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OPERABILITY OF THE OVER-DISCHARGED LITHIUM-ION SECONDARY CELL -LESSONS LEARNED FROM THE MALFUNCTION OF HAYABUSA-

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

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
Electrode Material	Positive	$LiCoO_2$
	Negative	Graphite
Weight		< 570 g
Energy Density / mass		> 85 Wh/kg
Energy Density / volume		> 215 Wh/L

1) The rated capacity assumed charging at 6.60 A (0.5 C) and discharging at 2.64 A (0.2 C) at 20℃.

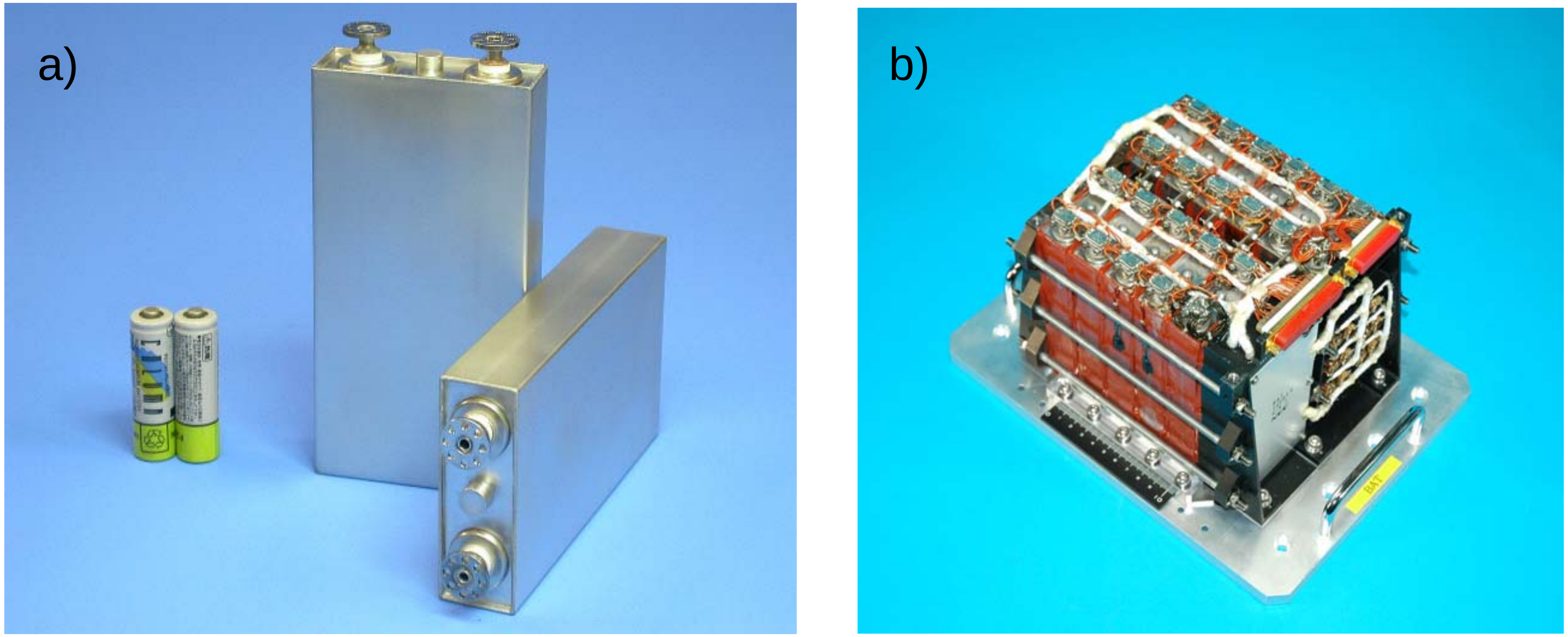


Fig. Photographs of the lithium-ion secondary cells (a), and battery (b).
The lithium-ion secondary cells (a) are compared to AA-size cells.

