Energy Storage Devices for Lunar and Planetary Missions

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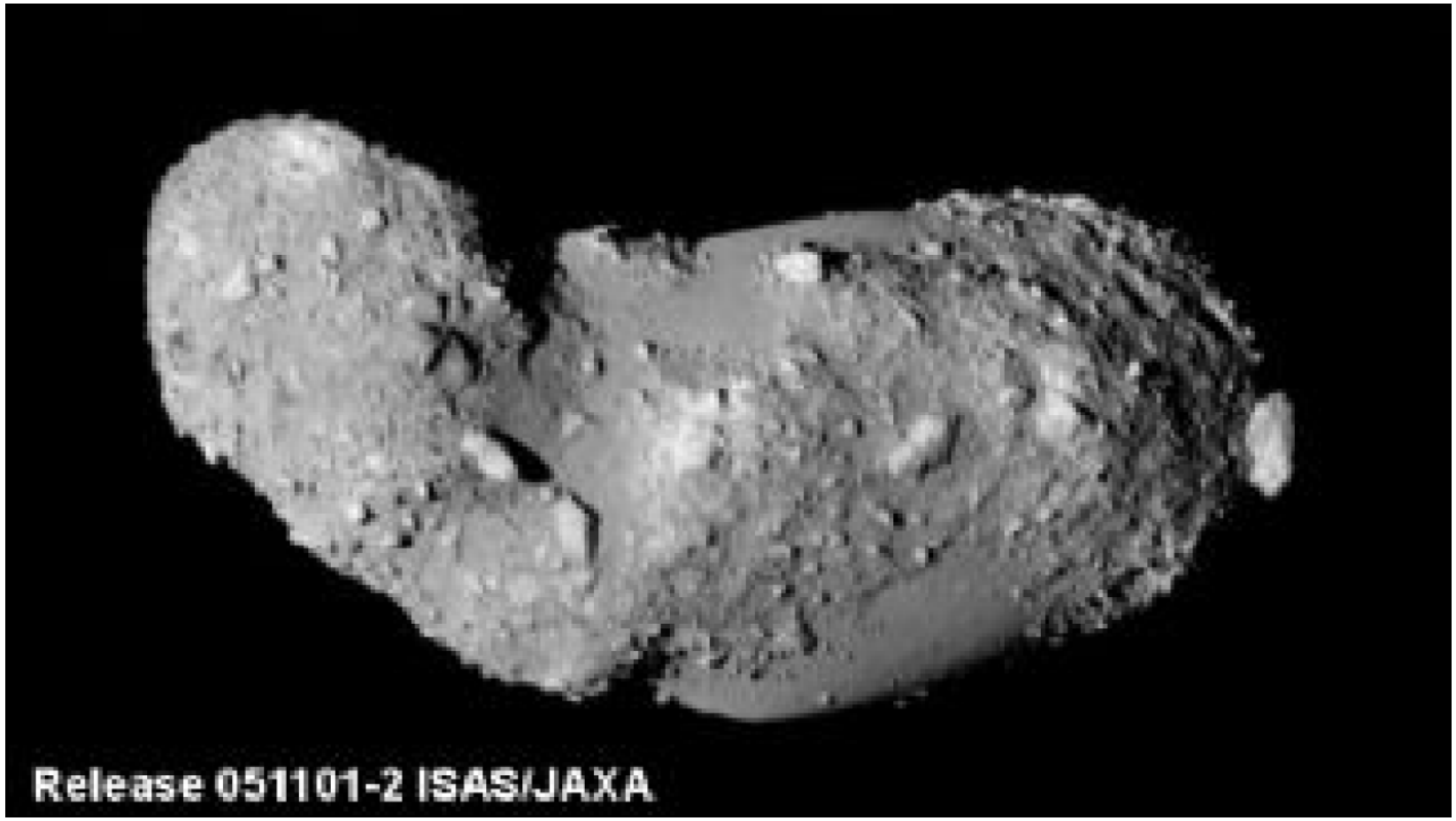
Today’s Topics

- Battery operation for the interplanetary spacecraft ‘HAYABUSA’
  - Lithium-ion secondary battery for the operation of the spacecraft
  - Lithium primary cell for the re-entry capsule
- The 100 W-class unitized regenerative fuel cell system targeting lunar and planetary missions
  - Back ground and current status

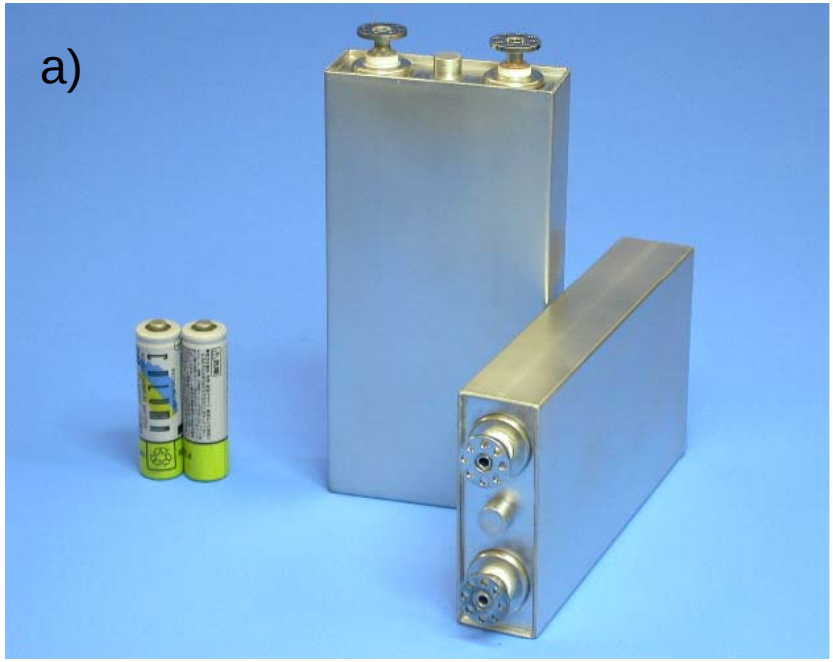
Battery operation for the interplanetary spacecraft ‘HAYABUSA’

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.

Fig. A photograph of the interplanetary spacecraft HAYABUSA under development (a), and an artist's view of the spacecraft touching down onto the asteroid ITOKAWA (b). The Earth re-entry capsule is marked in the images.



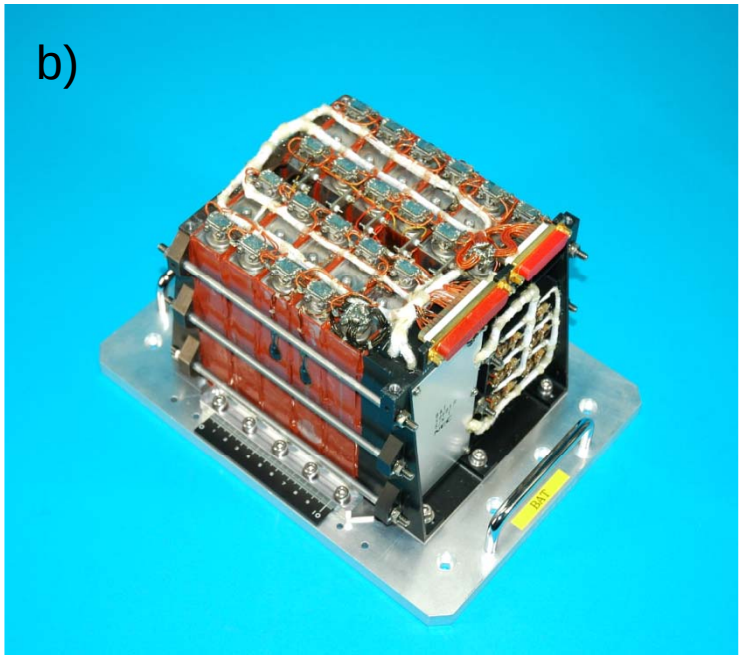


Fig. Photographs of the lithium-ion secondary cells (a), and battery (b). The lithium-ion secondary cells (a) are compared to AA-size cells.

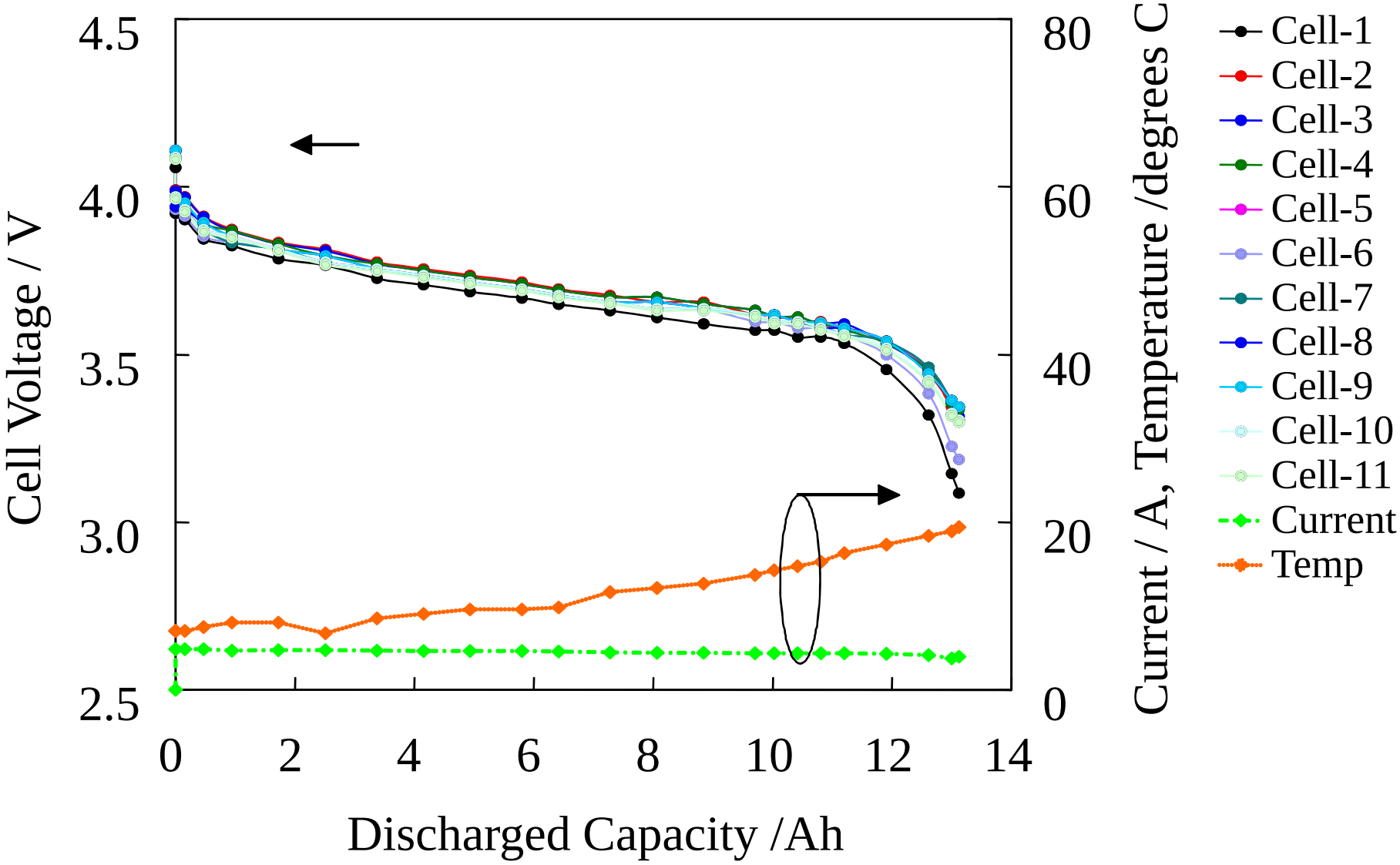
Specifications of the lithium-ion secondary cell used in HAYABUSA.

[1)]The nominal discharge rate is 0.2 C at 20 degrees C

Rated Capacity[1)]		13.2 Ah
Discharge Voltage (Average) [1)]		3.6 V
Size	Width	69.3 mm
	Height	132 mm
	Thickness	24.4 mm
Weight		< 570 g
Energy Density / mass		> 85 Wh/kg
Energy Density / volume		> 215 Wh/L

The capacity of the battery was measured in space.

- This was the very first case that the lithium-ion secondary cell with large capacity was used in space.
- The capacity was measured after the long-term storage in space in order to predict the future performance at the destination ‘ITOKAWA’.



Discharge performance of the lithium-ion cells during the on-orbit capacity measurement

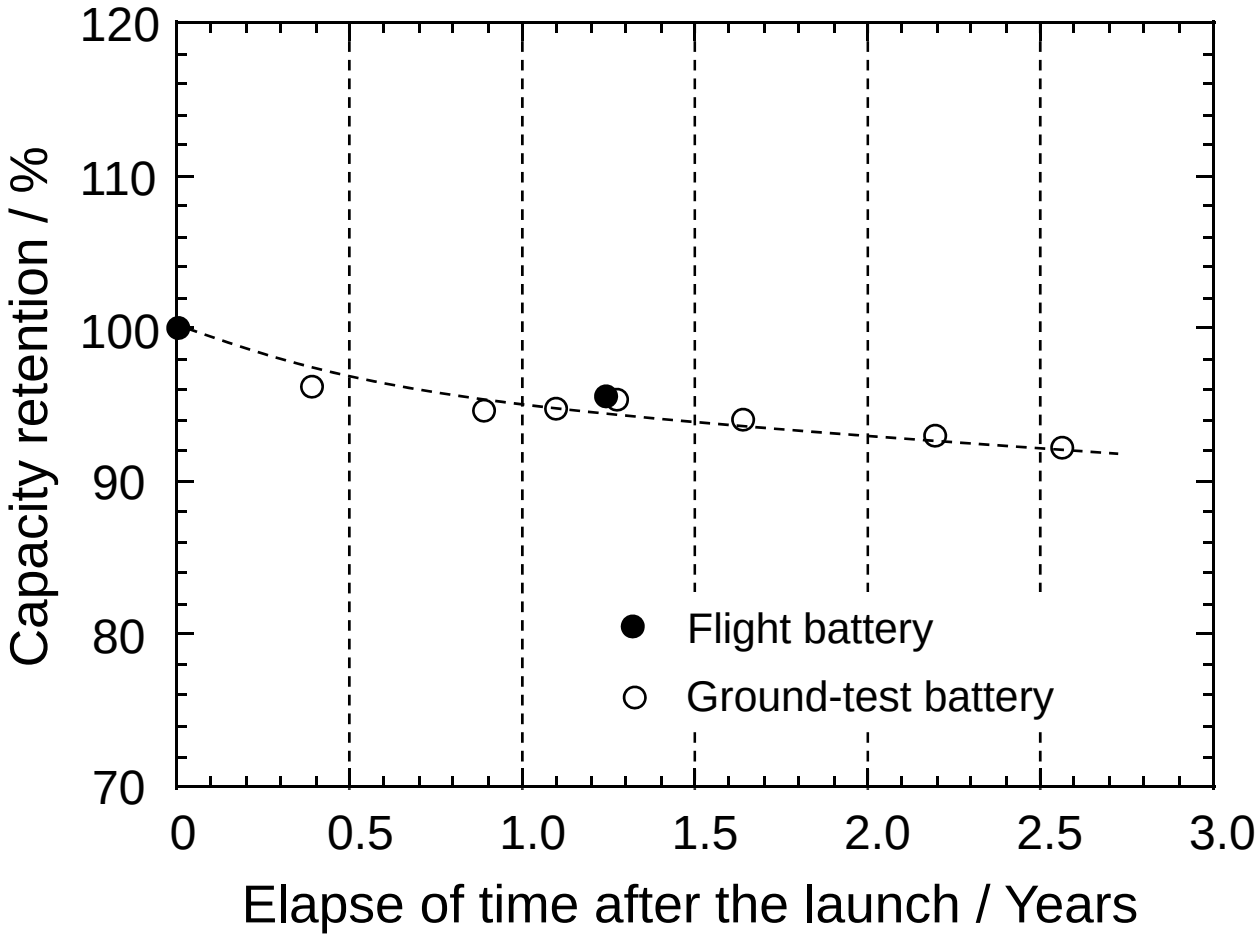


Fig. Trend of the capacity decay with the elapse of time.

