A Cell Selection Method and Validation Process for the Aerospace Battery

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  1) Cell screening and filtering Process
  2) Validation process for the cell selection/screening process

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Introduction

Why Cell model selection & screening test are important?

- Aerospace battery should supply power to the system at least 15 ~20 years without any interruption.

- Every cell has potential/intrinsic defects (Design, Manufacturing, and QC process), those can't be identified and extract from the manufacturing process in cell maker.
  : some potential/intrinsic defects have lead-time to be activated to the incident.

- The majority of standards-based testing is focused on abuse tolerance, but a vast majority of field failures happened under normal operating conditions.

- NASA has a Cell model selection & cell screening process, does not have a validation process to verify the efficiency of the cell selection/screening process.
  ➔ need to develop a validation process

cell maker/model selection → **cell screening & Filtering** → **validation process**

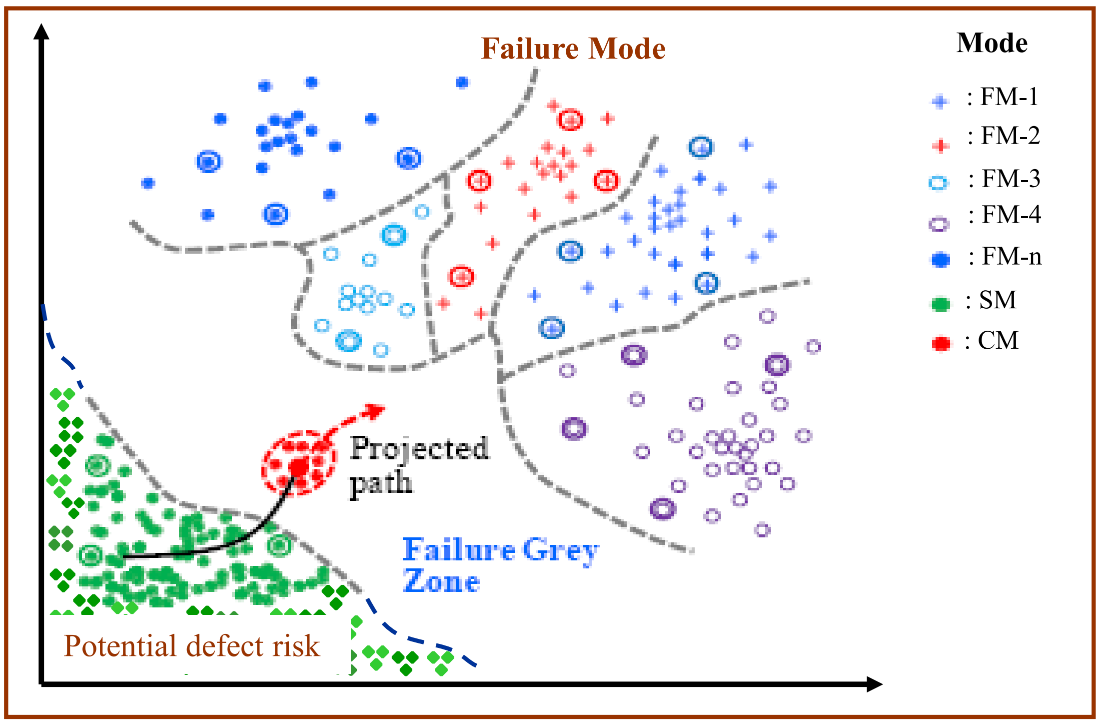
Role of Test and Certification

Filtering the potential risk (poor design & manufacturing) products out in advance.
The key is how to find the best adequate trigger which can lead samples to the failure mode.

Product → **Certification** → **Market**

Has potential risk

Audit/ Test/ Review



Test: find the trigger of the Failure Mode of the potential safety Risk.

- **-Electrical Impact**
- **-Mechanical Impact**
- **-Thermal Impact**
- **-Environmental Impact**

Potential Risk:

- **Design Defect**
- **Manufacturing Defect**
- **QC and approval Defect**

* Safety zone of the cell is depending on the host system & use conditions

Application, Power specification and Cell Type

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1. Application

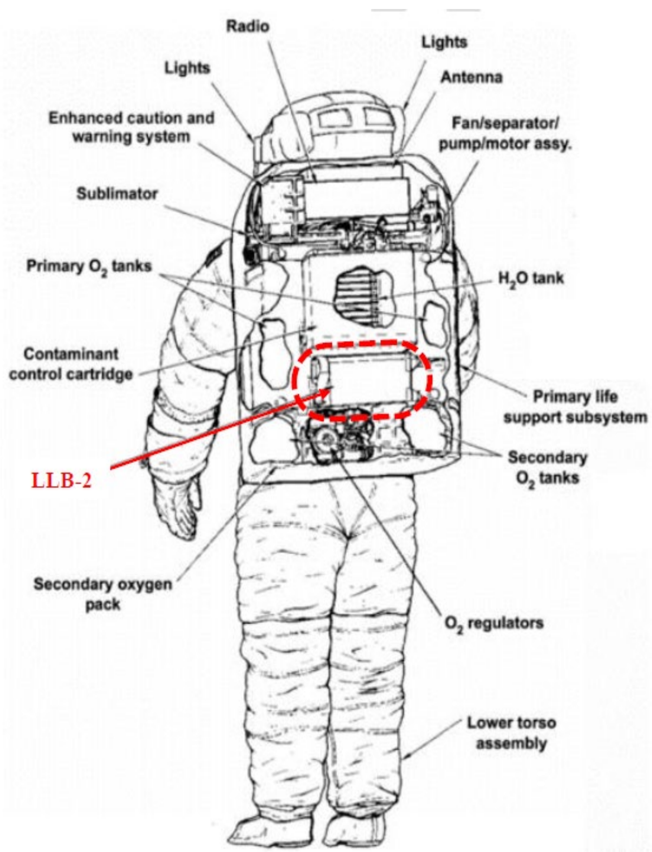


Figure 1. LLB-2 Location within the EMU PLSS

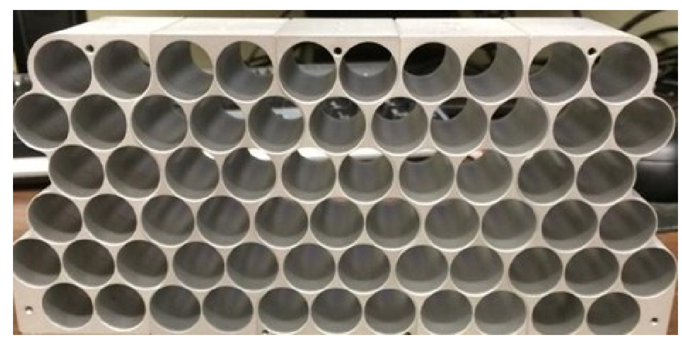
2. Power specification

Mission operating conditions of Human-space flight

The Power character convert to 18650, 2.6 Ah Cell
- Charge at C/8 with a 1hour taper to 4.2V
- Discharge at C/8 to 3.0V

3. Cell Type : 18650 cylindrical Cell:

Design for protecting each cell and prevent thermal propagation.



