# Evaluation of COTS Li-Ion Cells Targeting Deep Space Exploration

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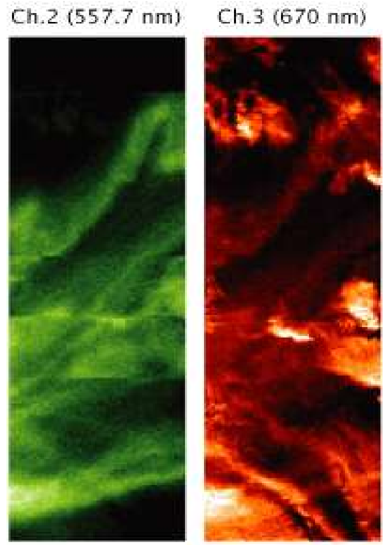
# JAXA's Lunar & Planetary Exploration Program

# Lithium-ion Secondary Cells

# REIMEI Battery

# REIMEI =「黎明(れいめい)」= Dawn

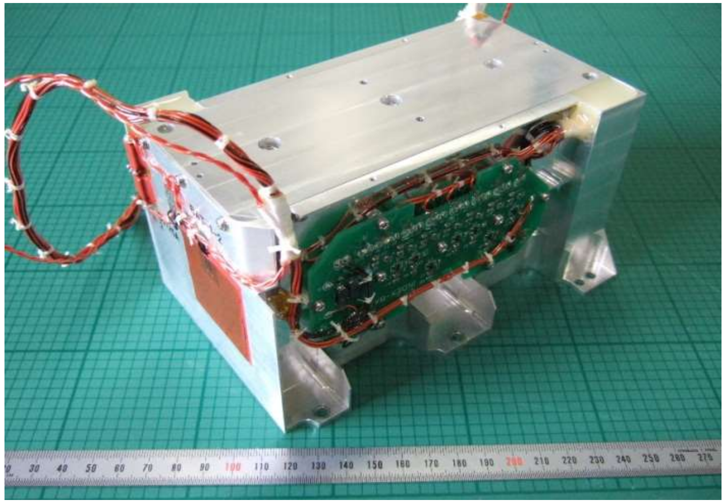
- REIMEI had three cameras for the aurora observation with different wave length.
- It was launched in August, 2005, and injected along the low-earth-polar orbit.




# Lithium-Ion cell and battery Specifications


Lithium-Ion pouch cell

| | | |
|---|---|---|
| Electrode | Positive | $LiMn_2O_4$ |
| | Negative | Graphite |
| Rated Capacity | | 3 Ah |
| Weight | | 75 g |
| Dimension | | 145 x 80 x 4 mm |
| Energy Density | Mass | 158 Wh/kg |
| | Volume | 340 Wh/L |
| Charge Voltage | | 4.1 V (4.2 V) |
| Lower Limited Voltage | | 3.0 V |



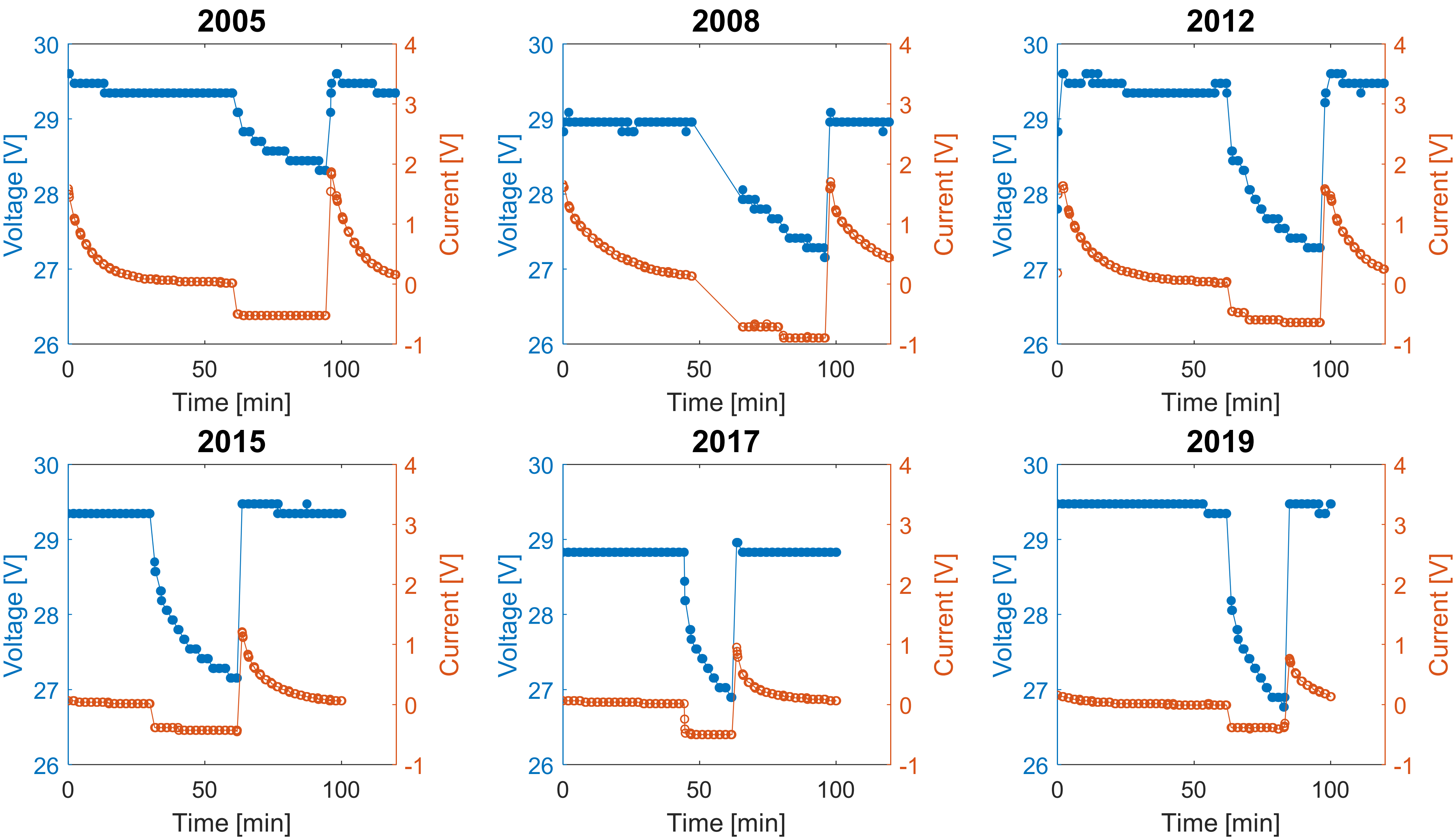
Lithium-Ion battery

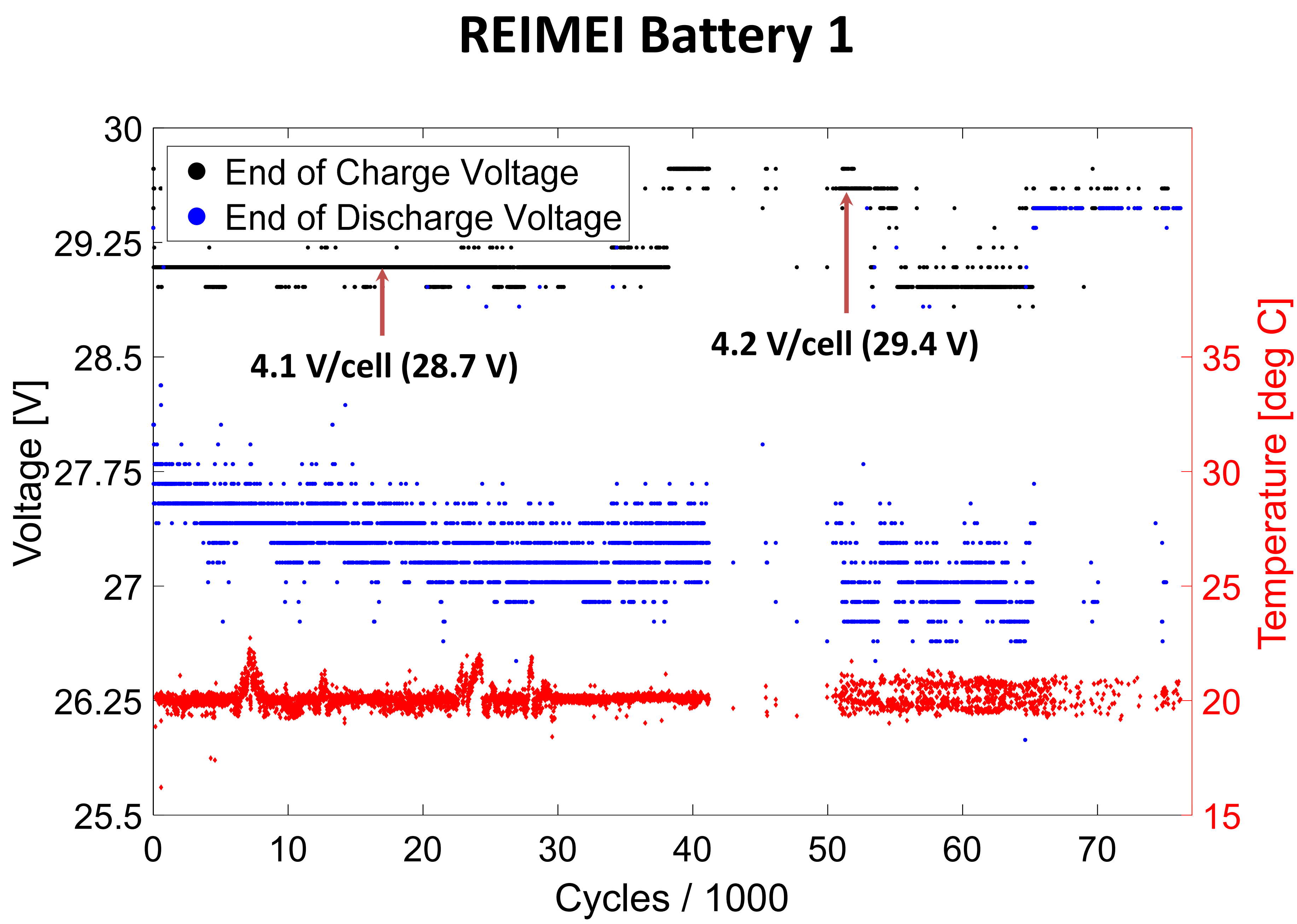
| | | |
|---|---|---|
| Configuration | 7 series of the cells<br>2 module installed<br>to the battery | |
| Potting Material | Epoxy Resin | |
| Case Material | Al | |
| Dimension | $168 \times 102 \times 96$ $mm^3$ | |
| Weight | 2.42 kg | |
| Energy Density | Weight | 70 Wh/kg |
| | Volume | 102.2 Wh/L |