Successful touched down!

- HAYABUSA touched down onto the surface of ITOKAWA on 19th and 25th in November, 2005.

Malfunction

- After the touch-down operation, the chemical thruster had a malfunction.
- HAYABUSA lost the attitude control.
- Communication could not be established.
- Communication was temporary re-established, which revealed the over-discharge of the battery.

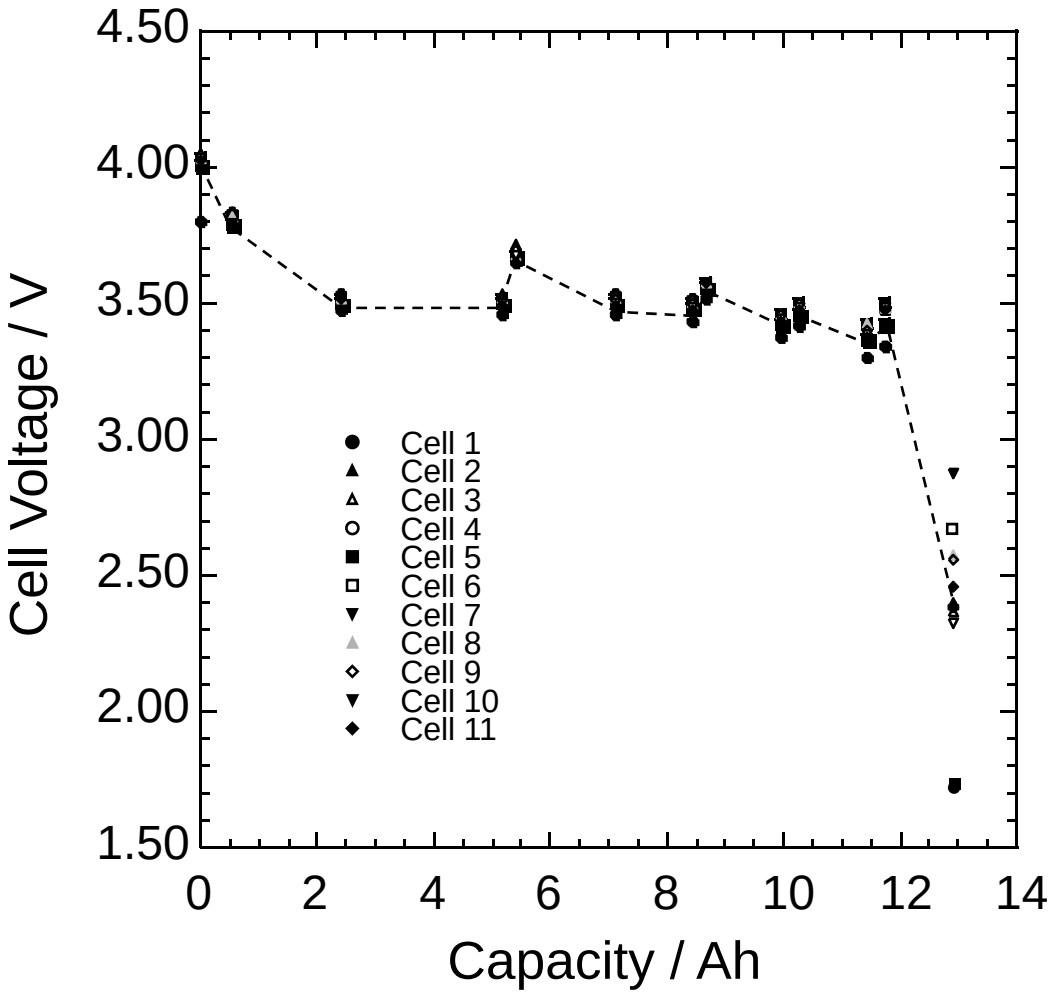


Fig. Discharge curves of the lithium-ion cells during the attitude control malfunction.

Lost

- The communication with the spacecraft was lost since 9th in December, 2005.
- We re-established the communication after 7 weeks.
- Four cells among 11 cells connected in series was over discharged.

Table Cell condition after the malfunction of the spacecraft HAYABUSA.

Cell No.	1	2	3	4	5	6	7	8	9	10	11
Voltage / V	0.58	1.74	3.69	1.28	4.11	4.05	4.09	4.09	4.09	4.09	4.06

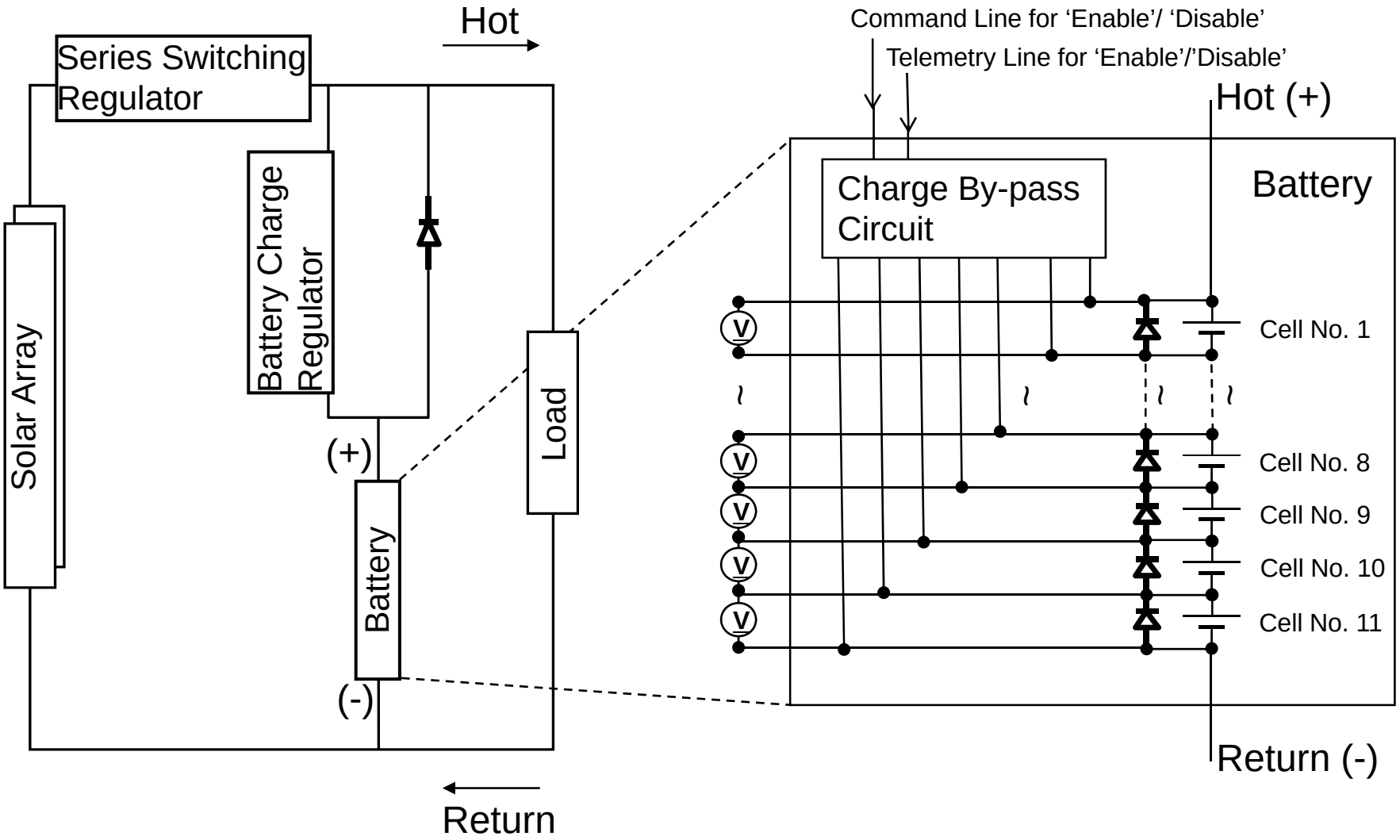


Fig. The block diagrams of the electrical power sub-system for HAYABUSA.

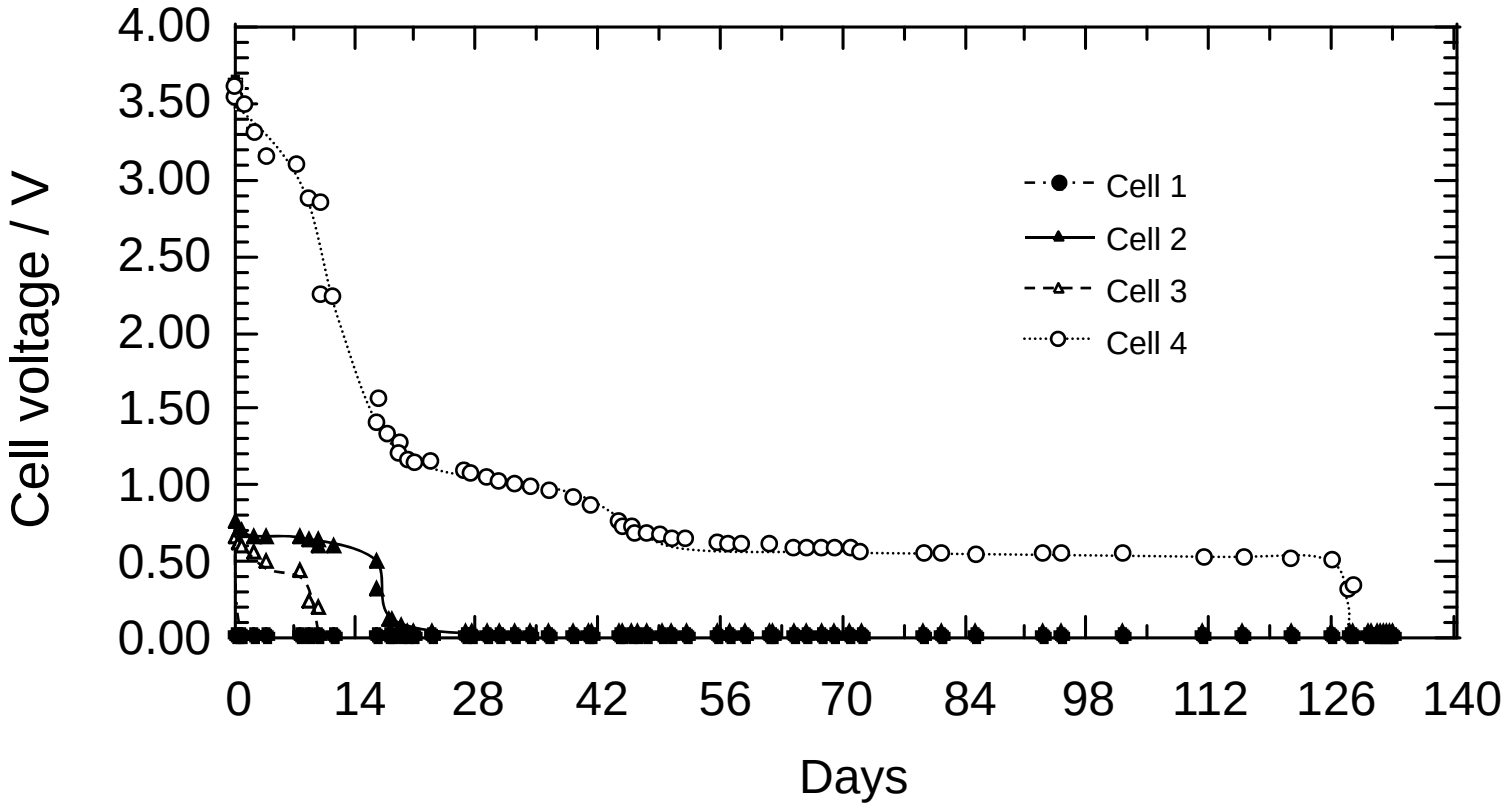


Fig. The trend of the voltage discharged by the monitoring circuit. Cells 1-4 seemed to be over-discharged during the out-of-communication period.