Insights from Safety Tests with an On-Demand Internal Short Circuit Device in 18650 Cells: Dr. Eric at the 2017 International Battery Seminar 21-23 Mar 2017

Experimental

- Cell model/maker and cell screening process
- Cell maker and model selection – 1 & 2
- Cell design and Electrode alignment Criteria
- Cell screening Test item and process
- Cell Sample and 4S String Type

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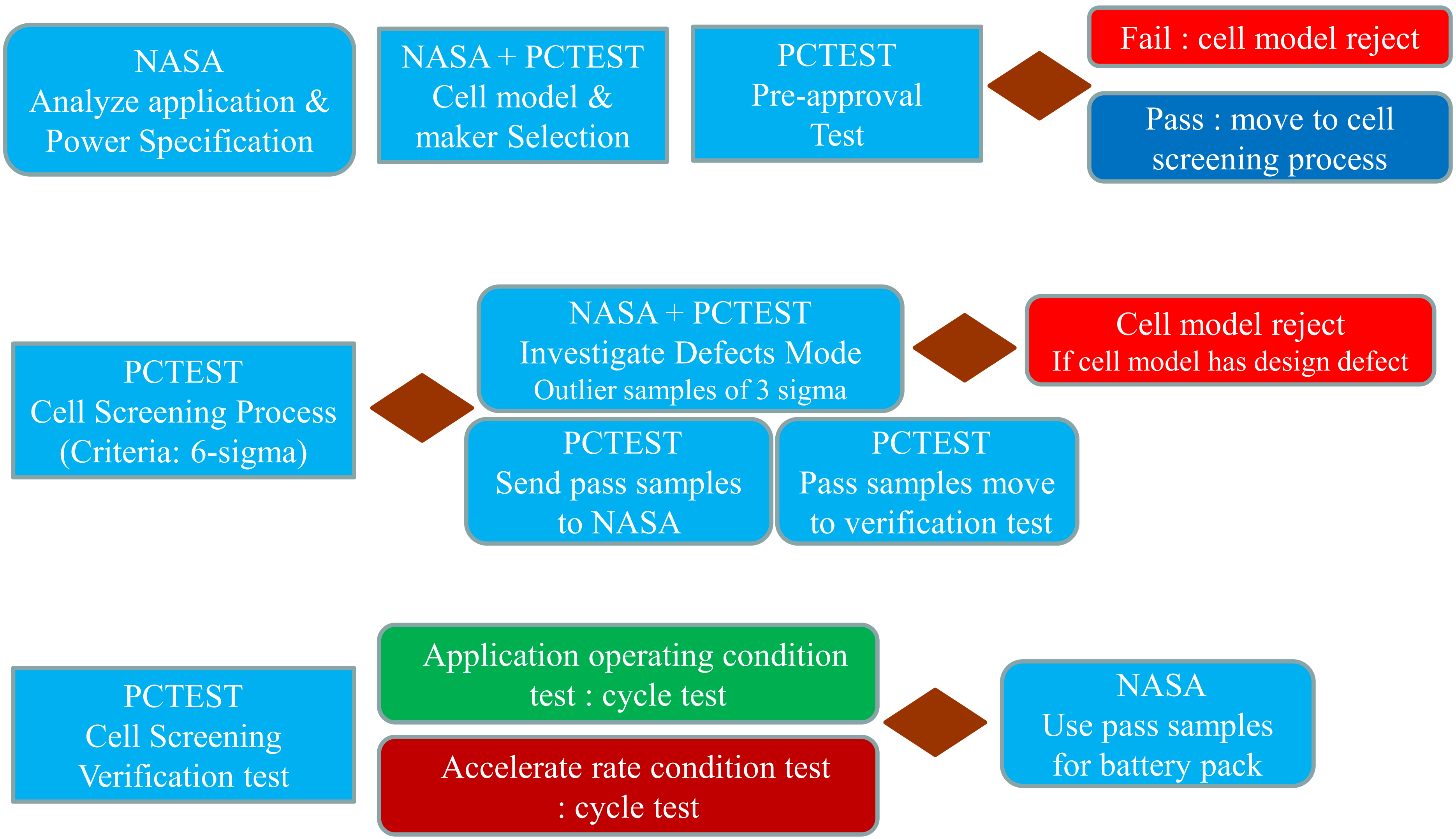
Cell model/maker and cell screening process



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Cell maker and model selection -1

1. Pre-requirement -1 Review : Certificate of cell model and makers

   1) Cell Manufacturer and Cell Manufacturing Site
      : Certificate of the ISO 9001: Design, manufacturing, QC and the site

   2) Cell Model
      a) Certificate of the UN 38.3 Manual Test

      b) Certificate of the UL 1642 or IEC62133

2. Cell design, battery safety, and operational reliability test

   1) Cell design check:

   2) Battery Safety test:

   3) Operational Reliability Test:

→ **Next Page**
Test item/condition/compliance

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Cell maker and model selection -2

3. Cell safety and reliability Test for a cell model selection

Test Item	Purpose	Test Condition	Compliance
Separator Isolation properties	The separator/cell design shall maintain isolation properties to maintain safety of the cell	150 °C , 10 min. Ramping: 5 +/-2 °C , 10 min.	No fire, smoke, explosion or breaching of the cell is allowed within the first 10 minutes
Cell design and alignment Criteria at Room Temp.	To ensure the electrode assembly (Anode: Separator: Cathode) design considers the shrinkage characteristics of the material to maintain the cell safe by separation	Measure the coverage on each side at ambient temperature	at least 0.1 mm coverage on each side of separator :Anode :Cathode
after high Temp.		Measure the coverage on each side after 1 Hr. at high temperature. (110 °C , 60 min.)	at least 0.1 mm coverage on each side of separator to Cathode.
Insulation mechanism	To prevent the cell Internal Short, the cell design identify and mitigate it by adequate Internal Short avoidance	To check all Insulation mechanism in the cell: tab, connection, electrode assembly, and case.	latent internal short are insulated over the projected lifetime of cell
Vent Mechanism	To ensure cell designs include a consistent vent mechanism/location.	Measure the activation pressure of the vent	Vent operates per specification and at its intended location.
Thermal Test	To ensure cells demonstrate thermal stability	150 °C , 10 min. Ramping: 5 +/-2 °C , 10 min.	Cells shall not flame or explode
Reliability Test Cell stability at each cycle test Condition.	To ensure cell designs include cell reliability at Cell specification. External short circuit test at 55 °C, 80 m Ohm, after 50 cycles at each temp.	1) Cycled at Room Temp.	No fire, no explosion, and maximum temperature less than 150 °C
		2) Cycled at minimum charging Temp.	
		3) Cycled at maximum charging Temp.	

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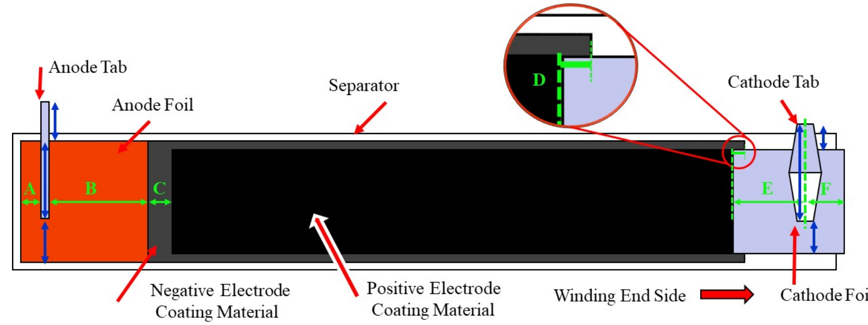
Cell design and Electrode alignment Criteria

4. Cell DPA Analysis and Gap measurement

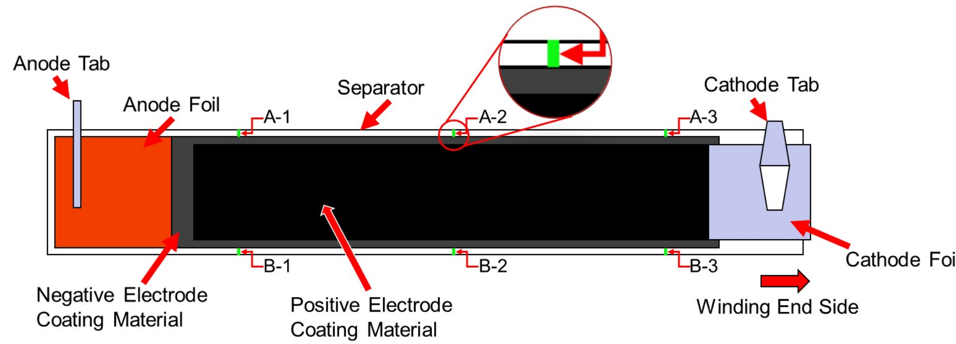
1) Check Cell geometry and component position