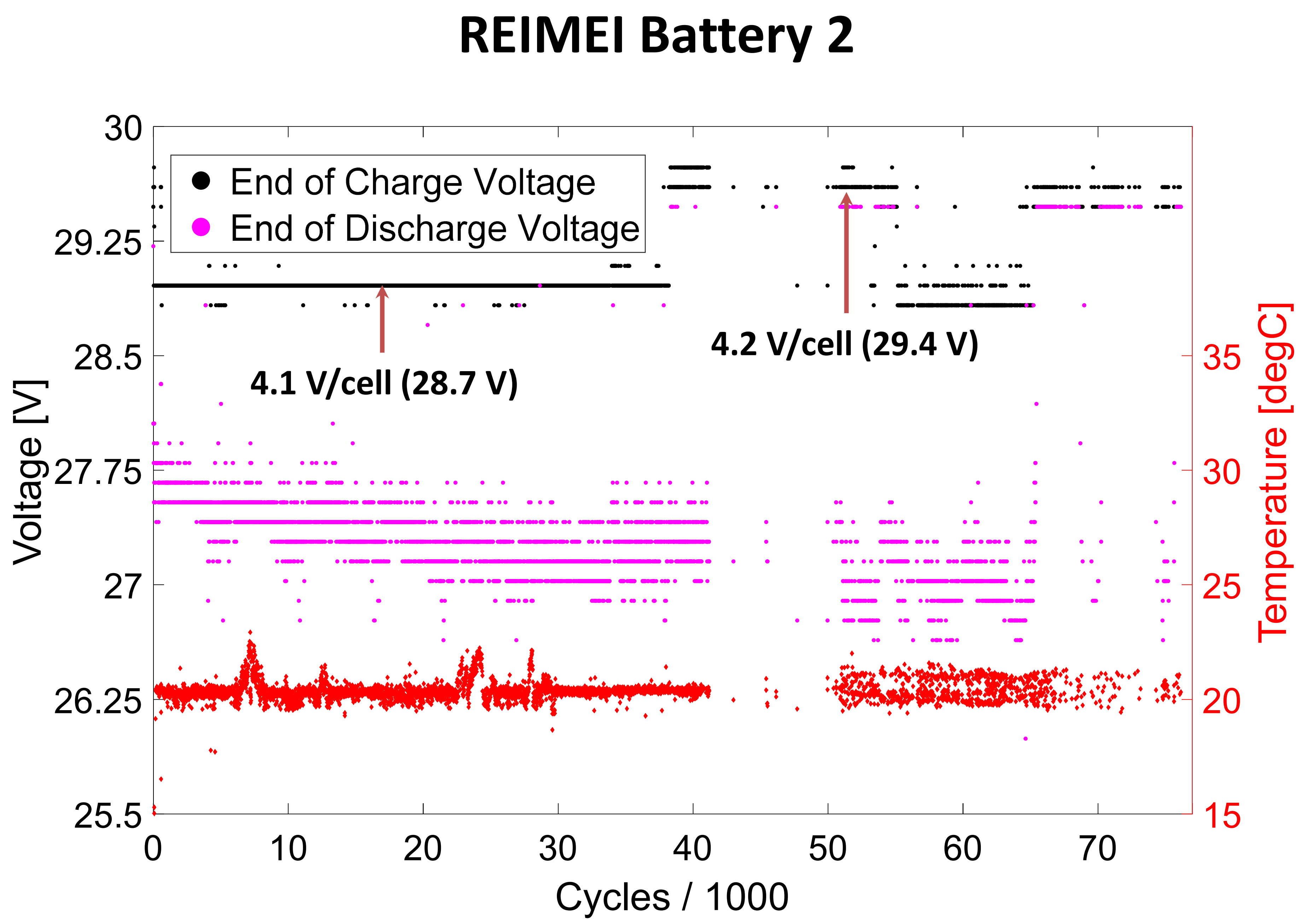
# Battery Operation

- 15 - 16 cycles a day
  - 1cycle:charge 60min. / discharge: 35 min.
  - DOD = 10~20 %
  - Charge by 1.5 A.
  - CC-CV charge : 4.10 V/cell (V2 mode),
    or 4.20 V/cell (V1 mode).
  - Discharge rate is less than 0.5 C
  - Temperature controlled between 19 and 22 ℃.
- Over 14 years has passed
  - Over 70,000 cycles

# Battery Telemetry data

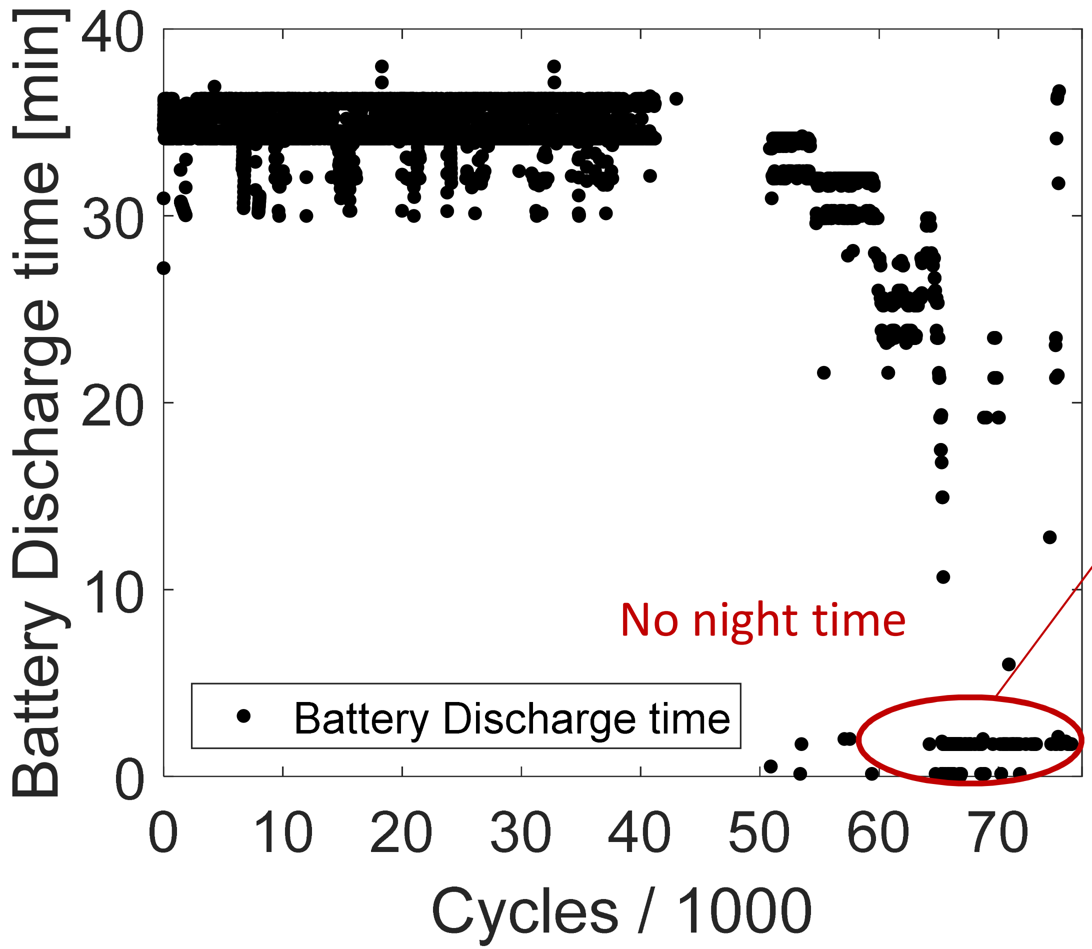


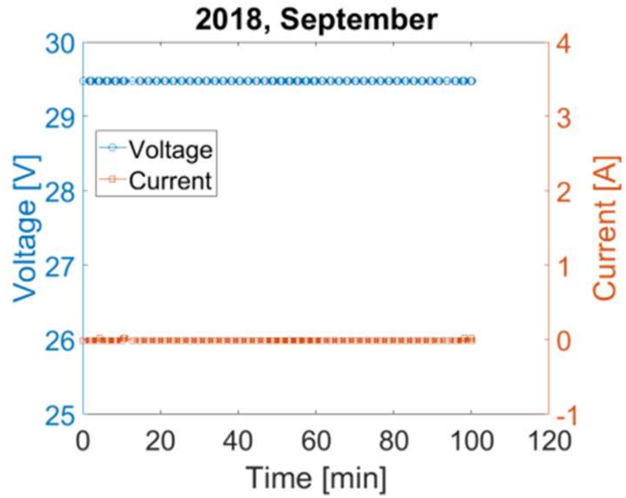

REIMEI Battery 1
End of Charge Voltage
End of Discharge Voltage
4.1 V/cell (28.7 V)
4.2 V/cell (29.4 V)
Voltage [V]
Temperature [deg C]
Cycles / 1000
30
29.25
28.5
27.75
27
26.25
25.5
0
10
20
30
40
50
60
70
35
30
25
20
15

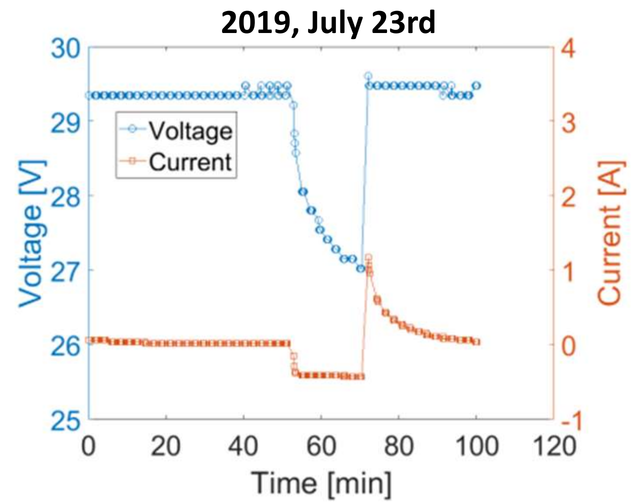

REIMEI Battery 2
End of Charge Voltage
End of Discharge Voltage
4.1 V/cell (28.7 V)
4.2 V/cell (29.4 V)
Voltage [V]
Temperature [degC]
Cycles / 1000
30
29.25
28.5
27.75
27
26.25
25.5
35
30
25
20
15
0
10
20
30
40
50
60
70