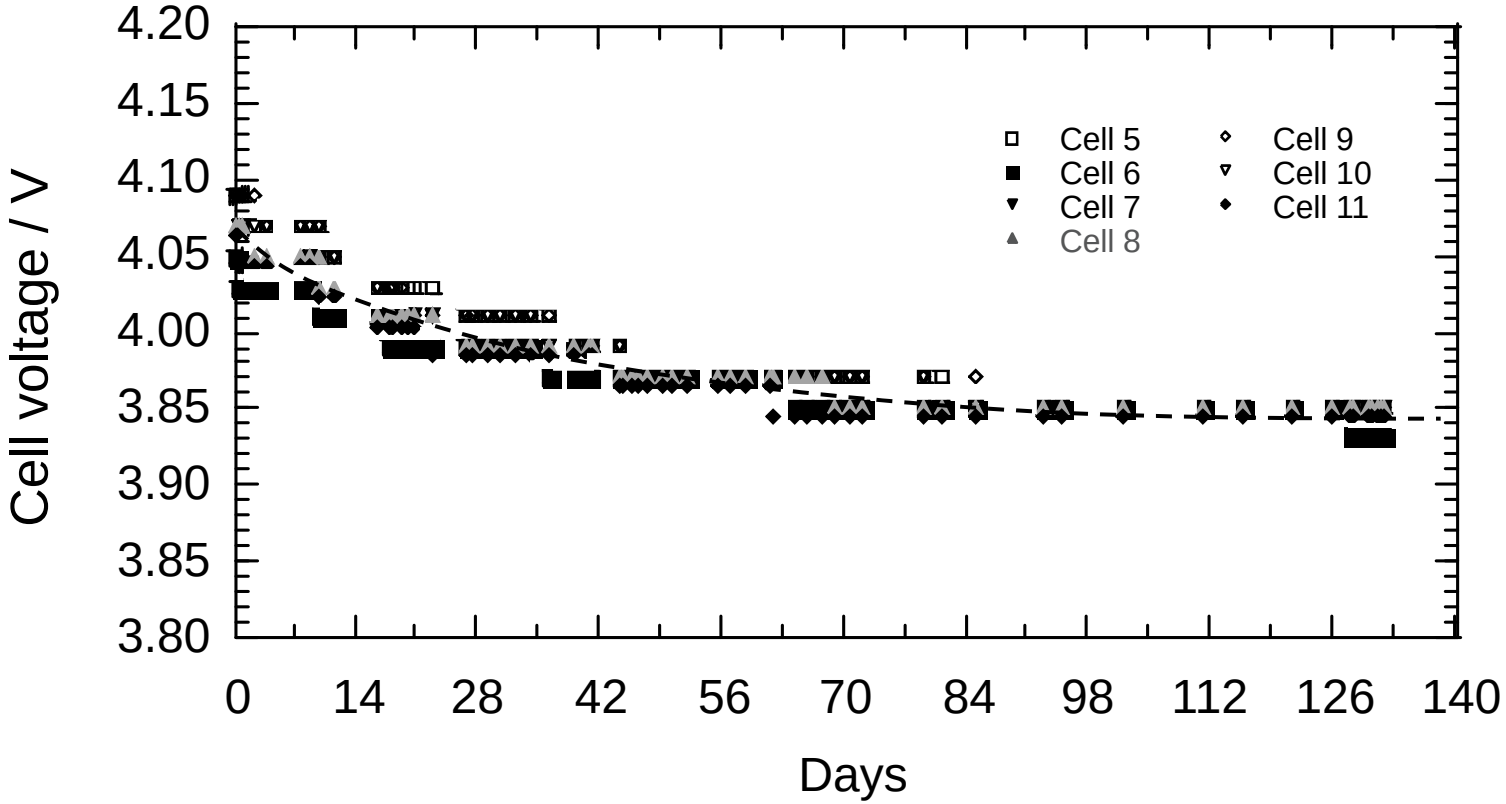


Fig. The trend of the voltage discharged by the monitoring circuit. The discharge curves of cells 5-11 showed high voltages even after the malfunction.

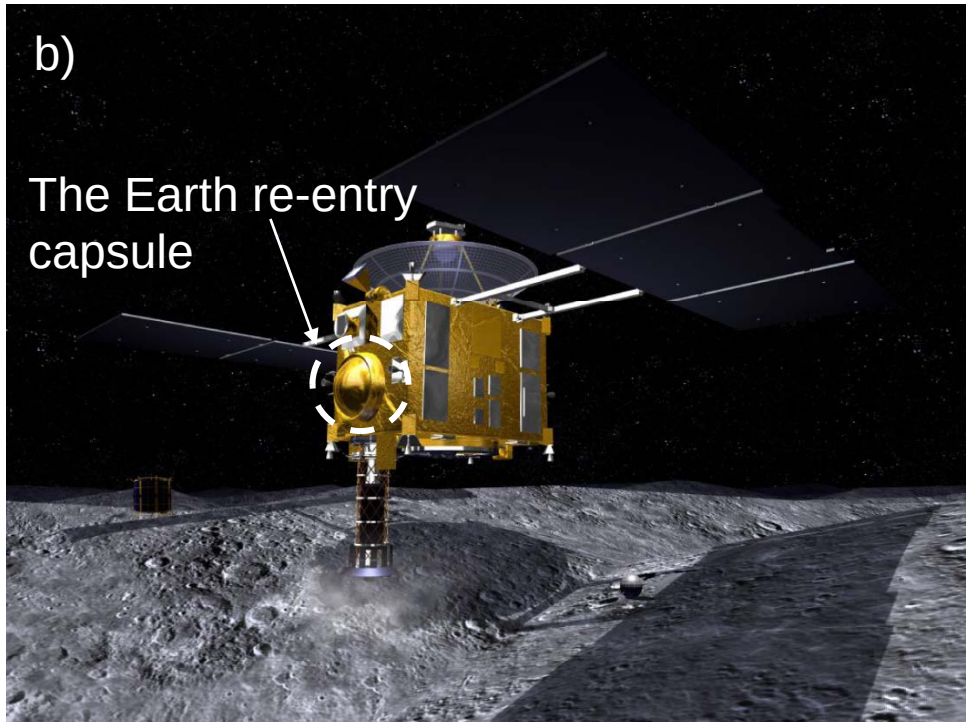
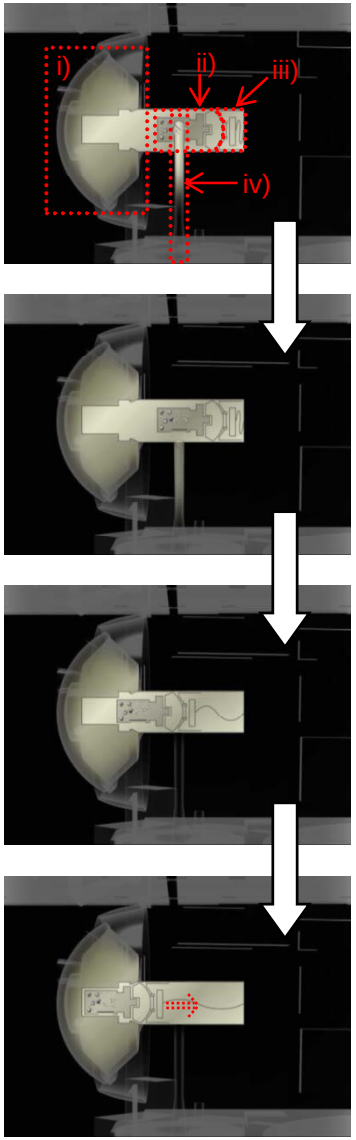


Fig. A photograph of the interplanetary spacecraft HAYABUSA under development (a), and an artist's view of the spacecraft touching down onto the asteroid ITOKAWA (b). The Earth re-entry capsule is marked in the images.



i) Earth re-entry capsule
ii) Asteroid sample container
iii) Lid cover and cable cutter
iv) Tube to guide the sample into the container

(a) The lid of the asteroid sample container is closed, and the tube to guide the sample into the sample container is pulled.

(b) The sample container is injected into the Earth re-entry capsule.

(c) The spring is released to latch and seal the container inside the Earth re-entry capsule. The cable is cut and the lid cover is set back.

Fig. The lid-closure procedure. The lid of the sample container had to be closed, and the sample container had to be inserted into the Earth re-entry capsule. To bring the sample back to Earth, this capsule needed to be latched and sealed.

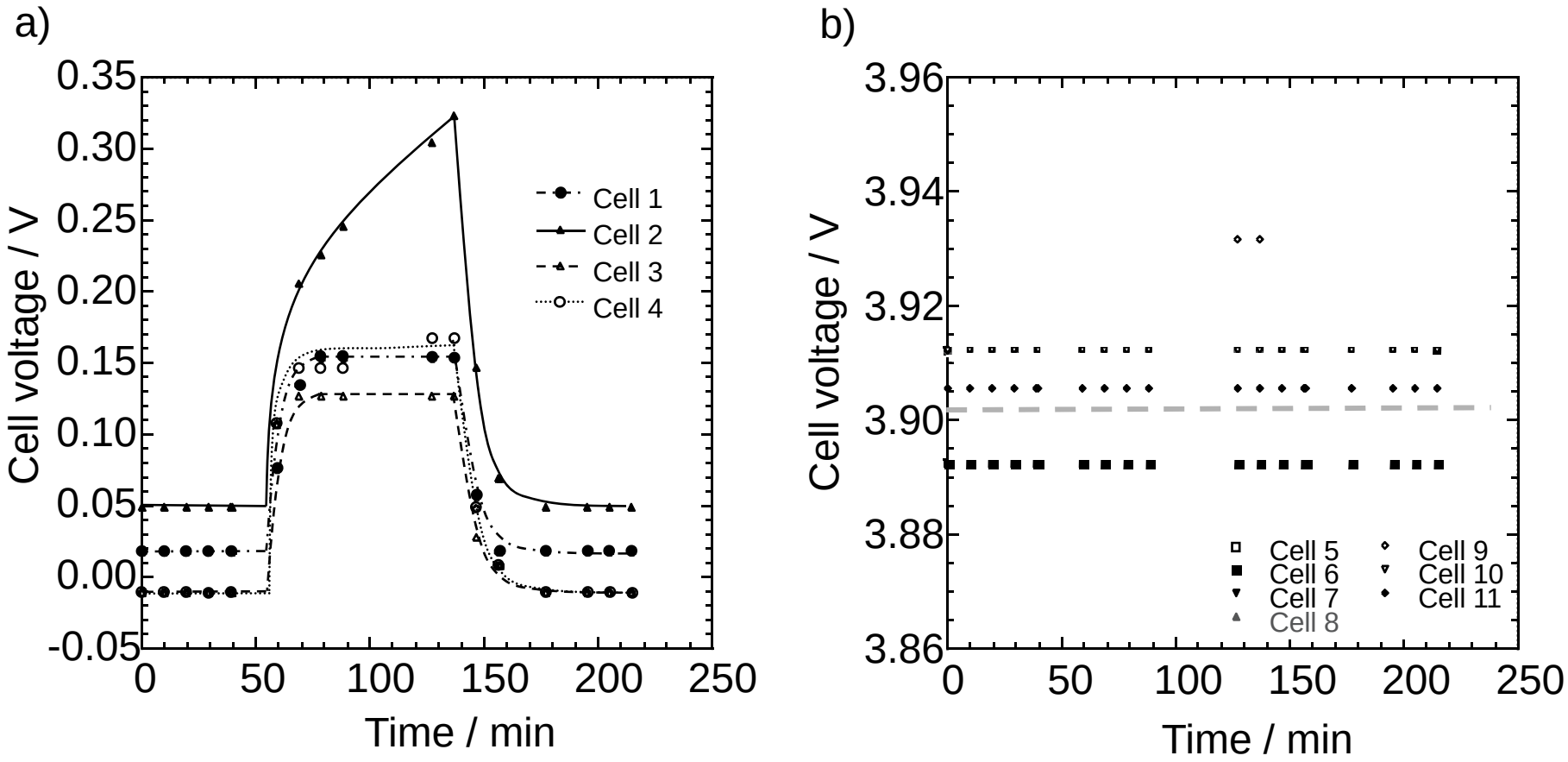


Fig. Charge curves of the flight cells with the bypass circuit enabled.
The voltages of cells 1-4 increased slightly (a), while the voltages of cells 5-11 did not change during the 1-day operation (b).

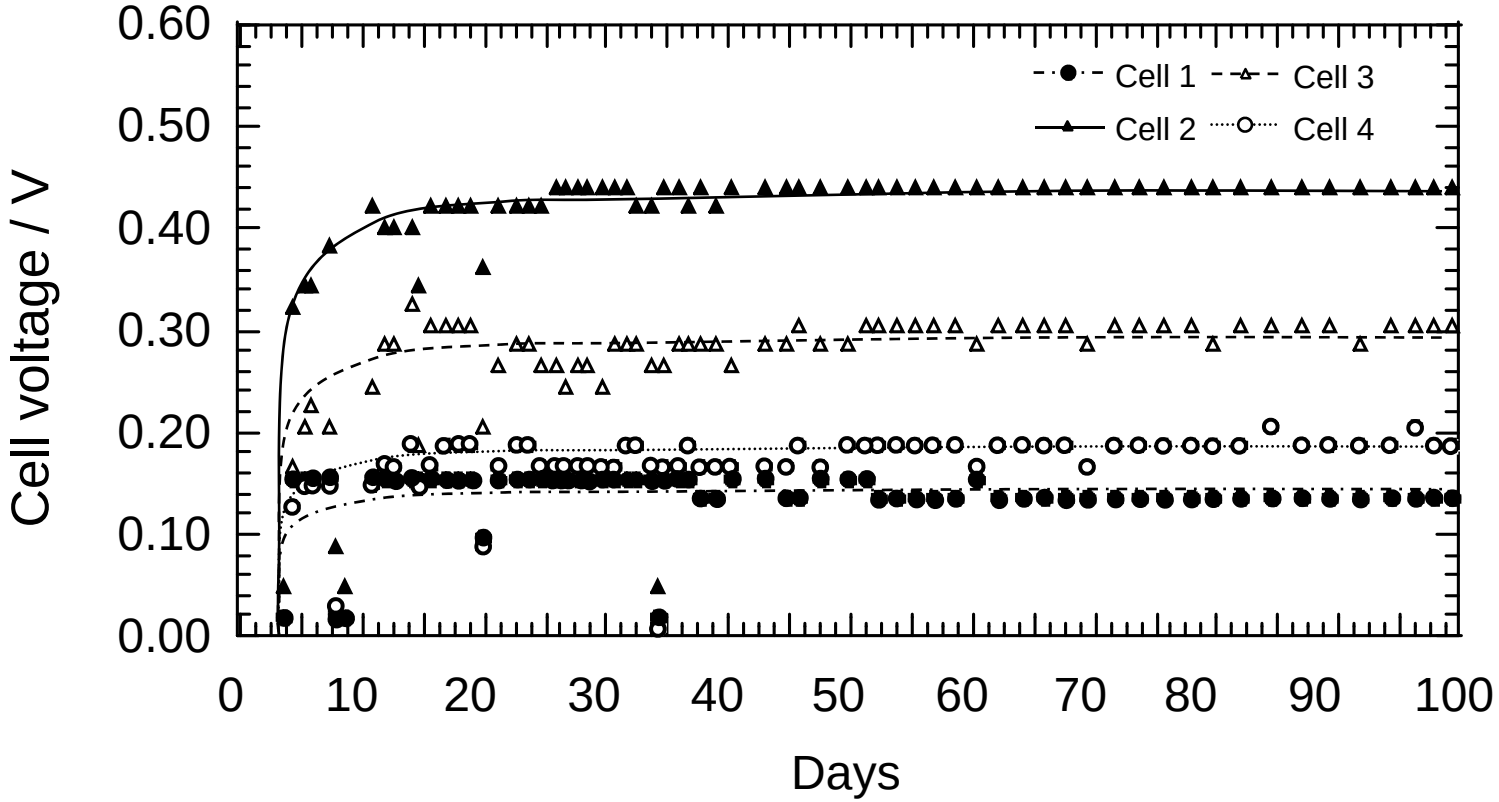


Fig. The day-to-day trend of the end-of-charge voltage (EoCV). Cells 1-4 showed a stable voltage less than 0.5 V.