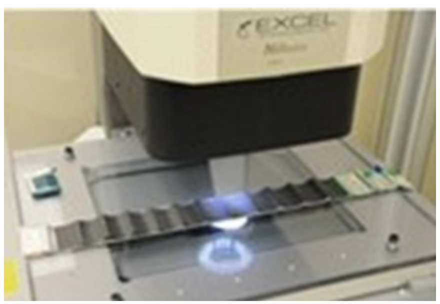
Inspect all cell components position, geometry, alignment and gap measurement including check the insulation mechanism

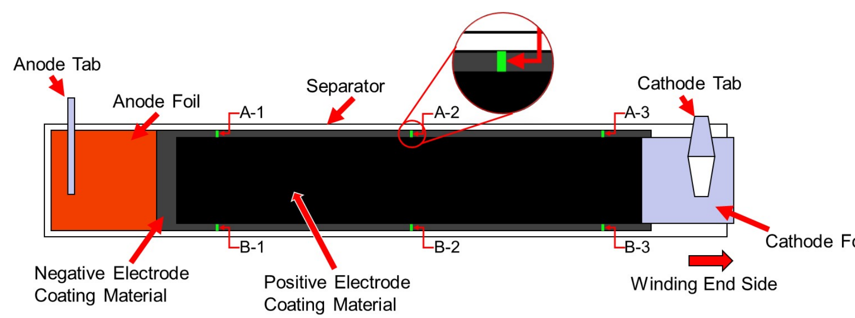


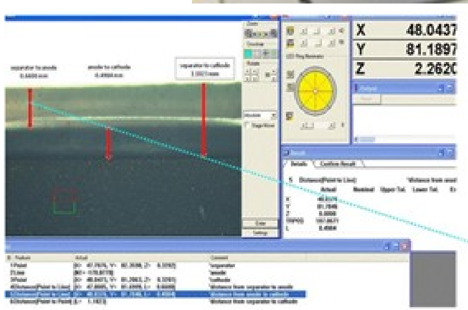
2) *Alignment* & Gap measurement -Room Temp.
:Separator to Anode to Cathode

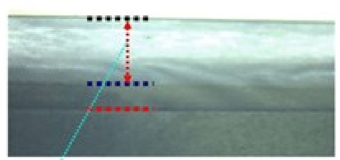
3) *Alignment* & Gap measurement –High Temp.
:Separator to Anode to Cathode











Gap Measurements	Distance (mm)
Separator-Anode	2.2514
Anode-Cathode	0.8781
Separator - Cathode	3.1590

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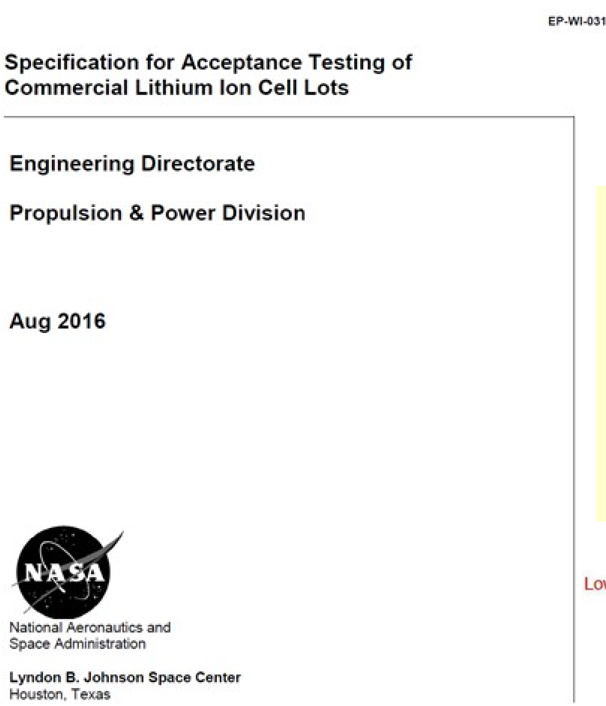
Cell screening Test item and process

1. Reference Document for Test

1) SOW (Statement of Work)

2) Specification for Acceptance Testing of Commercial Lithium Ion Cell Lots


EP-WI-031

Specification for Acceptance Testing of Commercial Lithium Ion Cell Lots

Engineering Directorate

Propulsion & Power Division

Aug 2016

National Aeronautics and Space Administration

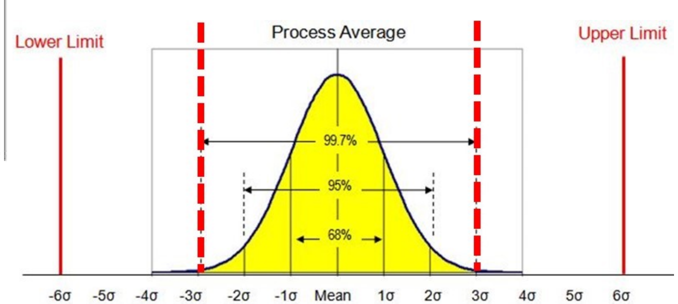
Lyndon B. Johnson Space Center
Houston, Texas

2. Pre-Acceptance Testing

1) Select random sampling
2) Identification of sample
3) Remove Insulating Sleeve/ID
4) Visual Inspection/ Mass
5) Measure Cell Dimension
6) OCV/ AC Impedance at 1 kHz.
7) CCV
8) Cycle to measure Capacity
9) X-ray CT-scan and DPA
   : corrosion, defects, anomaly

3. Full Lot Receiving Inspection

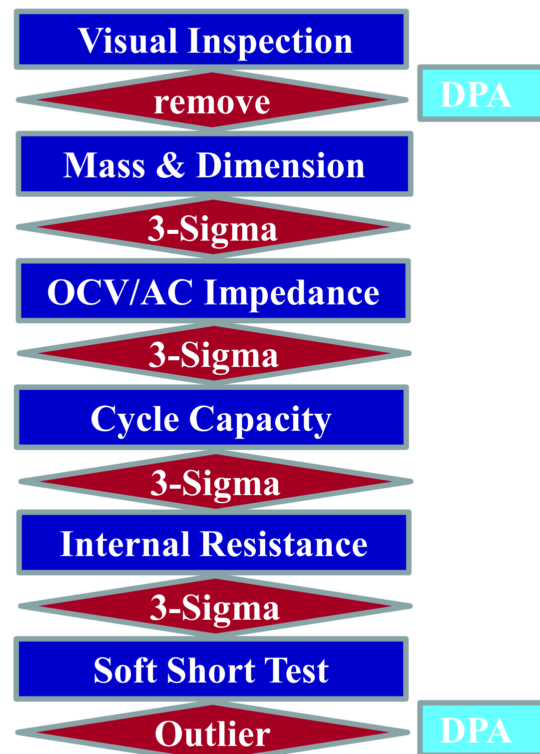
1) Identification of sample
2) Remove Insulating Sleeve/ID
3) Visual Inspection/ Mass
4) Cell Dimension by Go-No Go
5) Re-sleeving



4. Cell screening Test

1) OCV/ AC Impedance at 1 kHz.
2) Cycle to measure Capacity
3) Cell internal DC resistance
4) Soft Short Test for 15 days
   :declining voltages > 2.0 mV

5. Cell screening Process



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Cell Sample and 4S String Type

