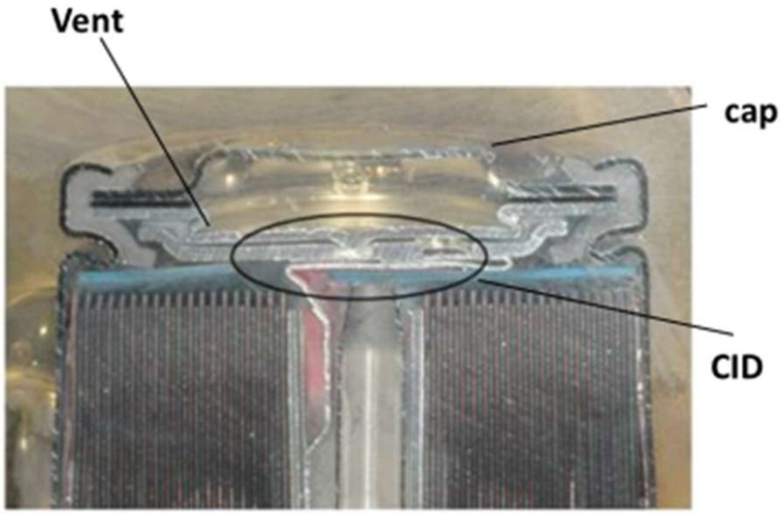


Positive electrode

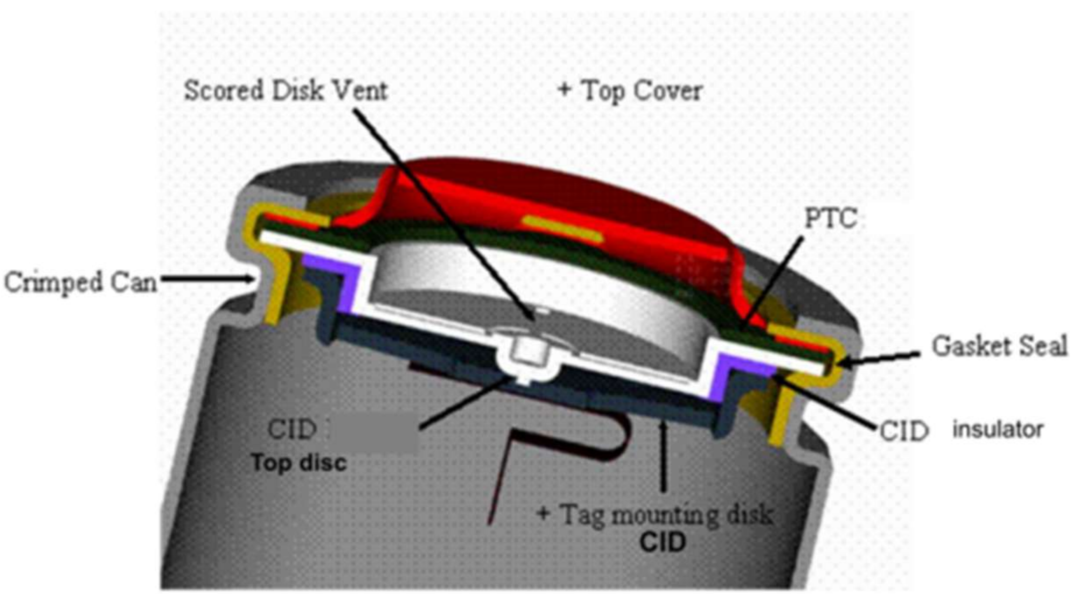
Separator

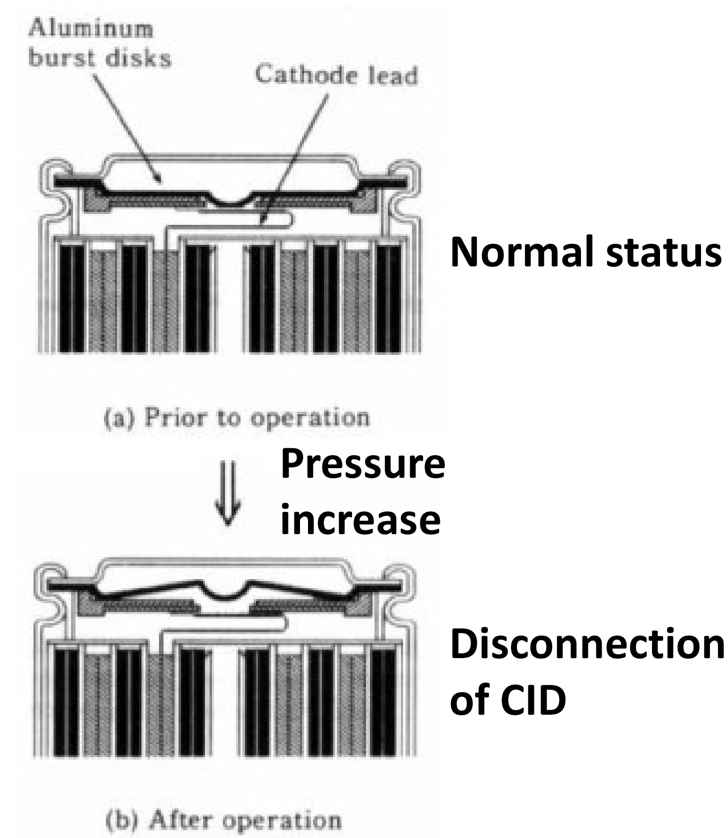
Negative electrode

CID Structure and Trigger



Cap assembly cross section of an 18650 cell with CID assembly weld point indicated (circle).

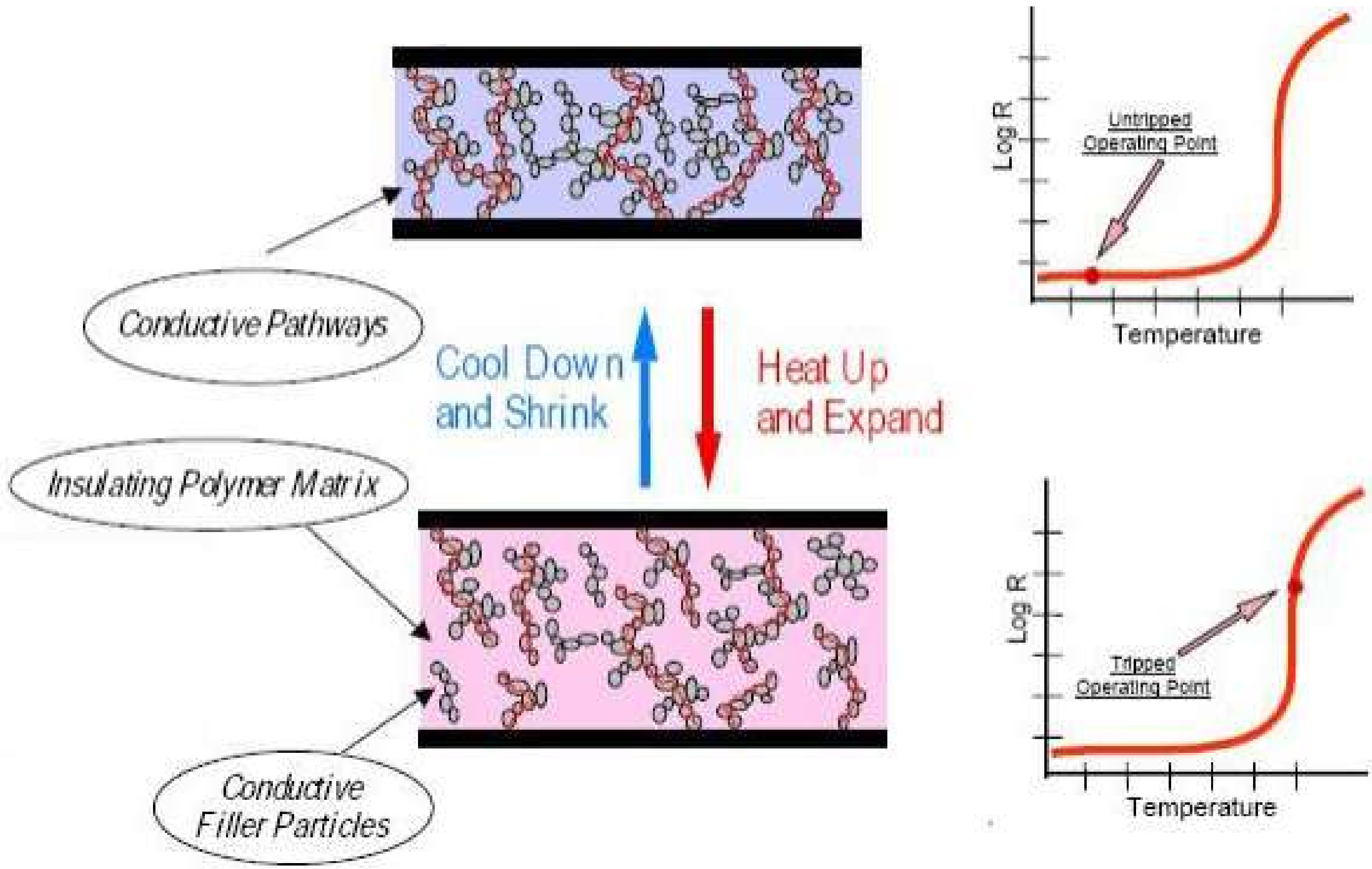




Overcharge or external heat can lead to increasing cell inner pressure.

PTC operation principle

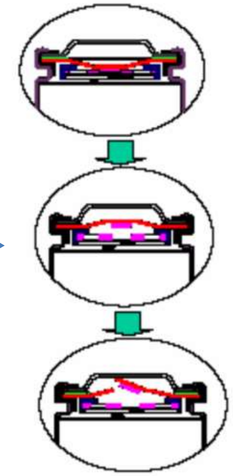
- Temp. increased → Polymer matrix expand → Resistance increased → PTC trip
- Temp. decreased → Polymer matrix contract → Resistance decreased
  (But Resistance could not be back to original value)



PTC is a low impedance device. When current flow through PTC, the temperature will rise. If the current is too high, the PTC temperature will raise and become high impedance. Then, the current will be limited to control the cell temperature.
PTC can protect cell from external short damage.

Safety devices of cylindrical, prismatic and polymer cell

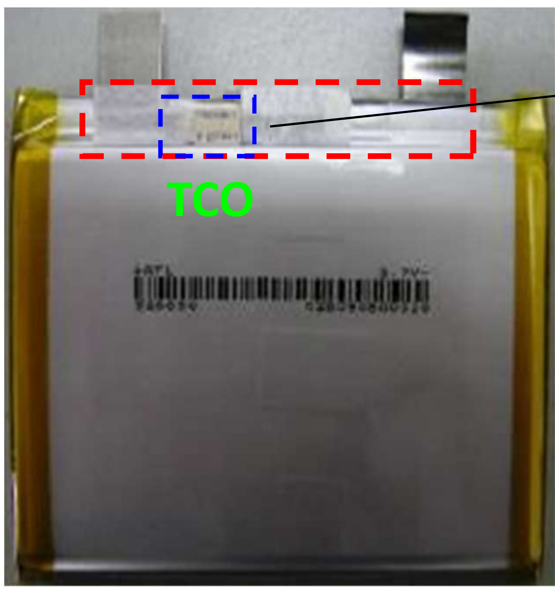
	Embedded safety device	Over charge
Cylindrical cell	CID+Vent	CID can protect cell
Prismatic cell	Vent	Add TCO
Polymer cell	No	Add TCO



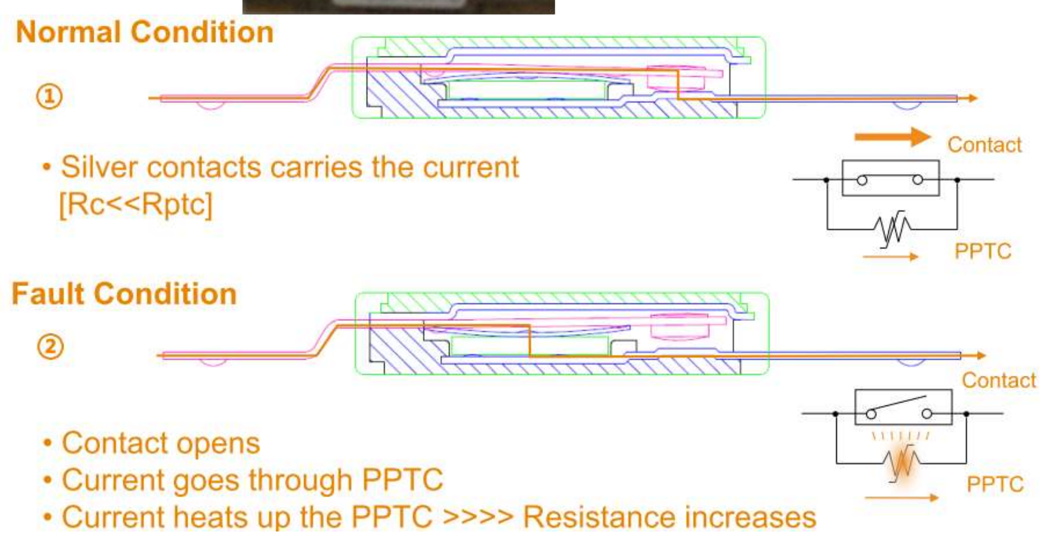
Pressure increase

CID activated Current cutoff

Vent activate Pressure released



Breaker



-Cylindrical cell has CID for overcharge protection. Prismatic and polymer cells need additional TCO (thermal cutoff) to protect itself.

-PTC and TCO will be triggered as high current is applied. It is not suitable for high power delivery application. Generally, cell without PTC/TCO is for this kind of application.

Standard Specification of Lithium Ion Battery

2. Description and Model

2.1 Description   Cell (lithium-ion rechargeable cell)

2.2 Model   ICR18650-22F

3. Nominal Specifications

Item	Specification
3.1 Nominal Capacity	2200mAh (0.2C, 2.75V discharge)
3.2 Charging Voltage	4.2V±0.05 V
3.3 Nominal Voltage	3.6V
3.4 Charging Method	CC-CV (constant voltage with limited current)
3.5 Charging Current	Standard charge: 1100mA Rapid charge : 2200mA
3.6 Charging Time	Standard charge : 3hours Rapid charge : 2.5hours
3.7 Max. Charge Current	2200mA
3.8 Max. Discharge Current	4400mA
3.9 Discharge Cut-off Voltage	2.75V
3.10 Cell Weight	44.5g max
3.11 Cell Dimension	Diameter(max.) : Φ 18.4 mm Height : 65mm max
3.12 Operating Temperature	Charge : 0 to 45℃ Discharge: -20 to 60℃
3.13 Storage Temperature	1 year : -20~25℃(1*) 3 months : -20~45℃(1*) 1 month : -20~60℃(1*)

Note (1): If the cell is kept as ex-factory status(50% of charge),
the capacity recovery rate is more than 80%.