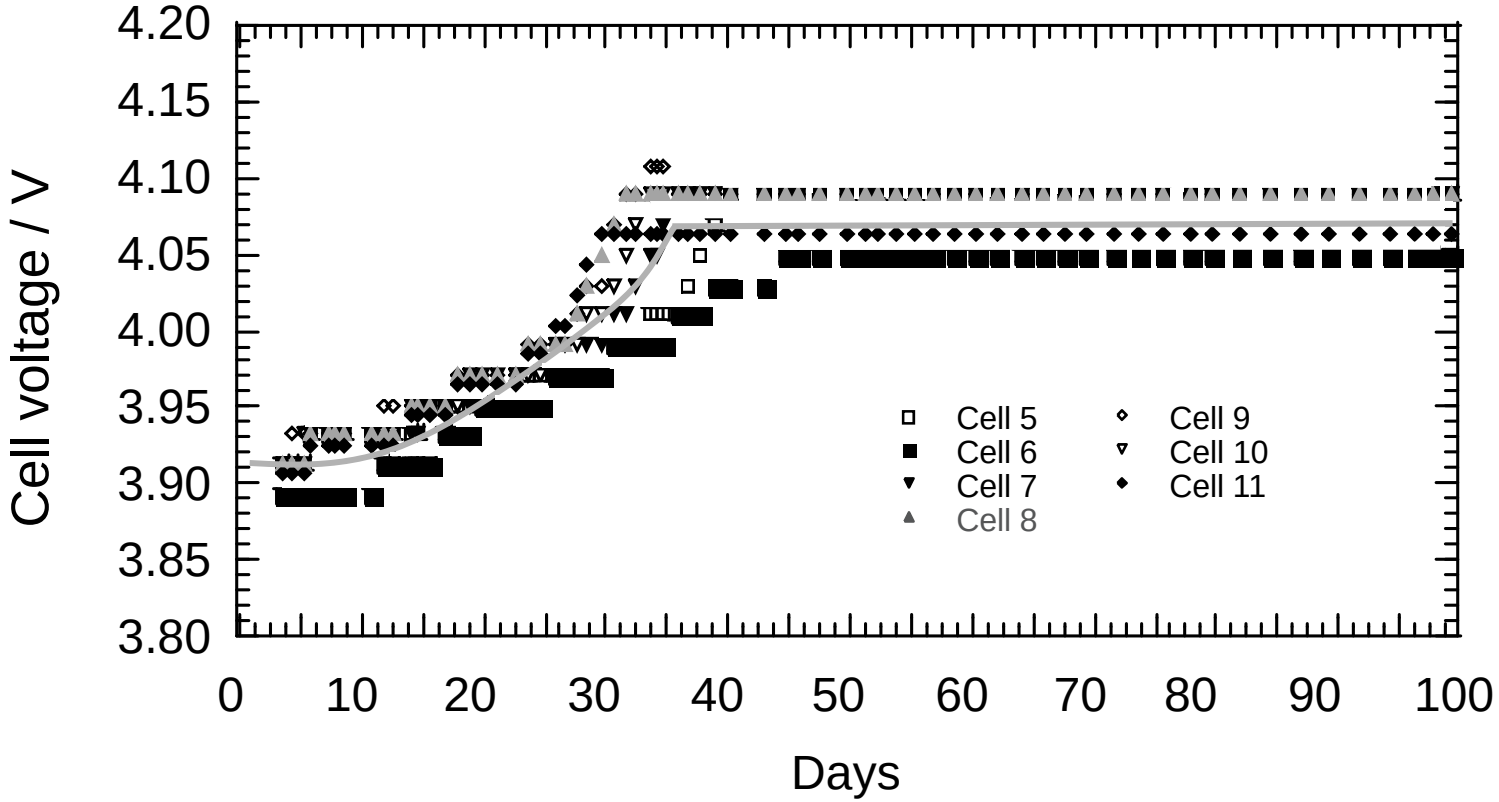


Fig. The day-to-day trend of the end-of-charge voltage (EoCV).
The voltage of cells 5-11 increased gradually and reached 4.05 - 4.10 V, after which the bypass circuit shunted the charging current.

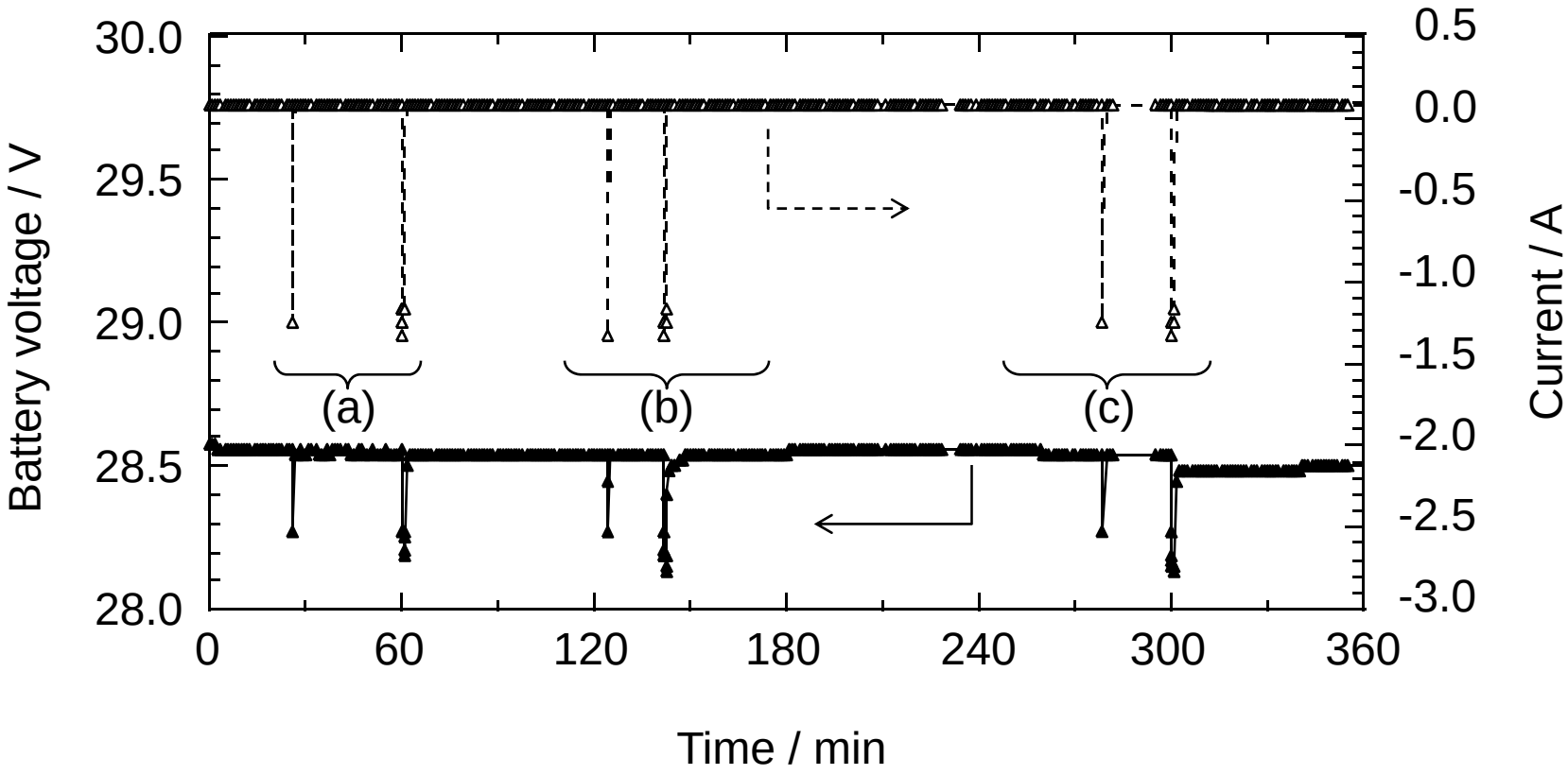


Fig. Telemetry data during HAYABUSA's lid-closure operation.
(a): The lid of the asteroid sample container was closed, and the tube to guide the sample into the sample container was pulled down.
(b): The sample container was injected into the Earth re-entry capsule.
(c): The spring was released to latch and seal the container inside the Earth re-entry capsule.

Publications

These topics were published in the following papers.

Y. Sone et al., ‘The Performance of the Lithium-ion Secondary Cells under Micro-Gravity Conditions. -In-Orbit Operation of the Interplanetary Spacecraft “HAYABUSA”’, Electrochemistry, pp. 518-522, Vol. 75 No. 7 (2007).

Y. Sone, et al., ‘Charge and Discharge Performance of Over-Discharged Lithium-ion Secondary Battery－ Lessons Learned from the Operation of the Interplanetary Spacecraft HAYABUSA’, Electrochemistry, pp. 950-957, Vol. 75 No. 12 (2007).

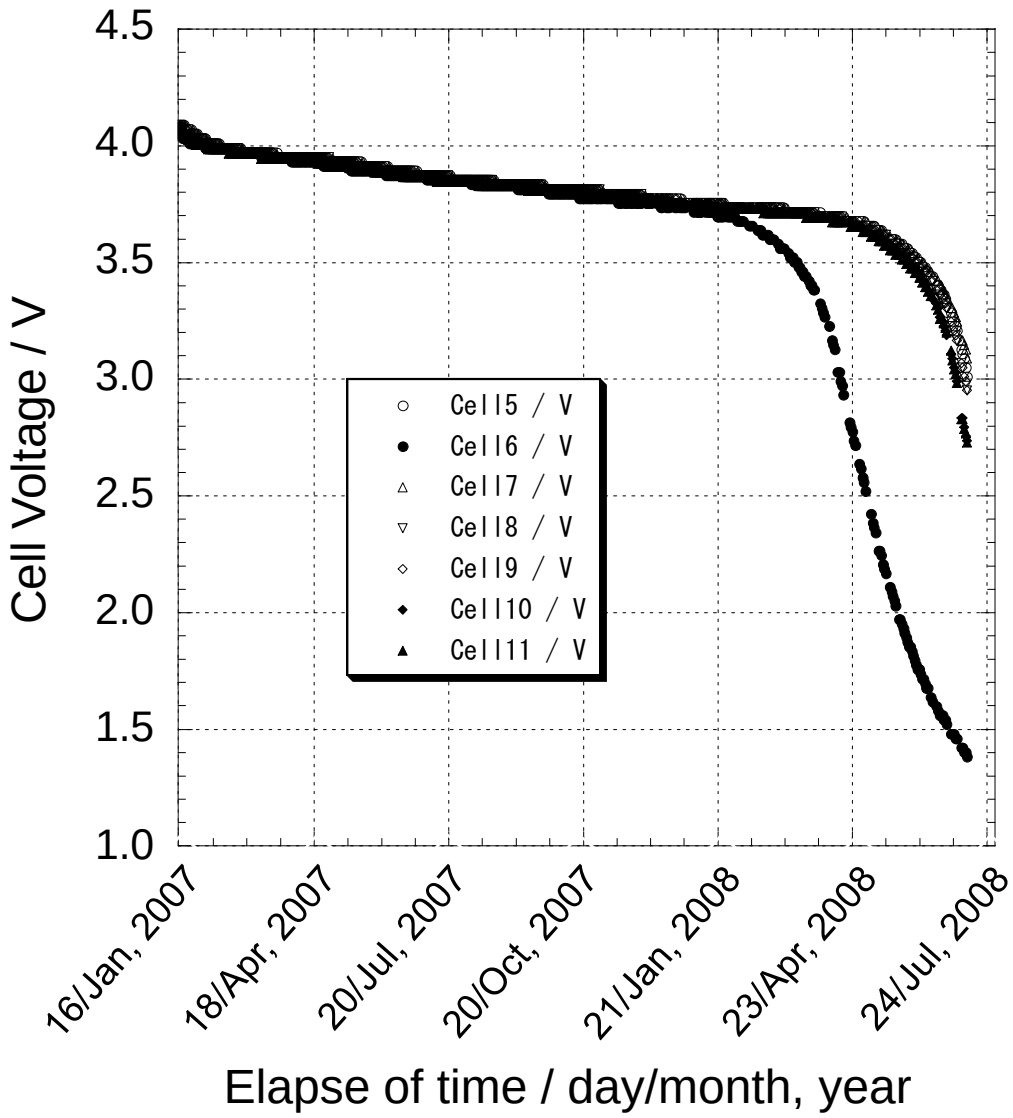


Fig. Trend of the cell voltages in flight after the recovery operation.

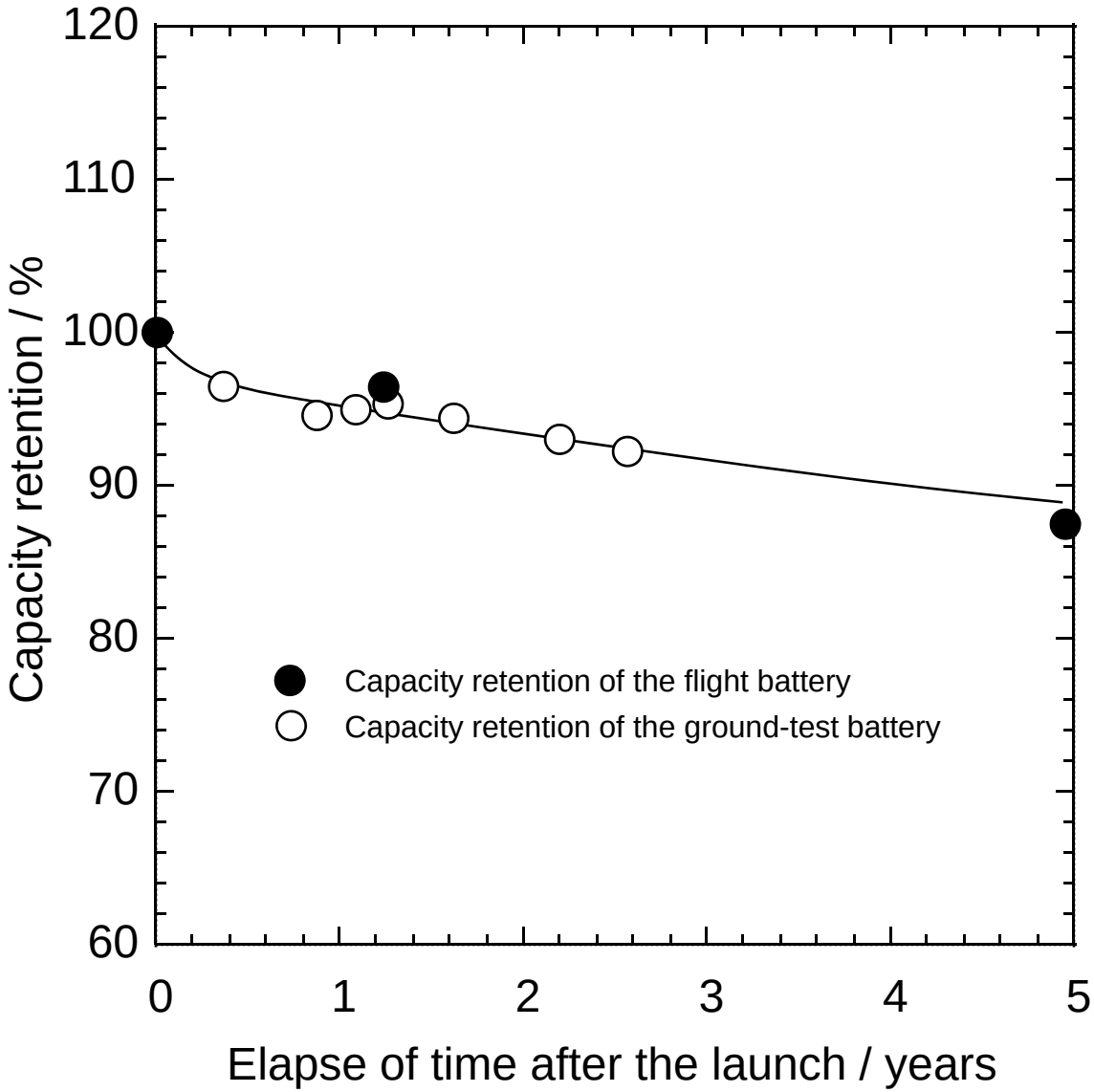


Fig. Capacity retention since the launch of the spacecraft.