# Additional information coming from the Battery data analysis

## Battery discharge time

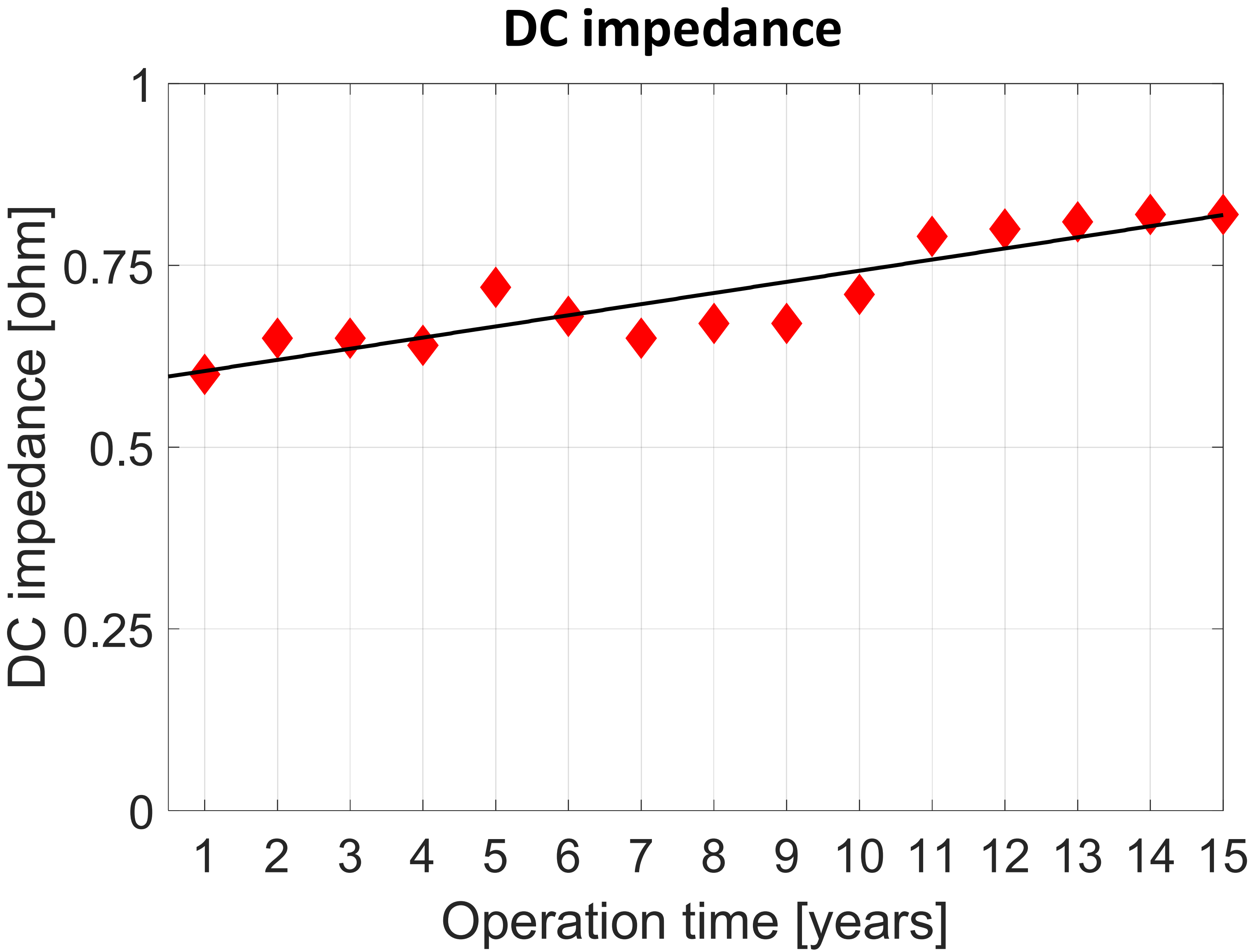



Last time that night time was detected

**Analysis of Battery data can be useful to keep and eye on the satellite orbit status**




Trend of the DC impedance calculated from the REIMEI battery. The DC impedance was calculated from the change in voltage and current at the beginning of eclipse time.

# Low temperature effect

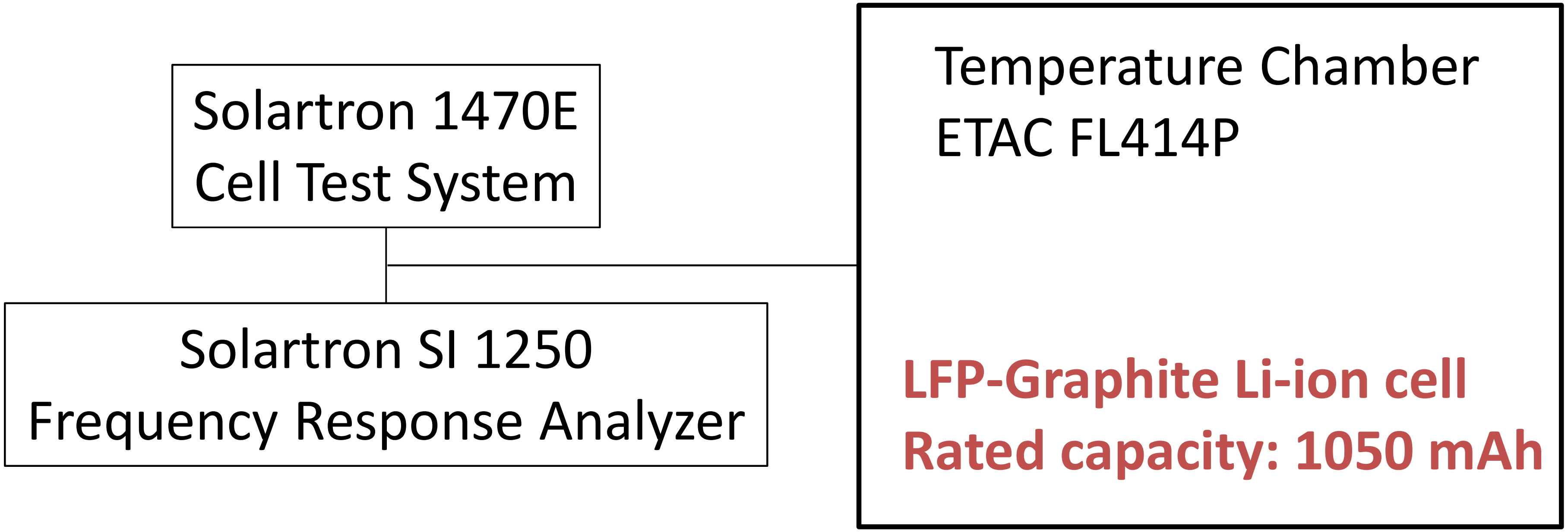
# Tests using COTS cells

# Experimental Methodology

**Electrochemical measurements:**

**-Charge-discharge cycling**

**-Electrochemical Impedance Spectroscopy**




| | |
|---|---|
| **Calendar degradation:** | Temperature = 60 °C<br>State of charge = 100%<br>Time = 4 weeks |



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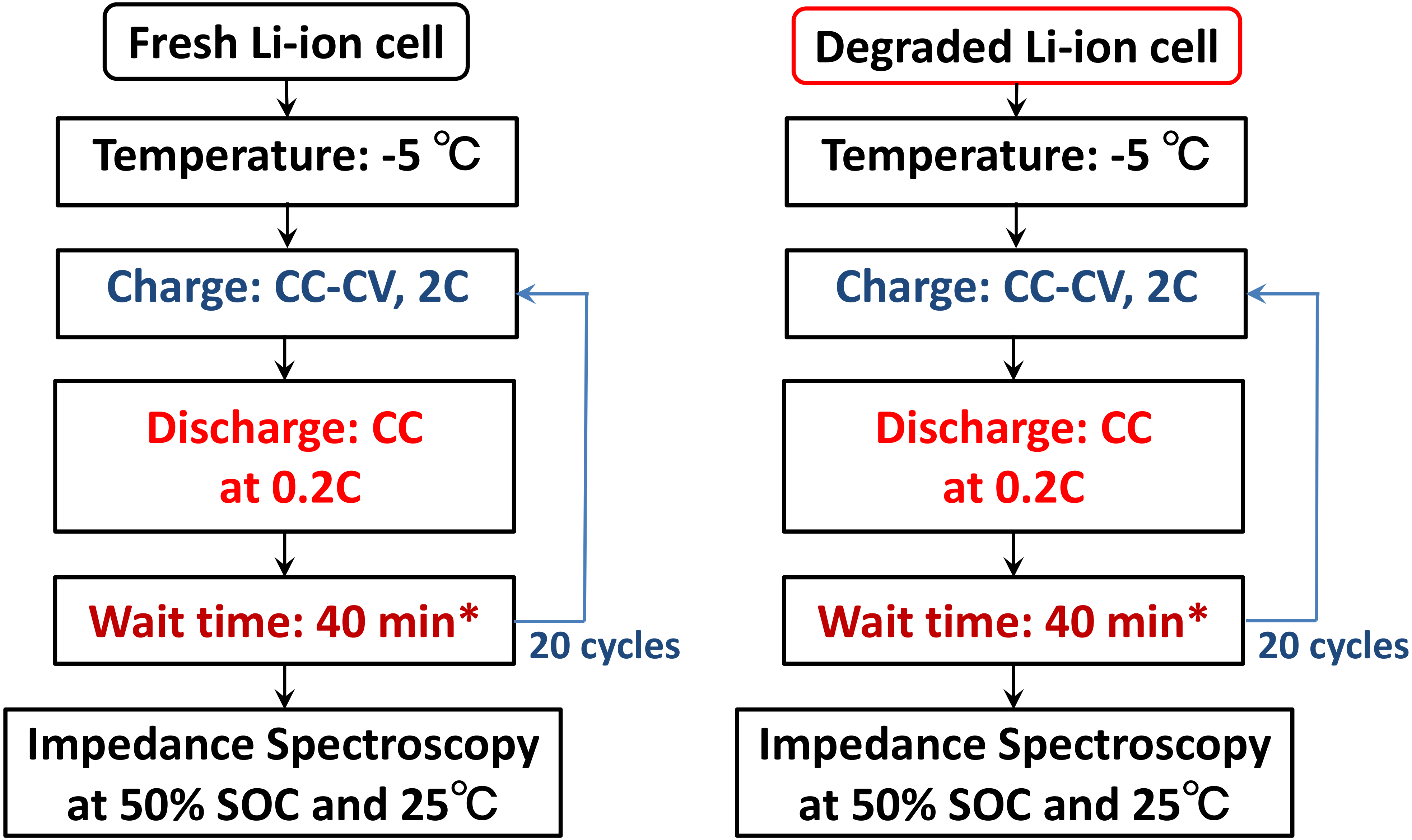
# Experimental Methodology