7.3 Initial internal impedance

Initial internal impedance measured at AC 1kHz after Standard charge.

Initial internal impedance ≤ 100mΩ

7.4 Temperature Dependence of Discharge Capacity

Discharge capacity comparison at each temperature, measured with discharge constant current 1100mA and 2.75V cut-off with follow temperature after the standard charging at 25℃.

Charge Temperature	Discharge temperature			
25℃	-10℃	0℃	25℃	45℃
Relative Capacity	50%	70%	100%	100%

7.6 Cycle Life

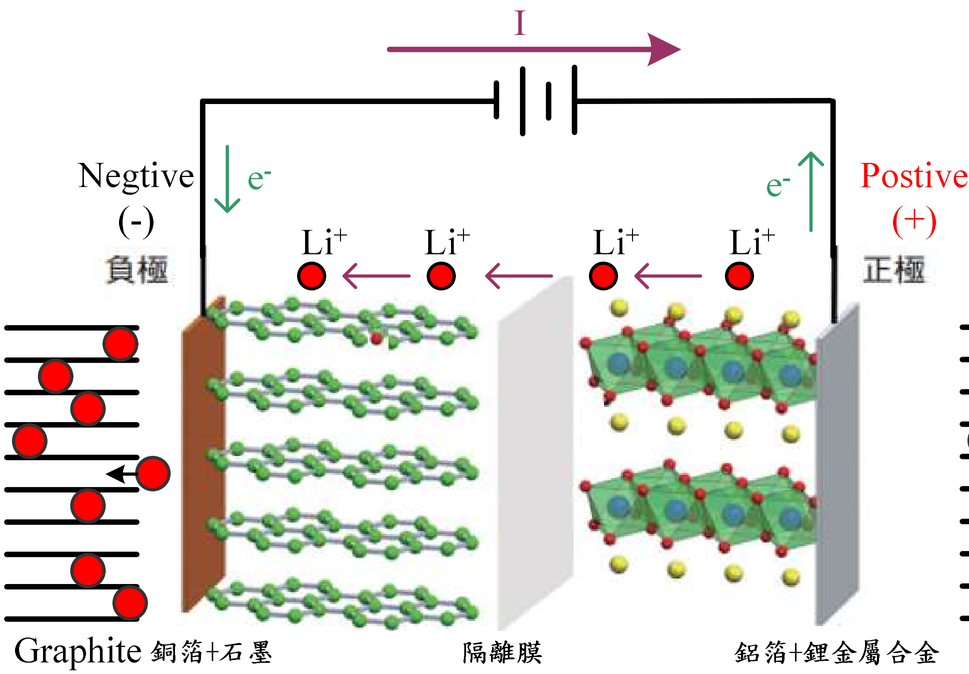
Each cycle is an interval between the charge (charge current 1760mA) and the discharge (discharge current 2200mA) with 2.75V cut-off. Capacity after 299cycles and plus 1 day, measured under the same condition in 7.2

Capacity ≥ 1500mAh

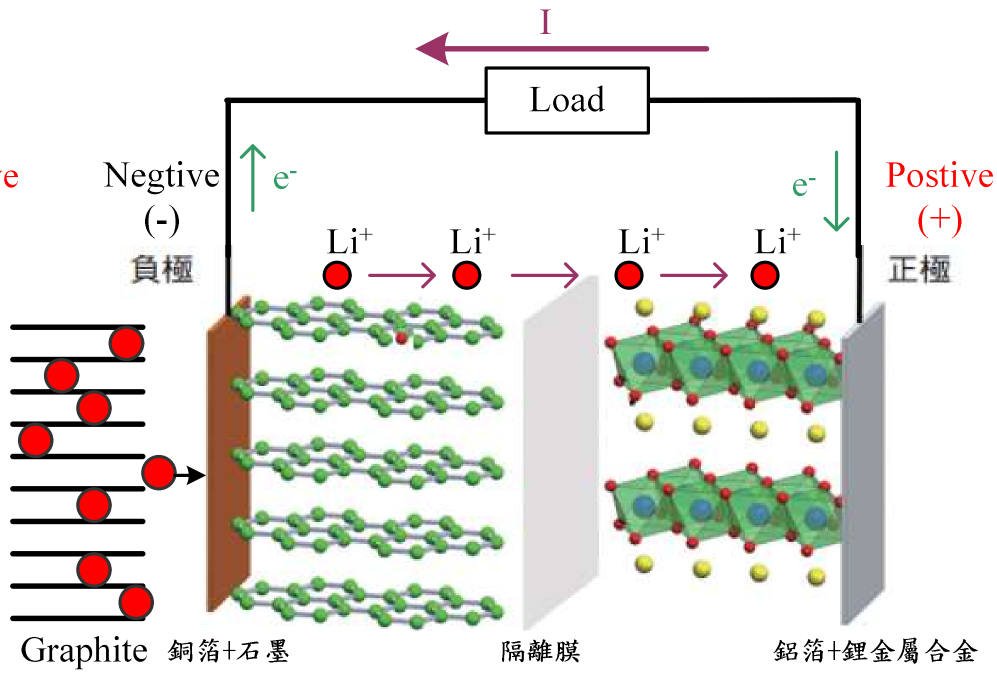
1C rate current: The current (1*A) can fully discharge the cell in 1 hour.
2C rate current: The current (2*A) can fully discharge the cell in 0.5 hour.
0.2C rate current: The current (0.2*A) can fully discharge the cell in 5 hour.

Lithium Battery Operating

- **Charge**



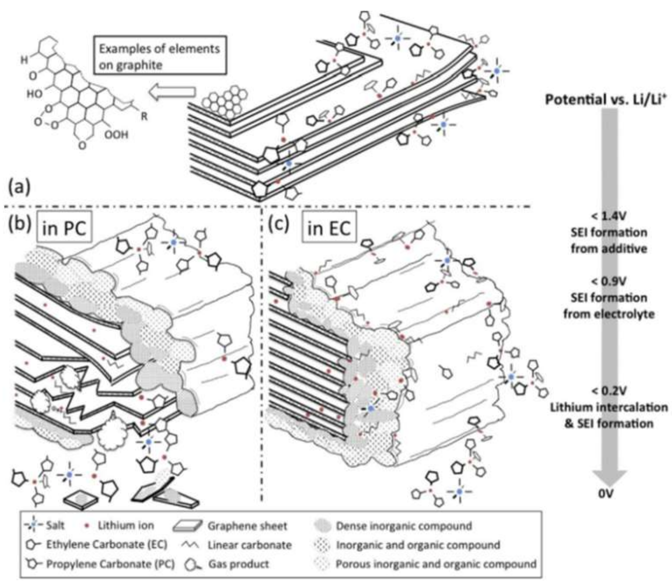
- **Discharge**



充電：
在鋰離子電池充電時，鋰離子會由正極嵌出，藉由電解液傳遞，穿過隔離膜至負極嵌入，而電子會經由外部電路傳到至負極.

放電：
在鋰離子電池放電時，鋰離子會由負極嵌出，藉由電解液傳遞，穿過隔離膜至正極嵌入，而電子會經由外部電路傳到至正極.

固液界面膜 (SEI膜)



* SEI : Solid Electrolyte Interface
EC : Ethylene(乙烯) Carbonate (碳酸鹽)
PC : Propylene(丙烯) Carbonate(碳酸鹽)

鋰離子充放電時，電解液中的溶劑 EC 與 PC 把鋰離子傳遞到碳材表面，而負極表面的電子和鋰離子進行電荷轉移，EC 或 PC 因為接受到電子產生還原反應，被分解後在負極的表面形成固液界面(SEI)膜，顧名思義就是固體(負極 碳材)和液體(電解液)之間所形成的界面膜。

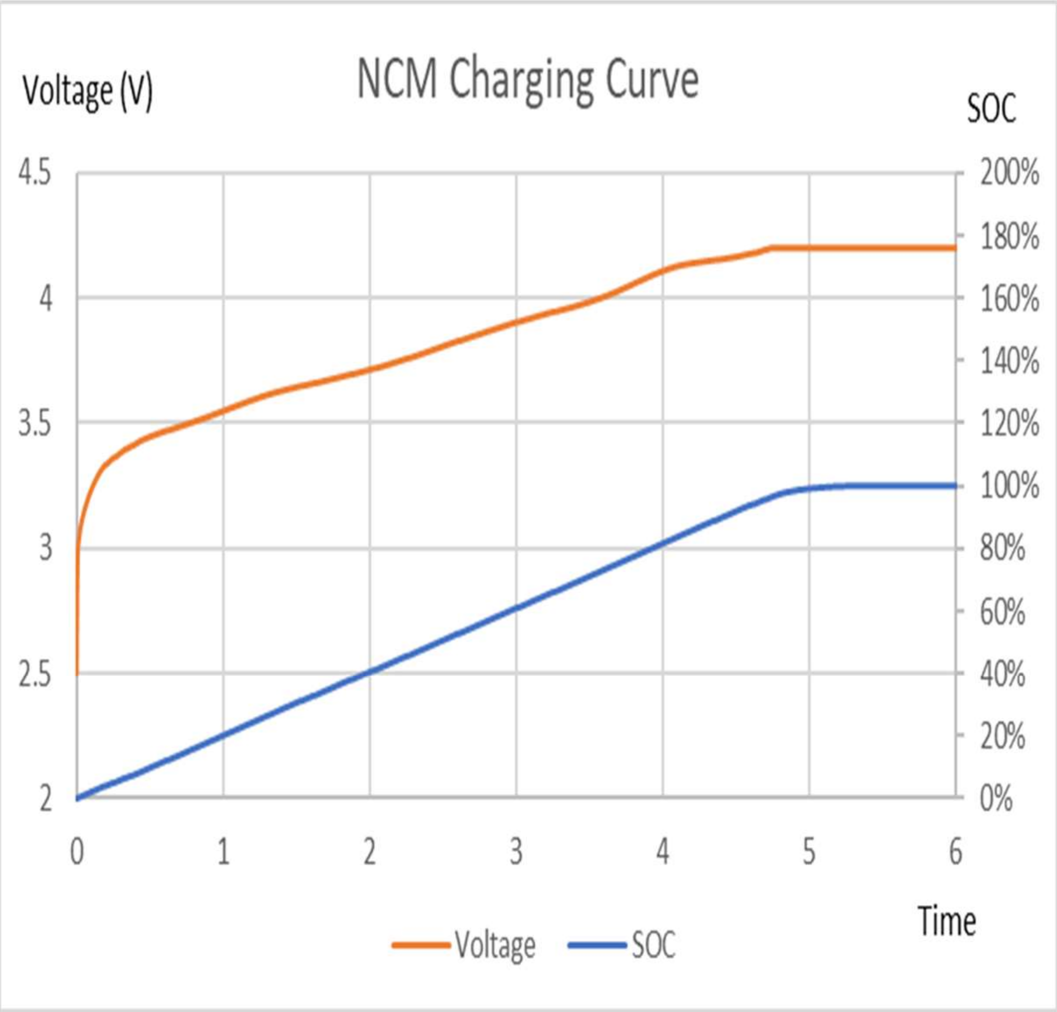
SEI 膜是由很多的有機化合物以及無機的化合物所組成，它可以幫助鋰離子傳導，也可以抑制電解質的分解。一般在負極形成的 SEI 膜厚度大約為 200 nm。

連續充放電時，因為材料表面的因素，SEI 膜會反覆地生成， 進而導致電池的循環壽命及使用效能下降，造成鋰電池老化。

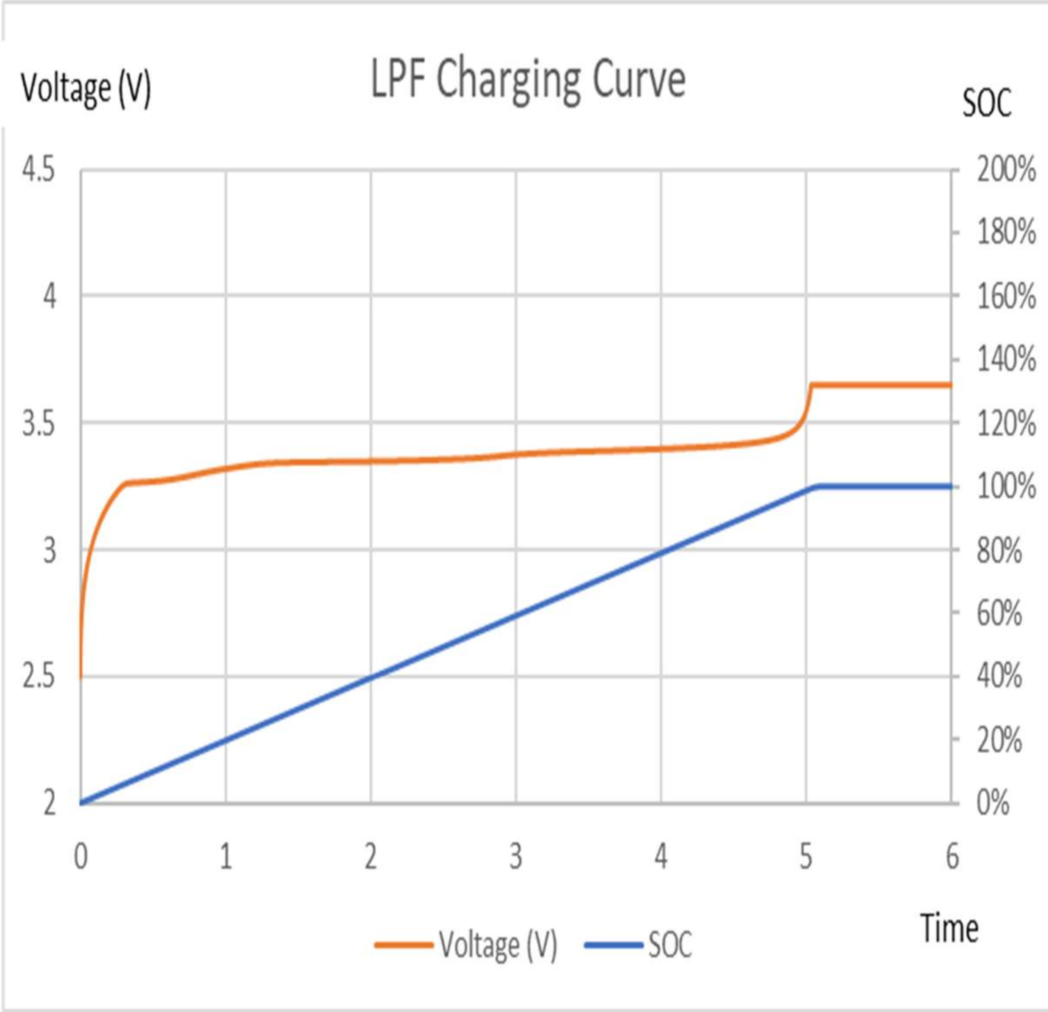
影響 SEI 膜結構的因素有：電解液的有機溶劑、鋰鹽、溫度、活性材料的種類以及添加物，若能良好的控制 SEI 膜增生，將可以有效提升電池的循環壽命及使用效 能。