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.

HAYABUSA came back to the Earth In June, 2010.

Return of Falcon

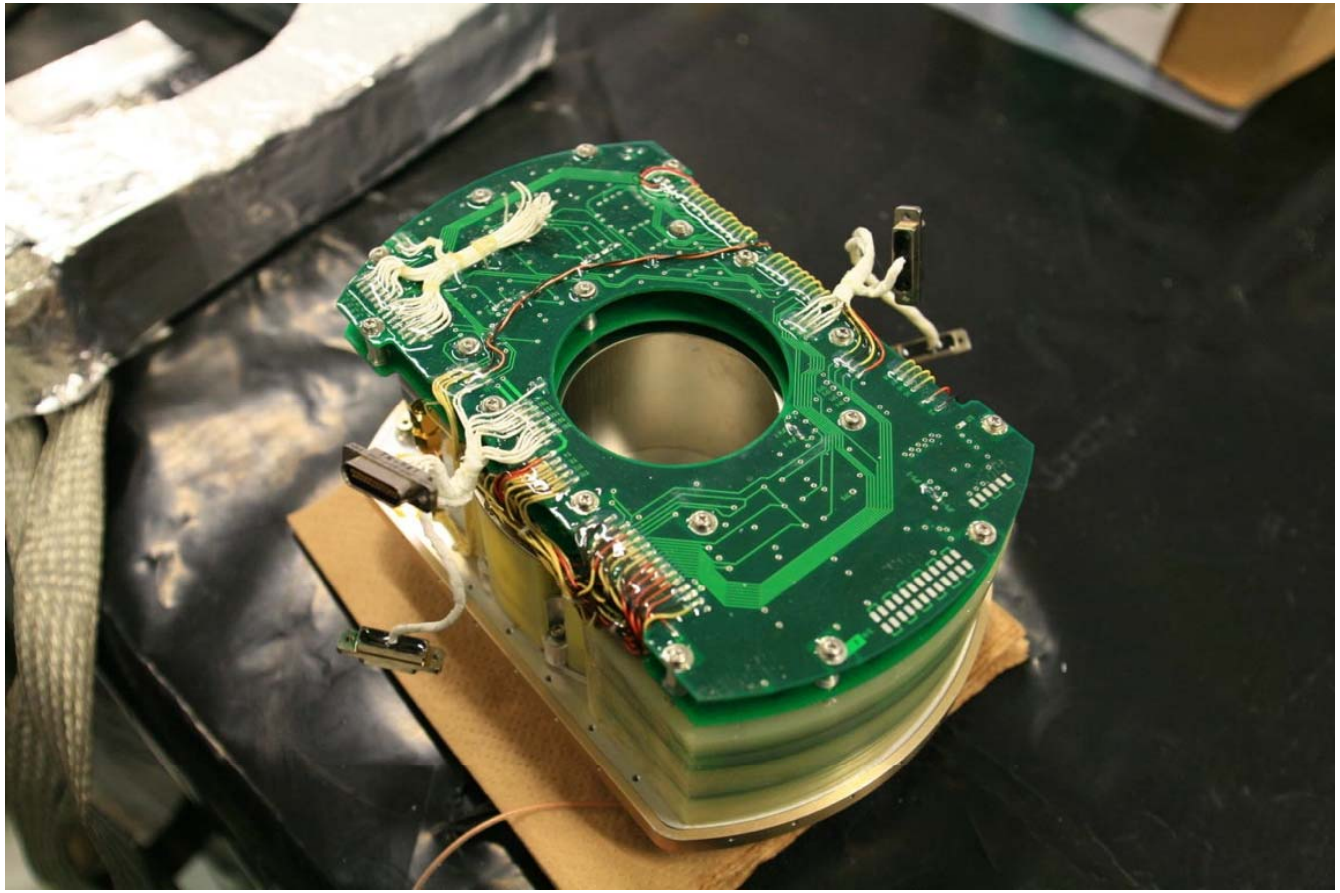


Fig. On-board electronics of the HAYABUSA re-entry capsule.
5 Ah-class lithium primary cells of 3 series and 2 parallel connection, and 1.8 Ah-class lithium-primary cells of 3 series and 4 parallel connection.

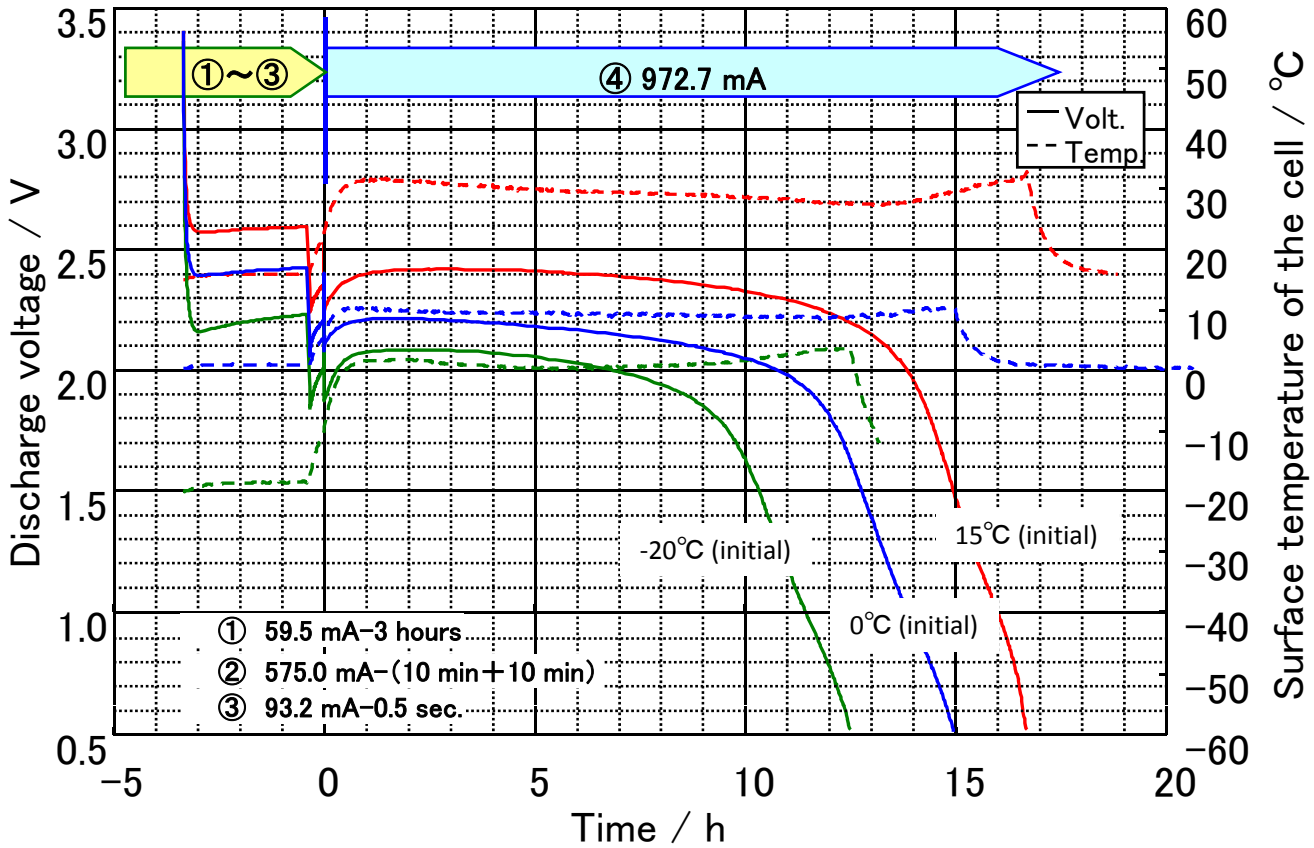
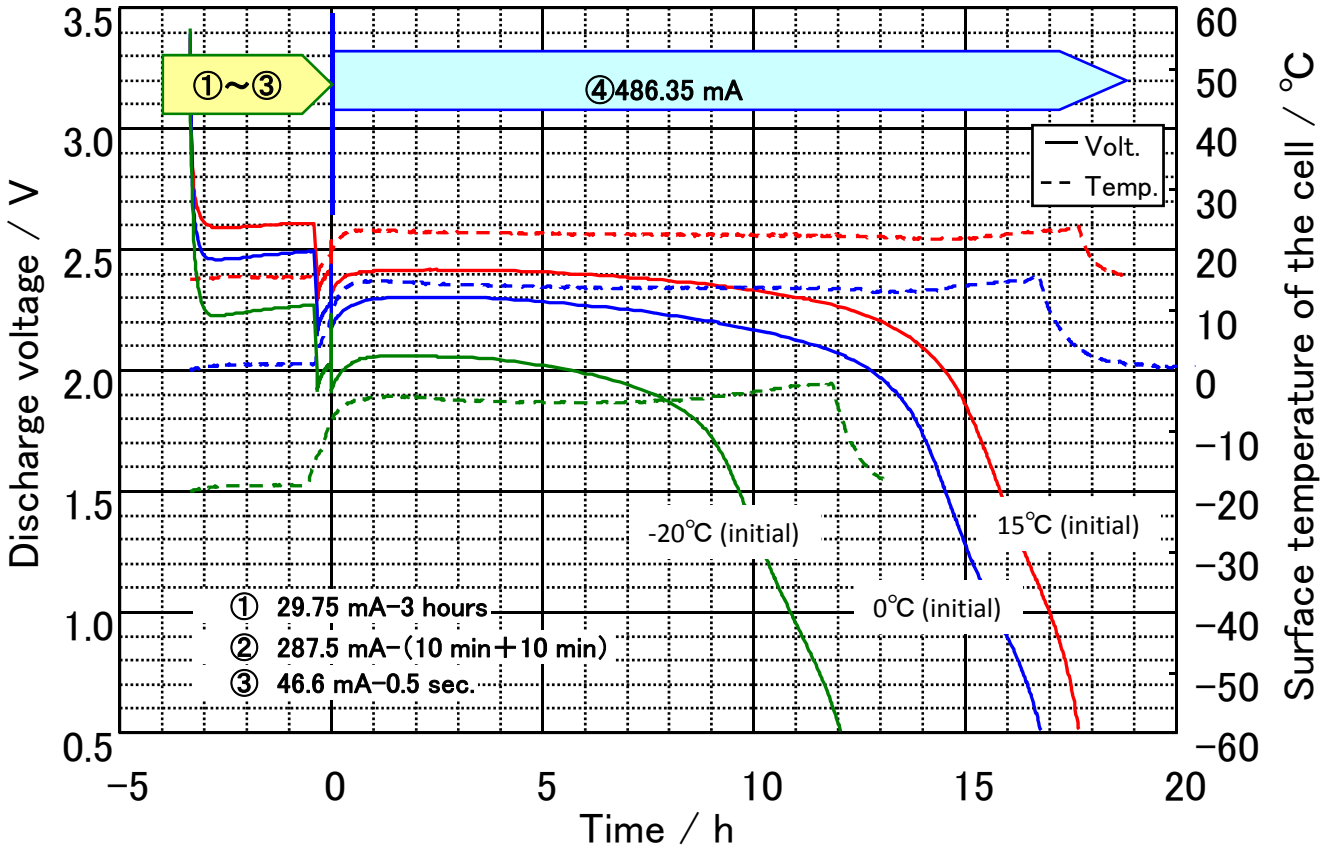


Fig. Discharge curves of the thermally degraded cells simulating 12 years storage.
①: Stand by for monitoring, ②: worm up of the analog line,
③: deploy the parachute / ignite the anchor,
and ④: send the radio beacon.



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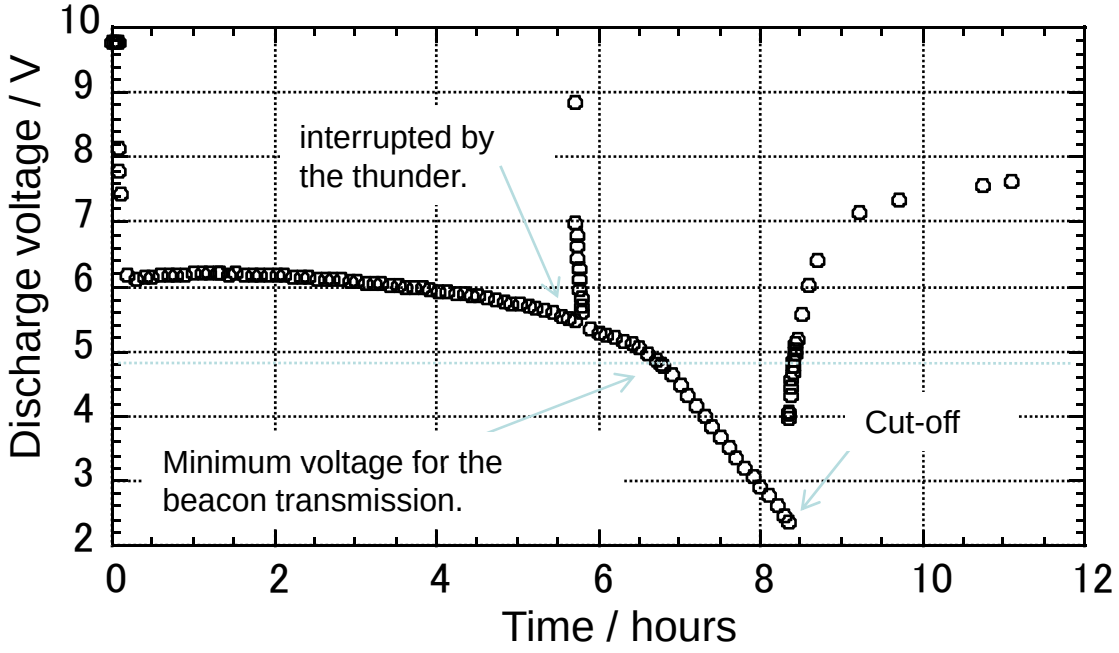


Fig. Discharge of the flight battery after the recovery operation.
The flight battery was discharged at 15℃.