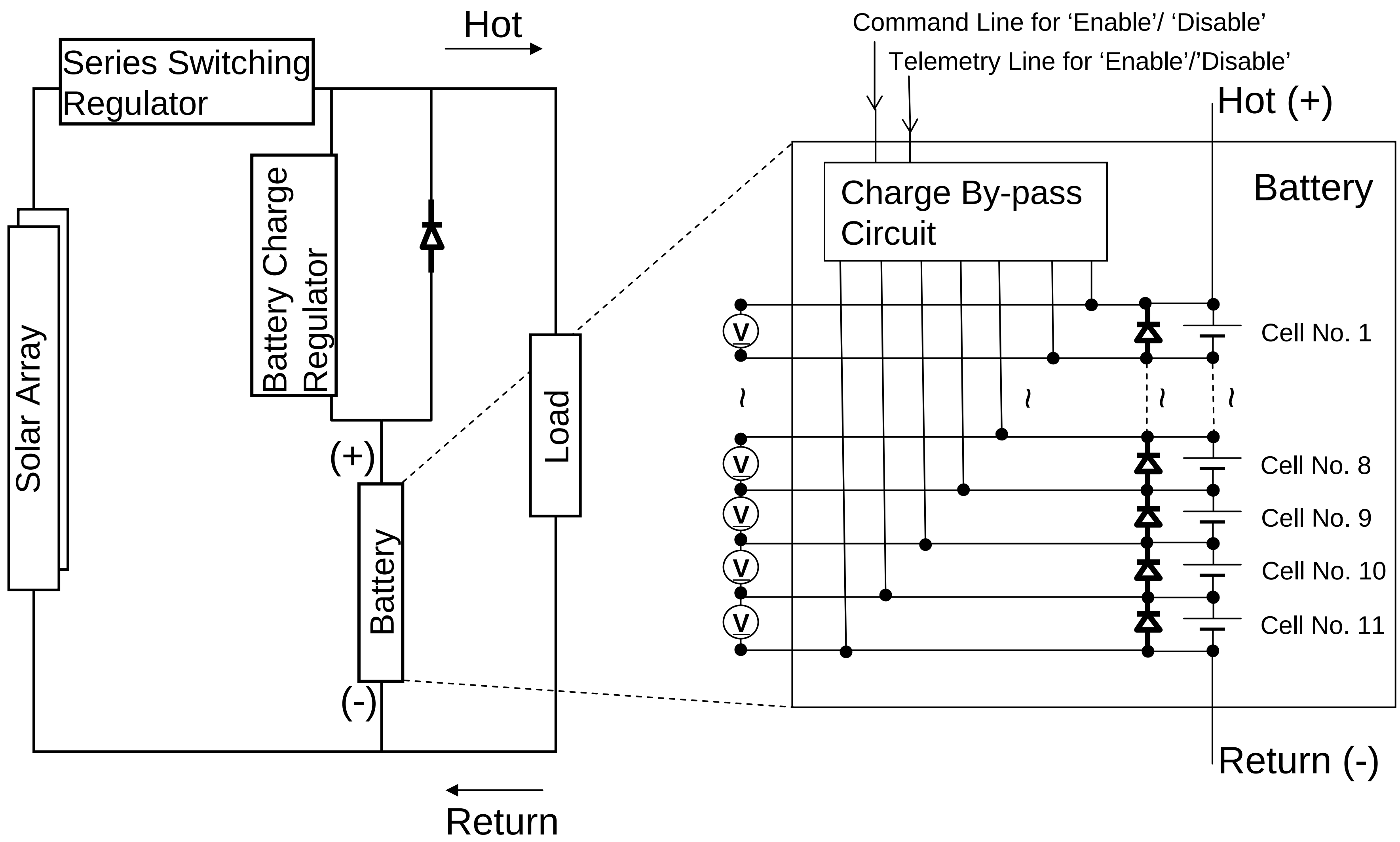


Fig. The block diagrams of the electrical power sub-system for HAYABUSA.

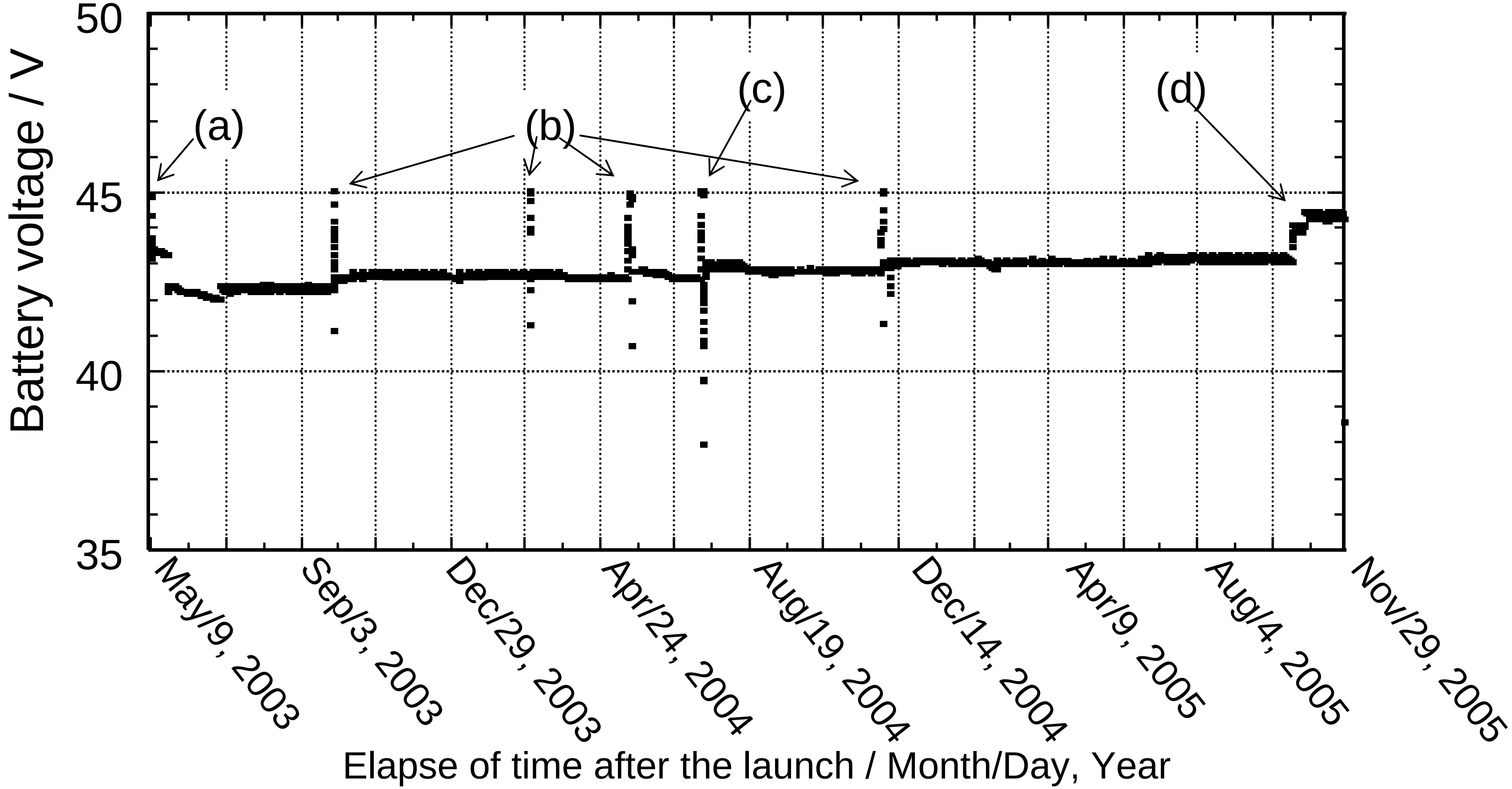


Fig. Trend of the battery voltage in flight.

(a) The battery was charged to 100% SOC for the launch.

(b) For compensating the SOC levels, the battery was charged using a balance circuit which by-passes the current when the cell voltage reaches 4.1 V. After being charged, the battery was discharged to ca. 50% SOC.

(c) The capacity of the battery was measured in space.

(d) Before HAYABUSA touched down the asteroid, the battery was charged up to 44 V (4.0 V/cell) so that the spacecraft could be operated for 40 minutes using the power of the battery.

- In November 2005, HAYABUSA arrived at the asteroid, ITOKAWA.
- After observing the surface, the spacecraft touched down.
- During these operations, the surface material of ITOKAWA possibly entered the sample container.