Charging Curve of Lithium Ion Battery

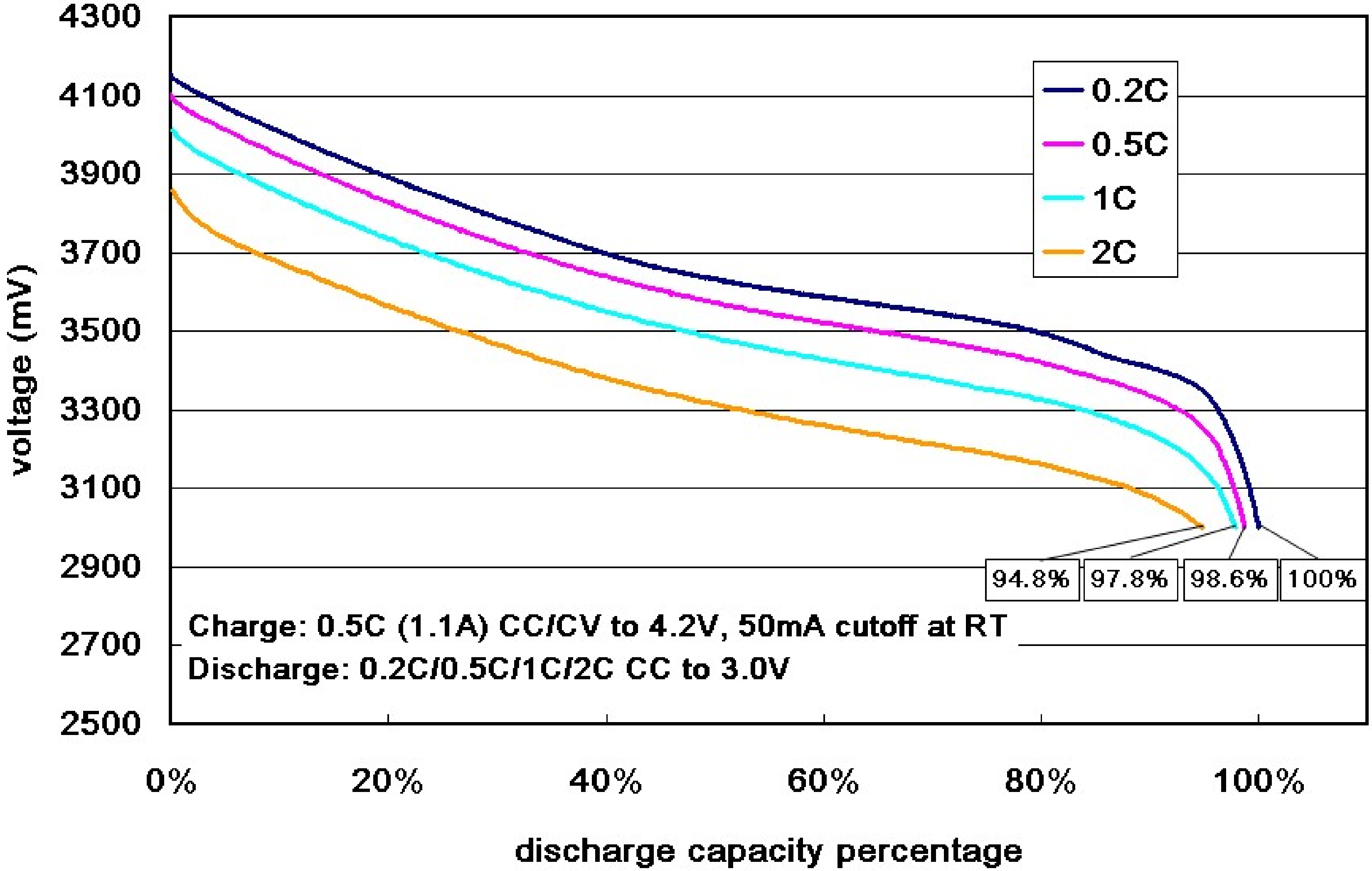
Ternary Lithium Ion Battery (@0.2C)



LFP Battery (@0.2C)



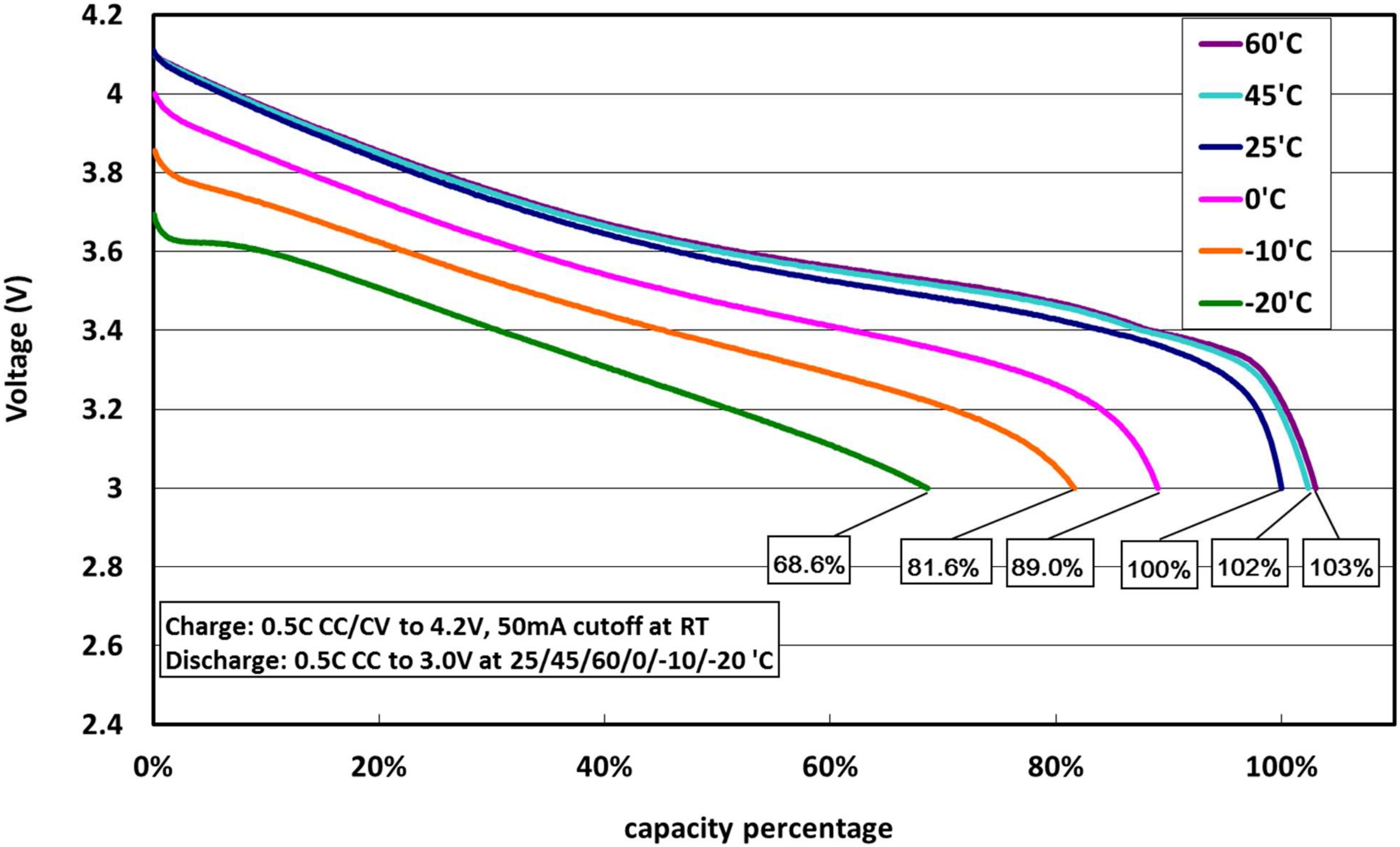
Discharging Curve with Different C-rate Discharging Current



***0.2C discharge capacity is as 100%**

➢ ***Discharging Capacity is different between different discharging Current***

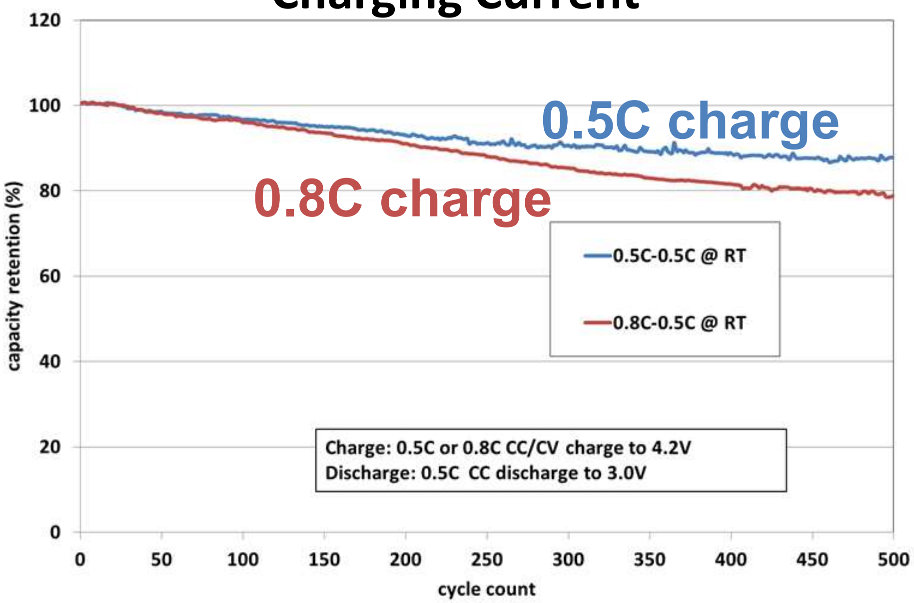
Discharging Curve on different temperature with 0.5C fixed Discharging Current



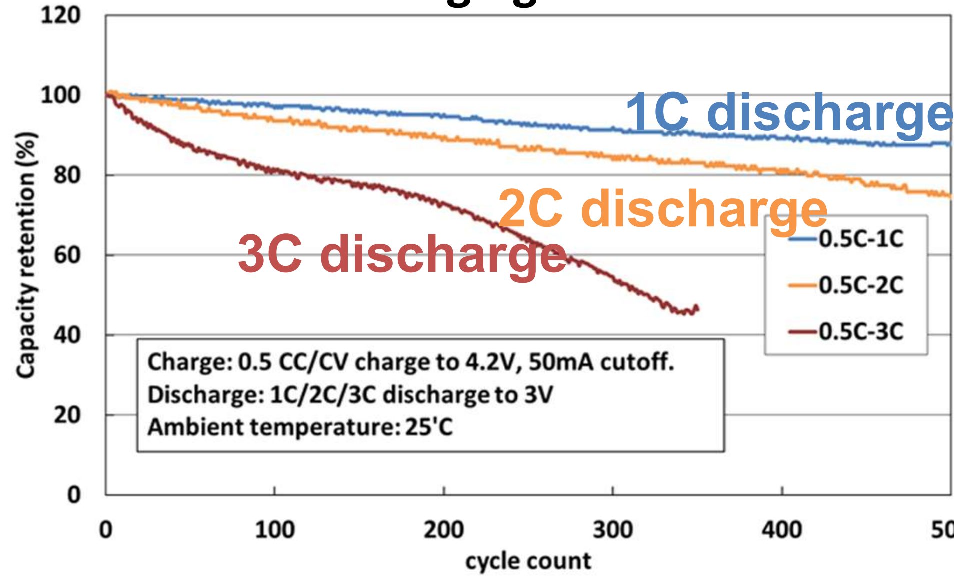
- **Discharge capacity at 25℃ is as 100%**
- **Discharging Capacity is different at different temperature**