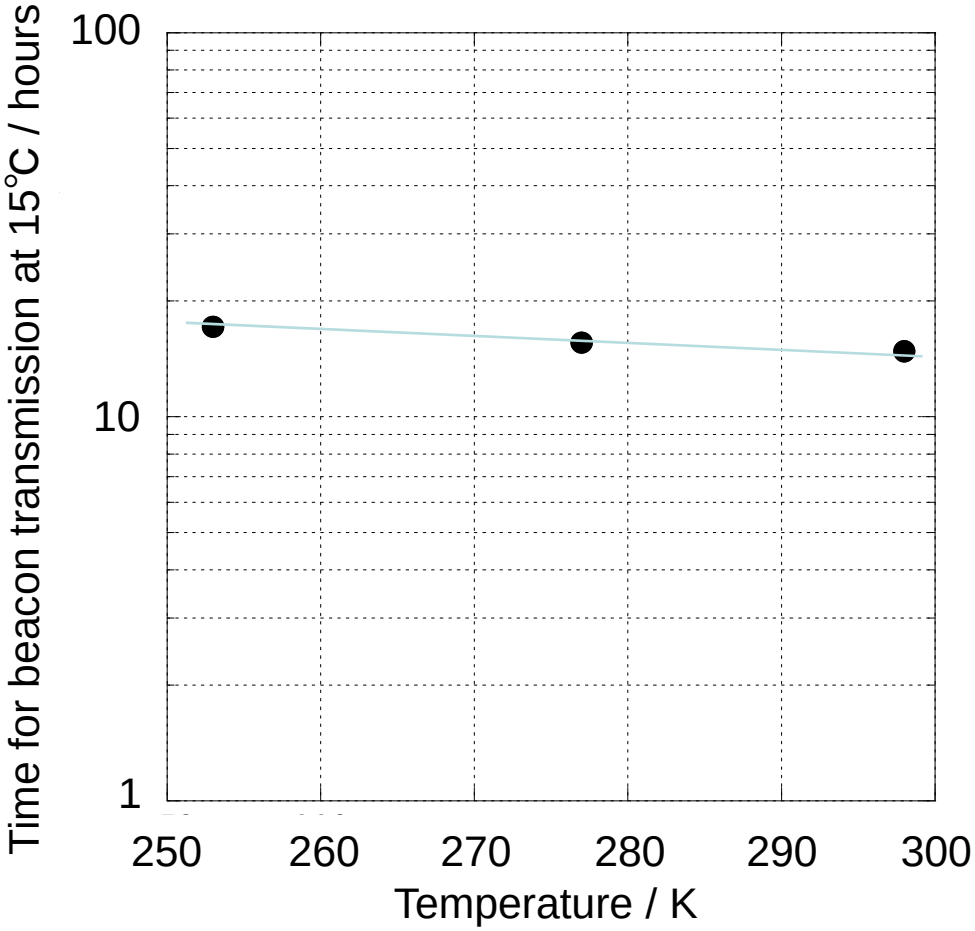


Fig. Effect of the storage temperature to the operability of the radio beacon.
Logarithmic expression for y-axis. Cells were discharged at 15℃.

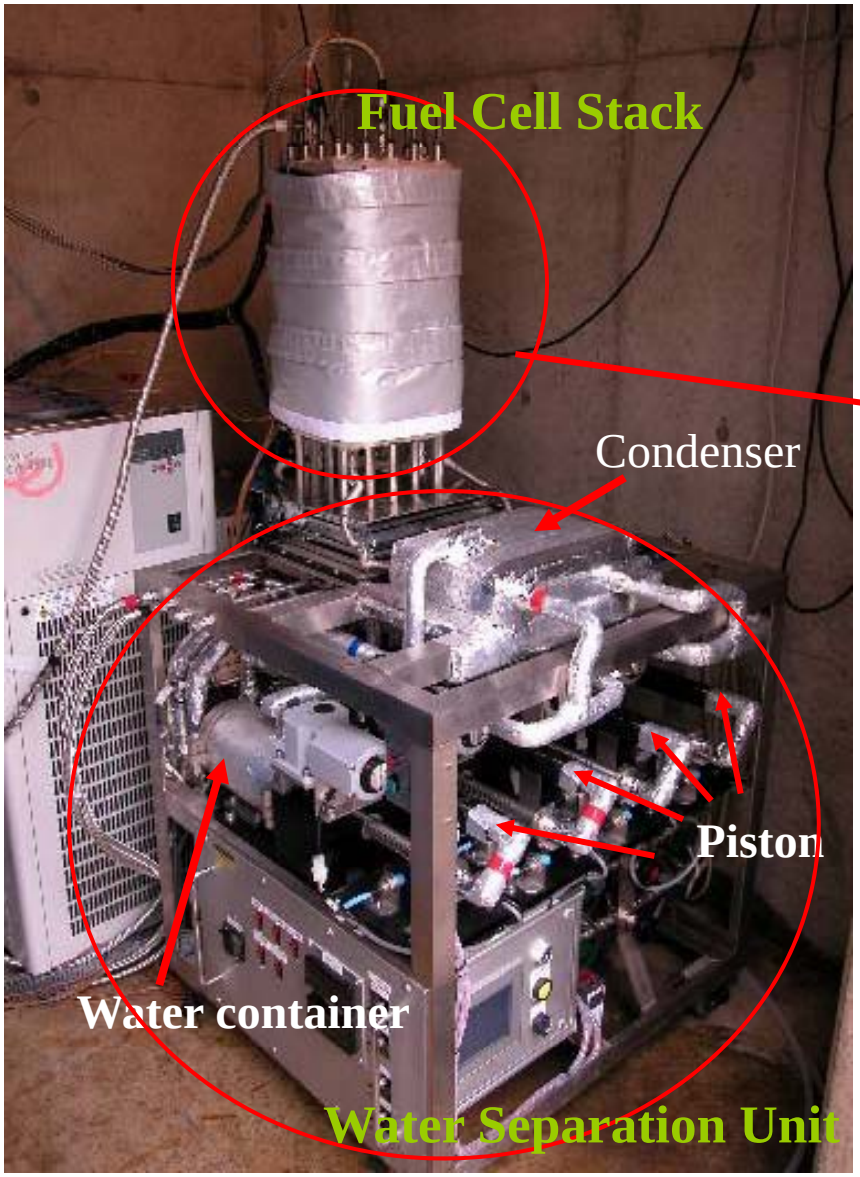
-lessons learned for lithium primary cells-

- 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℃.

The 100 W-class unitized regenerative fuel cell system targeting lunar and planetary missions

Back ground

- The Japan Aerospace Exploration Agency (JAXA) is developing a Regenerative Fuel Cell System that can be applied to the aerospace missions.
- Specially for the lunar and planetary missions, energy storage devices with high energy density is required .
- The energy density of the lithium-ion secondary cells is 160-180 Wh/kg. The energy density which can be realized by the lithium-ion secondary cell will be less than 300 Wh/kg, even in future.
- In order to realize the energy storage device with higher energy density for aerospace missions, the regenerative fuel cell system will be essential.



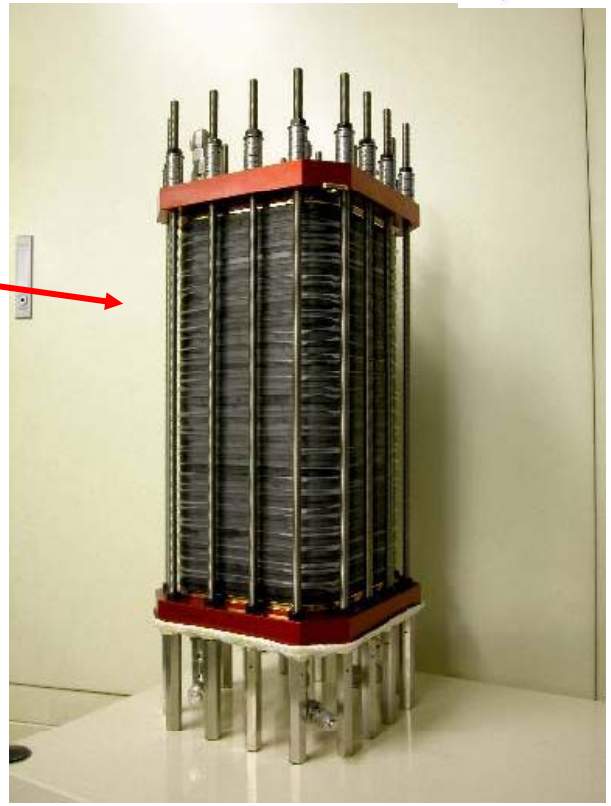


Fig. 4 kW-class fuel cell system.
Demonstration model for closed environment without external humidification.

Back ground -Fuel cell activity -

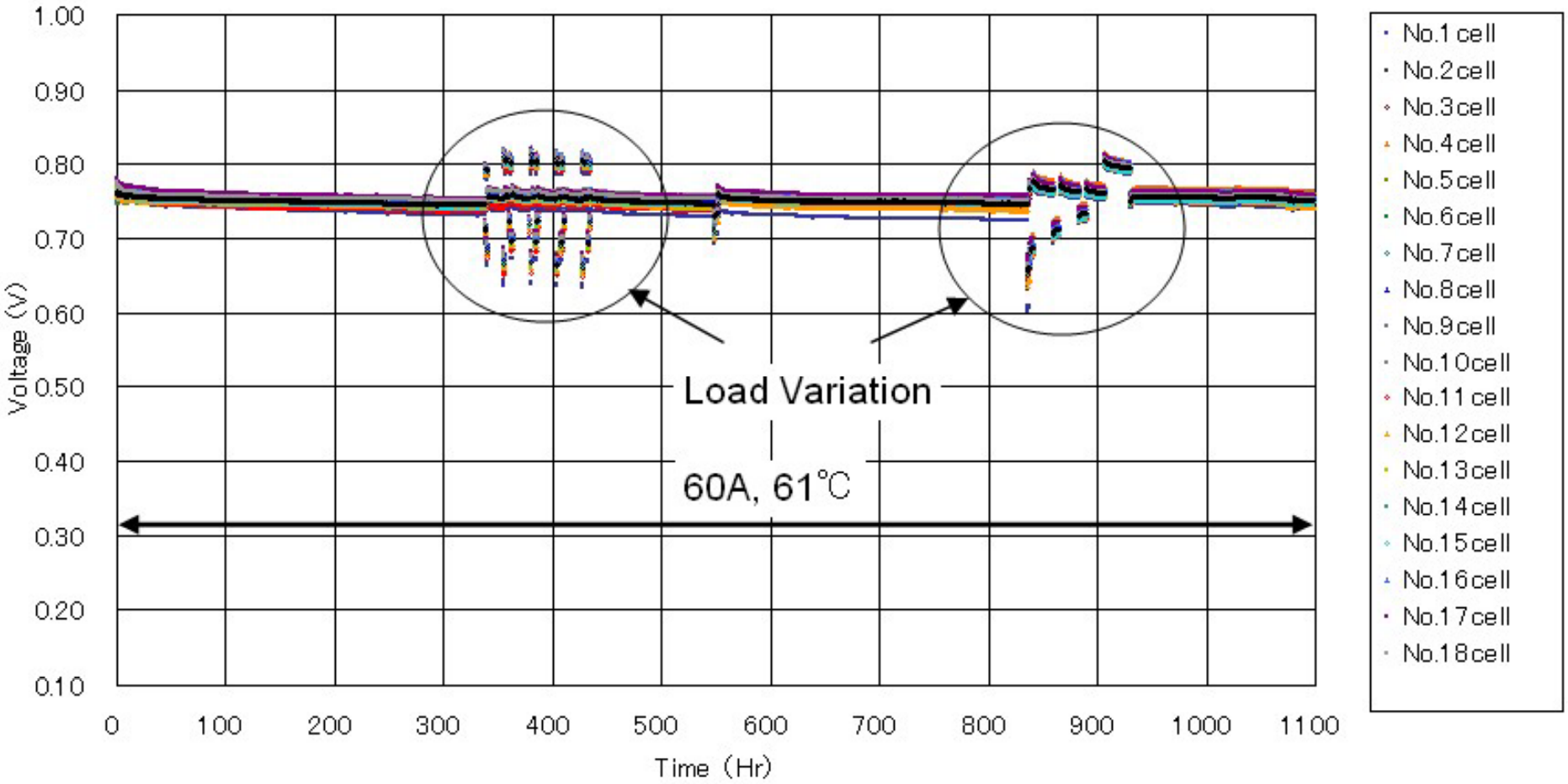
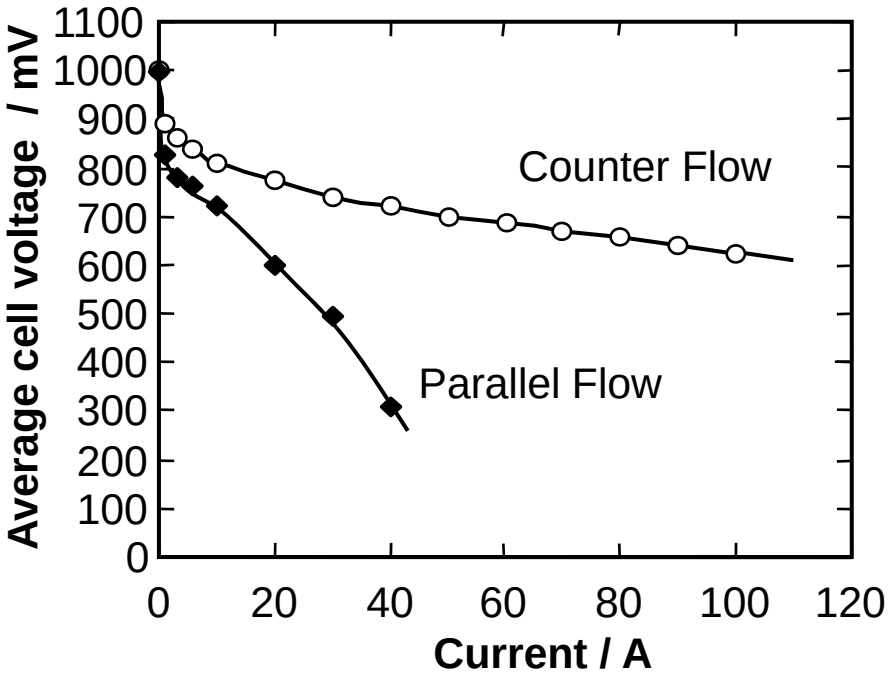
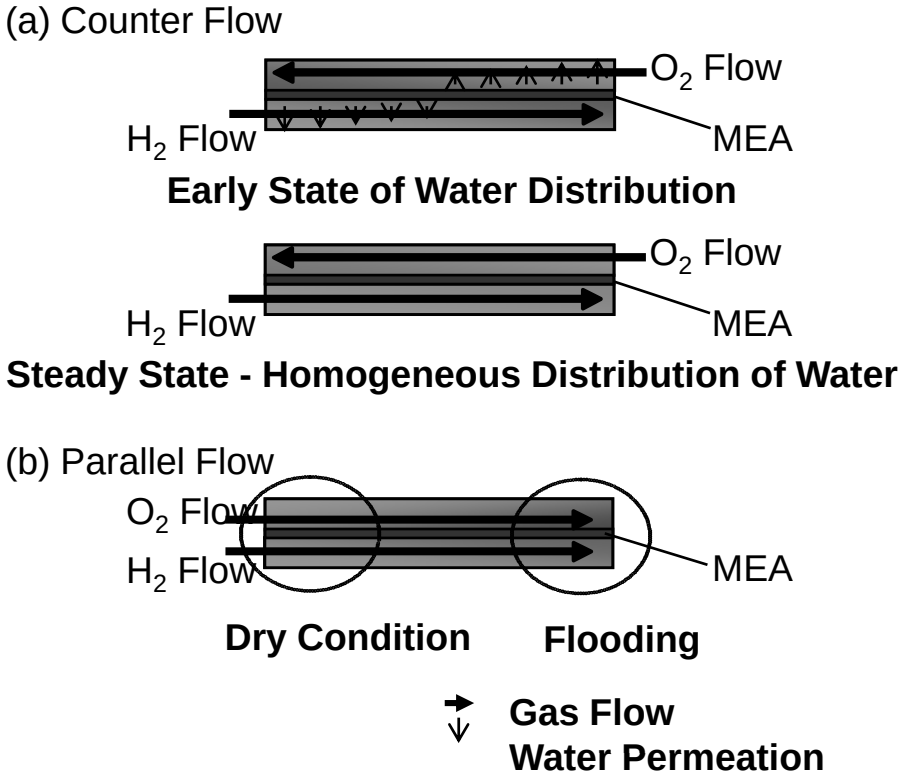