*To allow the Li-ion cell surface temperature to stabilize after charge



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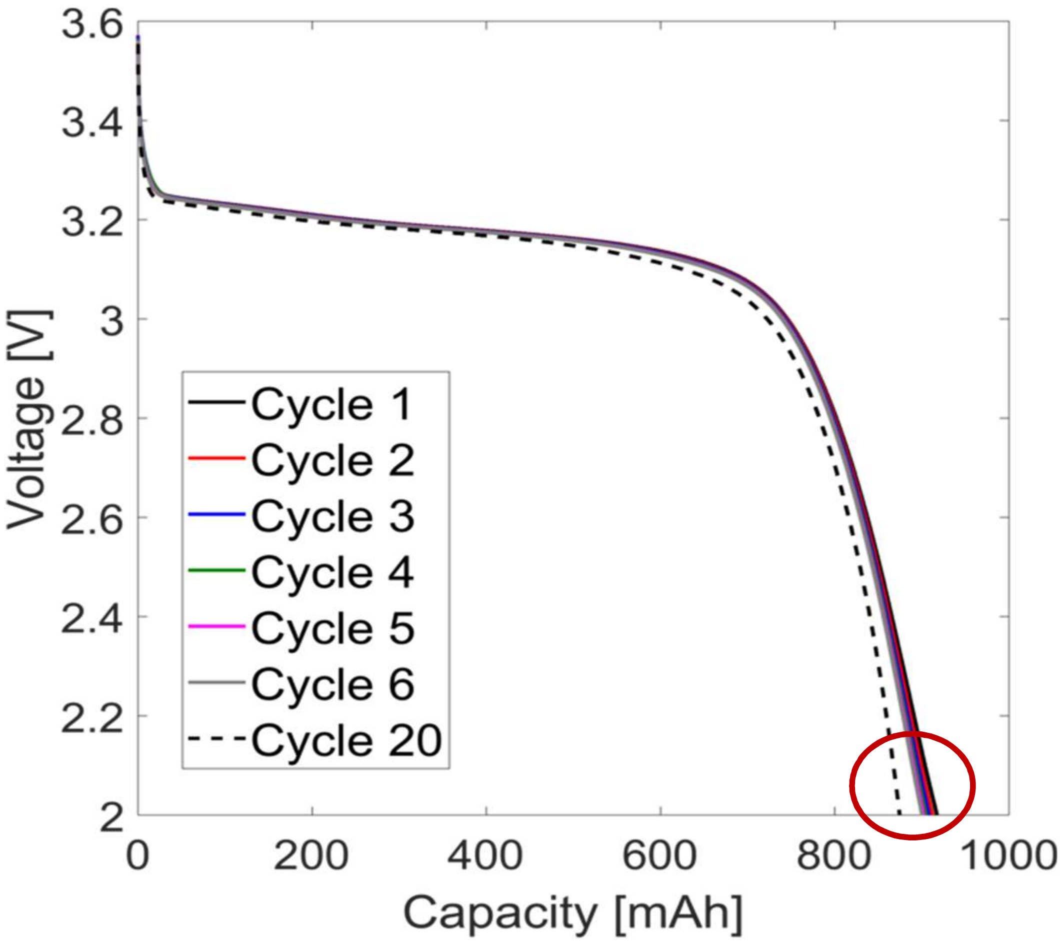
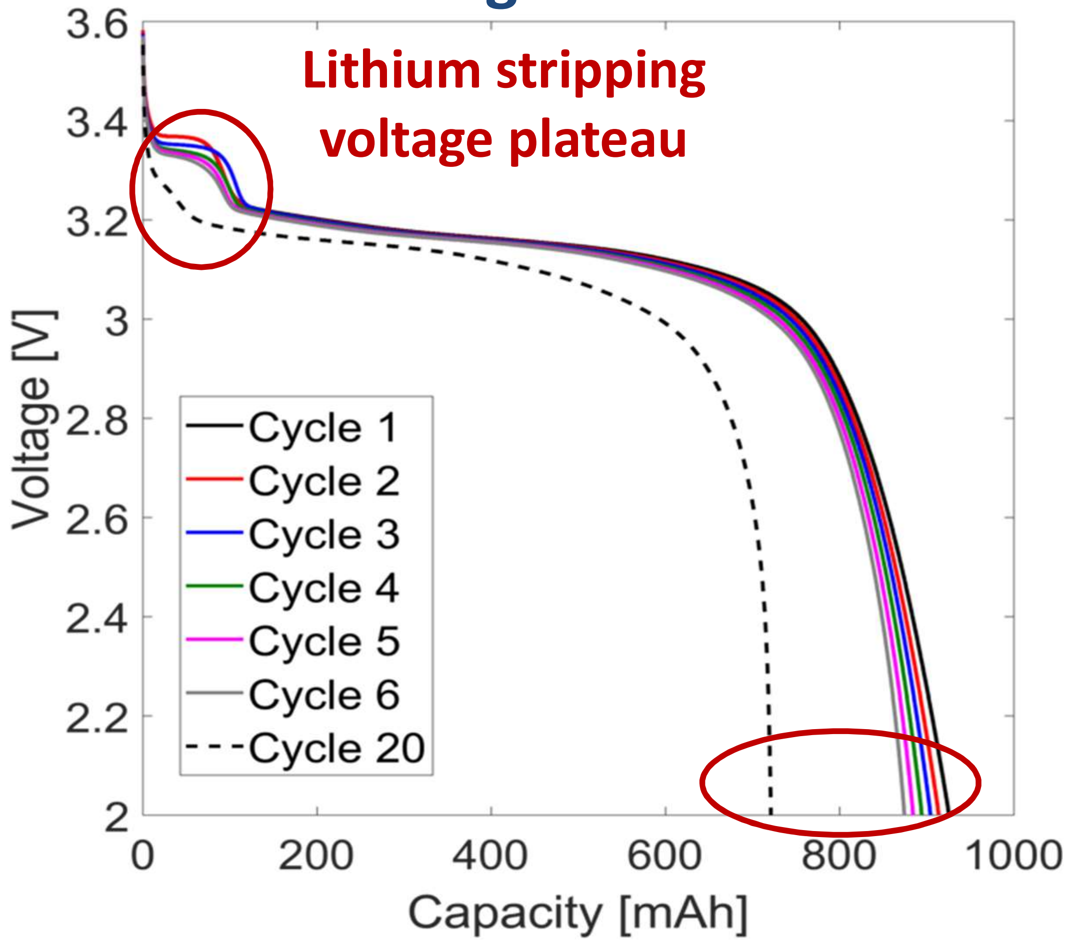
# Discharge curves after charge at -5℃

## Fresh Li-ion cell




## Calendar degraded Li-ion cell




The fresh cell does not exhibit a high voltage plateau, however a small capacity fade was observed.

The calendar degraded cell exhibited a high voltage plateau and a large capacity fade.



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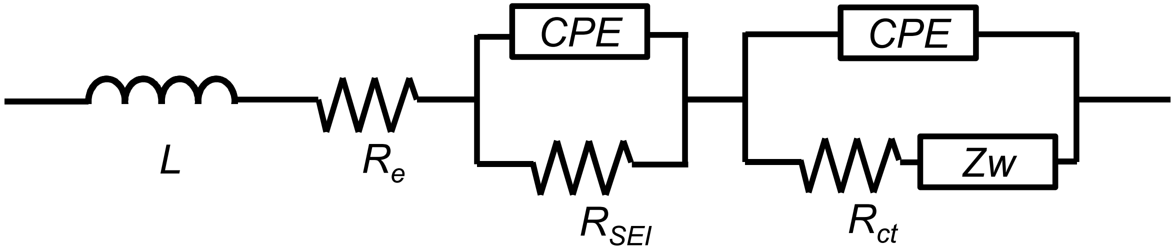
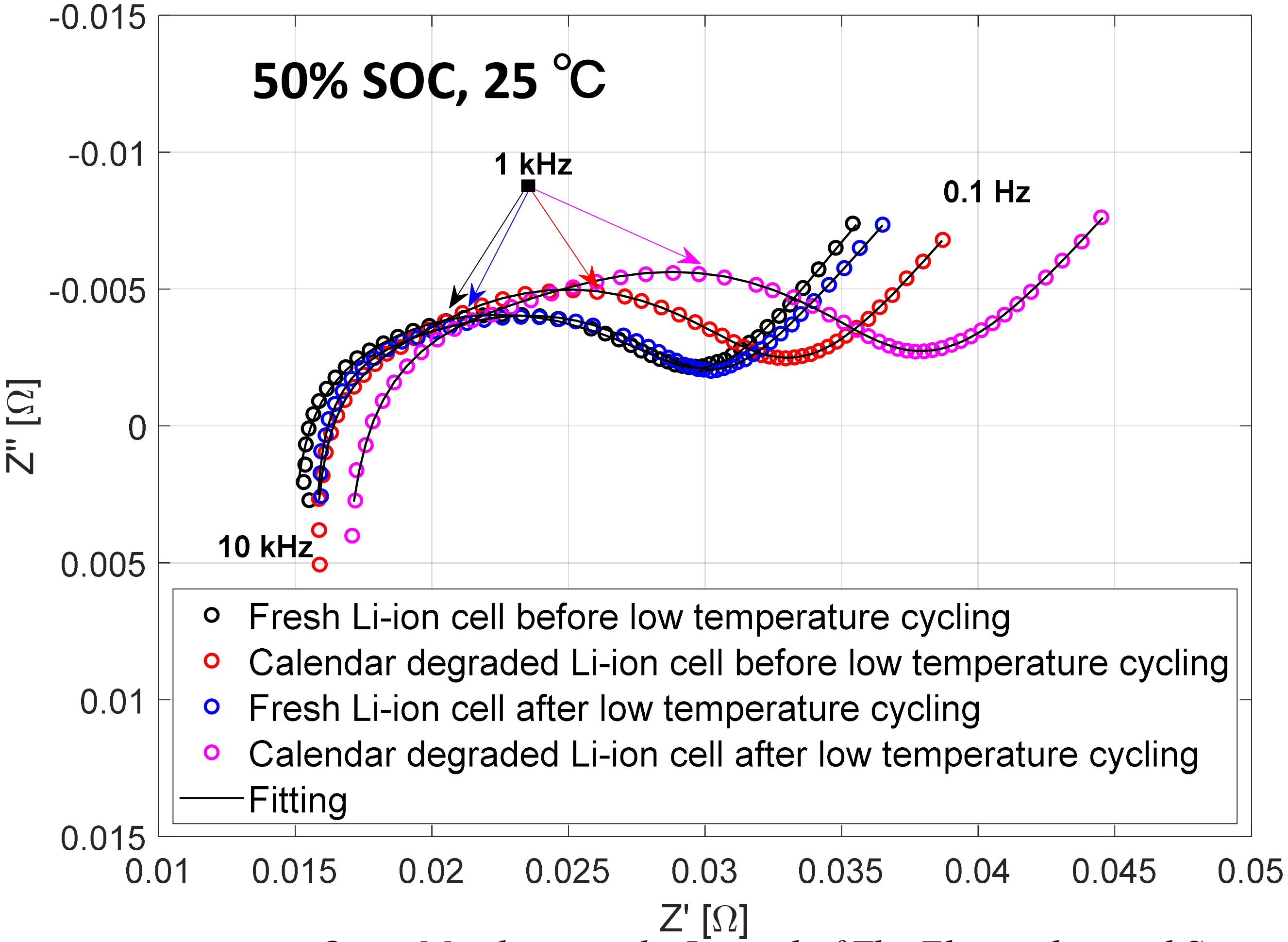
# Electrochemical Impedance Spectroscopy measurements