The Factor which Related to Lithium Battery Life

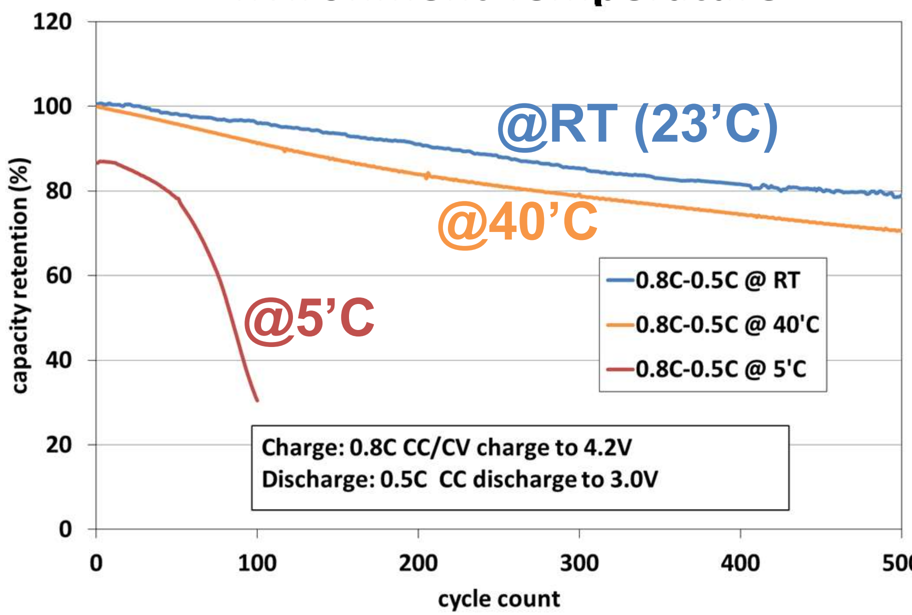
Charging Current



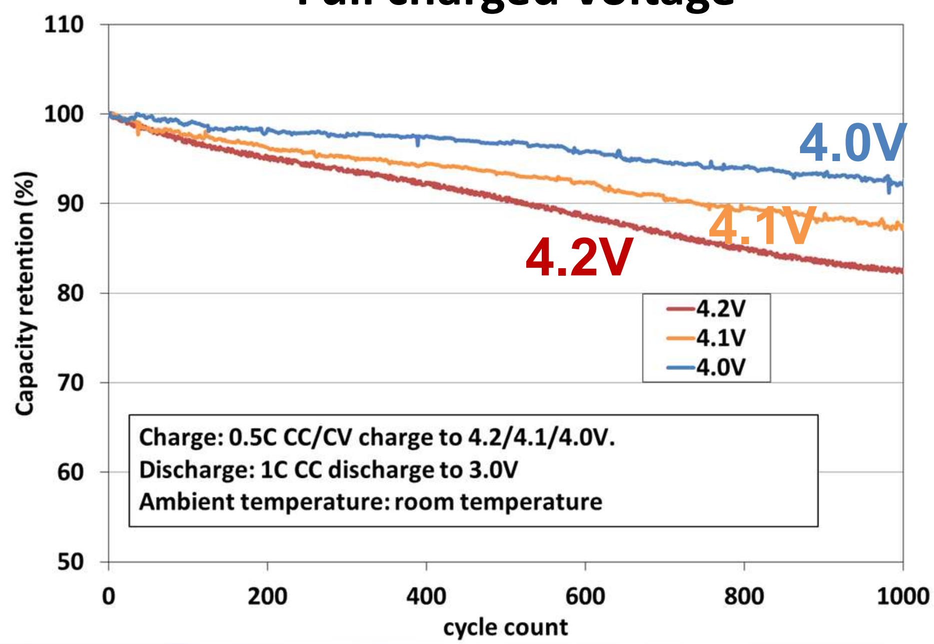
Discharging Current



Environment Temperature

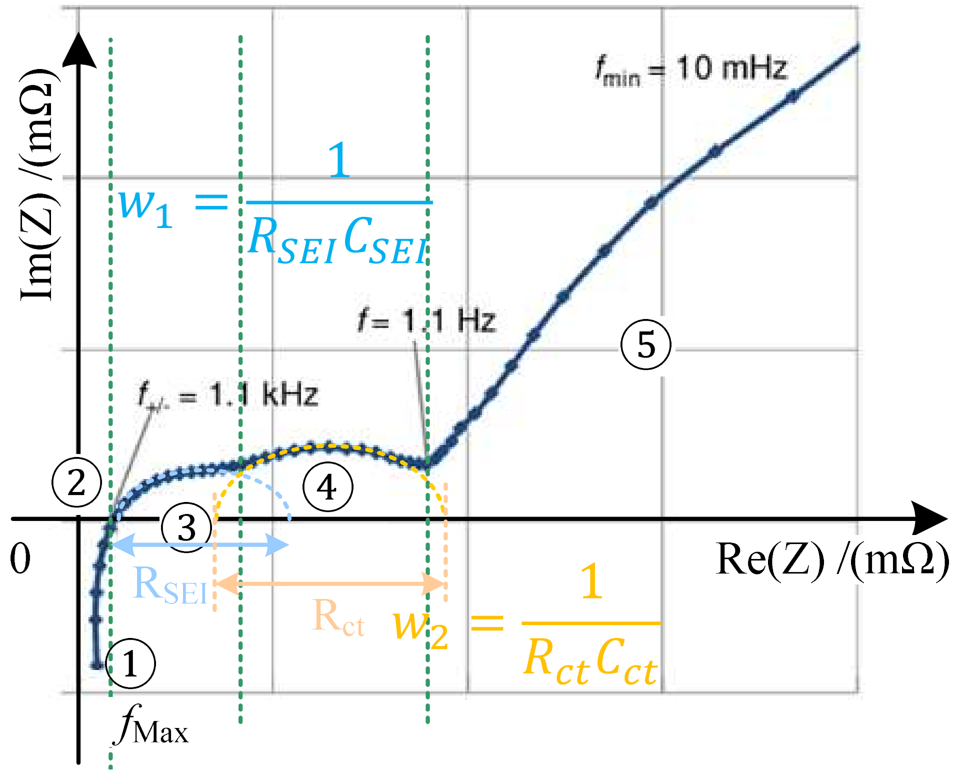


Full charged Voltage

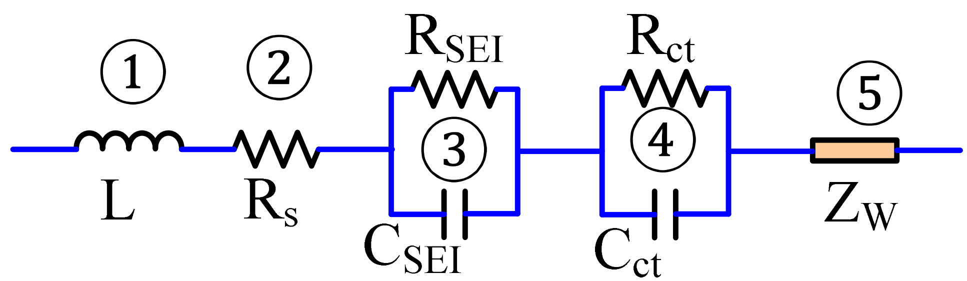


Lithium Battery Impedance(ACIR) and Frequency

Nyquist-plot



Cell Model



L：電池組裝結構所產生的電感效應

R_s ：電極與隔離膜的歐姆電阻

R_{SEI}/C_{SEI}：固體顆粒表面與電解質間(SEI膜)的電阻/電容

R_{ct}/C_{ct} ：電荷移轉的電阻與電容

Zw ：擴散效應的電阻與電容 + 飽和的總電阻和存儲電容

Safety Risk of Lithium Ion Battery

2007年9月，Dell筆電突然爆炸燃燒

2018年12月，彰化一對兄妹在家看電視，書桌上的筆電卻突然爆炸，哥哥趕緊拿滅火器滅火，但是筆電火滅掉後又再爆一次，哥哥非常冷靜再滅一次

Safety Risk of Lithium Ion Battery

特斯拉起火消防7小時狂灌10萬升水 罕見電動車火災竟成新難題

2022-07-22 20:44 香港01／撰文／洪怡霖 成依華

+ 車禍

圖為2022年6月美國一輛Tesla起火，幸無人傷亡，消防員花費大量功夫把火撲滅。圖／FB@Sacramento Metropolitan Fire District

2021年6月，台南傳出Gogoro電池充電交換站及鋰電池自燃火警

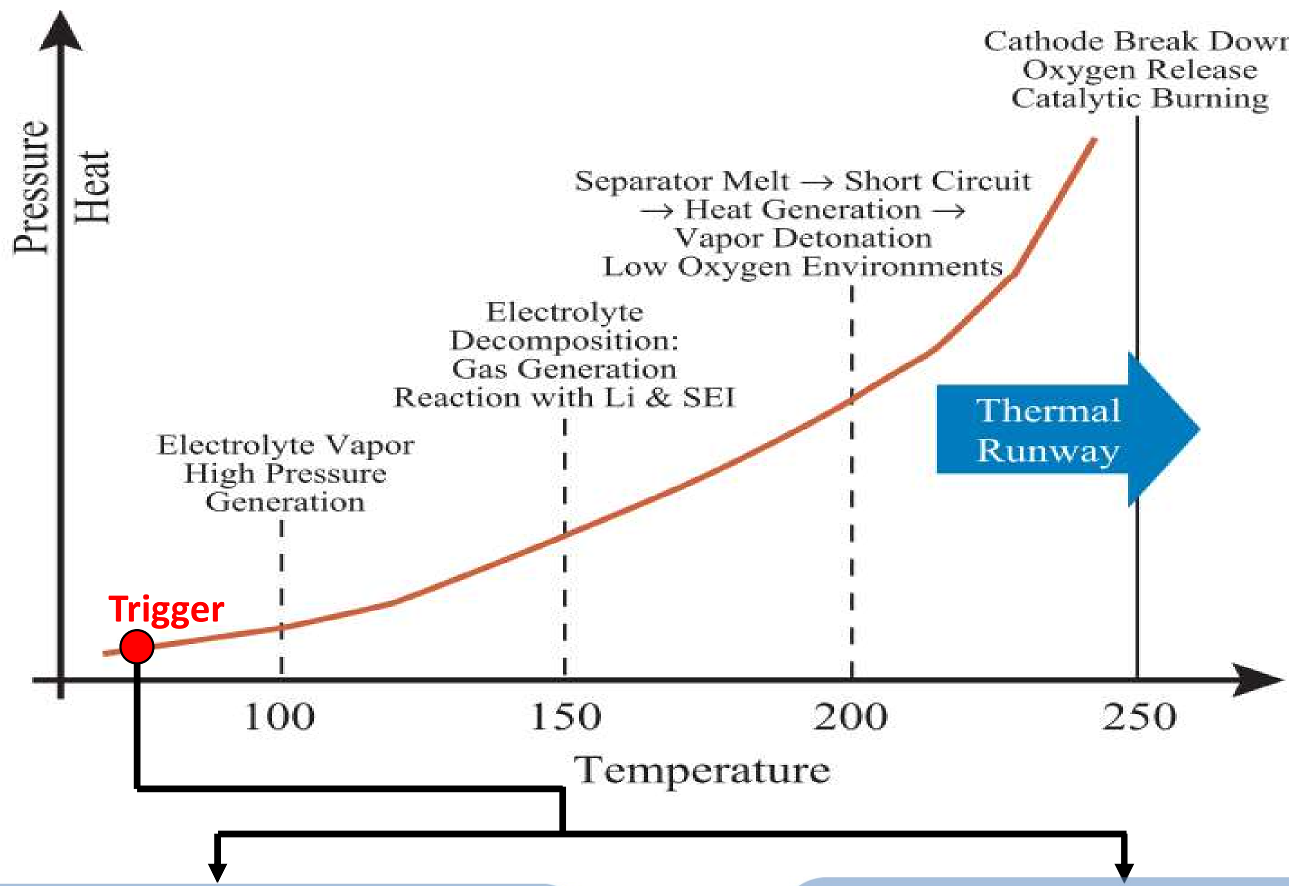
Safety Risk of Lithium Ion Battery

2019年9月，韓國風力發電站的電池儲能系統發生火災

2021年08月，澳大利亞的Victorian Big Battery在測試期間發生火災事故，一個裝載13噸鋰離子電池的特斯拉Megapack電池組起火燃燒。

美國加利福尼亞州蒙特雷（Monterey）的一個變電站著火，火源是由變電站中特斯拉 Megapack 的巨型電池儲能設備引發的

Safety Risk of Lithium Ion Battery



Poor Cell Quality

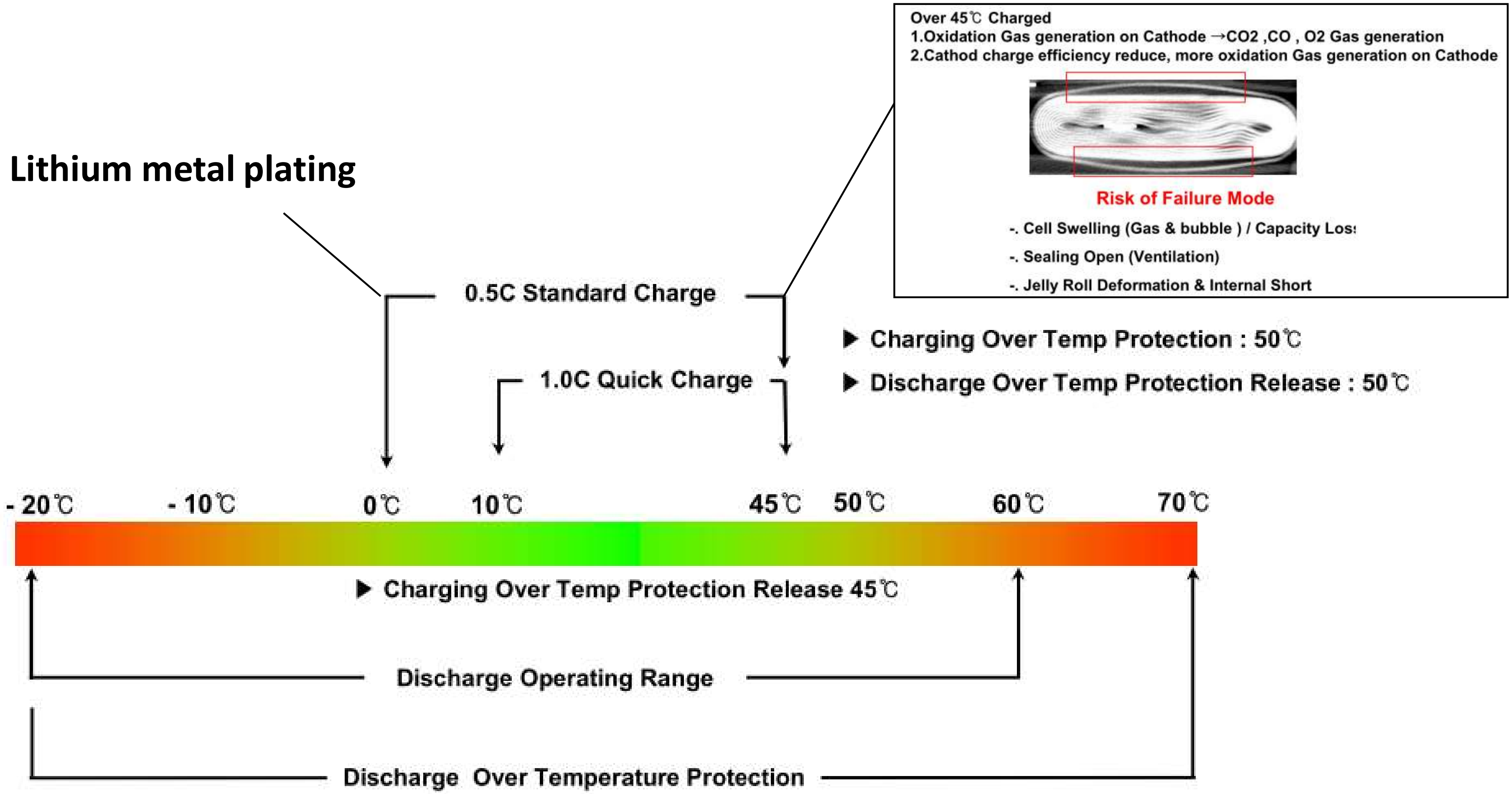
- Poor Cell Uniformity to cause Cell Imbalance
- Internal Short

Abuse Usage

- Over charge
- Over discharge
- Charge/discharge at over temperature range
- External short

A high safety lithium ion battery needs both Good Cell Quality Control & Precise BMU Protection Functions.