1. Cell Sample for Cell Screening process

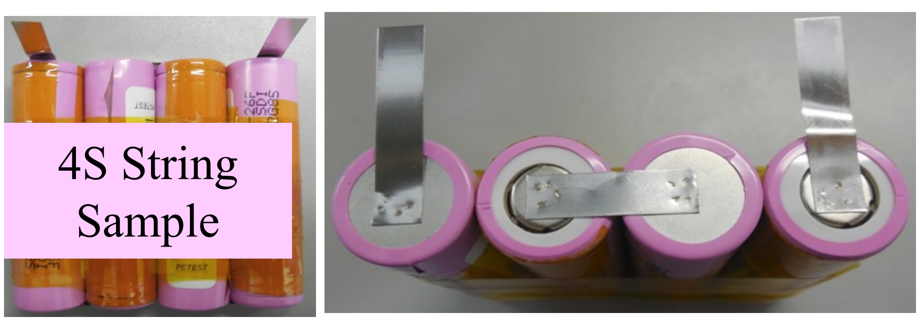
:All samples are the same lot and manufacturing date, after maker's filtering process

Character	Specification
Capacity	Nominal: 2,600mAh, Minimum : 2,550mAh (0.2C to 2.75V)
Charging	Voltage: 4 . 2 V CC-CV, Current: -Standard : 1,300 mA, -Max. Charge : 2,600mA
Discharge	Cut-off Voltage: 2.75V, Max. Current: 5,200mA

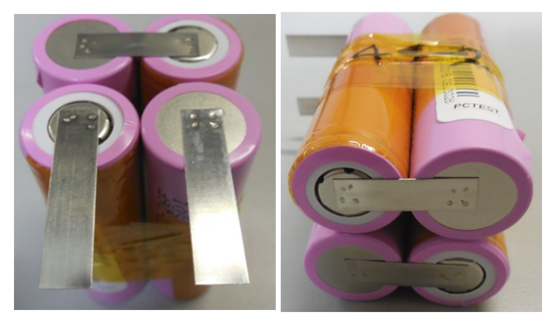
2. Validation Process - 4S String sample

Type : bar-type and ring type, all the cells used for 4S String were the passed cell samples from the cell screening process

1) bar-type 4S String



2) Ring-type 4S String



Result and Discussion

- Cell Screening test and Process
- Soft Short Test Process and outlier
- Result of soft short testing & defects
- Result of soft short testing & defects

Result of the Cell maker/model selection

1) Cell Maker and the Manufacturing Site has a Certificate of the ISO 9001
   ➔ Meet the criteria of the compliance.

2) Cell Model has Certificate of the UN 38.3 Manual Test and the UL 1642
   ➔ Meet the criteria of the compliance.

3. Cell safety and reliability Test for a cell model selection
   1) Cell design check, 2) Battery Safety test, and
   3) Operational Reliability Test: ; a) Separator Isolation properties,
      b) Cell design and alignment Criteria, c) Insulation mechanism,
      d) Vent Mechanism, e) Thermal Test, and
      f) Reliability Test Cell stability at each cycle test Conditions: at
         - Cycled at Room Temp., - Cycled at minimum charging Temp., and
         - Cycled at maximum charging Temp.
      : all the detailed test results are not available here caused by page limitation.

   ➔ Test Result : pass all the criteria of the test items on the list.

➔Meet all the criteria of the compliance. ➔ select this cell model for experimental.

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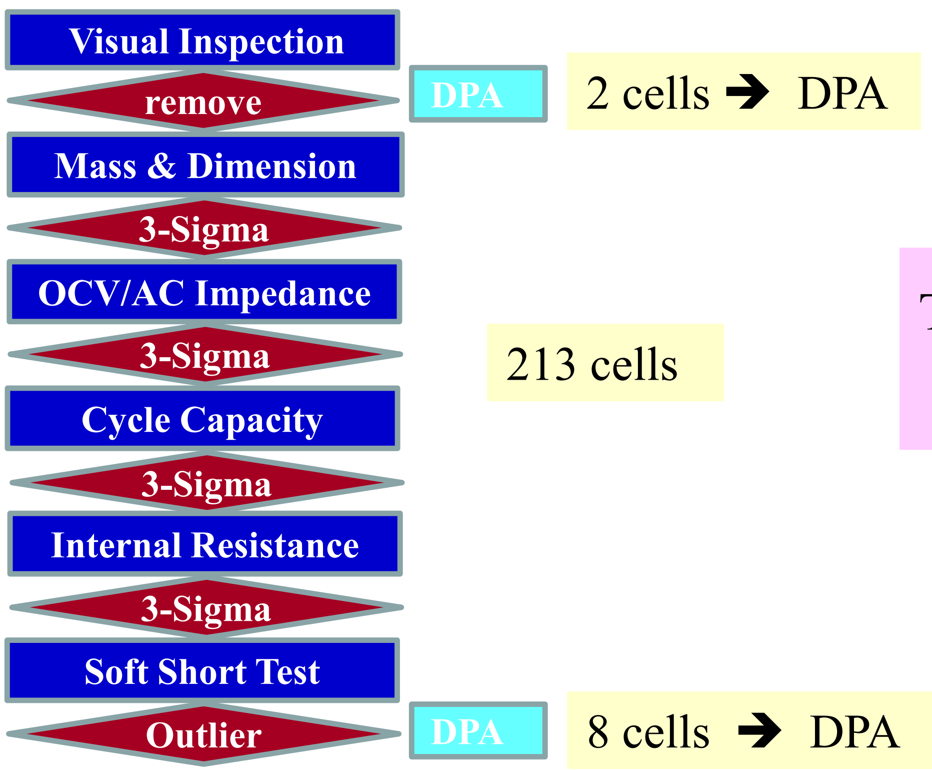
Result and Discussion – Cell Screening

Rejected cells from cell sourcing process.

- Categories applied 6-sigma statistics: 7 iterations - Mass, OCV, DC Resistance, AC-Impedance, Charge & Discharge Capacity ➔ Outlier were rejected
  : upper and lower limits of 3-sigma for each category

- 8 cells are rejected from Soft short testing ➔ DPA , rejected by dents ➔ DPA

Cell screening Process & rejected cell sample



Total rejected: 223 / 3,000

Rate 7.4 % < Criteria: < 15%

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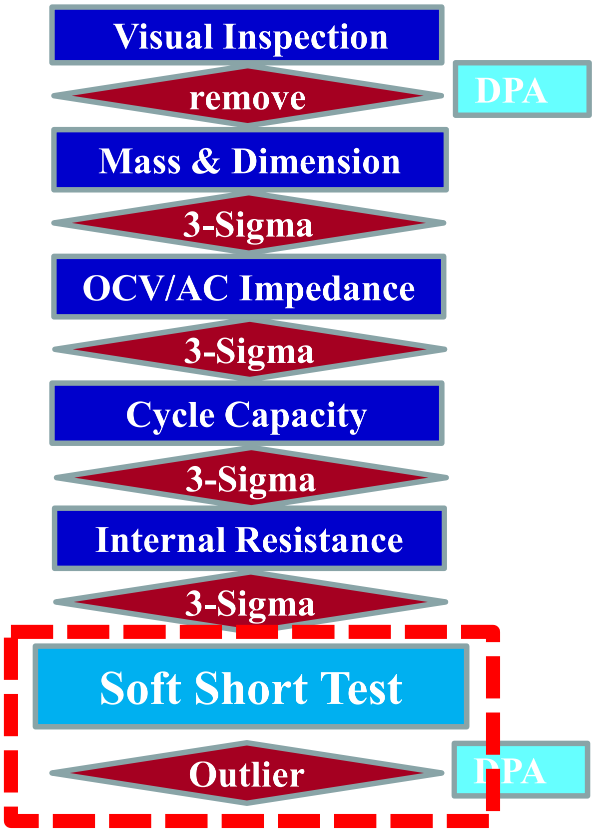
Soft Short Test Process and outlier



Soft Short Test Process

Discharge : - Voltage : minimum allowable voltage specified by the manufacturer specification.
- Current : 1/10 C ➔ 1/25 C ➔ 1/50 C ➔ 1/100 C rate