Fig. Continuous Operation of the 18-cells Stack Fuel Cell System simulating the closed environment.

Back ground -Fuel cell activity -





For the stable operation of the fuel cell without external humidification, counter flow of hydrogen and oxygen was important.

Back ground -Fuel cell activity -

・12V/100 W-class polymer electrolyte fuel cell

・The inlet and outlet gas pressure was controlled.

・Fuel cell was operated without external humidification.

・The thermal condition of the system was passively controlled.

Total mass : 80 kg

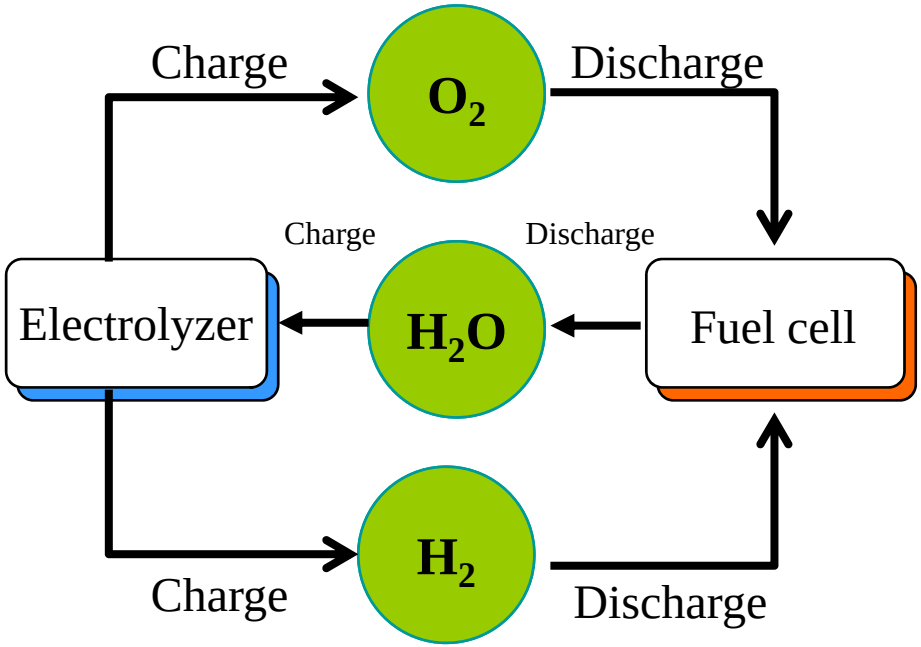
size : 500 mm × 500 mm × 600 mm

Fuel cell system was launched by the high altitude balloon which reached to the stratospheric are in August 2008.

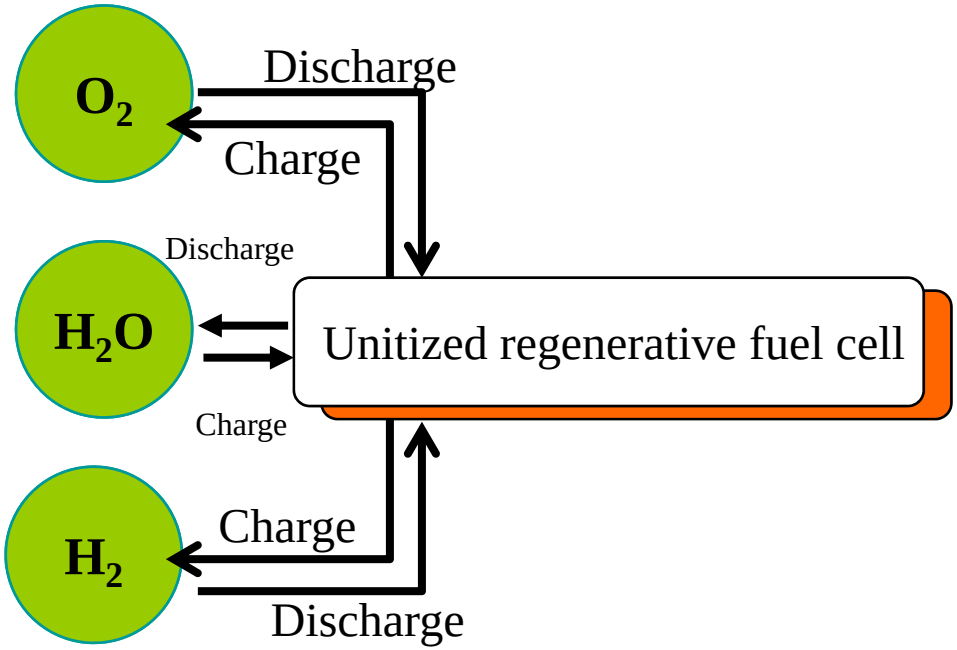
Back ground -Fuel cell activity -

- Polymer Electrolyte Fuel Cell (PEFC) systems that can be operated under isolated low-gravity and closed environments have been studied.
- The system concept was demonstrated the fuel cell operation for 1,000 hours under isolated closed environment.
- The system with passive thermal control without external humidification was demonstrated using the stratospheric balloon in August 2008.

Concept of the regenerative fuel cell



Separated-type regenerative fuel cell



Unitized regenerative fuel cell

If the unitized (or reversible) regenerative fuel cell system can be realized, it must be the small energy storage system with high energy density.
The electrolyzer requests wet condition for electrolysis, while the fuel cell requests rather dry condition for gas reaction. If one cell stack performs as an electrolyzer and a fuel cell, smaller system with higher energy density can be realized.

This work

100 W-class Unitized Regenerative Fuel Cell

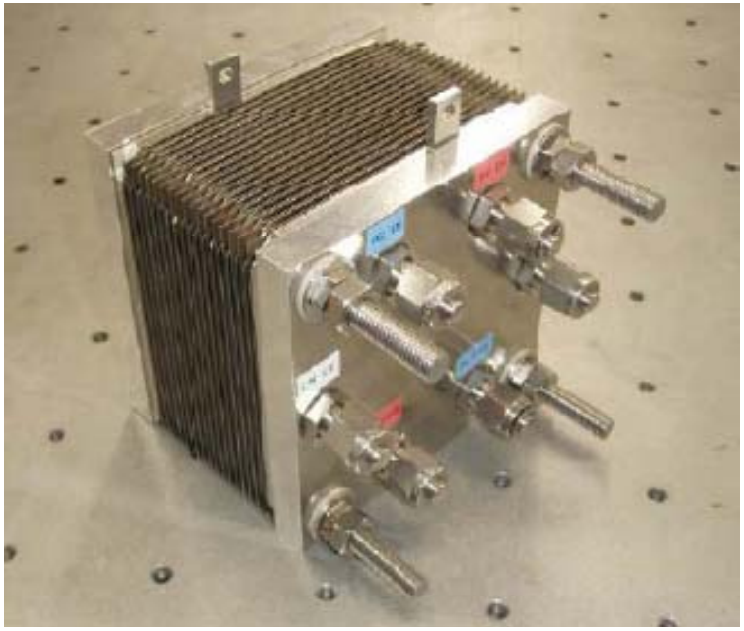
Specifications

- Fuel cell (FC) mode
  1) Power :100 W-class
  2) Out put voltage :12 V-class

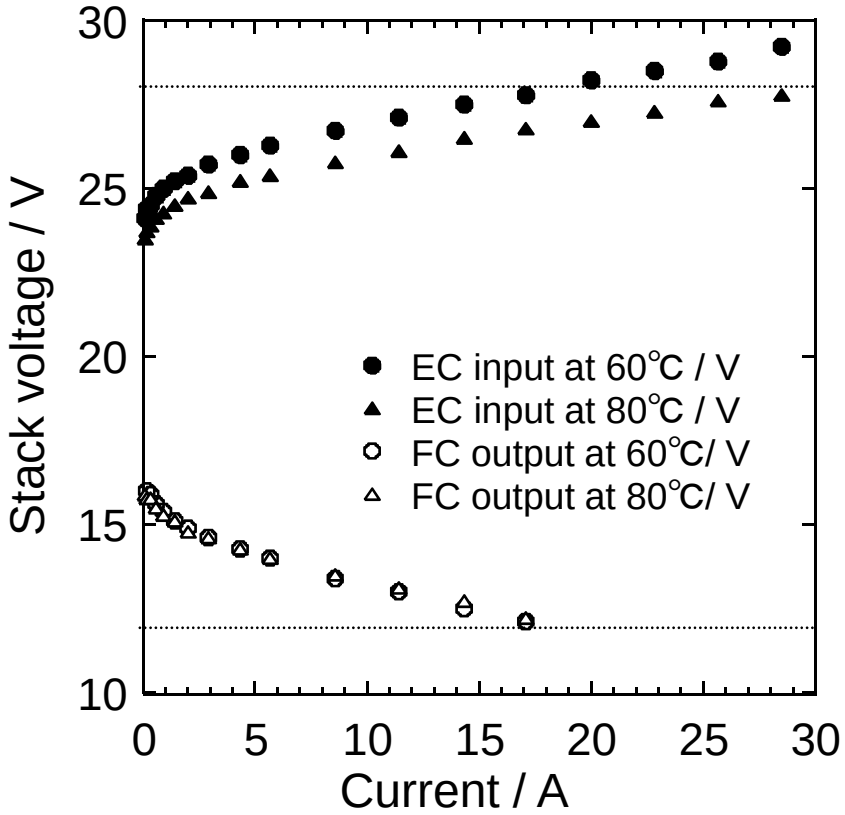
- Water electrolysis (WE) mode
  1) Input voltage :28 V-class

- Operational conditions
  1) Temperature :Above room temperature
  2) Current :0.3-0.6 A/cm^2

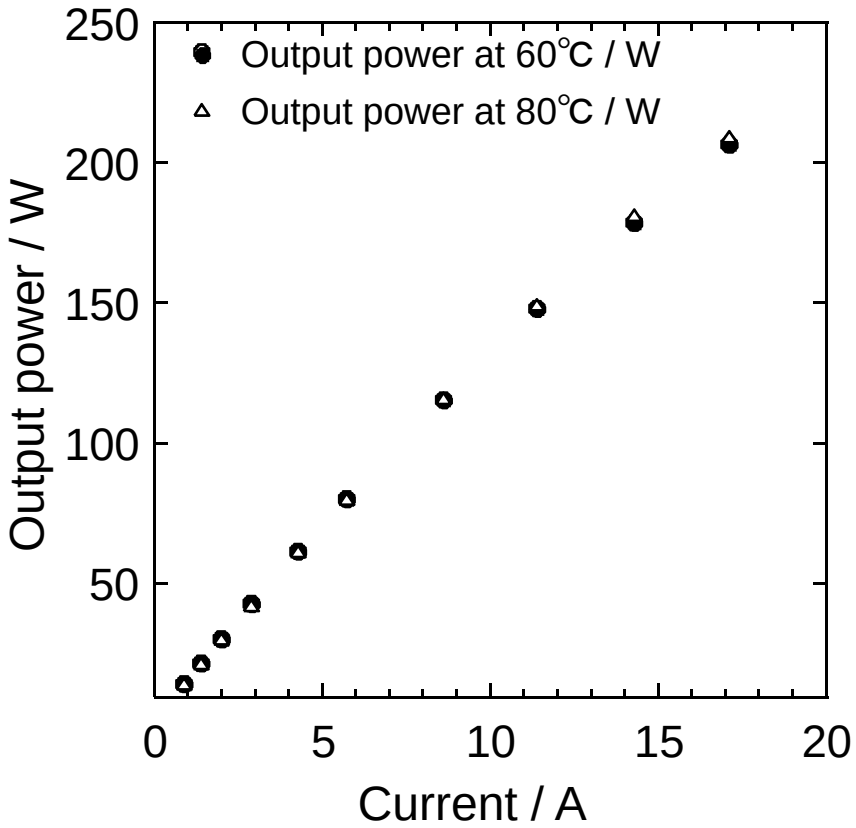
- Stack design
  1) 17 cells stack
  2) 27 cm2/cell surface area
  3) Water coolant