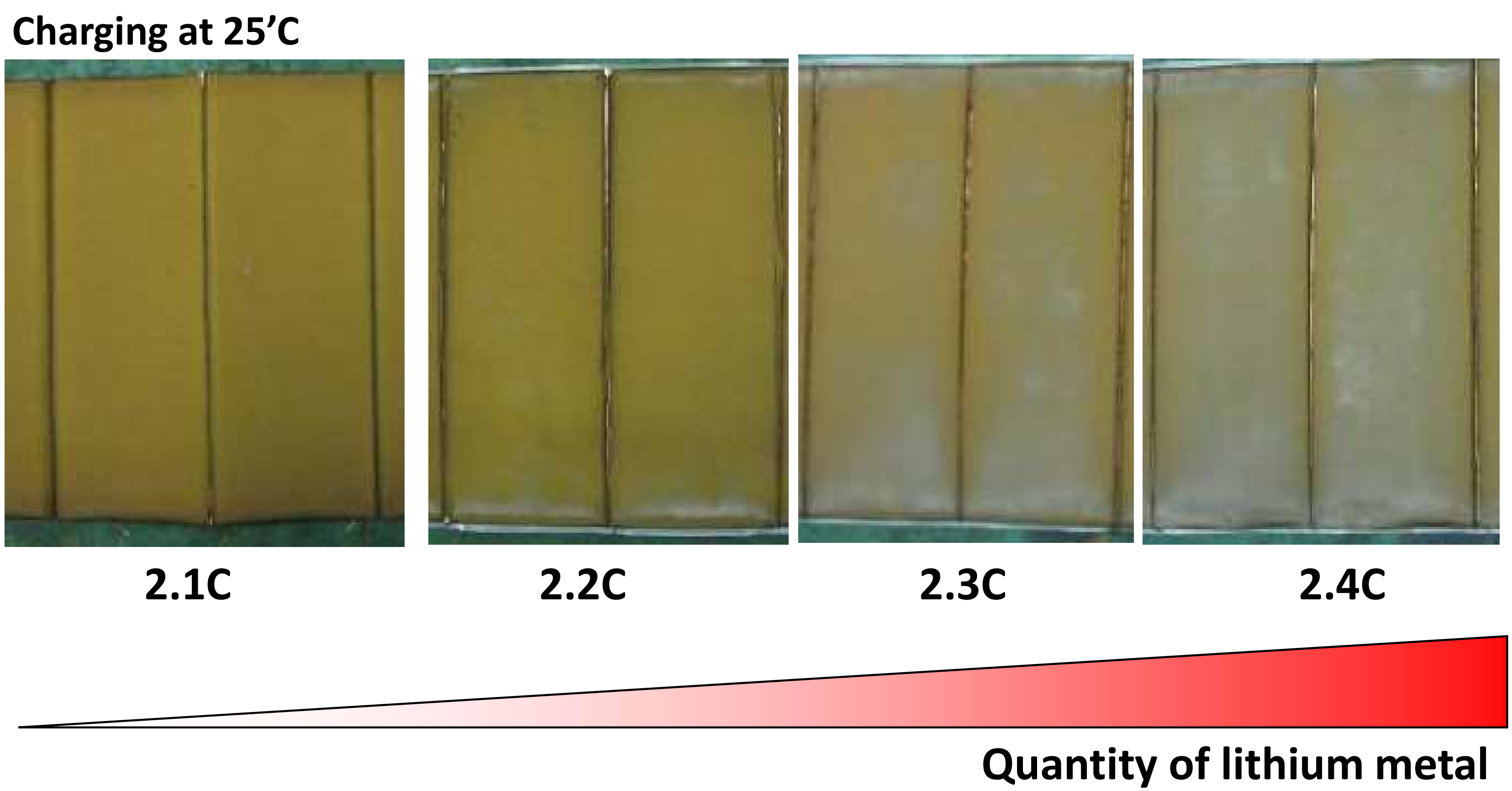
Operating Temperature Range---(VS Graphite)



Charge	OTP	Charge	OCP
Discharge	OTP	Discharge	OCP
Charge	UTP		
Discharge	UTP		

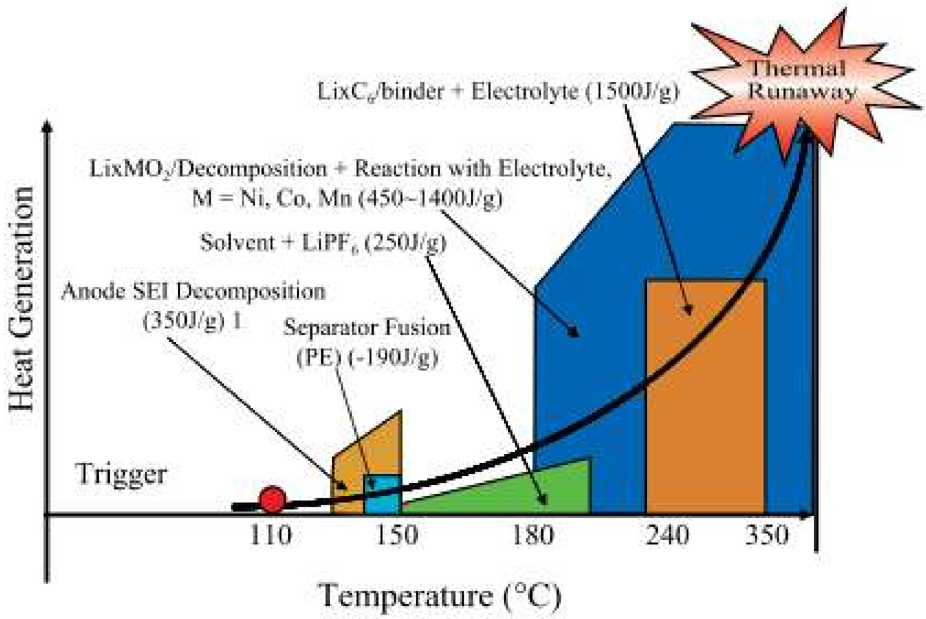
O: over
U: under
T: Temperature
P: protection
C: current

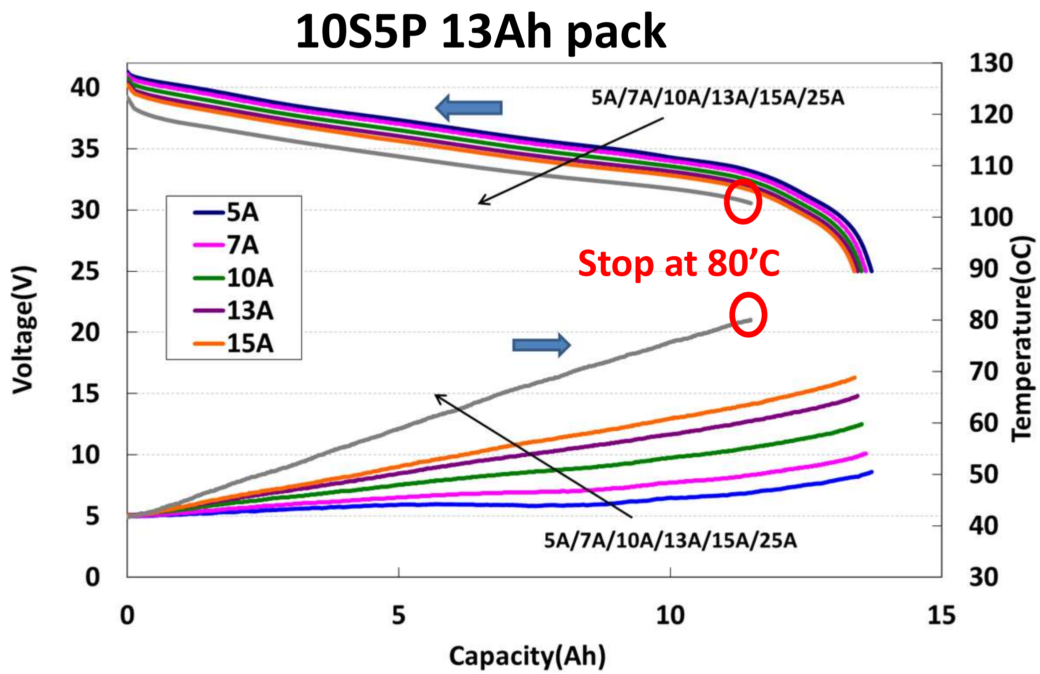
Over Current Charging Risk
--- Lithium Metal Plating on Anode



1. **1C is the max. charging rate for this cell.**
2. **Quantity of lithium metal will be increased by higher charging current.**
3. **Lithium metal may penetrate separator to cause internal short, and then thermal runaway.**

Over Current Discharging Risk- Over Heat



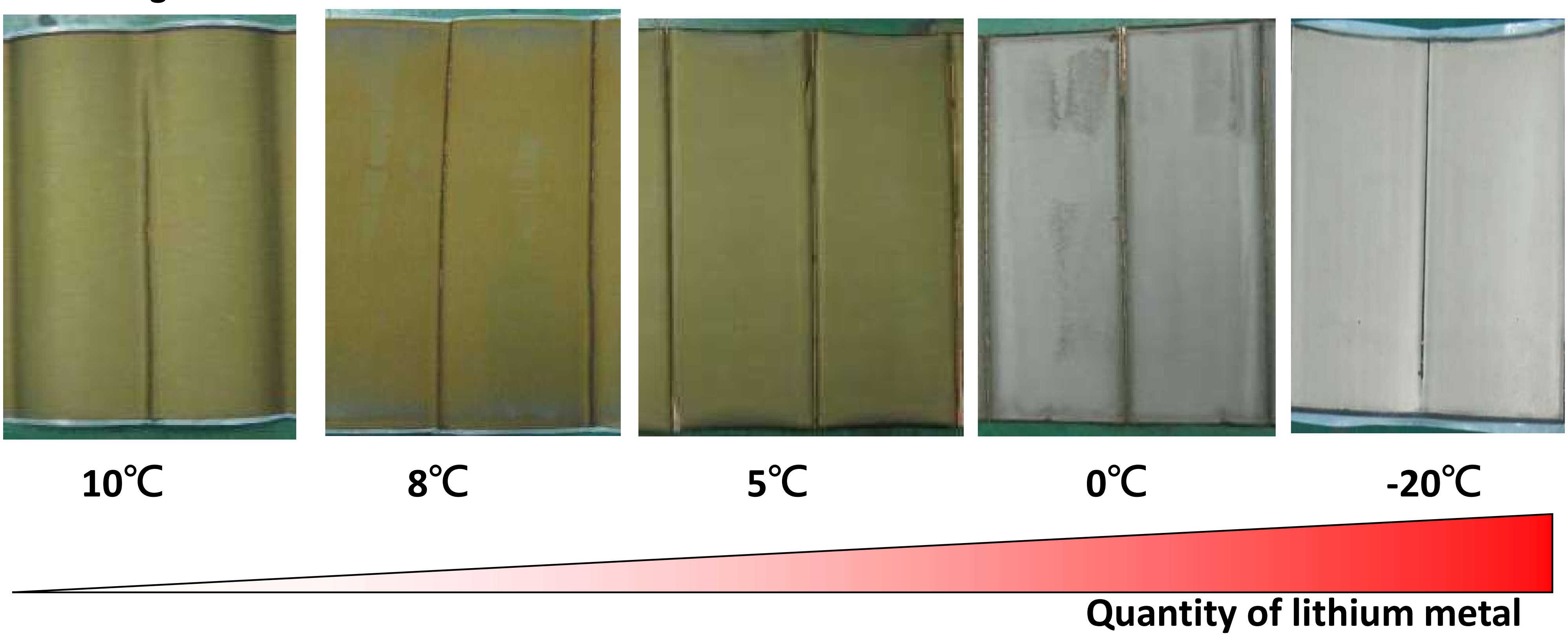


1. **Heat will be generated during discharging, higher rate cause higher temperature rising.**
2. **As battery temperature is over 130'C, separator will be melted and cause internal short, then chain reaction happens and thermal runaway is expected.**

Low Temperature Charging Risk

---Lithium Metal Plating on Anode

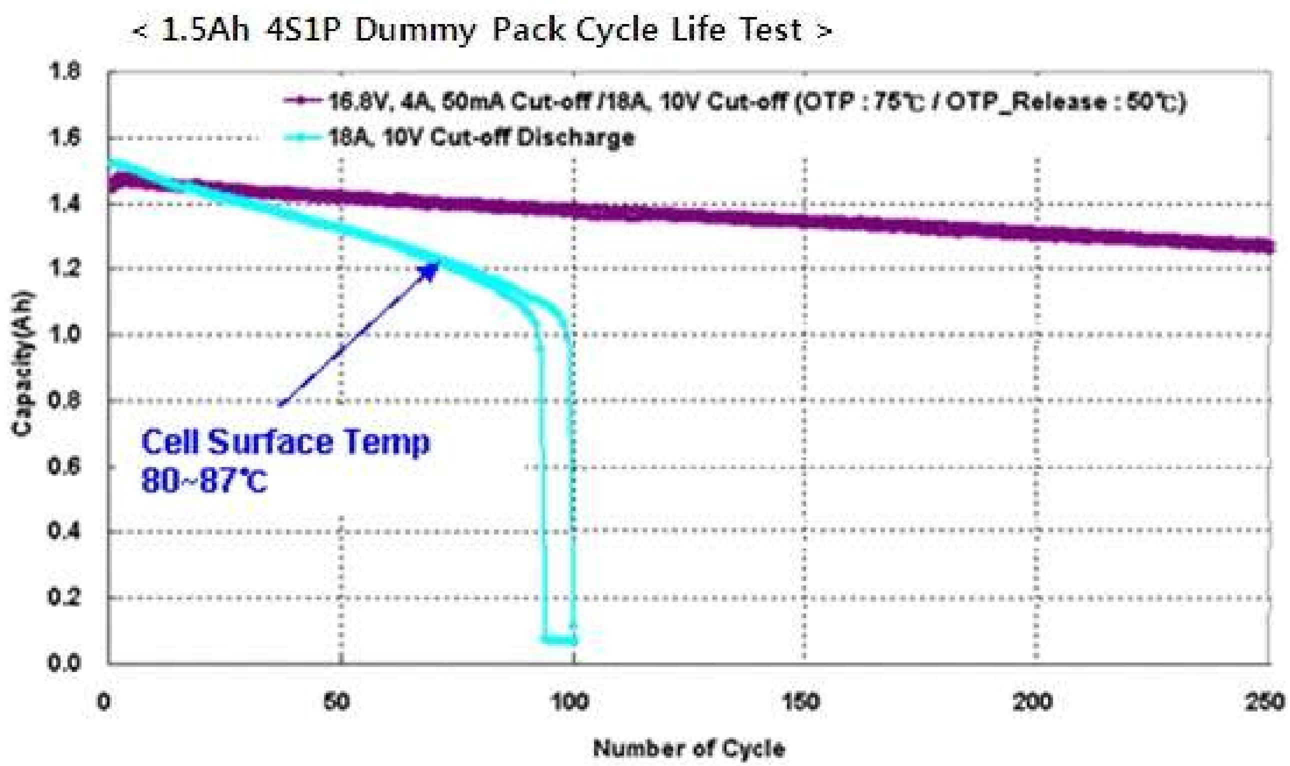
0.8C charge to 4.2V



1. **Quantity of lithium metal will be increased at lower temperature charging.**
2. **Lithium metal may penetrate separator to cause internal short, and then thermal runaway.**