- The spacecraft lost control of its attitude due to a leakage of the chemical propellant.
- From December 9, 2005, HAYABUSA was out of communication for seven weeks.
- In January 2006, communications with HAYABUSA were re-established.
- The telemetry data from the spacecraft revealed that 4 of the spacecraft’s 11 cells had over-discharged during the time when solar power was unavailable due to the spacecraft’s tumbling motion.

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

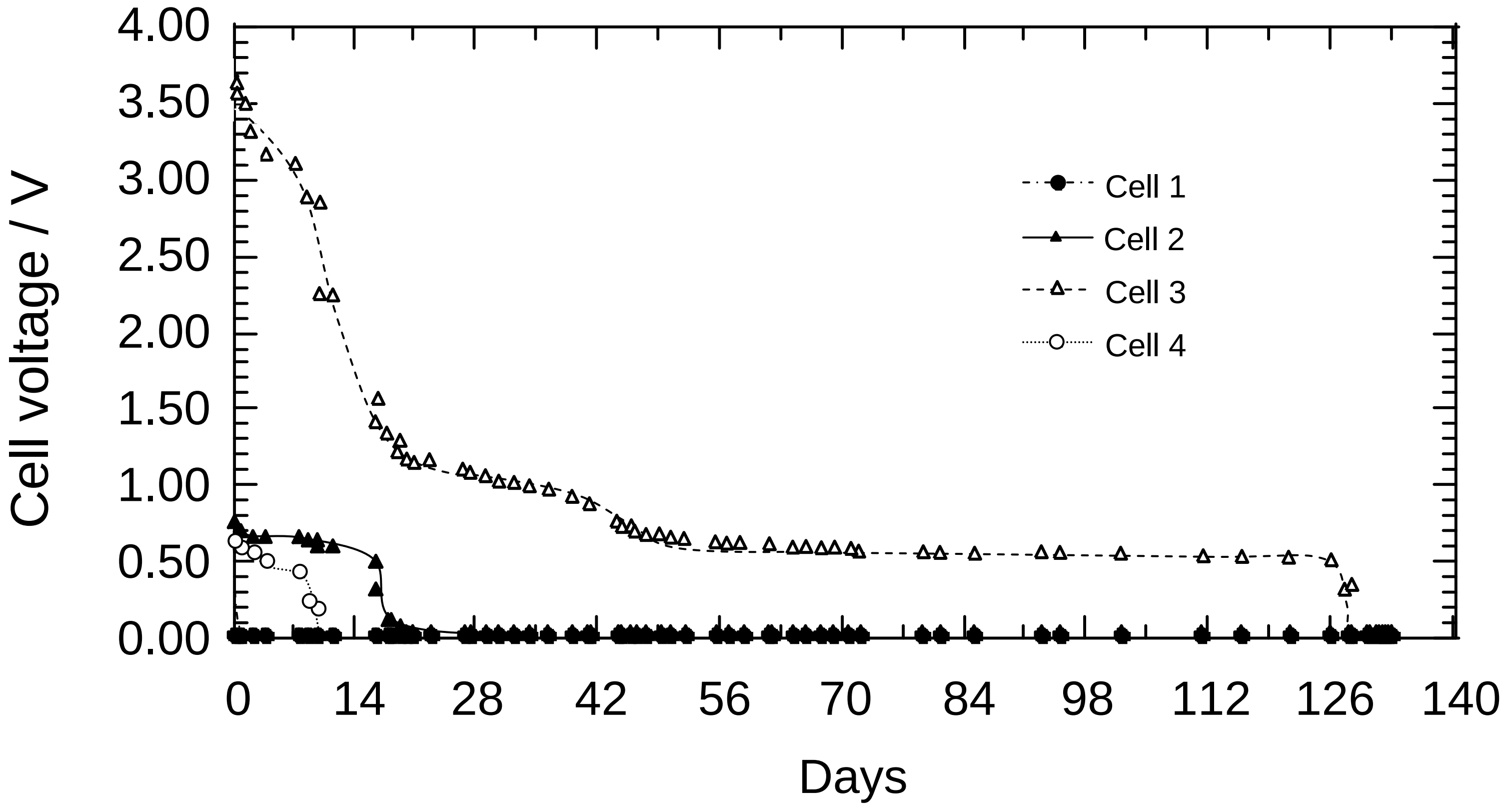


Fig. The trend of the voltage discharged by the monitoring circuit.
Cells 1-4 seemed to be over-discharged during the out-of-communication period.