$R_e$ **= electrolyte resistance,** $R_{SEI}$ **= SEI resistance,** $R_{ct}$ **= charge transfer resistance**



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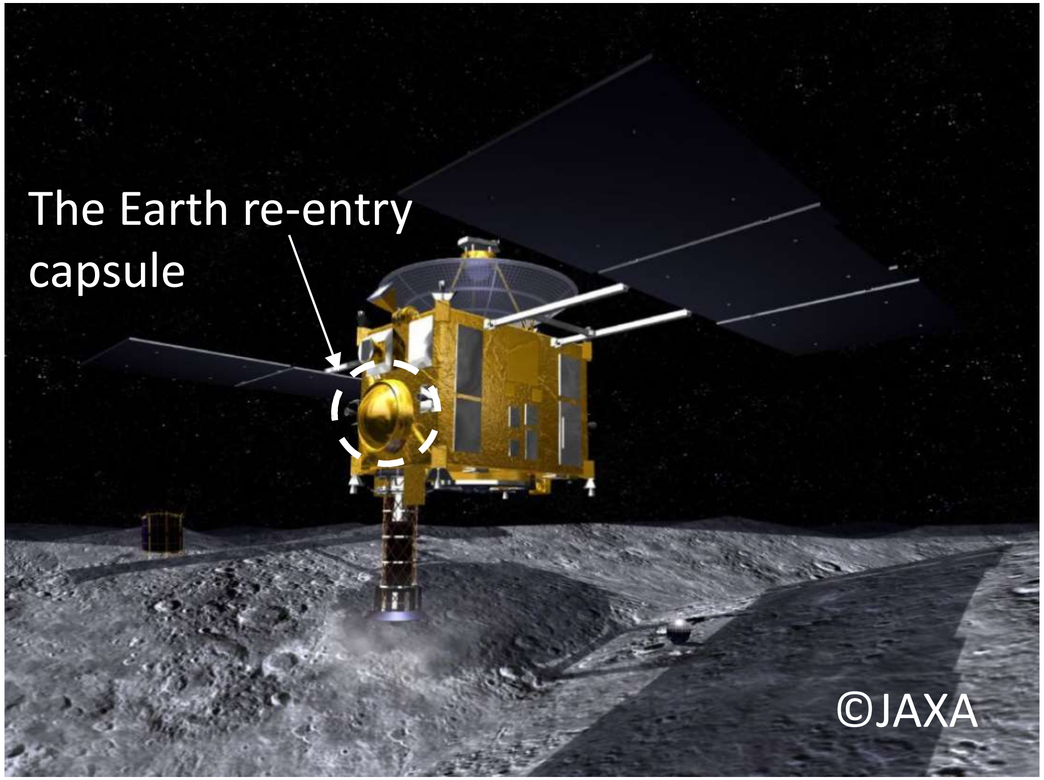
# Summery

- REIMEI satellite, where the commercially available lithium-ion secondary cells were used, has been operated for over 14 years with 7500 charge/discharge cycles.
- For future missions, we started the testing of COTS cells with different electrode material.
- Considering the deep space missions, we tested the charge/discharge performance of lithium-ion secondary cells under low temperature, which revealed obvious lithium plating from the initial cycle under low temperature.

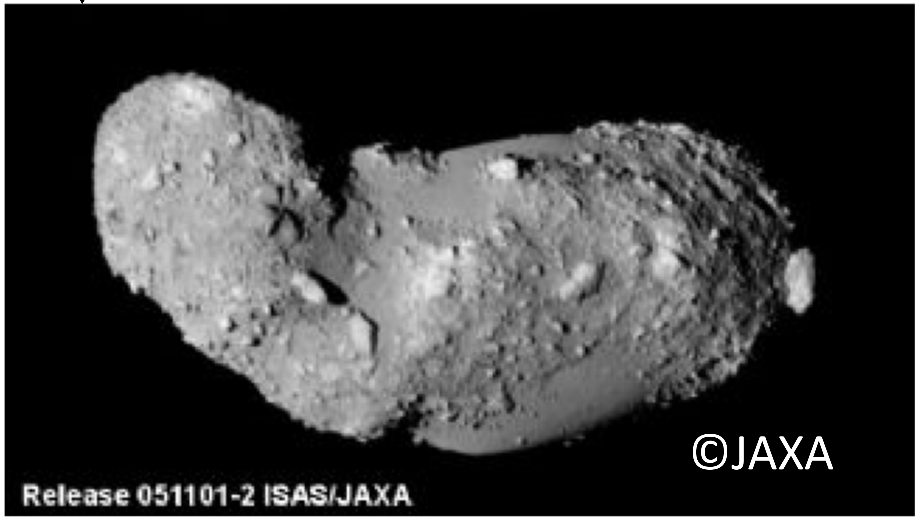
# ACKNOWLEDGEMENT

- This research is partially supported by ‘International Joint Research Program for Innovative Energy Technology’ of Ministry of Economy, Trade and Industry (METI).
- A Part of the tests were supported by Murata Manufactureing Co. Ltd.

# Lithium Primary Cells

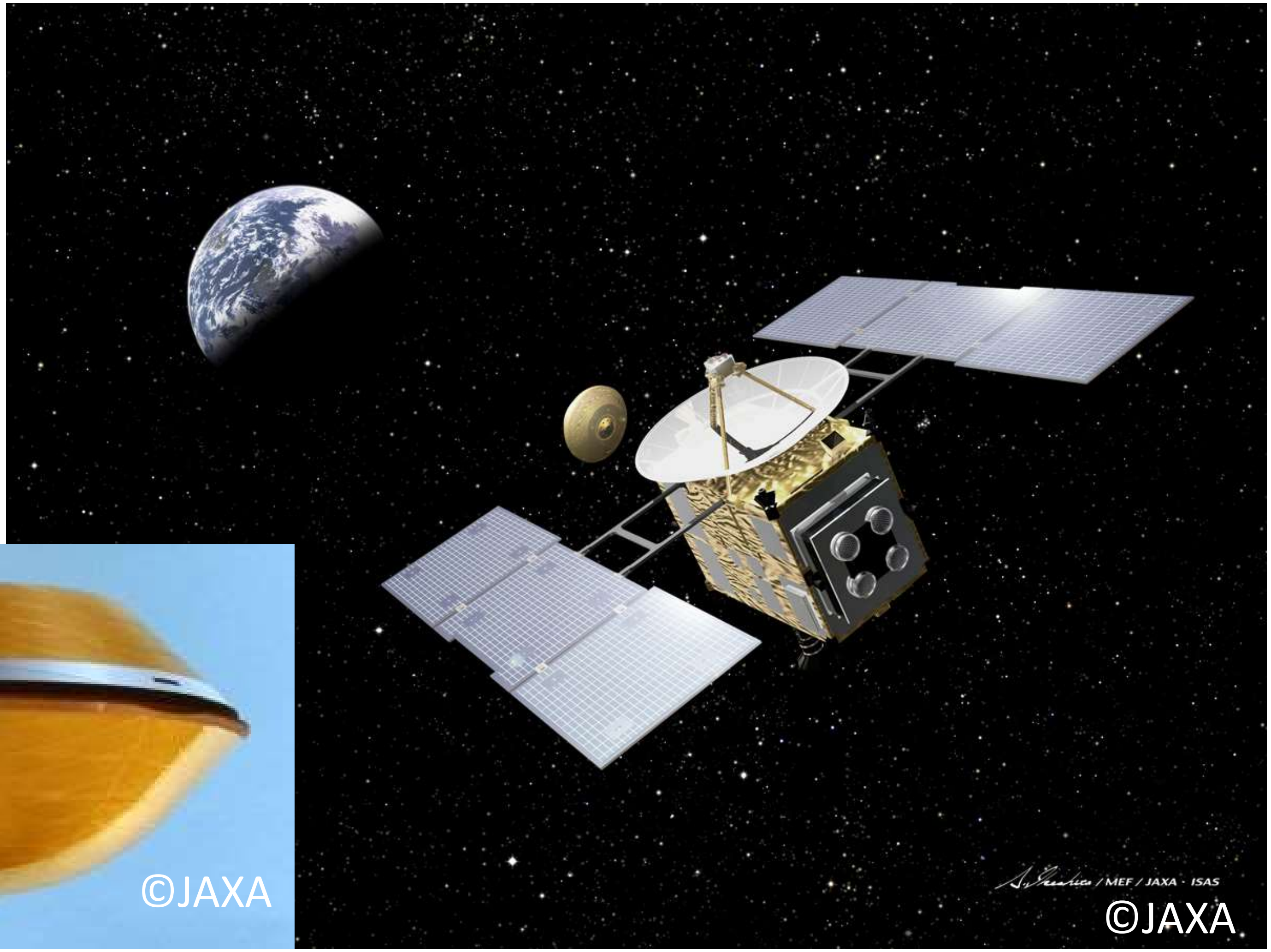



Spacecraft : HAYABUSA
Destination : ITOKAWA




The Distance between ITOKAWA and Japan was 300,000,000 km.
The spacecraft spent 7 years to travel 6,000,000,000 km to travel back to the Earth.