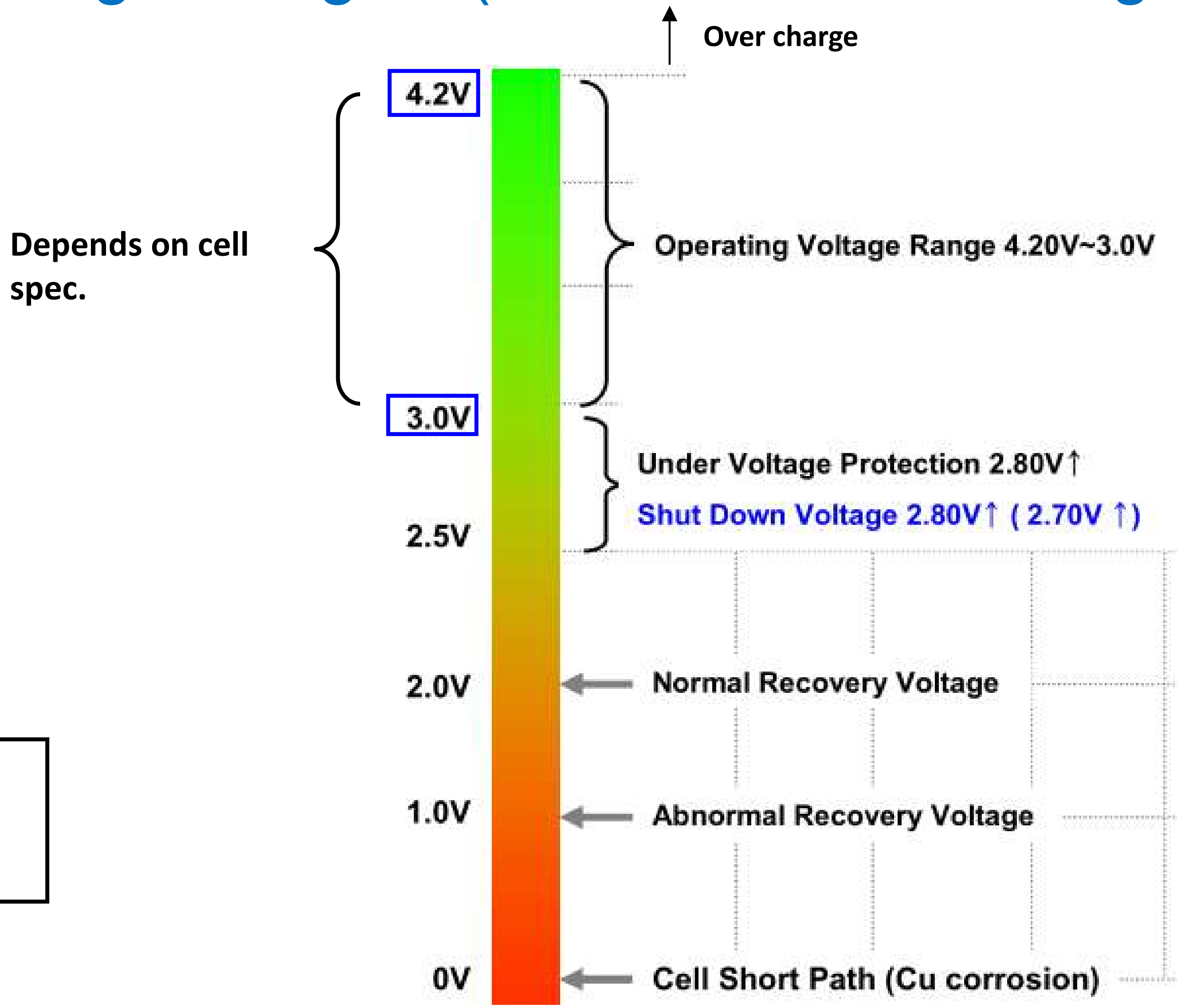
***There is no risk to discharge at low temperature.**

High Temperature Operating Risk
---Poor Cycle Performance



1. This is an example of 4S1P with 1.5Ah cell.
2. As cell surface temperature is over 80 ℃, the cycle life would fade much faster than OTP 75℃.
3. As temperature is higher than 130'C, the cell will have thermal runaway risk.

Operating Voltage Range---(LCO/NCM/NCA VS graphite)



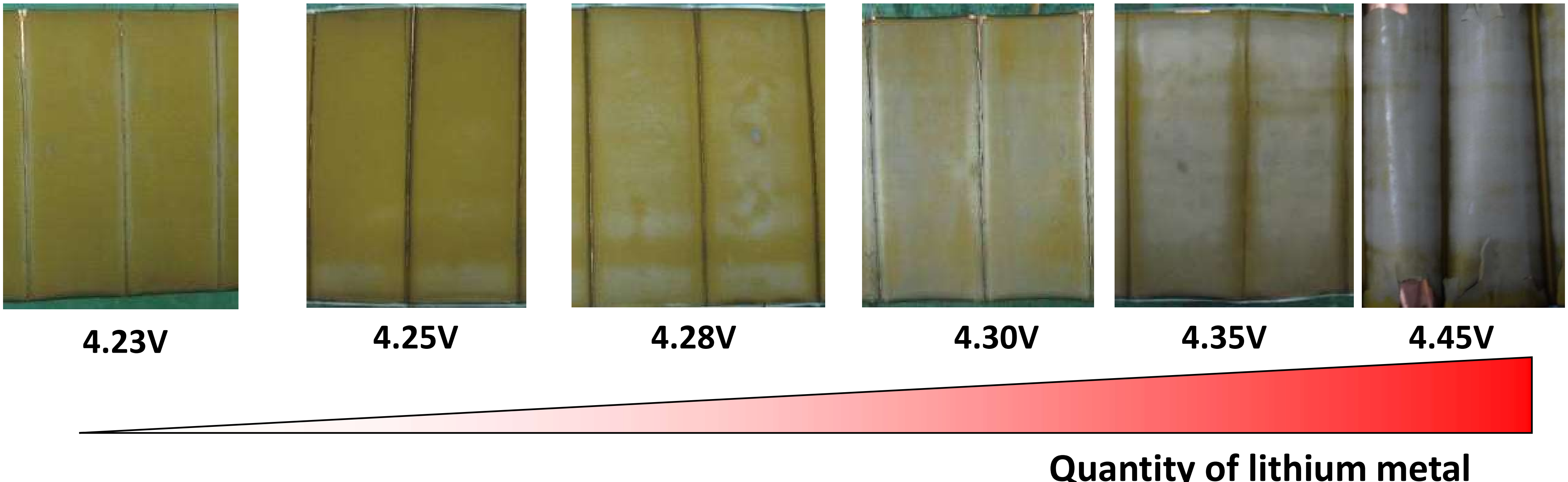
Charge	OVP
Discharge	UVP

O: over
U: under
V: voltage
P: protection

Overcharge

Risk-1---Lithium plating on anode

Charging at 25'C

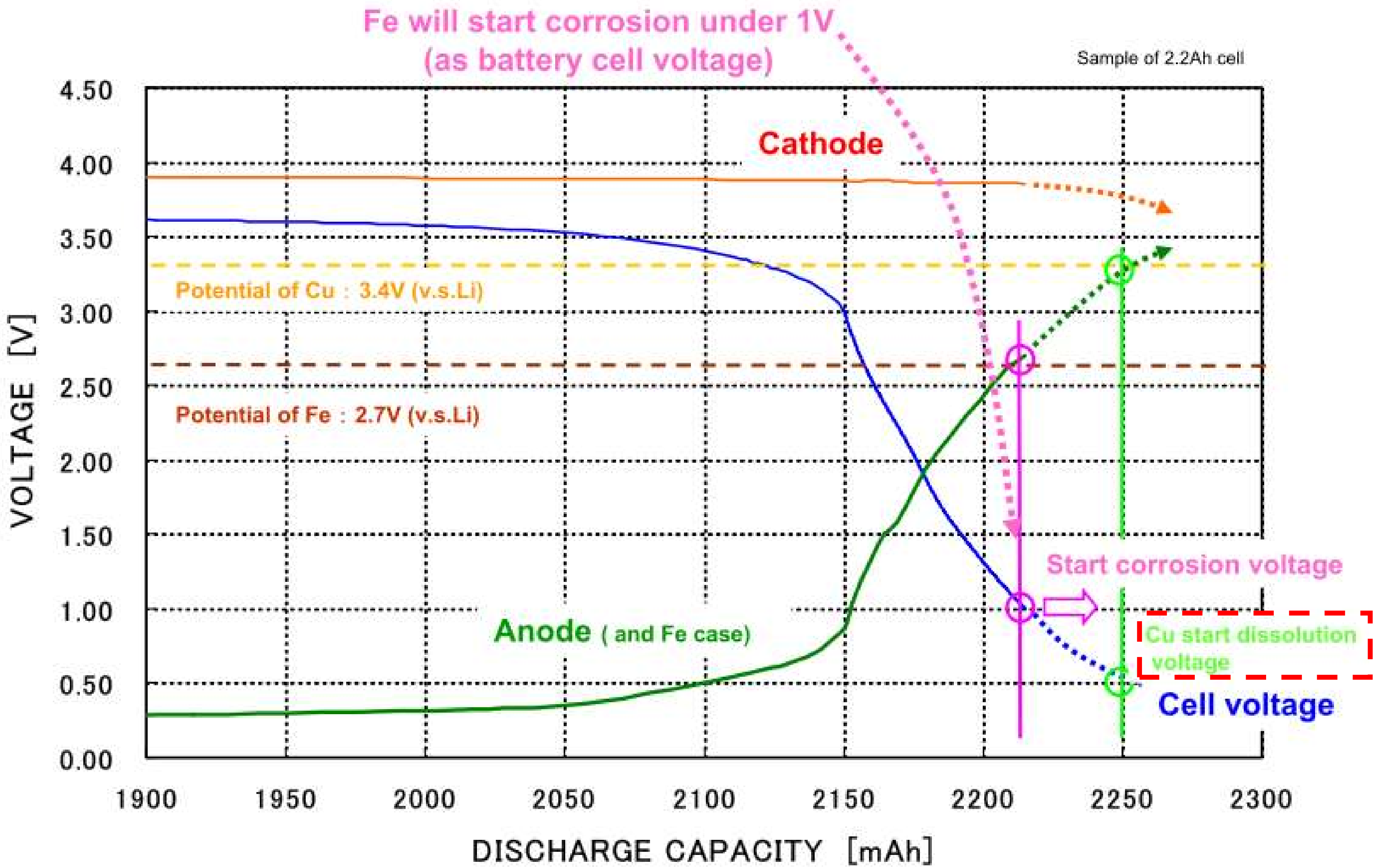


1. **4.2V is the max. charging voltage for this cell.**
2. **Quantity of lithium metal will be increased by higher voltage.**
3. **Lithium metal may penetrate separator to cause internal short, and then thermal runaway.**

Risk-2--- heat up and oxygen release

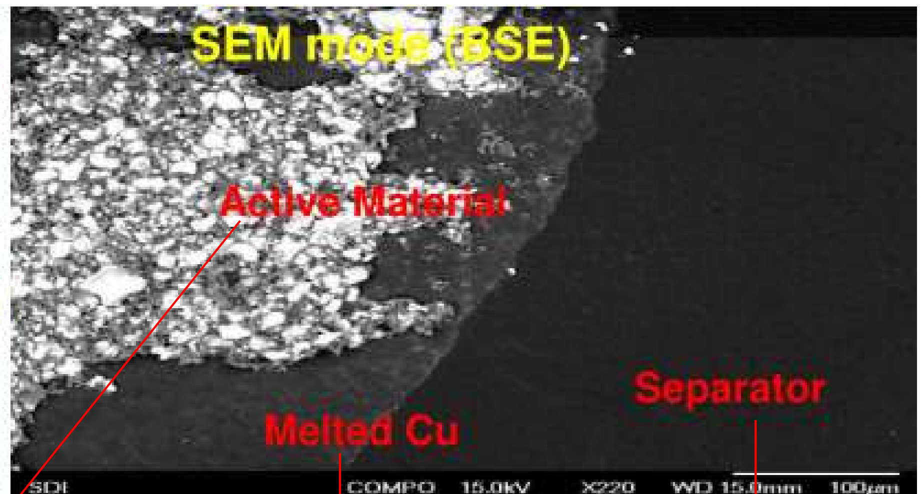
As for over-charge, the cell will be self heated and start releasing oxygen. Because there are heat, electrolyte and oxygen inside cell, the fire and explosion is expected.

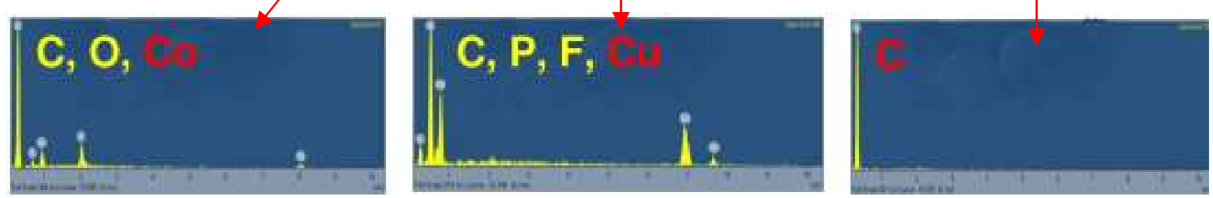
Over-Discharge Reaction and Risk



Cu at anode starts to dissolve when cell voltage is less than 0.5V

Example:





Over discharge

$Cu \rightarrow Cu^{2+} + 2e^{-}$ --- Cu dissolution

Charge after over discharge

$Cu^{2+} + 2e^{-} \rightarrow Cu$ --- Cu reduction

When the cell voltage is lower than 0.5V, Cu will dissolve to Cu ion. If this cell is charged after over-discharge, Cu ion would plate to be Cu metal. There is possibility that Cu metal may penetrate separator to cause cell internal short. This is a safety risk.