Rest condition : - Temperature: 22 C +/- 1 C controlled
- No electric connection to the sample

OCV measurement : regularly on-time for 15 days at accurately temperature-controlled room:
- after 1, 3, 7, 10, and 14 days after rest

Criteria : Cell voltages declining > 2.0 mV shall be rejected

Rejected sample number : 8 cells

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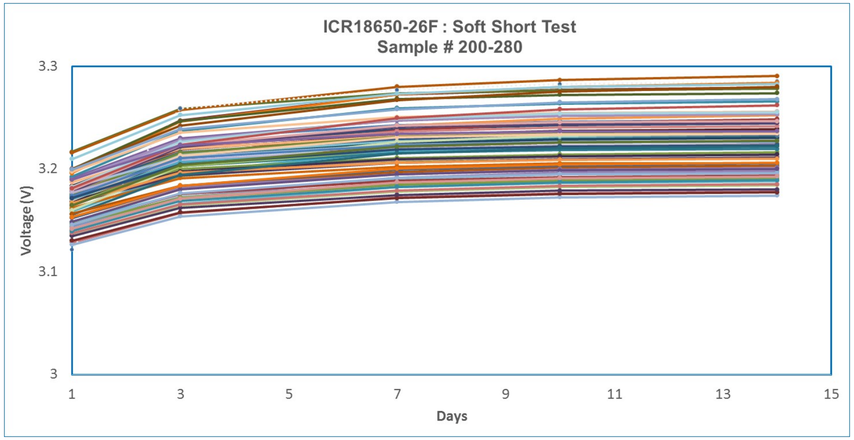
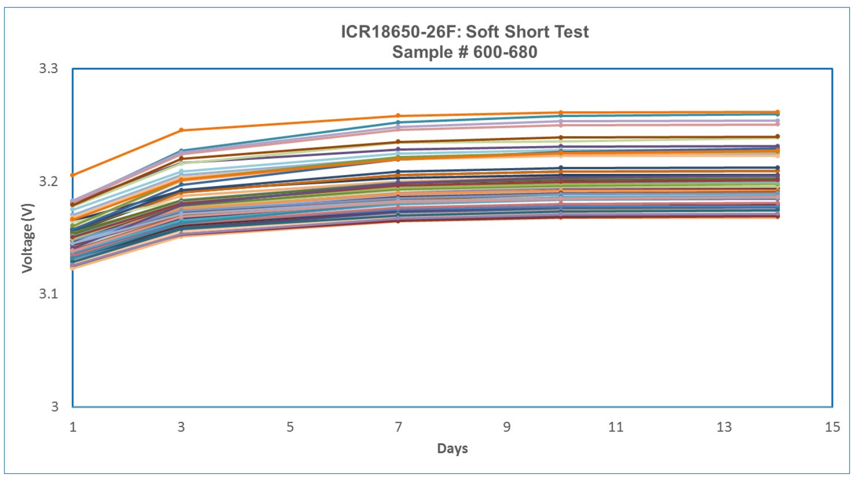
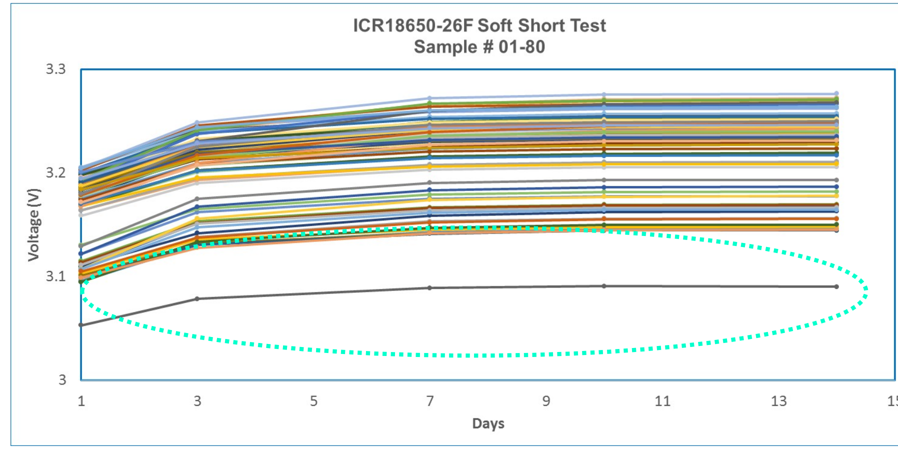
Result of soft short testing & defects

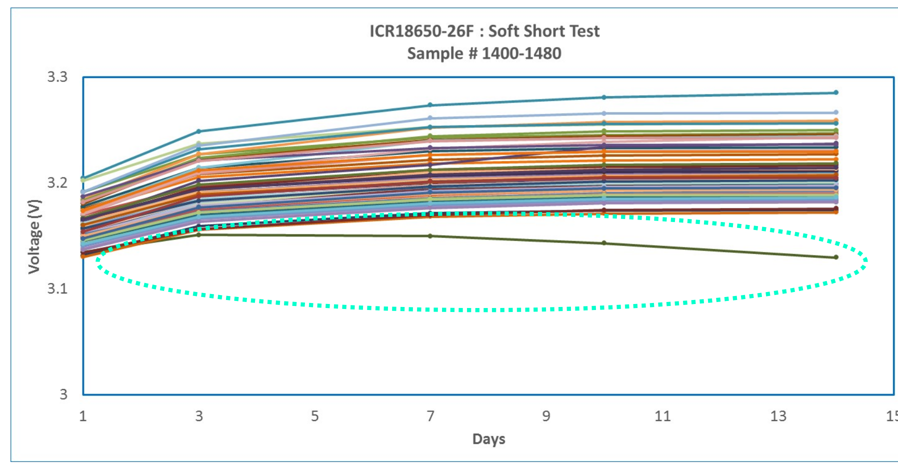
Example of Pass Sample

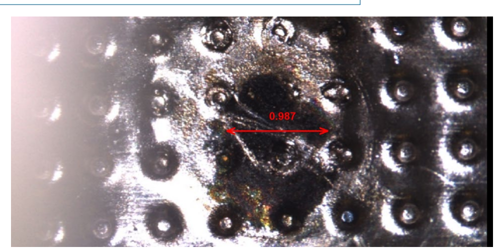


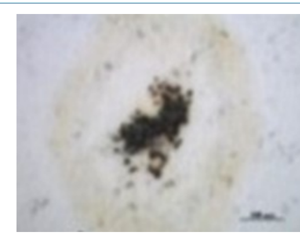


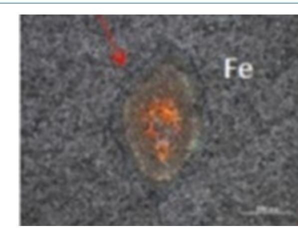
Example of Fail Sample











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Validation process for the cell selection/screening process

- 4 S String structure and cells
- 250 cycle test at mission operating conditions of the Human-space flight
- Accelerated cell cycle test
- Internal Resistance of cell & 4S String
- DPA and SEM-EDS of the 4S String

Validation Experimental

Purpose: to validate whether our cell screening process is beneficial to the battery performance and safety compare to unprocessed cells

Experimental Type :

1) Cycle Test at mission operating conditions
   :use screen passed cells with different combinations ad type
   a) Good combination: select the same character cell samples -flat or bundle-ring type
   b) Bad combination: select different character cell samples -flat or bundle-ring type

➔ **Criteria of compliance:** ***The performance difference between the combinations should be maintained within the allowable range.***

2) Cycle Test at Accelerated cell cycle test condition
   : The worst charging available conditions in the cell specification.
   - Cycle at 45 °C, 1C rate CC-CV mode to 4.2V, discharging 1C, CC mode to 2.75V
   : used a) screen process passed cells and b) unprocessed cells for the comparison.