# Operation of the lithium primary cells for the 'HAYABUSA' Earth re-entry capsule.



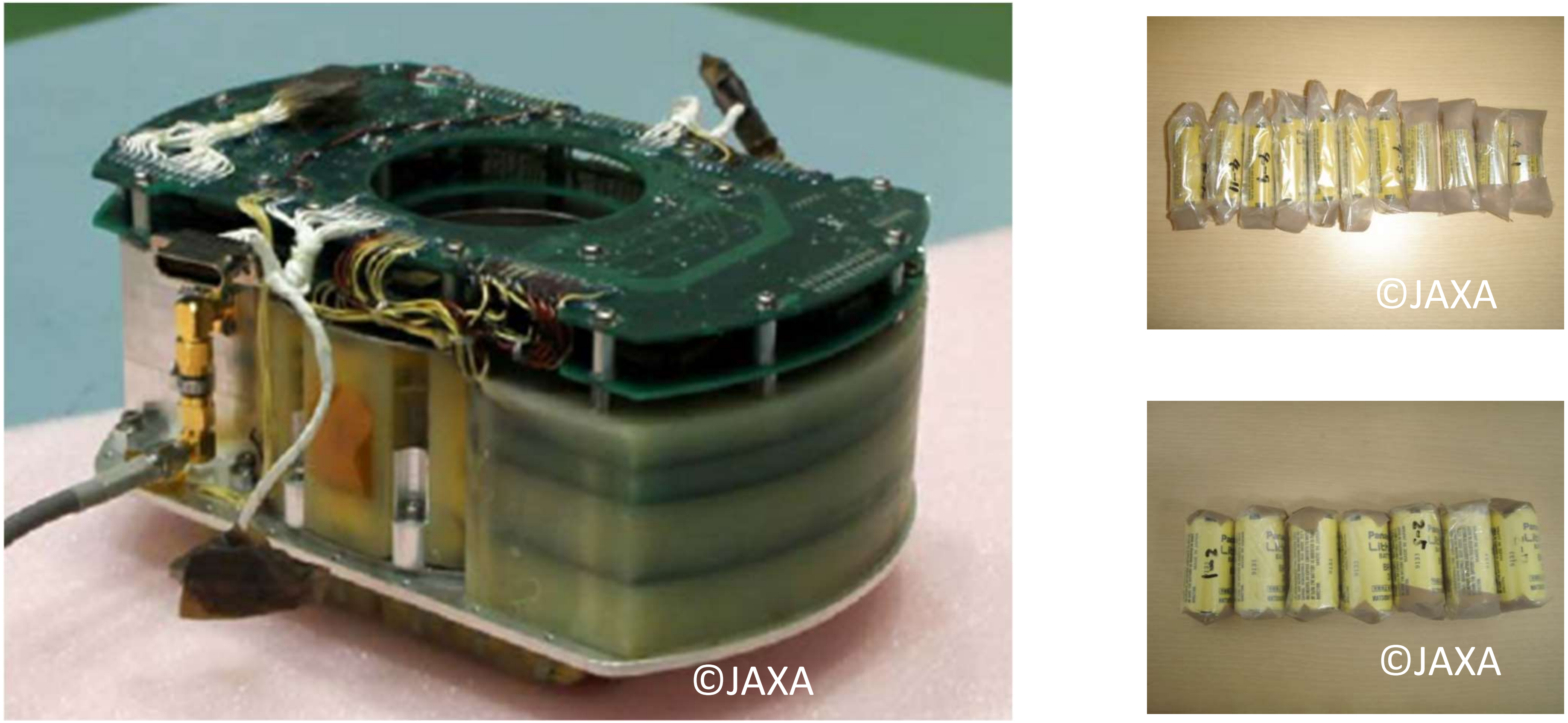




Fig. On-board electronics of the HAYABUSA re-entry capsule.
5 Ah-class lithium primary cells of 3 series and 2 parallel connection, and 1.8 Ah-class lithium-primary cells of 3 series and 4 parallel connection.

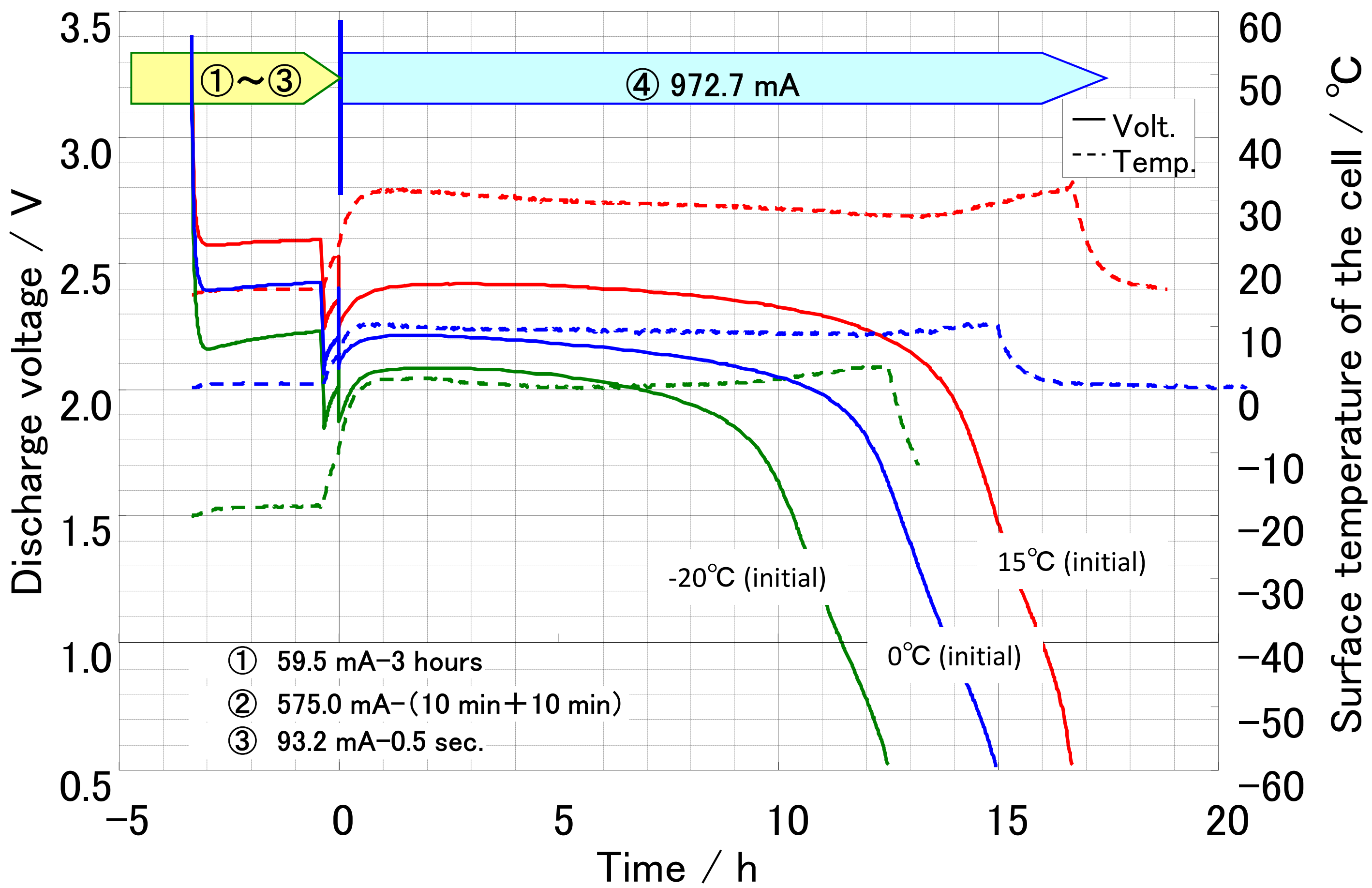
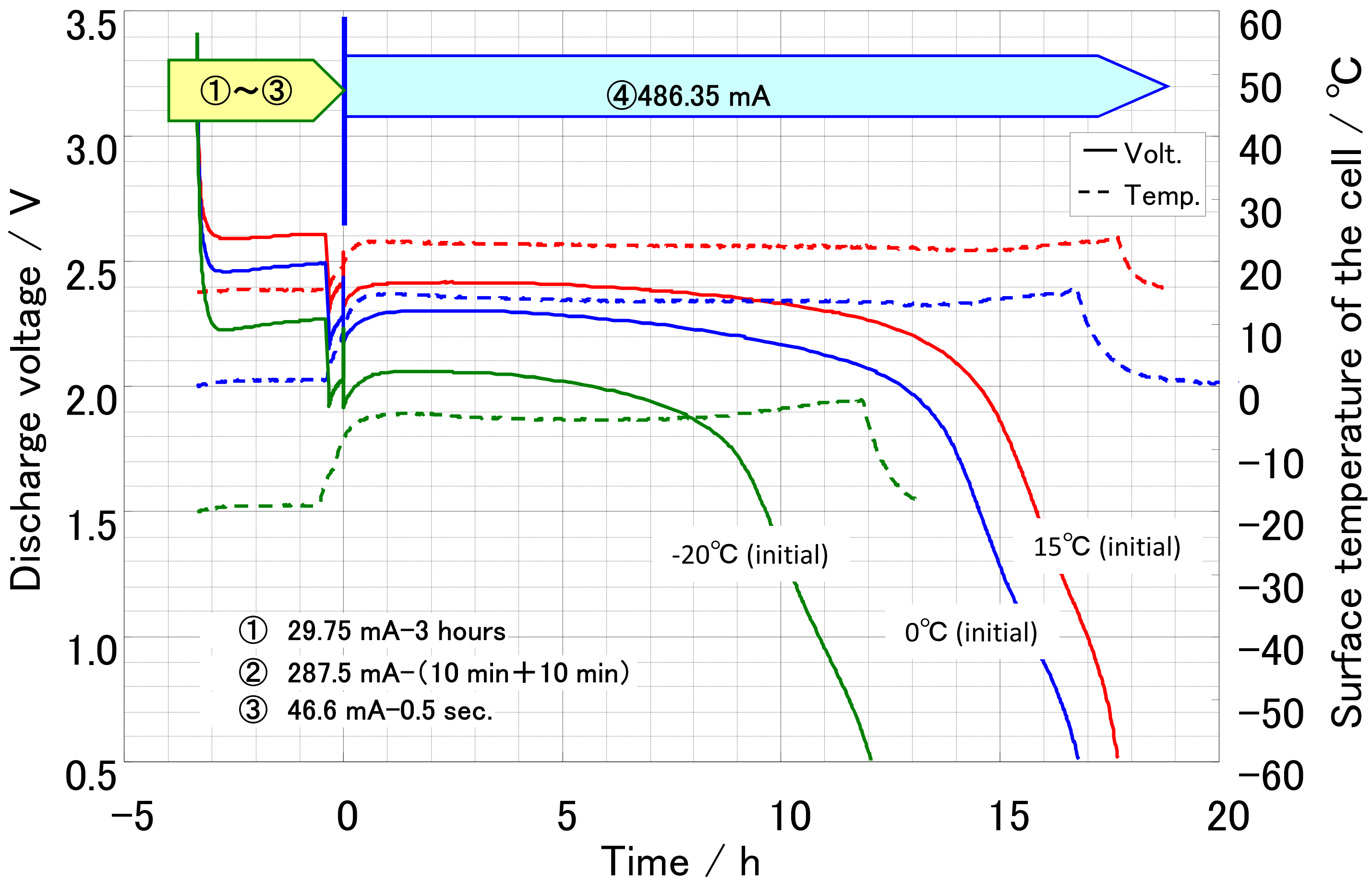



Fig. Discharge curves of the thermally degraded cells simulating 12 years storage. (60℃ for 84 days≒23℃ for 12 years)
①: Stand by for monitoring (59.5mA for 3 hours),
②: worm up of the analog line (575.0mA for 10min. ×2 times),
③: deploy the parachute / ignite the anchor (93.2mA for 0.5s),
and ④: send the radio beacon (972.7 mA).