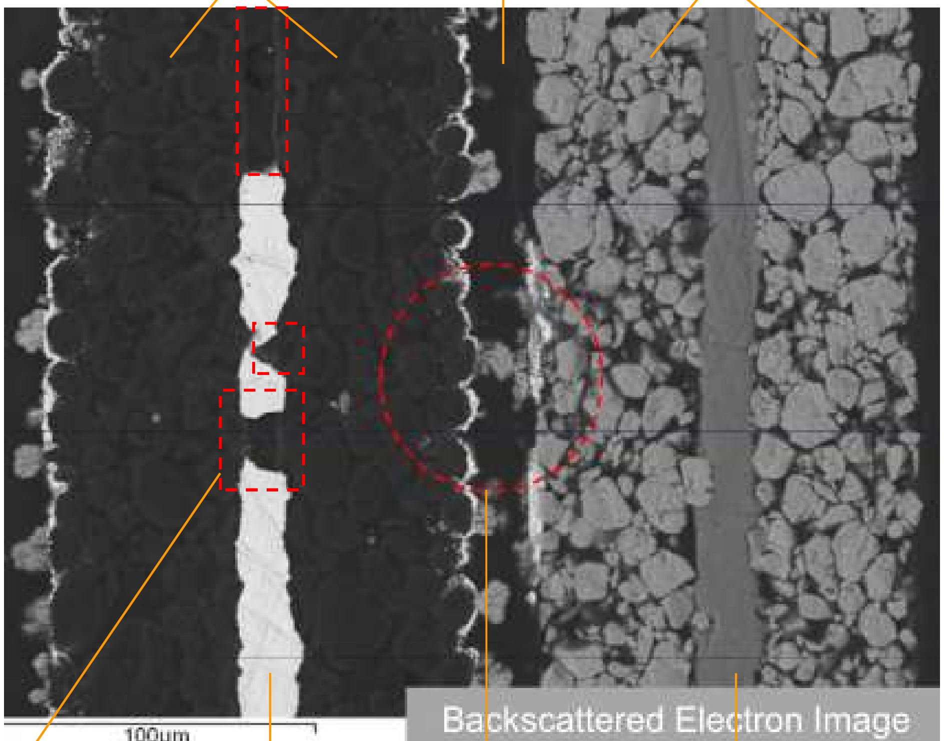
Example:

SEM Photo

Anode electrode

Separator

Cathode electrode



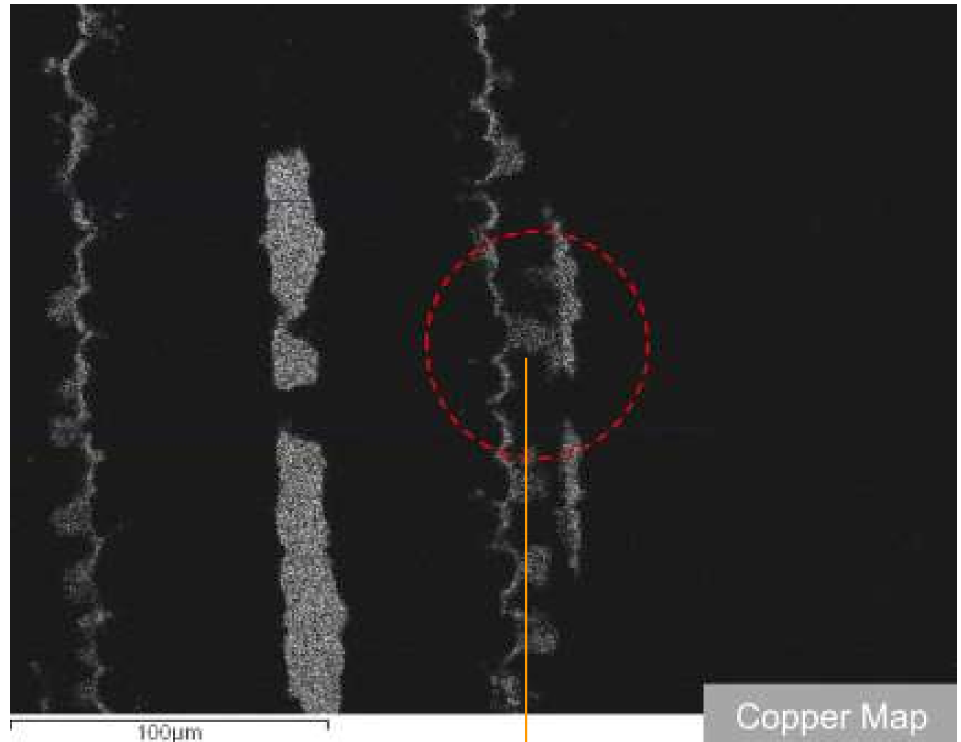
Cu dissolution

Cu foil

Cu metal

Al foil

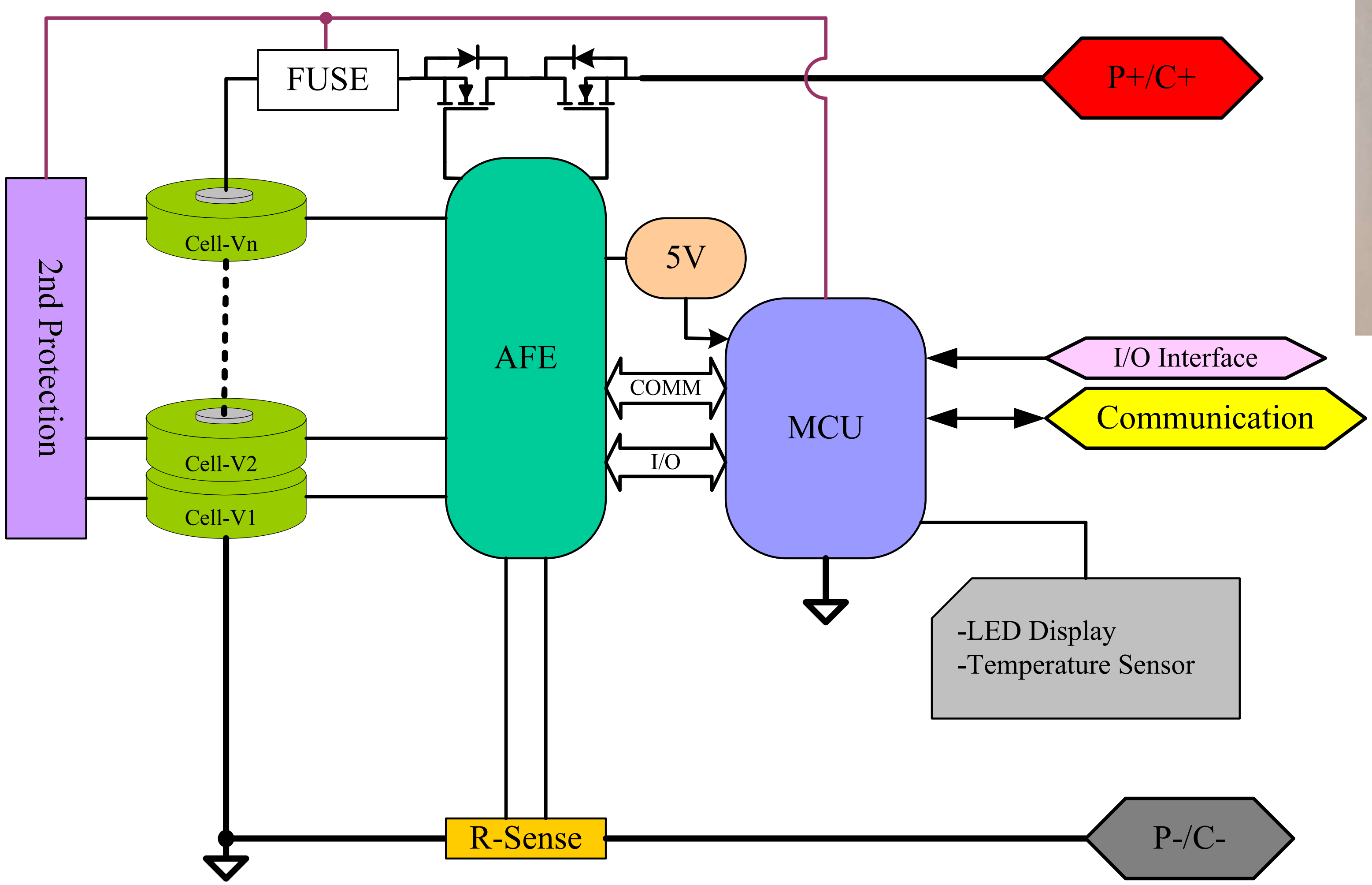
Cu element only



Cu metal exists between cathode and anode, this is the evidence of cell internal short

Figure 8. Copper dendrite formation observed on the separator due to repetitive overdischarge.

Basic BMS Function Block



BMS Protection requirement for safety concerns

	Item
1	OVP (Over Voltage Protection)
2	UVP (Under Voltage Protection)
3	COTP (Charge Over Temperature Protection)
4	DOTP (Discharge Over Temperature Protection)
5	CUTP (Charge Under Temperature Protection)
6	DUTP (Discharge Under Temperature Protection)
7	COCP (Charge Over Current Protection)
8	DOCP(Discharge Over Current Protection)
9	OVPF(Permanent Failure of Over Voltage Protection)
10	UVPF(Permanent Failure of Under Voltage Protection

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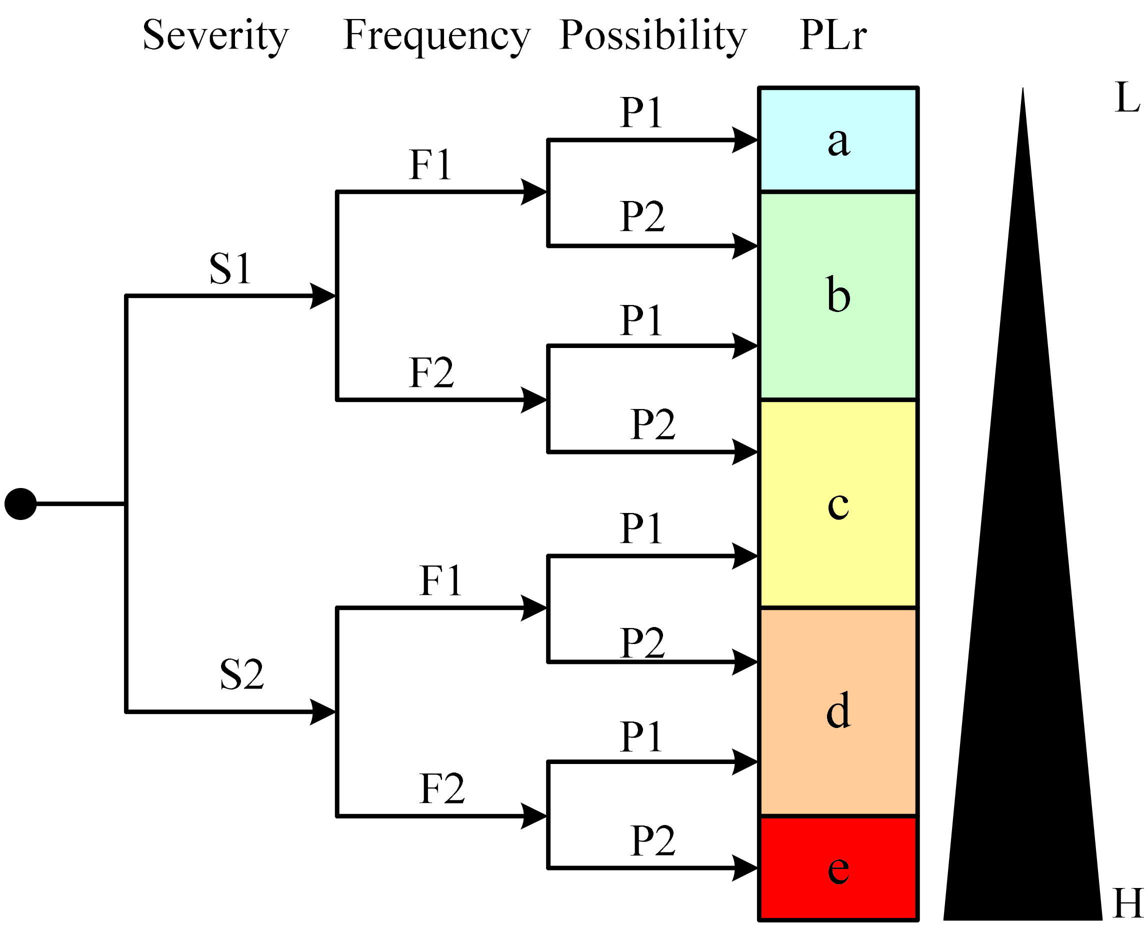
1. Risk Assessment → Required Performance Level (PLr)



PL	Average Probability of dangerous failure per hour (PFH_D)
a	$\geq 10^{-5}$ to $< 10^{-4}$
b	$\geq 3 \times 10^{-6}$ to $< 10^{-5}$
c	$\geq 10^{-6}$ to $< 3 \times 10^{-6}$
d	$\geq 10^{-7}$ to $< 10^{-6}$
e	$\geq 10^{-8}$ to $< 10^{-7}$

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2. Performance Level (PL) Validation

Estimation Items	Description
Category (類別)	Classification of the safety-related parts of a control system in respect of their resistance to faults and their subsequent behavior in the fault condition.
$MTTF_D$	Mean time to Dangerous failure (發生危險性故障的平均時間) →評估元件在發生危險故障前的平均壽命
DC_{avg}	Average Diagnostic Coverage (平均診斷涵蓋率) →評估系統含軟體對於偵測故障的涵蓋程度
CCF	Common cause failures (共因失效) →評估系統對於預防共因失效的設計程度 (Requirement : Score ≥ 65)

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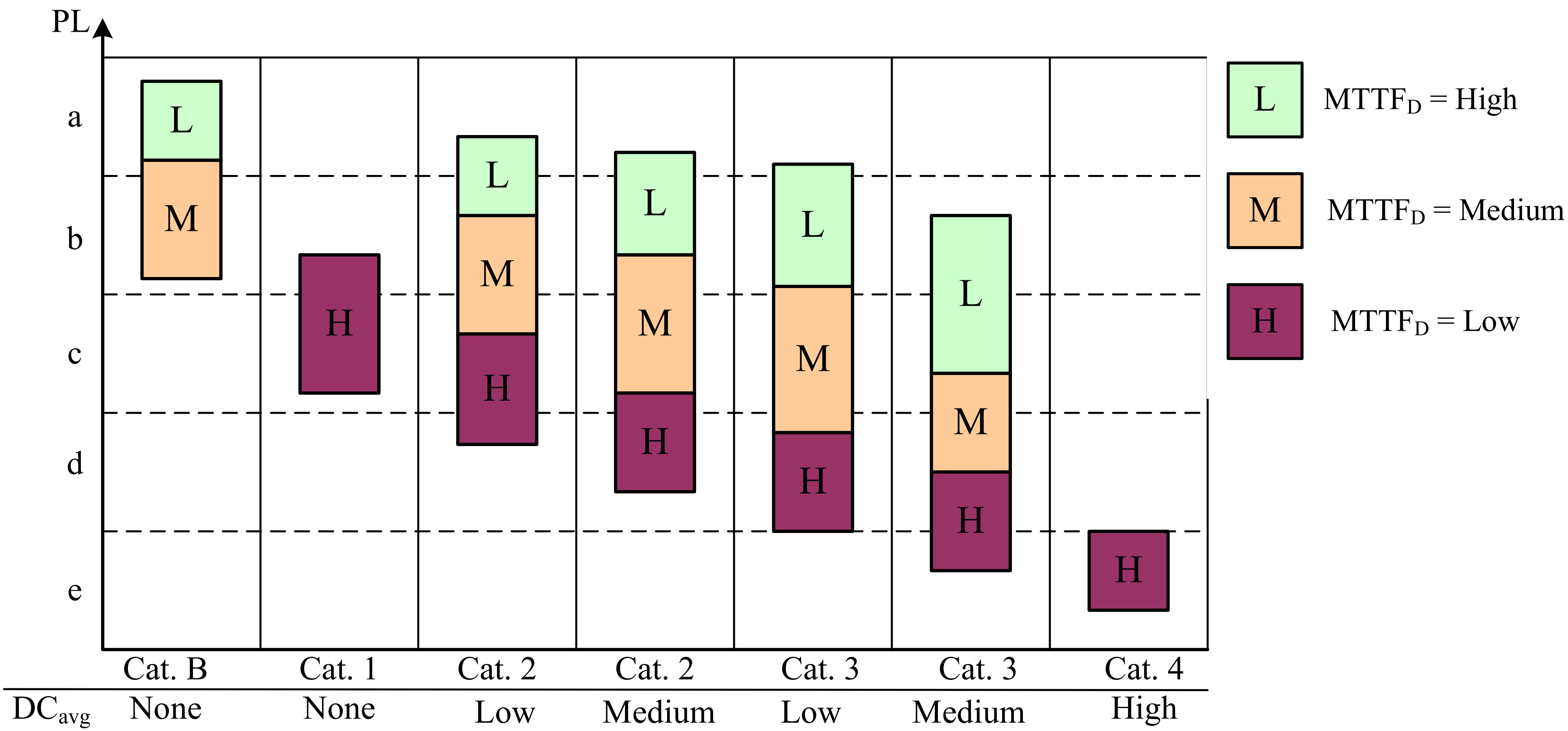