➔ **Criteria of compliance:** ***The performance difference between the combinations should be maintained beyond the allowable range.***

Cycle condition and structure of the 4S String

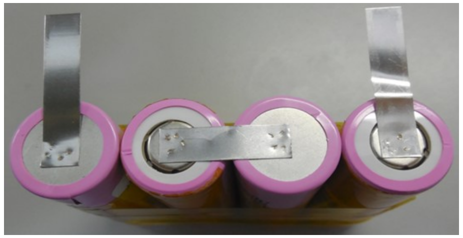
Experimental: Cycle Life Testing with the 4S string to 250 cycles
:250 cycles protocol: mission operating conditions of the Human-space flight

1) Cycle protocol and condition: at room temperature
   - Charge at C/8 with a 1hour taper to 4.2V, rest for 15min,
   - Discharge at C/8 to 3.0V, rest for 15min.

2) Cell sample for the 4S string: used screening passed cell
   * All cells used for 4S string were passed the criteria of the cell screening process.

3) Cell combination for the 4S string
   a) Type of 4S string : bar-flat type , bundle-ring type
   b) Cell Selection : -Capacity, -AC-impedance, - DC-IR at Voltage at 50% SOC
   c) Combination: - Good combination : totally same on all the factors
   - Bad combination: two cells has high + two cells has low level

- **250 Cycle test result**
- AC-Impedance & DC-Resistance
- Cell DPA analysis
- Cell SEM-EDS analysis


Bar-flat type 4S string


bundle-ring type 4S string

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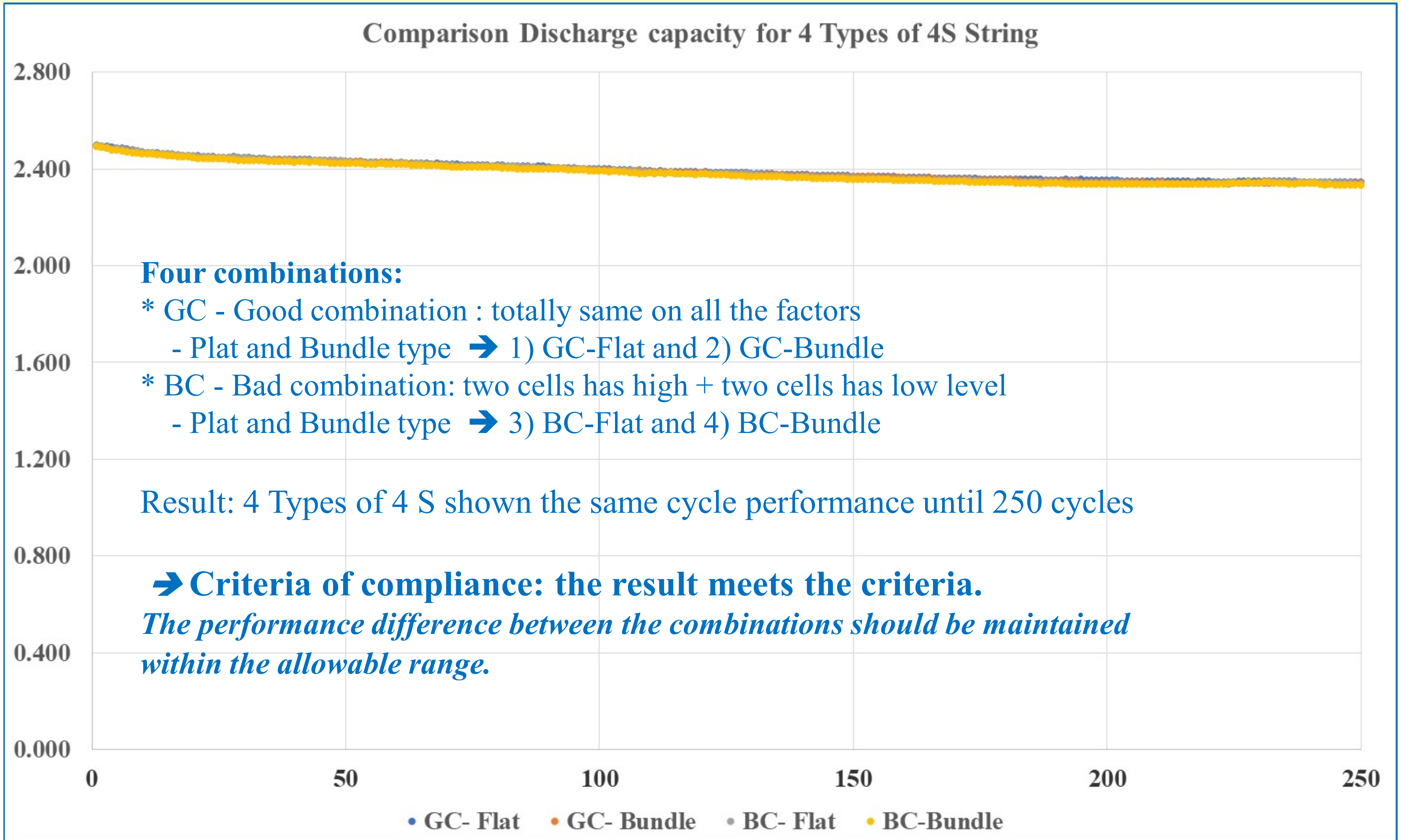
Cycle Test Result at mission operating conditions

Four types of 4S string shown the similar cycle performance results until 250 Cycle test.
: Capacity decline (6.4 ~ 6.5%) and resistance increase trends by cycle are similar among 4 type 4S String
- Good Combination: totally same factors, - Bad Combination: two cells: high + two cells: low level
- **All cells used for 4S string were screened cells.**



Four combinations:
* GC - Good combination : totally same on all the factors
  - Plat and Bundle type ➔ 1) GC-Flat and 2) GC-Bundle
* BC - Bad combination: two cells has high + two cells has low level
  - Plat and Bundle type ➔ 3) BC-Flat and 4) BC-Bundle

Result: 4 Types of 4 S shown the same cycle performance until 250 cycles

➔ Criteria of compliance: the result meets the criteria.
The performance difference between the combinations should be maintained within the allowable range.

Accelerated cell cycle test

Experimental: Accelerated cell cycle life test for comparison the 4S string between "Screened cell -4S" and "Unscreened cell - 4S".
Rational: A cell has potential defect it can be triggered by Accelerated conditions

1) Accelerated cell cycle test condition
- Accelerated Temperature Condition : 45 °C degree
- Accelerated Voltage: maximum charging Voltage on cell Specification ➔ 4.2 V
- Accelerated Current: maximum charging Current on cell Specification ➔ 1 C rate

2) Type of 4S string :
a) The cells passed the cell screening process : Screened cells
b) The cells do not process the cell screening : Unscreened cells

3) Result & Discussion: comparison between screened and unscreened
- **Cycle test result of the 4S String**
- DC Resistance and Cell AC Resistance of **4S String**
- **Cell SEM-EDS analysis after DPA.**