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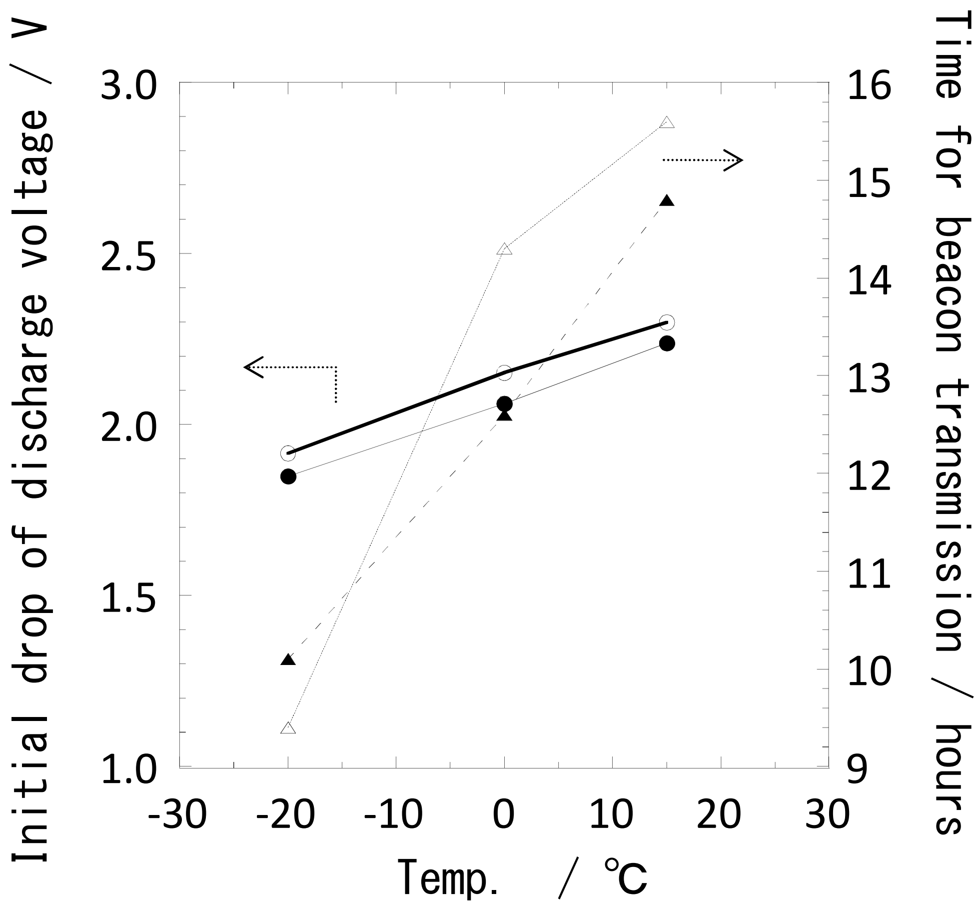



Fig. Initial discharge voltage and operable period of the capsule after the earth reentry.

Voltage drop of the flight-lot-cell.

The transmission of the beacon for the flight-lot-cell

Voltage drop of the thermally degraded cell.

The transmission of the beacon for thermally degraded cell.

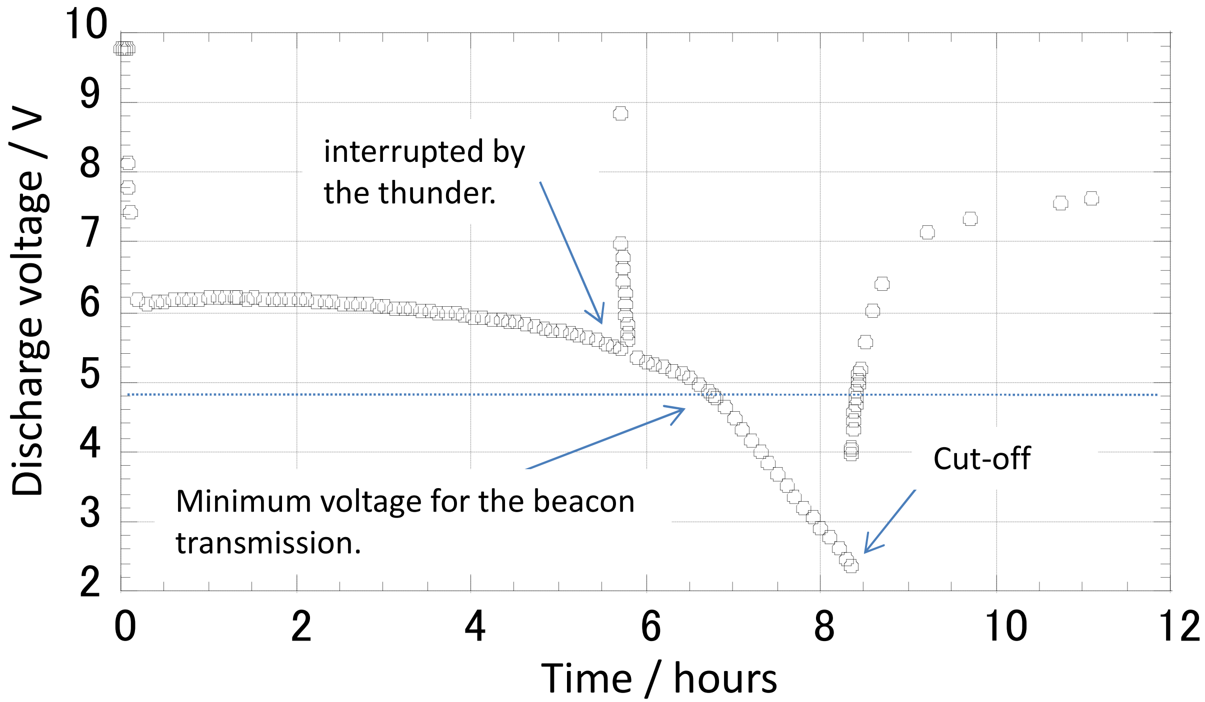



Fig. Discharge of the flight battery after the recovery operation. The flight battery was discharged at 15℃.

The discharge line of the battery cut off in 10.5 hours after the initiation of the beacon transmittance.

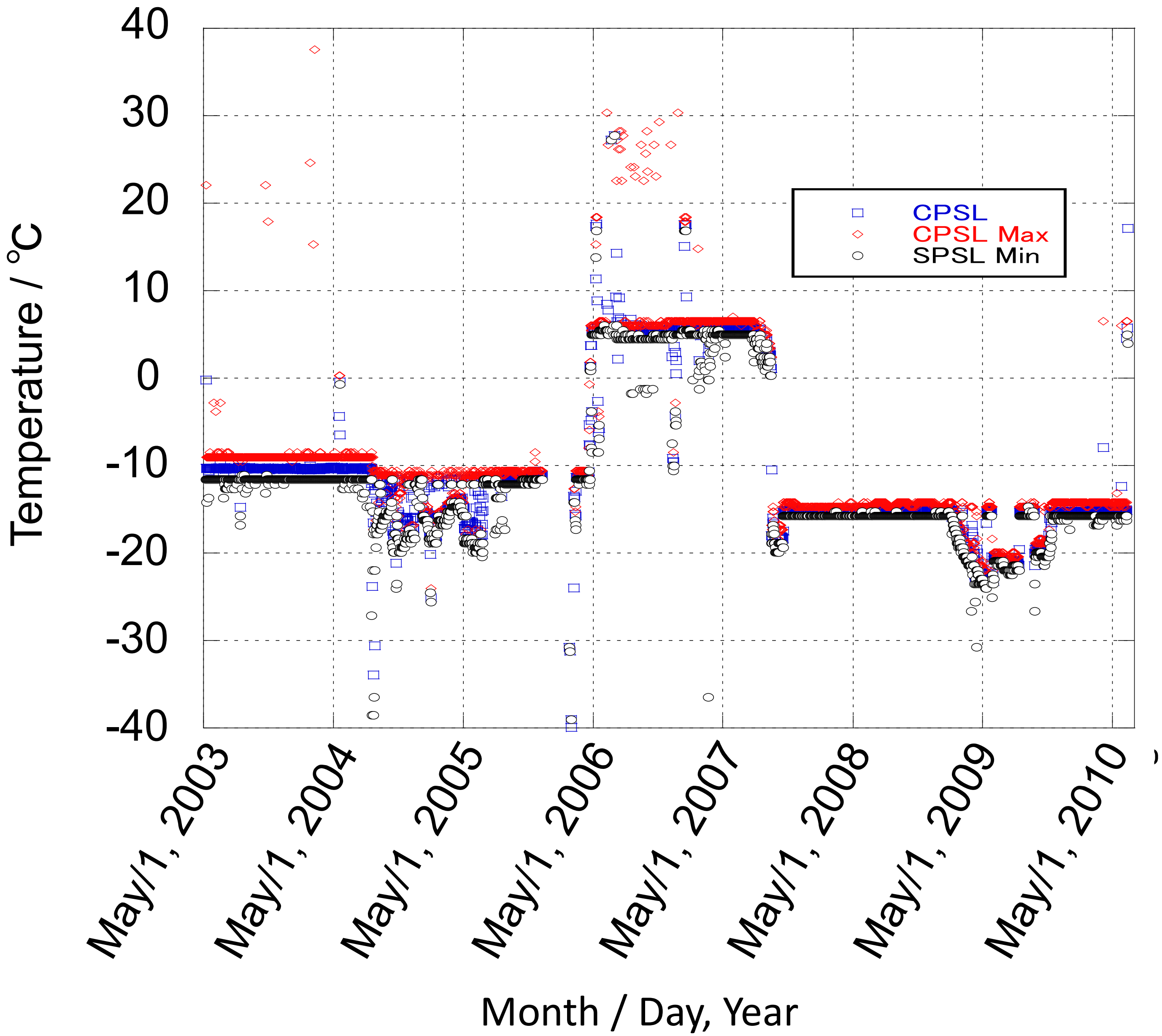



Fig. Trend of the temperature around the on-board electronics.