MTTFD Level	Range
Low	3 years ≤ $MTTF_D$ < 10 years
Medium	10 years ≤ $MTTF_D$ < 30 years
High	30 years ≤ $MTTF_D$ < 100 years

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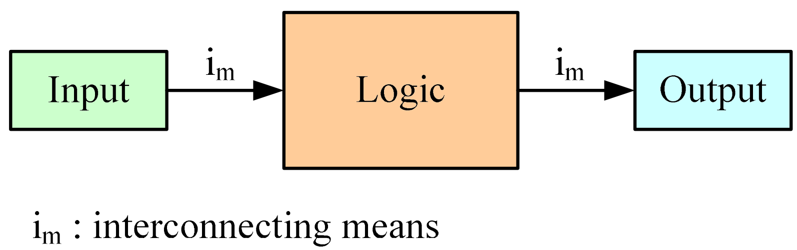
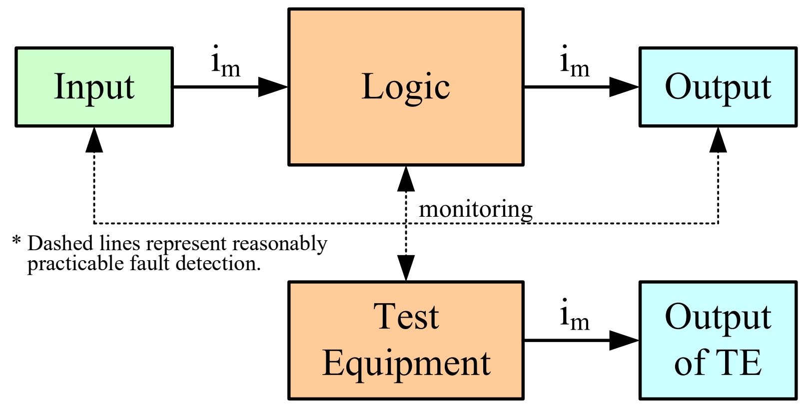
3. Category

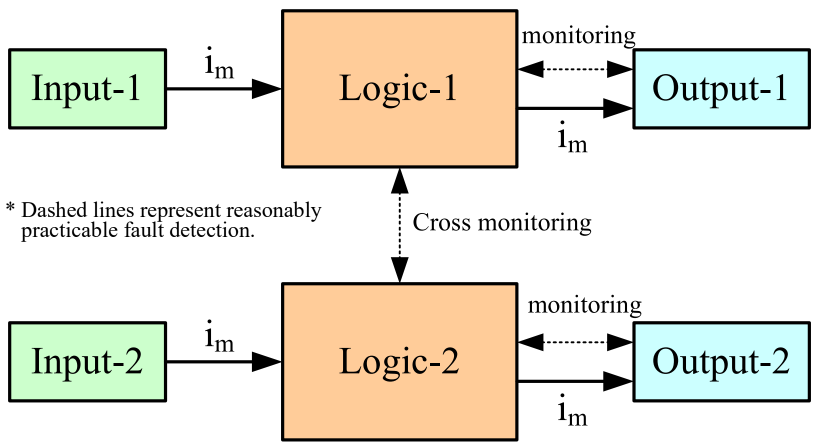
Category B / Category 1



Category 2



Category 3 / Category 4



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3. $MTTF_D$

元件失效與時間關係的方程式 $F[t] = 1 - e^{-\lambda t}$, λ: constant dangerous failure rate
因為大部份元件製造商只提供元件發生10%不良的平均週期，這也提供了一種利用此數據來計算$MTTF_D$的方法

因為$F[t] = 1 - e^{-\lambda t}$ 當發生10%不良的時間為T_{10D}

$$\rightarrow F[T_{10D}] = 1 - e^{-\lambda_D T_{10D}} = 10\%$$

$$\rightarrow e^{-\lambda_D T_{10D}} = 90\% \qquad \rightarrow -\lambda_D T_{10D} = \ln(0.9)$$

$$\rightarrow \lambda_D = -\frac{\ln(0.9)}{T_{10D}} \approx \frac{0.1}{T_{10D}} = \frac{0.1 \times n_{op}}{B_{10D}}$$

$$\rightarrow MTTF_D = \frac{T_{10D}}{0.1} = \frac{B_{10D}}{0.1 \times n_{op}}$$

其中， $n_{OP} = \frac{d_{OP}(days/year) \times h_{OP}(hours/day) \times 3600(secs/hour)}{t_{Cycle}}$

B_{10D} : The mean number of cycles till 10% of the components fail dangerously *(cycles)*
T_{10D} : The mean time until 10% of the components fail dangerously *(year)*
n_{OP} : The mean number annual operations *(cycles/year)*

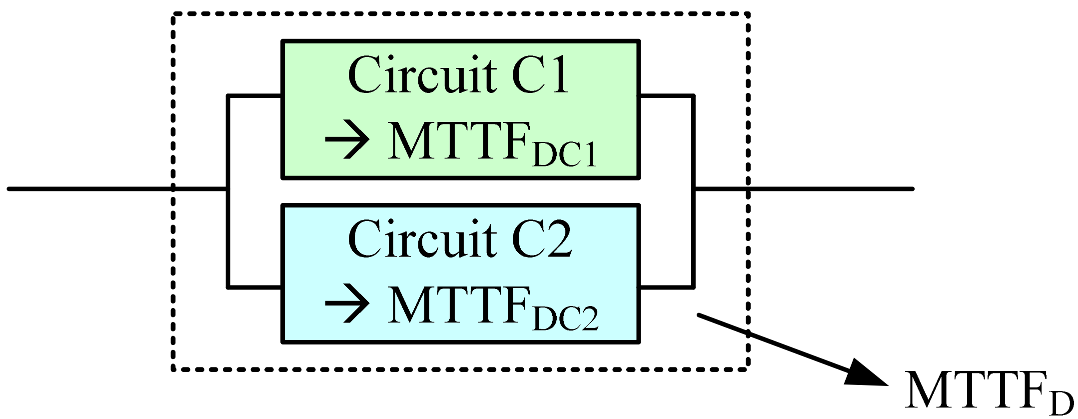
計算個別通道危險故障平均時間($MTTF_D$)的方法

$$\frac{1}{MTTF_D} = \sum_{i=1}^{N} \frac{1}{MTTF_D} = \sum_{j=1}^{N} \frac{n_j}{MTTF_{D_j}}$$

當一個冗餘系統路徑上具有兩個通道且兩個通道具有不同 $MTTF_D$ 值，可以使用以下公式計算這個冗餘系統通道的 $MTTF_D$值。

$$MTTF_D = \frac{2}{3}\left[MTTF_{DC_1} + MTTF_{DC_2} - \frac{1}{\frac{1}{MTTF_{DC_1}} + \frac{1}{MTTF_{DC_2}}}\right]$$

其中$MTTF_{DC_1}$、 $MTTF_{DC_2}$為冗餘系統二個通道個別的MTTFD值



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4. Diagnostic Coverage DC and DC_{AVG} 診斷涵蓋率

Input Device	
Measure	**DC**
Cyclic test stimulus by dynamic change of the input signals	90%
Plausibility check, e.g. use of normally open and normally closed mechanically linked contacts	99%
Cross monitoring of inputs without dynamic test	0 % to 99 %, depending on how often a signal change is done by the application
Cross monitoring of input signals with dynamic test if short circuits are not detectable (for multiple I/O)	90%
Cross monitoring of input signals and intermediate results within the logic (L), and temporal and logical software monitor of the program flow and detection of static faults and short circuits (for multiple I/O)	99%
Indirect monitoring (e.g. monitoring by pressure switch, electrical position monitoring of actuators)	90 % to 99 %, depending on the application
Direct monitoring (e.g. electrical position monitoring of control valves, monitoring of electromechanical devices by mechanically linked conptact elements)	99%
Fault detection by the process	0 % to 99 %, depending on the application; this measure alone is not sufficient for the required performance level e!
Monitoring some characteristics of the sensor (response time, range of analogue signals, e.g. electrical resistance, capacitance)	60%

Logic Device	
Measure	**DC**
Indirect monitoring (e.g. monitoring by pressure switch, electrical position monitoring of actuators)	90 % to 99 %, depending on the application
Direct monitoring (e.g. electrical position monitoring of control valves, monitoring of electromechanical devices by mechanically linked con-tact elements)	99%
Simple temporal time monitoring of the logic (e.g. timer as watchdog, where trigger points are within the program of the logic)	60%
Temporal and logical monitoring of the logic by the watchdog, where the test equipment does plausibility checks of the behavior of the logic	90 %
Start-up self-tests to detect latent faults in parts of the logic (e.g. pro-gram and data memories, input/output ports, interfaces)	90 % (depending on the testing technique)
Checking the monitoring device reaction capability (e.g. watchdog) by the main channel at start-up or whenever the safety function is demanded or whenever an external signal demand it, through an input facility	90 %
Dynamic principle (all components of the logic are required to change the state ON-OFF-ON when the safety function is demanded), e.g. interlocking circuit implemented by relays	99 %
Invariable memory: signature of one word (8 bit)	90 %
Invariable memory: signature of double word (16 bit)	99 %
Variable memory: RAM-test by use of redundant data e.g. flags, markers, constants, timers and cross comparison of these data	60 %
Variable memory: check for readability and write ability of used data memory cells	60 %
Variable memory: RAM monitoring with modified Hamming code or RAM self-test (e.g. "Galpat" or "Abraham")	99 %
Processing unit: self-test by software	60 % to 90 %
Processing unit: coded processing	90 % to 99 %
Fault detection by the process	0 % to 99 %, depending on the application; this measure alone is not sufficient for the required performance level "e"!

Output Device	
Measure	**DC**
Monitoring of outputs by one channel without dynamic test	0 % to 99 % depending on how often a signal change is done by the application
Cross monitoring of outputs without dynamic test	0 % to 99 % depending on how often a signal change is done by the application
Cross monitoring of output signals with dynamic test without detection of short circuits (for multiple I/O)	90 %
Cross monitoring of output signals and intermediate results within the logic (L) and temporal and logical software monitor of the program flow and detection of static faults and short circuits (for multiple I/O)	99 %
Redundant shut-off path with monitoring of the actuators by logic and test equipment	99 %
Indirect monitoring (e.g. monitoring by pressure switch, electrical position monitoring of actuators)	90 % to 99 %, depending on the application
Fault detection by the process	0 % to 99 %, depending on the application; this measure alone is not sufficient for the required performance level “e”!
Direct monitoring (e.g. electrical position monitoring of control valves, monitoring of electromechanical devices by mechanically linked con-tact elements)	99 %

在系統中，可能會使用多種故障檢測措施。這些措施可以檢查控制系統中安全相關的部分且不同部分具有不同的 DC ，但對於 PL的評估，其實只適用一個平均DC。故DC 可以定義為檢測到的危險故障的失效率與總危險故障的失效率之間的比率。 根據此定義，平均診斷覆蓋率 DC_{avg} 可以由以下公式估算而得：

$$DC_{avg} = \frac{\frac{DC_1}{MTTF_{D1}} + \frac{DC_2}{MTTF_{D2}} + \cdots + \frac{DC_N}{MTTF_{DN}}}{\frac{1}{MTTF_{D1}} + \frac{1}{MTTF_{D2}} + \cdots + \frac{1}{MTTF_{DN}}}$$

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5. Common Cause Failure (CCF) 共因失效

No	Measure against CCF	Score
1	Separation/ Segregation (分離/隔離)	
	Physical separation between signal paths, for example: — separation in wiring/piping; — detection of short circuits and open circuits in cables by dynamic test; — separate shielding for the signal path of each channel; — sufficient clearances and creepage distances on printed-circuit boards.	15
2	Diversity (多樣性)	
	Different technologies/design or physical principles are used, for example: — first channel electronic or programmable electronic and second channel electromechanical hardwired, — different initiation of safety function for each channel (e.g. position, pressure, temperature),and/or digital and analog measurement of variables (e.g. distance, pressure or temperature) and/or Components of different manufactures.	20
3	Design/application/experience (設計/應用/經驗)	
3.1	Protection against over-voltage, over-pressure, over-current, over-temperature, etc.	15
3.2	Components used are well-tried.	5
4	Assessment/analysis (評估/分析)	
	For each part of safety related parts of control system a failure mode and effect analysis has been carried out and its results taken into account to avoid common-cause-failures in the design.	5
5	Competence/training (能力/培訓)	
	Training of designers to understand the causes and consequences of common cause failures.	5
6	Environmental (環境的)	
6.1	For electrical/electronic systems, prevention of contamination and electromagnetic disturbances (EMC) to protect against common cause failures in accordance with appropriate standards (e.g. IEC 61326–3-1). Fluidic systems: filtration of the pressure medium, prevention of dirt intake, drainage of com-pressed air, e.g. in compliance with the component manufacturers' requirements concerning purity of the pressure medium. NOTE. For combined fluidic and electric systems, both aspects should be considered.	25
6.2	Other influences Consideration of the requirements for immunity to all relevant environmental influences such as, temperature, shock, vibration, humidity (e.g. as specified in relevant standards).	10

Q & A