Type of 4S string

Accelerated cell cycle test result

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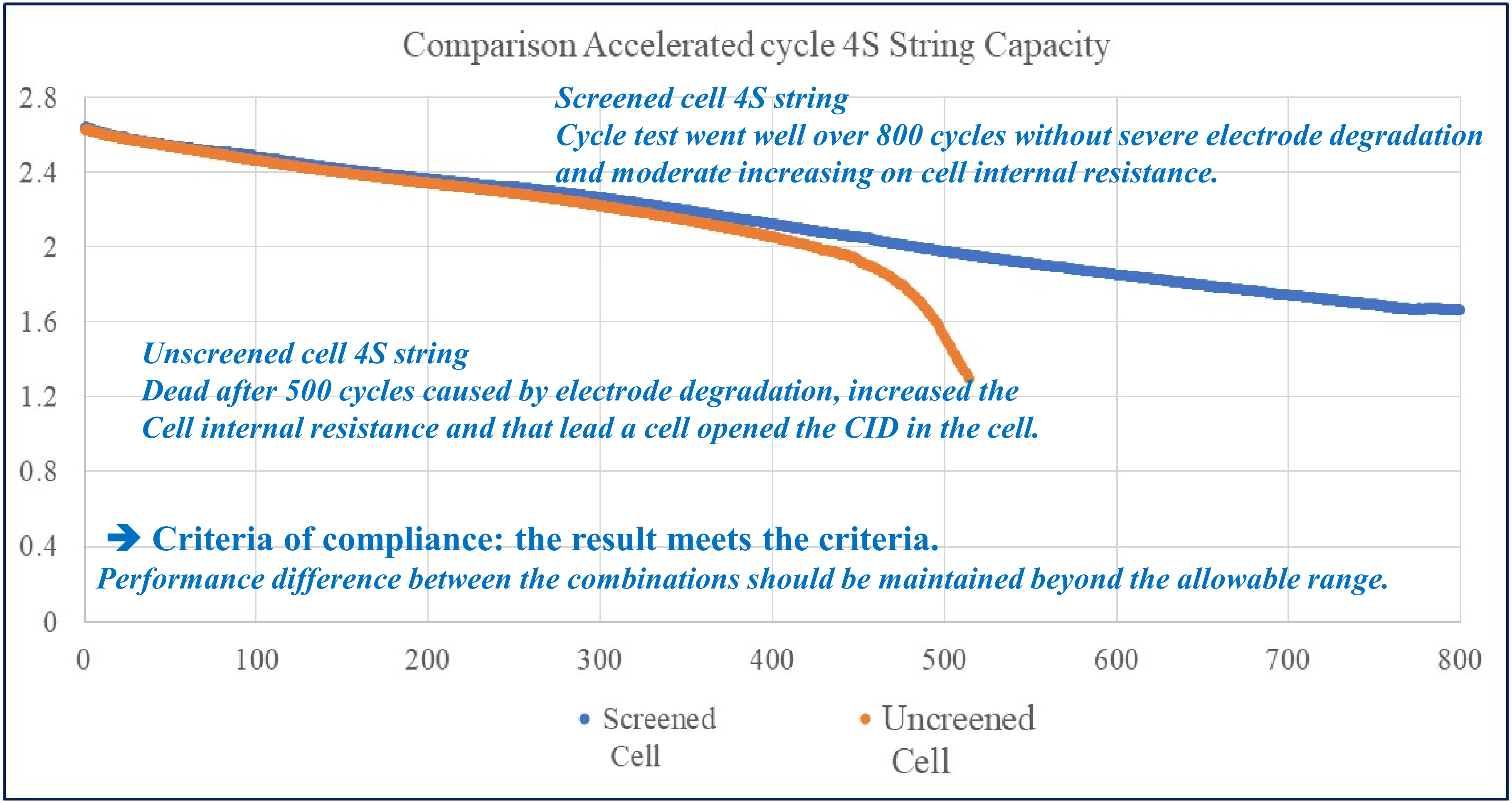
Comparison Cycle between 1) Cell screened and 2) Cell unscreened 4S String.

1) Cell screened 4S String maintained capacity 63% of initial at 800 cycles.
2) Cell unscreened 4S String was dead after 510 cycles : Root Causes: cell CID Open



Review the result of validation

1. Cycle Test at mission operating conditions
   1) The result meets the criteria of compliance - *The performance difference between the combinations should be maintained within the allowable range.*
   2) The four types of screened cell 4S string shown similar performance among them. :The type of cell combinations within the screened cell do not affect the performance of the 4S string. ➔ the screening process filter the outlier cells out from the process.

2. Cycle Test at Accelerated cell cycle test condition
   1) The result meets the criteria of compliance - *The performance difference between the combinations should be maintained beyond the allowable range.*
   2) The apparent difference was shown between screened cell 4S and unscreened cell 4S.

3. Proposed degradation mechanism of the unscreened cell 4S
   1) The performance of the unscreened cell 4S shown the similar performance of the screened 4S until 250 cycles after then capacity decline happened gradually until it dead at the 511 cycles.
   2) For the point of the cell balance among the 4 Cells in the 4S string, the cells in a screened cell 4S would be better than that of the unscreened cell 4S string.
   3) Even though the difference of cell balance among the 4 cells of the unscreened cell 4S string at initial cycles was small, that can increase the differentiation of cell balance more by cycling , and that can lead the 4S string dead eventually.

➔This Cell Screening Process is valid and is recommended for long term life applications.

Internal Resistance of cell & 4S String

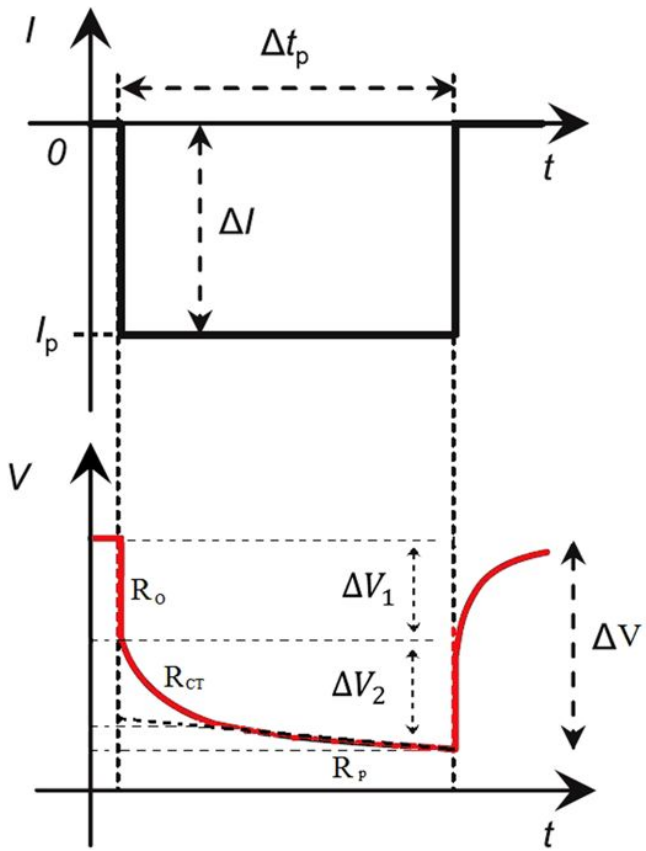
1. DC-resistance comparison among cell, 4S fresh and after 250 Cy and Accelerated.
   - DC-resistance of the 4S after 250 Cycles increased about 1.2 times that of fresh 4S, and all the 4 types of 4 S strings maintained similar level of Internal resistance increase.
   - Changes of the DC-resistance of each cell in the dead 4S String was not similar between.