# Discharge capability of the primary cells after the storage.

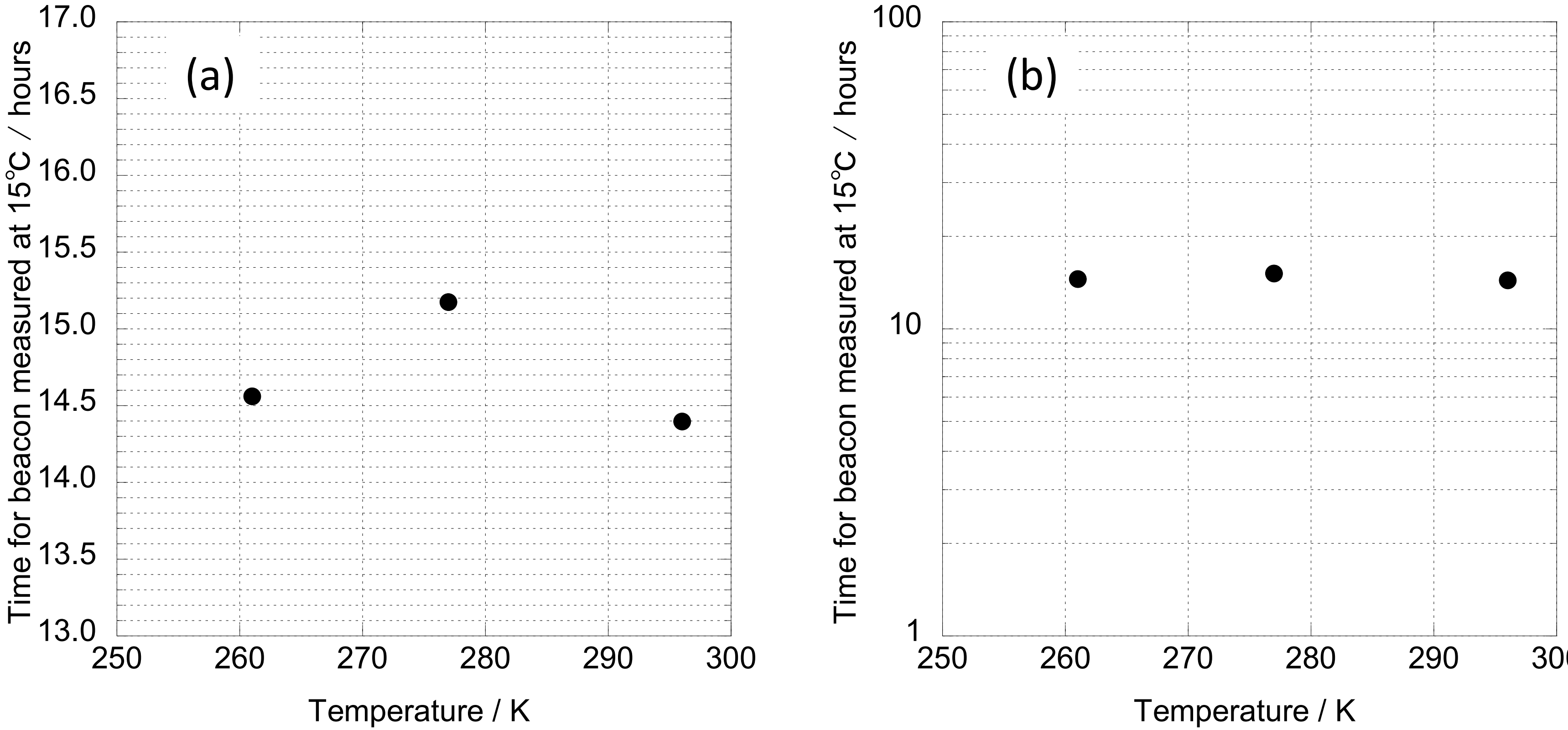



Fig. Effect of the storage temperature to the operability of the radio beacon.
Cells were discharged at 15℃.
The y-axis was linearly expressed for (a) and logarithmically expressed for (b).

# Off-gas from the on-board electronics.

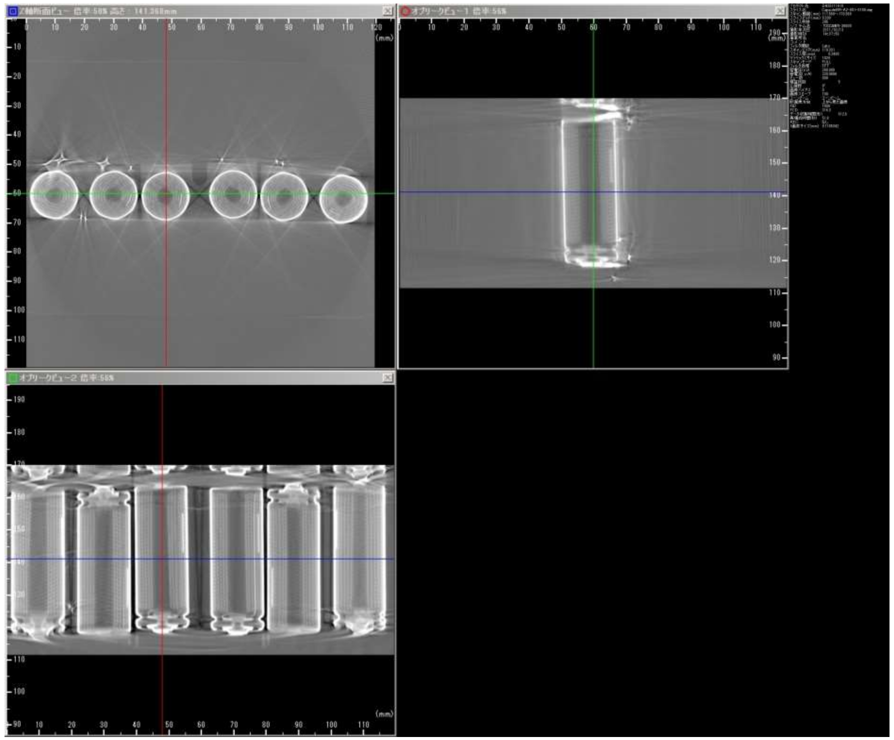
| | |
|---|---|
| • Test chamber volume | : 10.3 L (9.3 L free volume) |
| • Test chamber temperature | : 49℃±3℃ |
| • Test chamber pressure | : 78 kPa |
| • Test chamber temperature | : Room temp. |
| • Chamber atmosphere | : Air |
| • Duration time | : 163 hours |

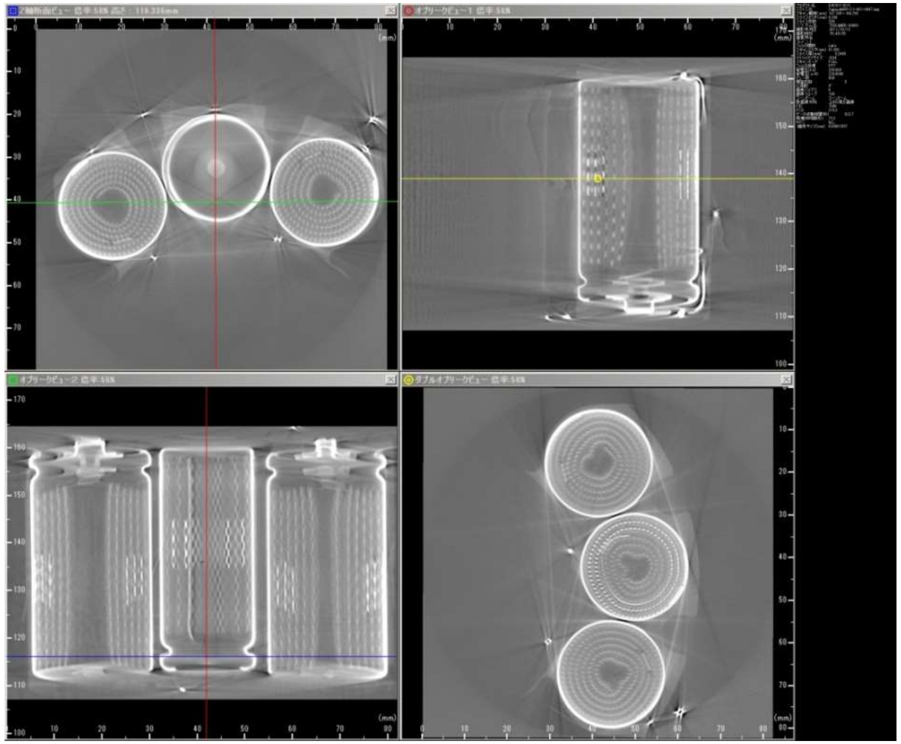
→3.72 μg electric solvent was detected.

# The battery of the on-board electronics.


# 搭載電子機器部のCT撮像

- 1.8 Ah級セルCT撮像結果
  - 電極材料の滑落にかかる痕跡は無し.
  - セル内部に歪み無し.
- ５ Ah級セルCT撮像結果
  - 電極材料の滑落に係る痕跡は無し.
  - セル内部に歪み有り.





# Summery -Lessons Learned-

- The battery storage performance in orbit is predictable using the ground-test battery.
- Even after the five year storage in space, the battery capacity can be simulated from the ground tests.
- The capsule could be operated using lithium primary cells after the 12 years storage / 7 years space flight.
- The performance of the lithium primary cells could be predicted based on the thermally accelerated tests.
- In the case of the flight battery, the performance was highly maintained due to the storage under the low temperature less than 0℃.

# ACKNOWLEDGEMENT


- Evaluation of the on-board electronics for HAYABUSA capsule recovery mission was supported by Panasonic Co. Ltd.
- Radiational tolerance was technically supported by Dr. Isao Yoda of Tokyo Institute of Technology.
- Distructive physical analysis of lithium primary cells was proceeded under the contract with  SANYO Energy Nandan Co.,Ltd and Panasonic Co. Ltd.