WE／FC operability



Water electrolysis and fuel cell reaction



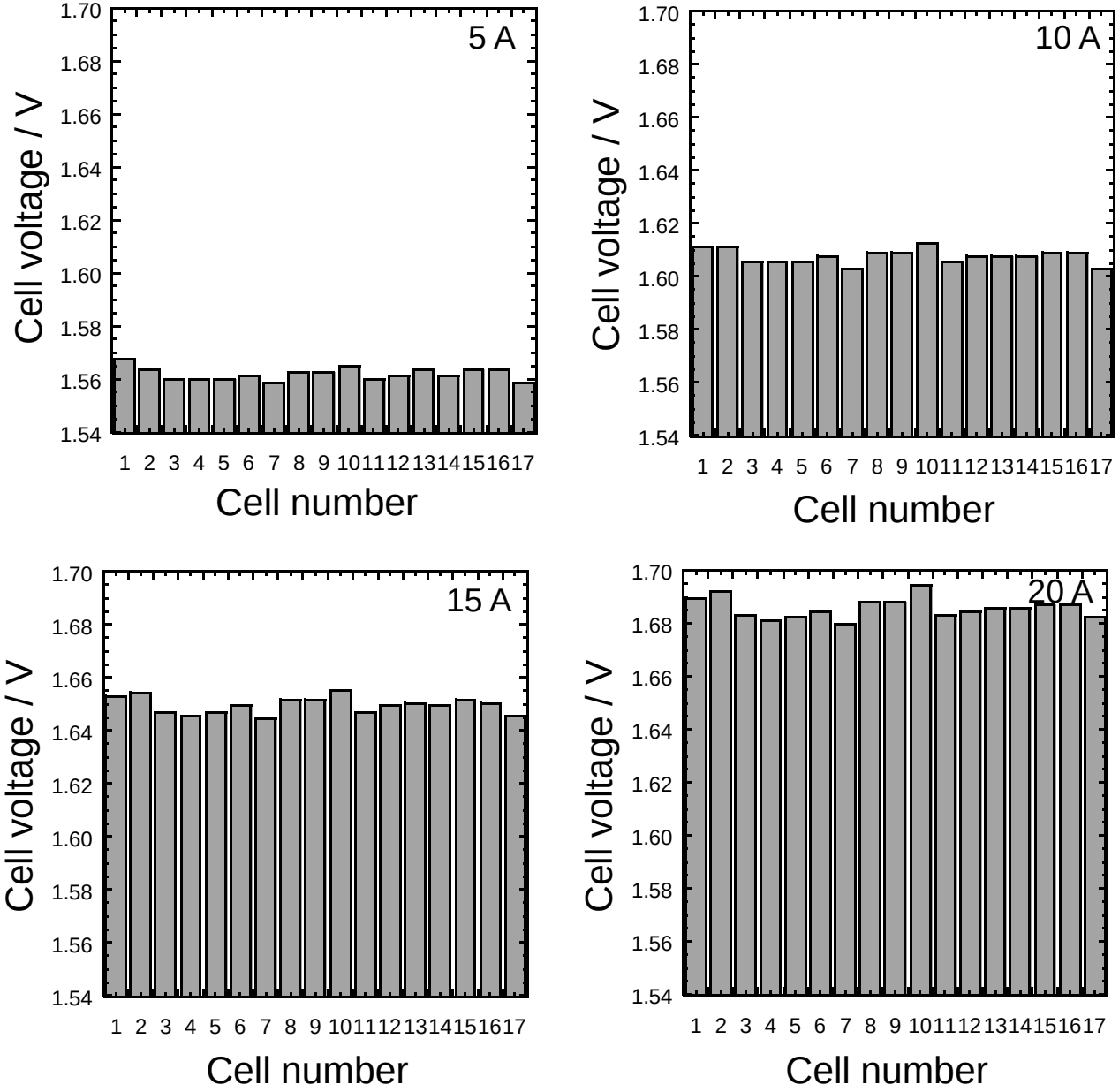
Output power curve for fuel cell reaction

For the above operation,

・When the electrolysis was operated at 28 V, efficiency was 86.3% at 60℃ and 90.4% at 80℃.

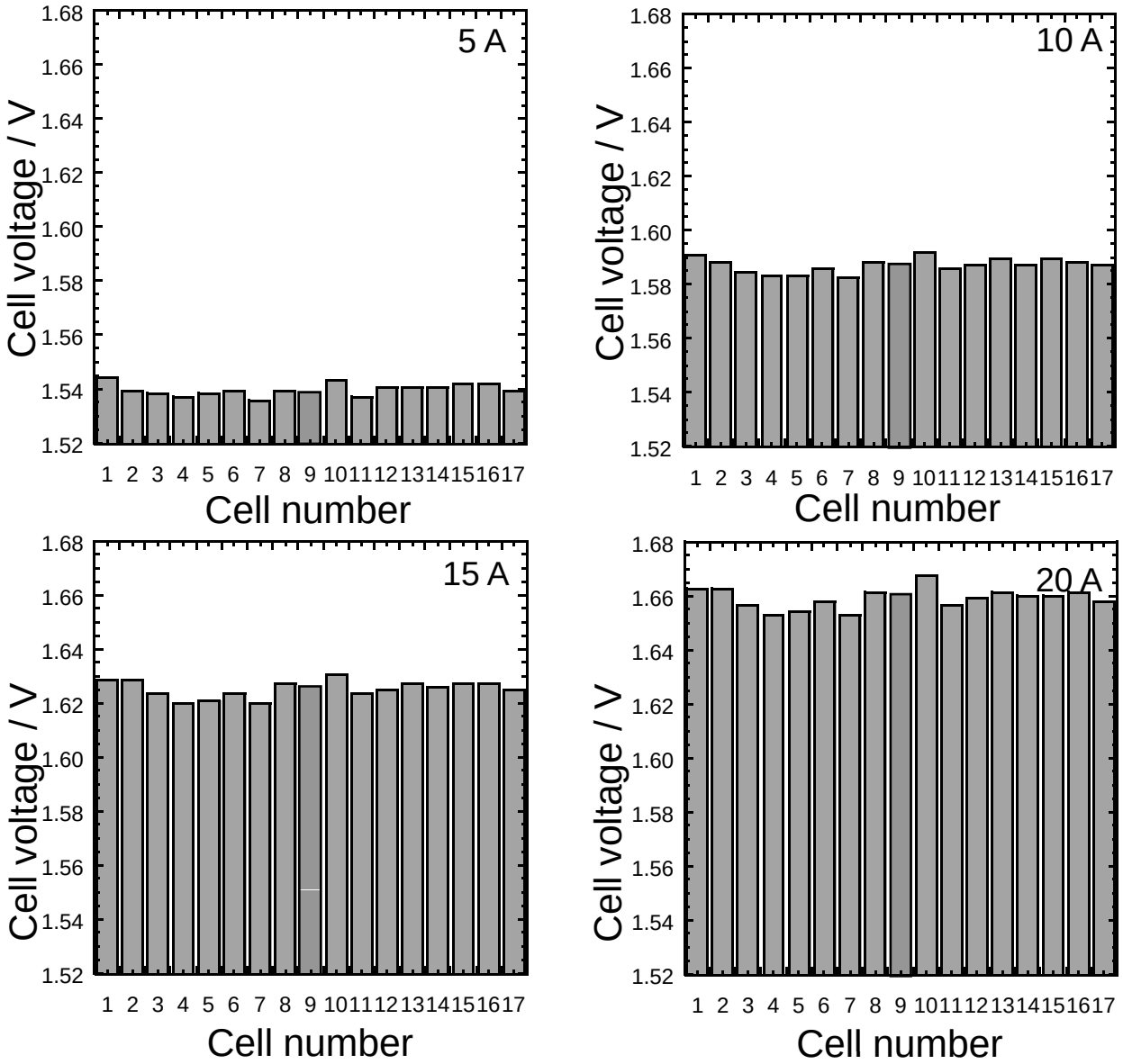
・When the fuel cell reaction was operated at 12 V, efficiency was 48.1% at 60℃ and 48.6% at 80℃.

Cell voltage for the electrolysis at 40℃



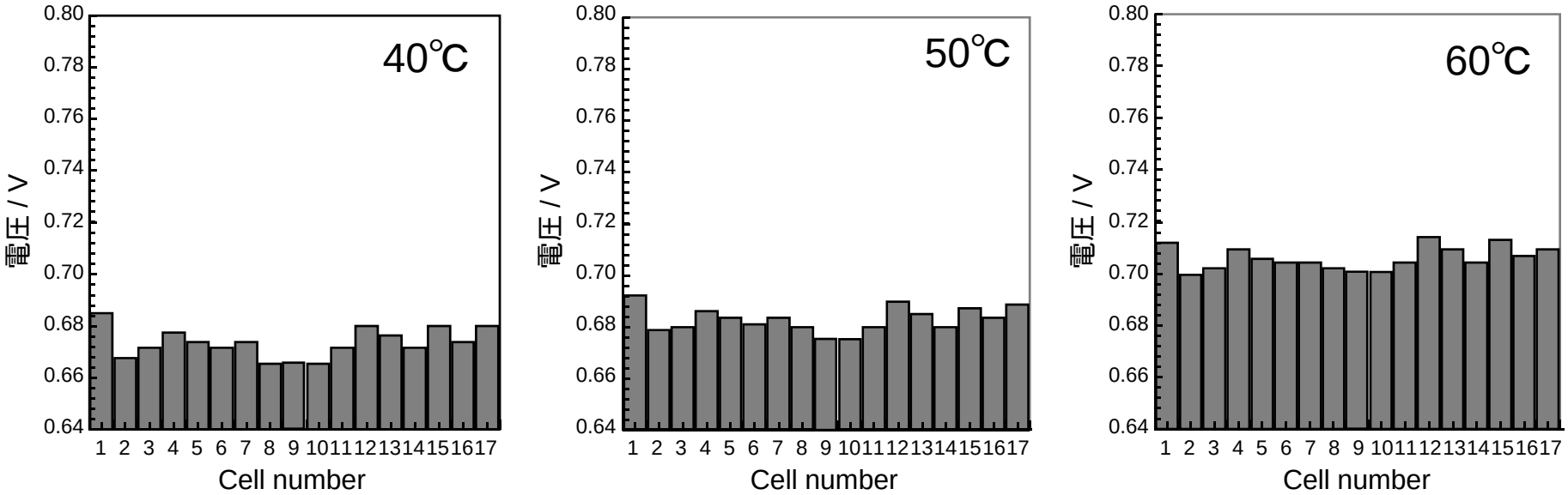
Difference of the cell voltage was ca. 10 mV at 10 A, and ca. 20 mV at 20 A

Cell voltage for the electrolysis at 50℃



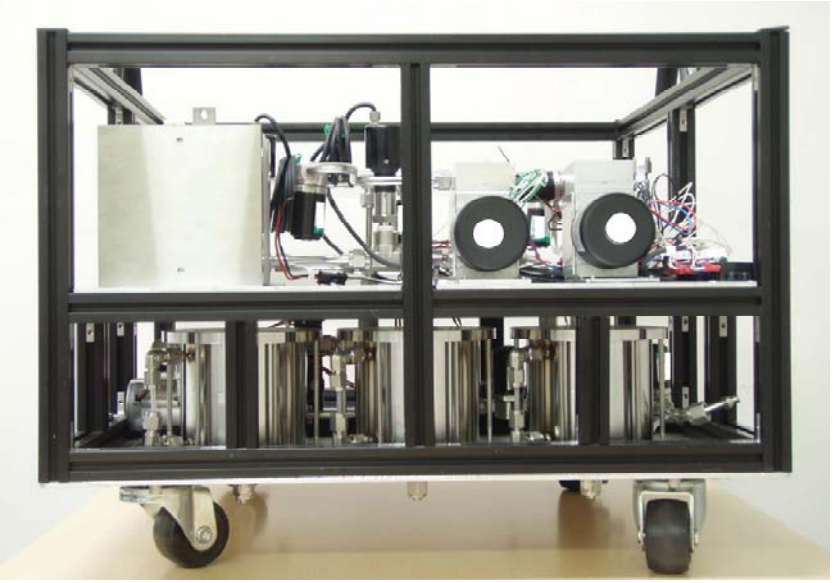
The distribution of the cell voltage was almost the same as in the case of 40℃.
It was within 10 mV at 10 A, and 20 mV at 20 A.
The voltage for the electrolysis decreased with increasing temperature.

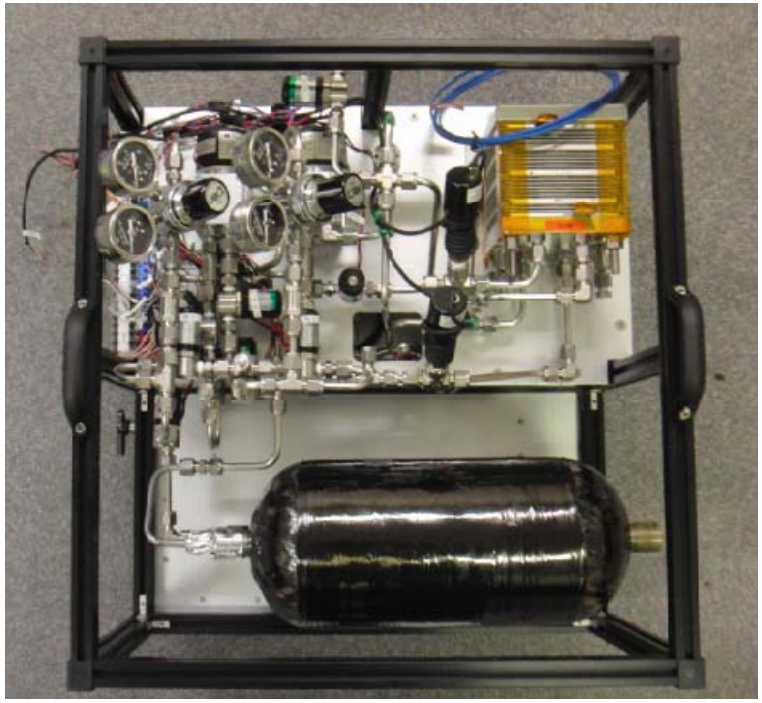
Fuel cell reaction
Cell voltages by the 5 A generation



Generally, the influence of the impedance appears during the operation at lower temperature. The Distribution of the output voltage was monitored within 20 mV at 40℃, which suggested that the gas and water condition inside was uniform. Based on these data, we are going to decide the operational condition of the URFC system.

System design of the 100 W-class URFC demonstration model





- The 100 W-class URFC system was designed.
- Using this system, we are going to decide the condition for the automatic operation of the regenerative fuel cell system.

Summery

- The demonstration model of the 100 W-class unitized regenerative fuel cell was prepared.
- For the electrolysis, the distribution of the cell voltage was less than 10 mV at 10 A, and 20 mV at 20 A.
- For the fuel cell, the distribution of the output voltage was monitored within 20 mV at 40℃, which suggested that the gas and water condition inside was uniform.
- The URFC system which can be automatically operated was also prepared as a system demonstrator of the URFC.