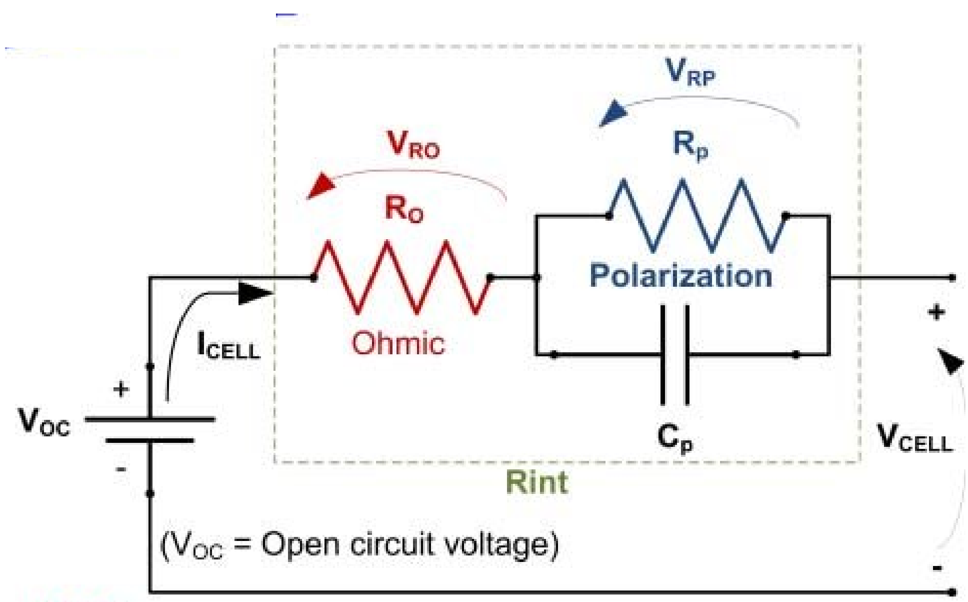
2. AC- Impedance comparison

*** The test result data and discussion of these topic will be updated after a paper published.***

DC resistance measurement method

The method is defined in the "USABC Electric Vehicle Battery Test Procedures Manual" and has been used in EV industry for decades as a best practices to measure cell internal resistance.

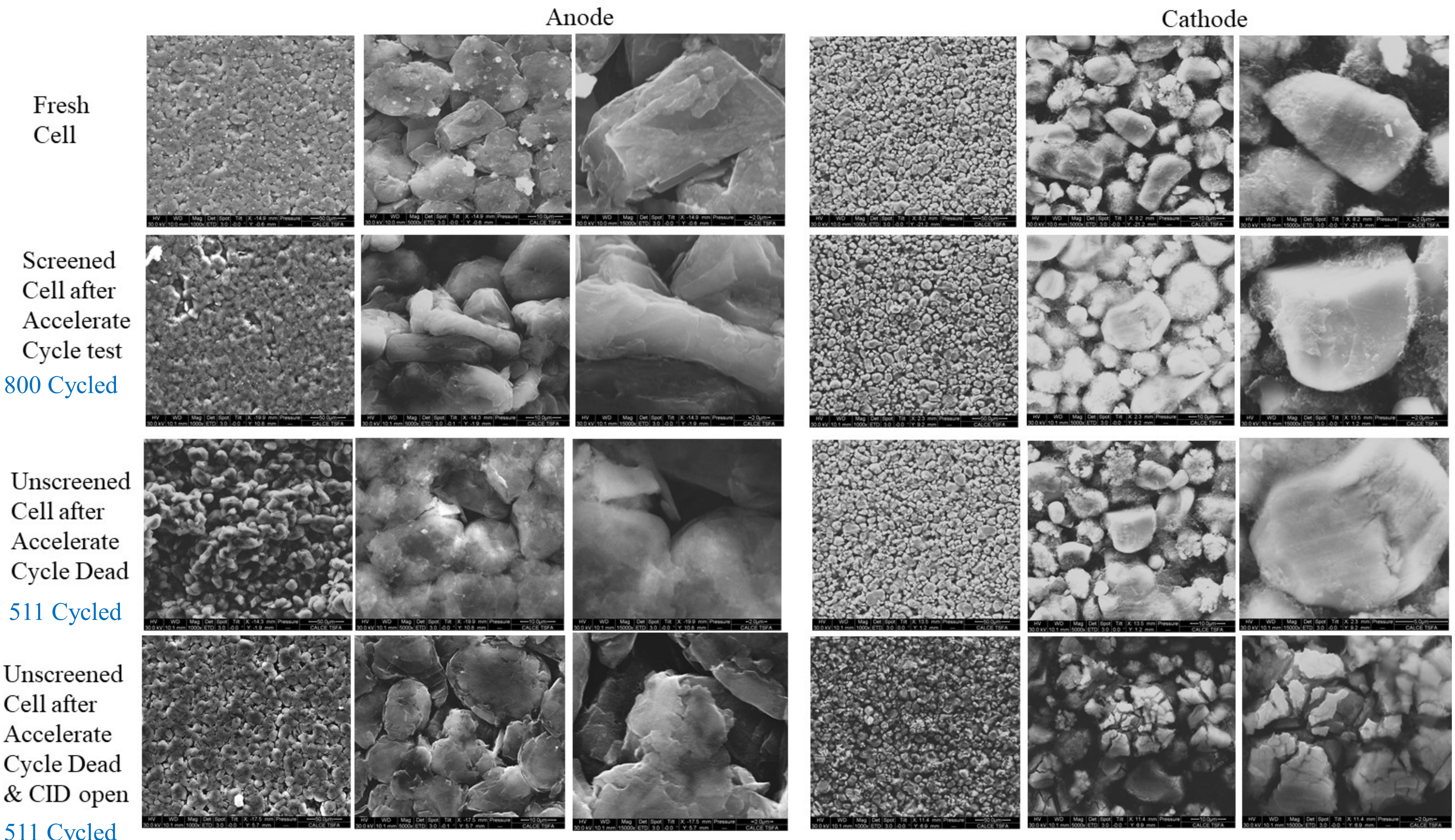




Differential resistance R = dV/di
Where dV is affected by applied current and test data sampling time (dT).

DPA and SEM-EDS of the 4S String

Cathode electrode particle broken of the unscreened cell 4S after accelerate cycle test 510 Cy. Anode electrode and particle dose not changed much compare to that of Cathode.



Conclusion

- A cell model/manufacturer was selected per cell model & manufacturer selection process.

- A cell model was performed per pre-acceptance test, and safety and reliability testing.

- Cell Screening process has filtered the potential safety risk cells & outliers of 3-sigma out.

- Verification process validates the cell Screening process through cycle test of the 4S String both under “Mission operating condition to 250” and “Accelerated cycle test” condition.

- Analysis results from the Cycle tests, DPA/SEM-EDS, and DC-resistance/EIS identified and compared the cell degradation mechanism between the screened and unscreened cells in the 4S String. That validate the efficiency of the Cell Screening and validation process.

-This result recommends a cell Screening and validation process for a cell model used for the lengthy spam life battery application, like Aerospace applications.

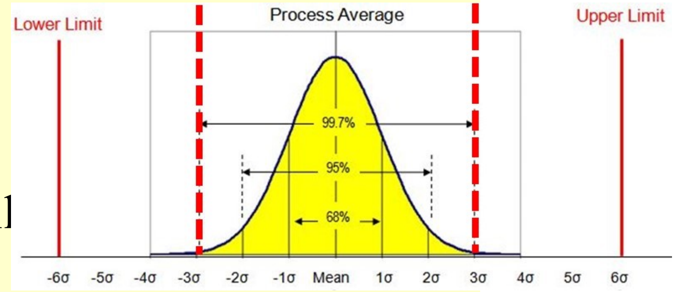
Future Works for testing and validation process

1. Develop an improved process of :
   1) Cell manufacturer, Cell type, & cell model selection,
   2) A cell model pre-acceptance test, 3) cell screening and filtering, and
   4) Validation for the efficiency of the cell selection and screening

2. Develop an improved Validation for the efficiency of cell selection and screening

   1) Cycle test :
      a) Mission operating conditions of the Human-space flight
      b) Accelerated cycle test

   2) Cell Combinations for the 4S String
      a) Cell combination with the rejected cells
      b) Cell combination with mixing rejected and passed cell



   3) Test and Evaluation methods
      a) Test method: -cell model pre-acceptance, -cell screening/fingering, - Cycle
      b) Evaluation method : DPA, EIS, DC-resistance, SEM-EDS and other tools

PCTEST battery team has been providing the best technical solutions of the testing, certification, and technical supporting for the Lithium ion battery System's performance, reliability, safety, risk assessment, surveillance and failure analysis, and safety mechanism together with 13-years of internal R&D activities.

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