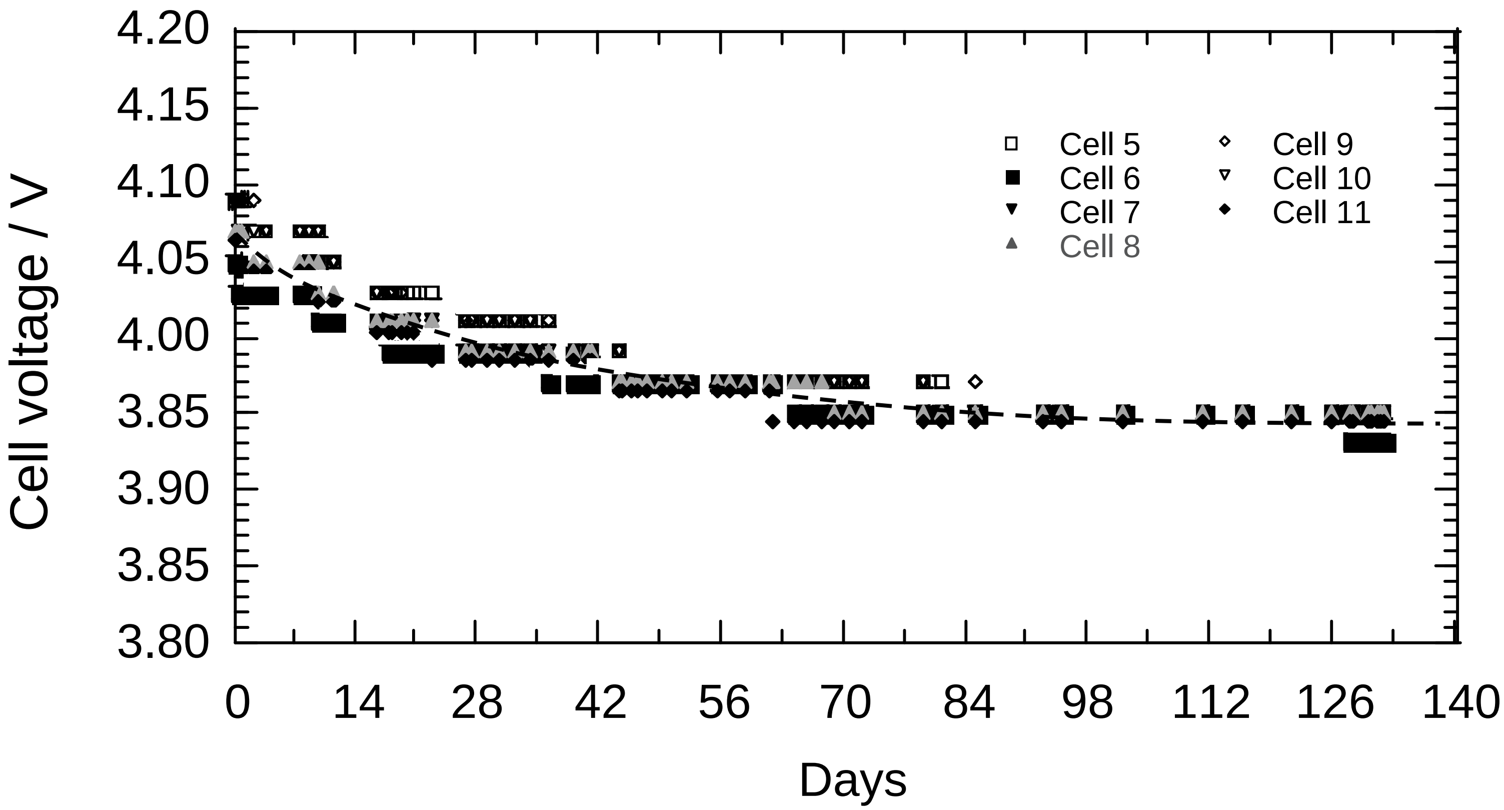
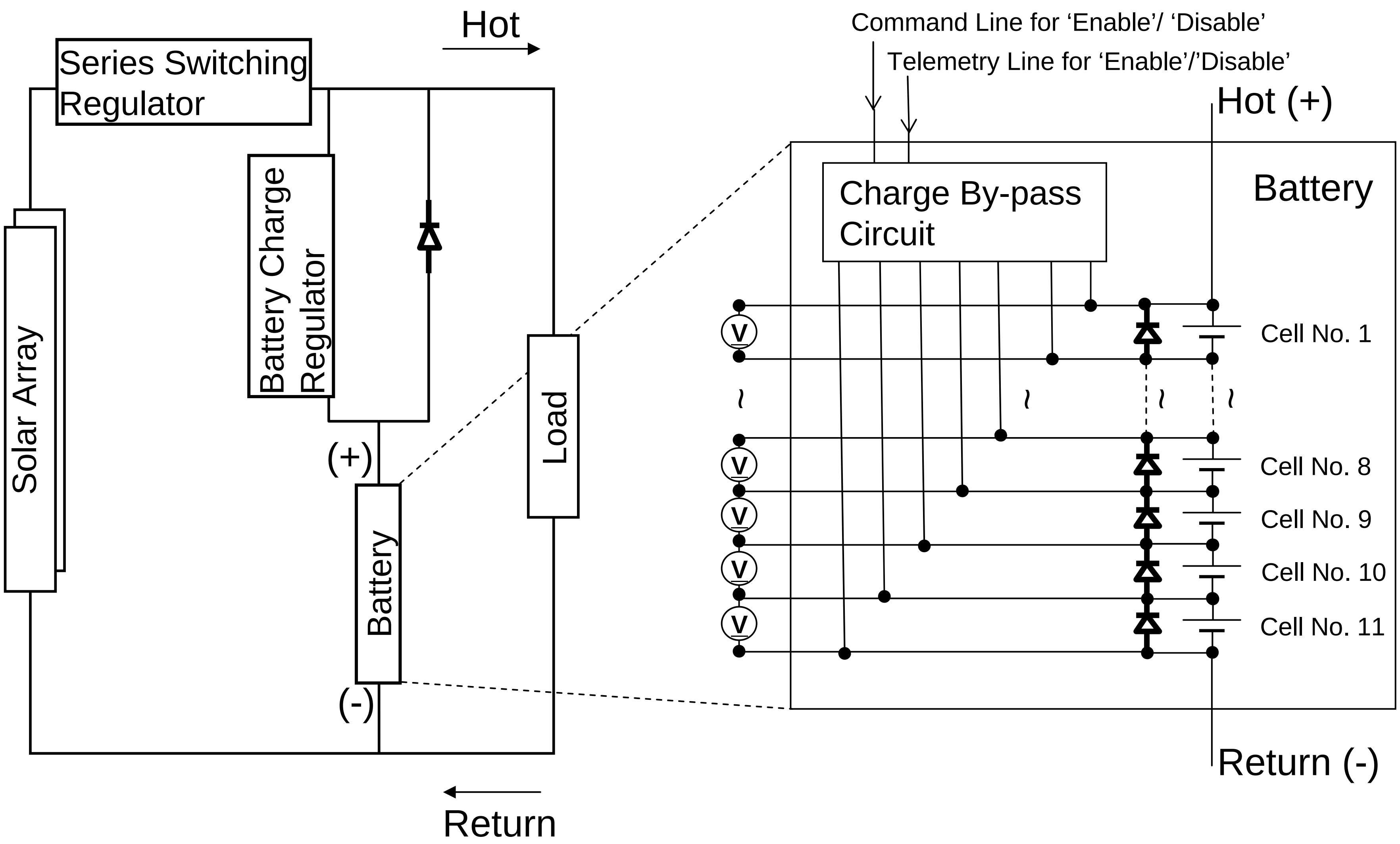


Fig. The trend of the voltage discharged by the monitoring circuit. The discharge curves of cells 5-11 showed high voltages even after the malfunction.



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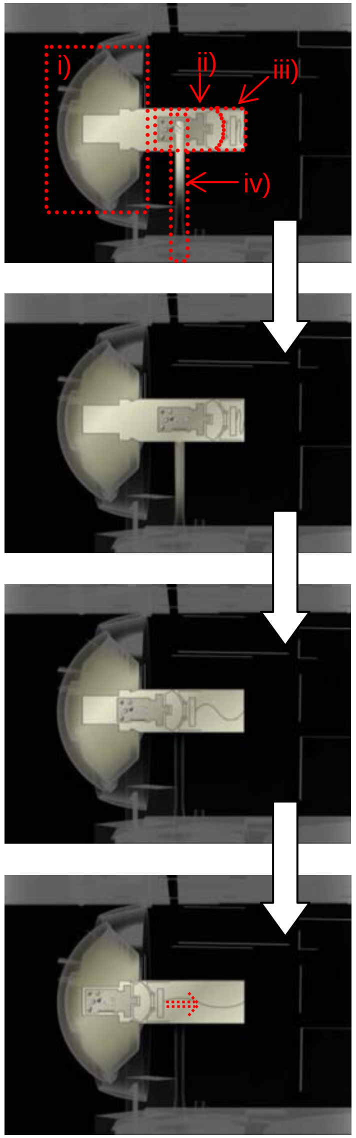
- By carefully examining the telemetry data, it was found that the lid of the container for the asteroid sample was still open.
- To return the sample from ITOKAWA to Earth, the lid of the sample container had to be closed, the container had to be inserted into the re-entry capsule, and the capsule had to be latched as well as sealed.
- These processes all required battery power (2 A, 28 V), which was critical to the mission.



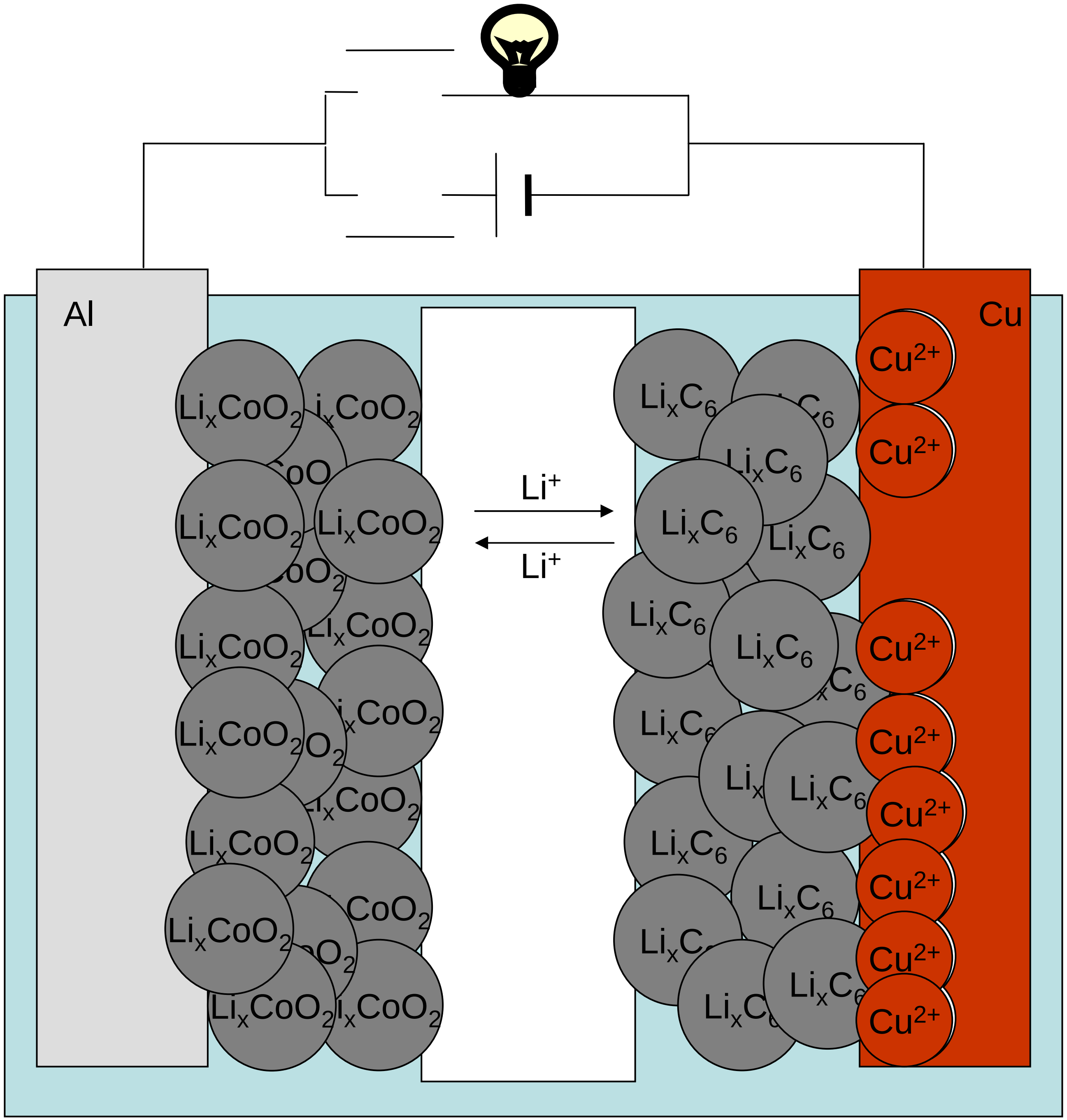
i) Earth re-entry capsule
ii) Asteroid sample container
iii) Lid cover and cable cutter
iv) Tube to guide the sample into the container

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

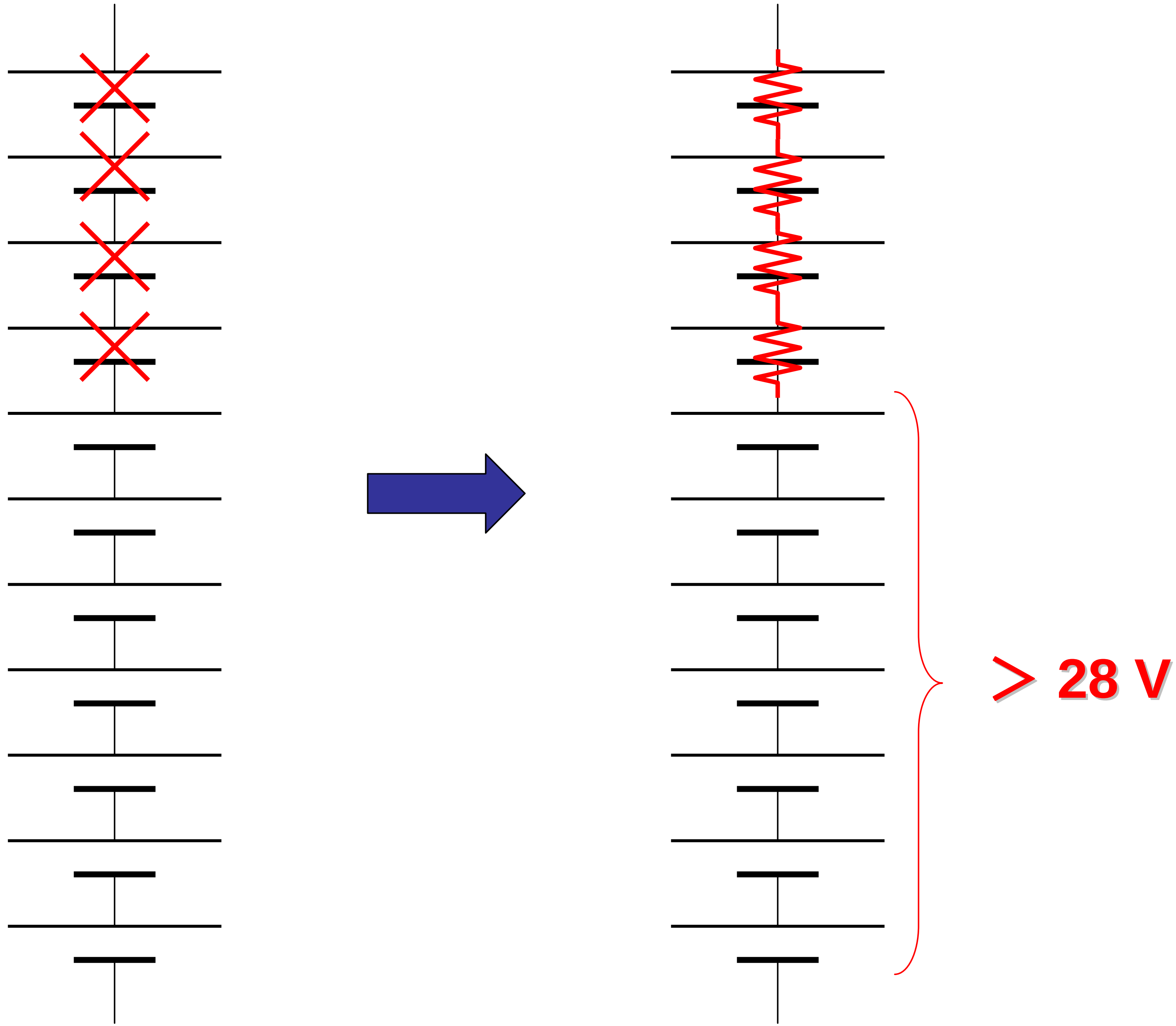
(b) The sample container is injected into the Earth re-entry capsule.

(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.



Al
Cu
Li^+
Li^+
Li_xCoO_2
Li_xC_6
Cu^{2+}


> 28 V

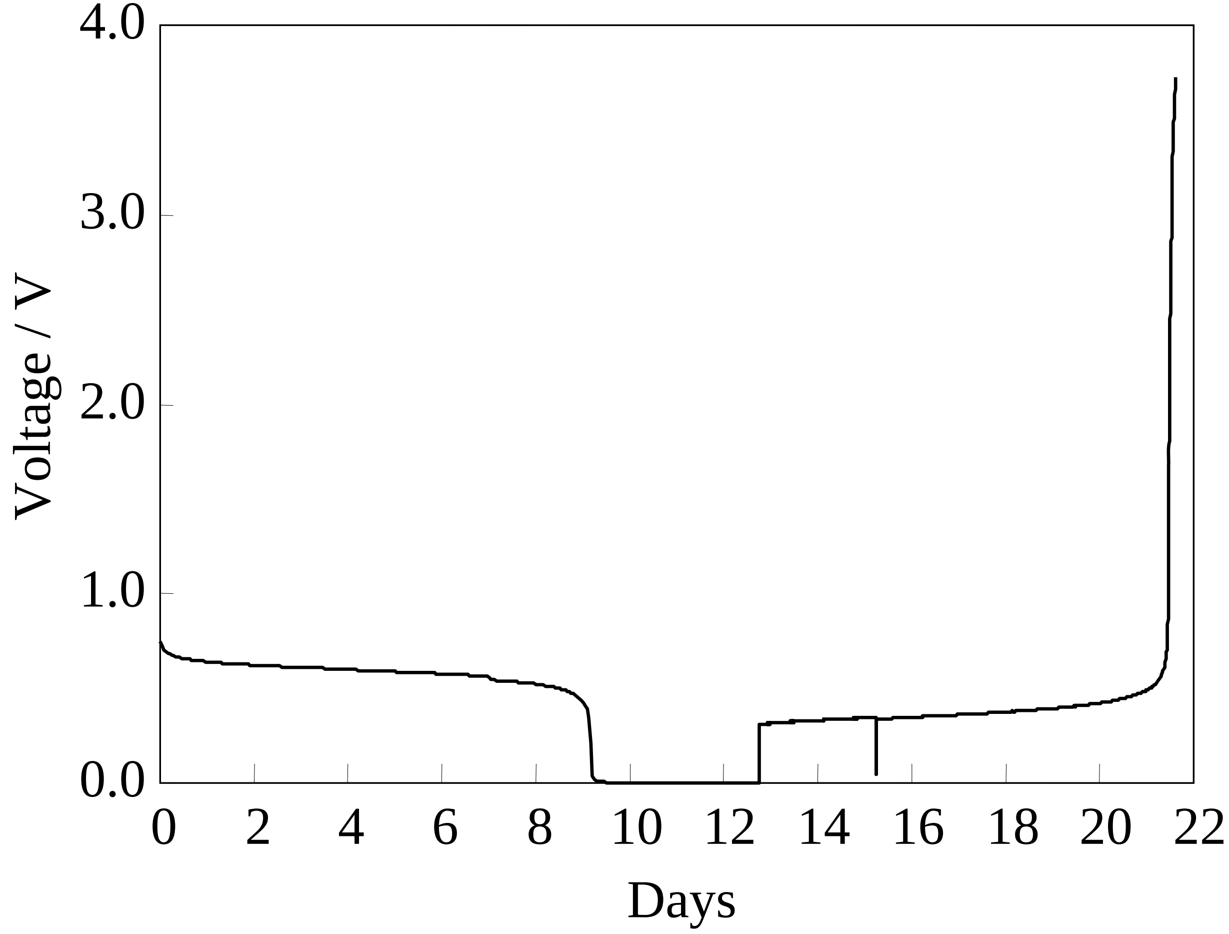
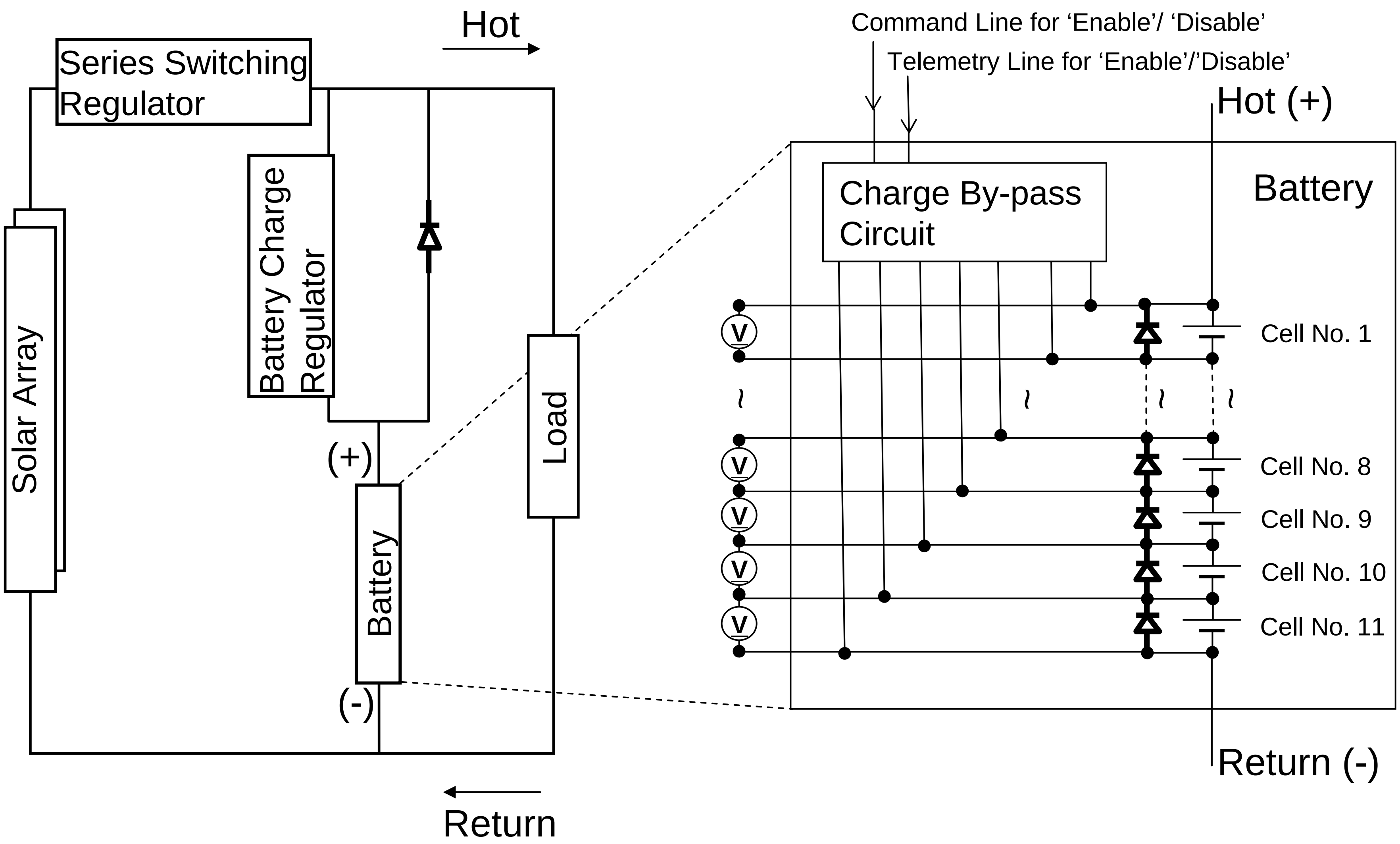


Fig. The simulation test for discharging and charging of a test cell. First, the cell was discharged to 0 V using a 300 mΩ resistor, before being charged at 500 mA.



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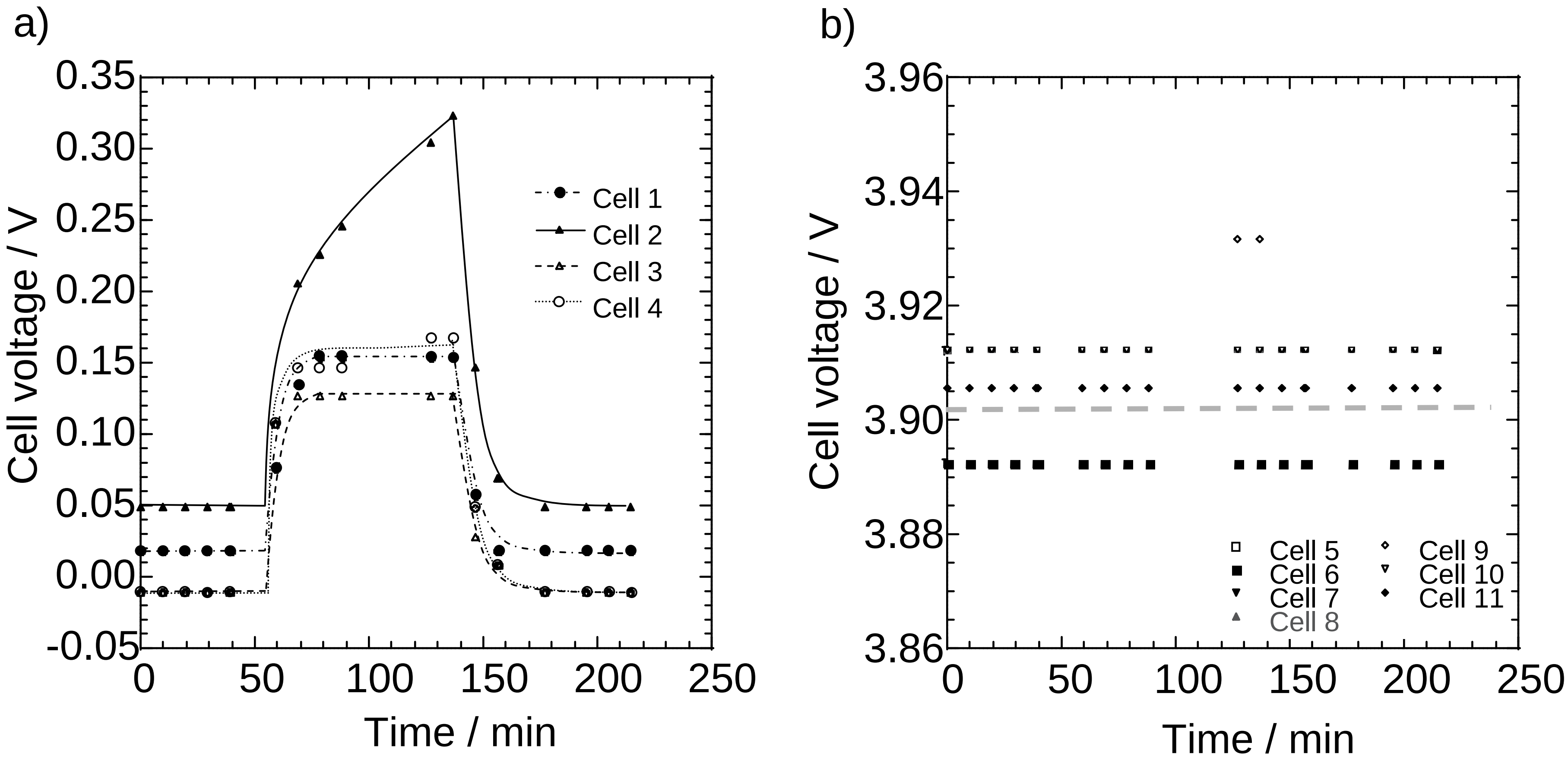

Fig. Charge curves of the flight cells with the bypass circuit enabled.
The voltages of cells 1-4 increased slightly (a), while the voltages of cells 5-11 did not change during the 1-day operation (b).

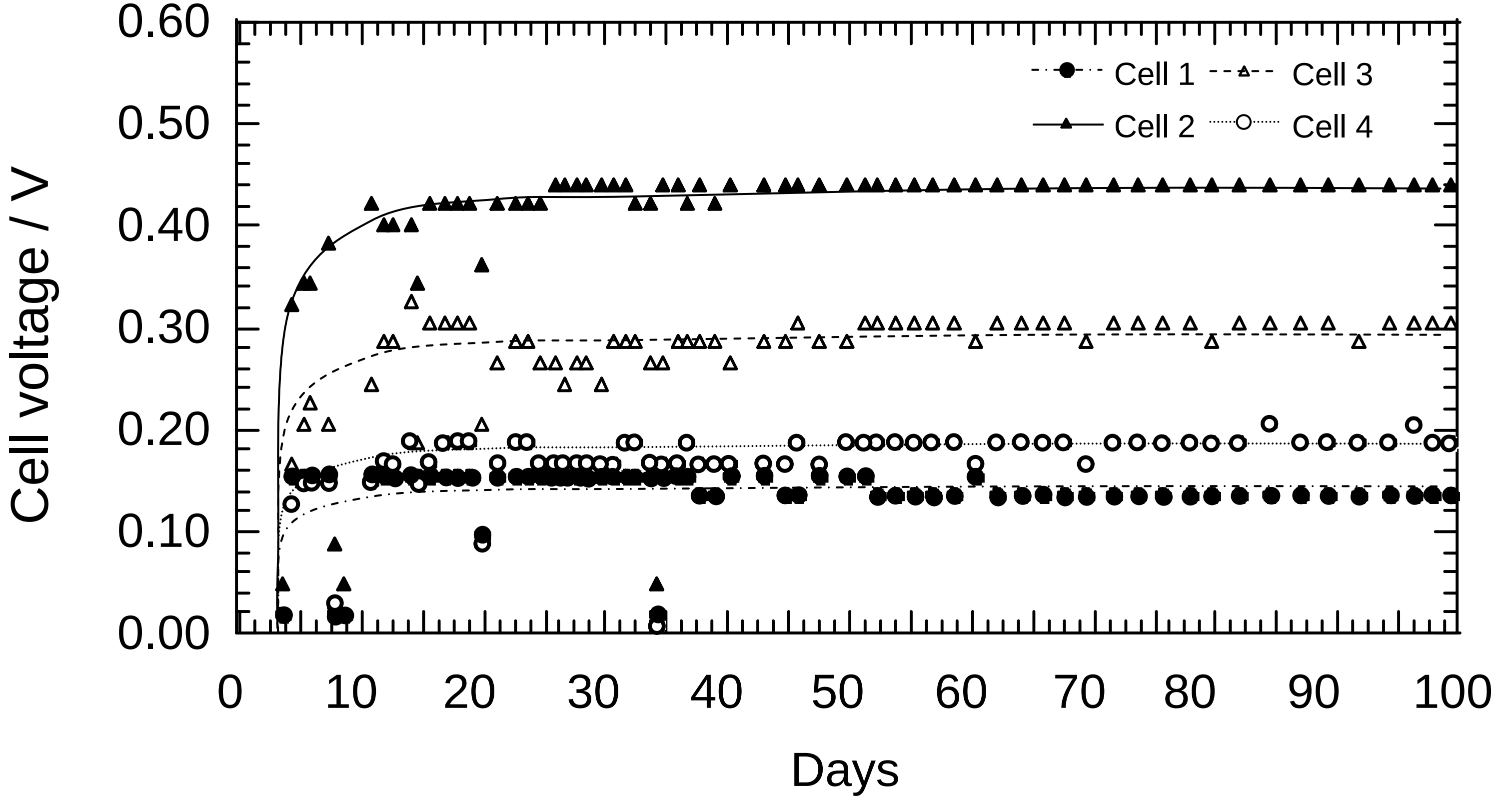

Fig. The day-to-day trend of the end-of-charge voltage (EoCV).
Cells 1-4 showed a stable voltage less than 0.5 V.

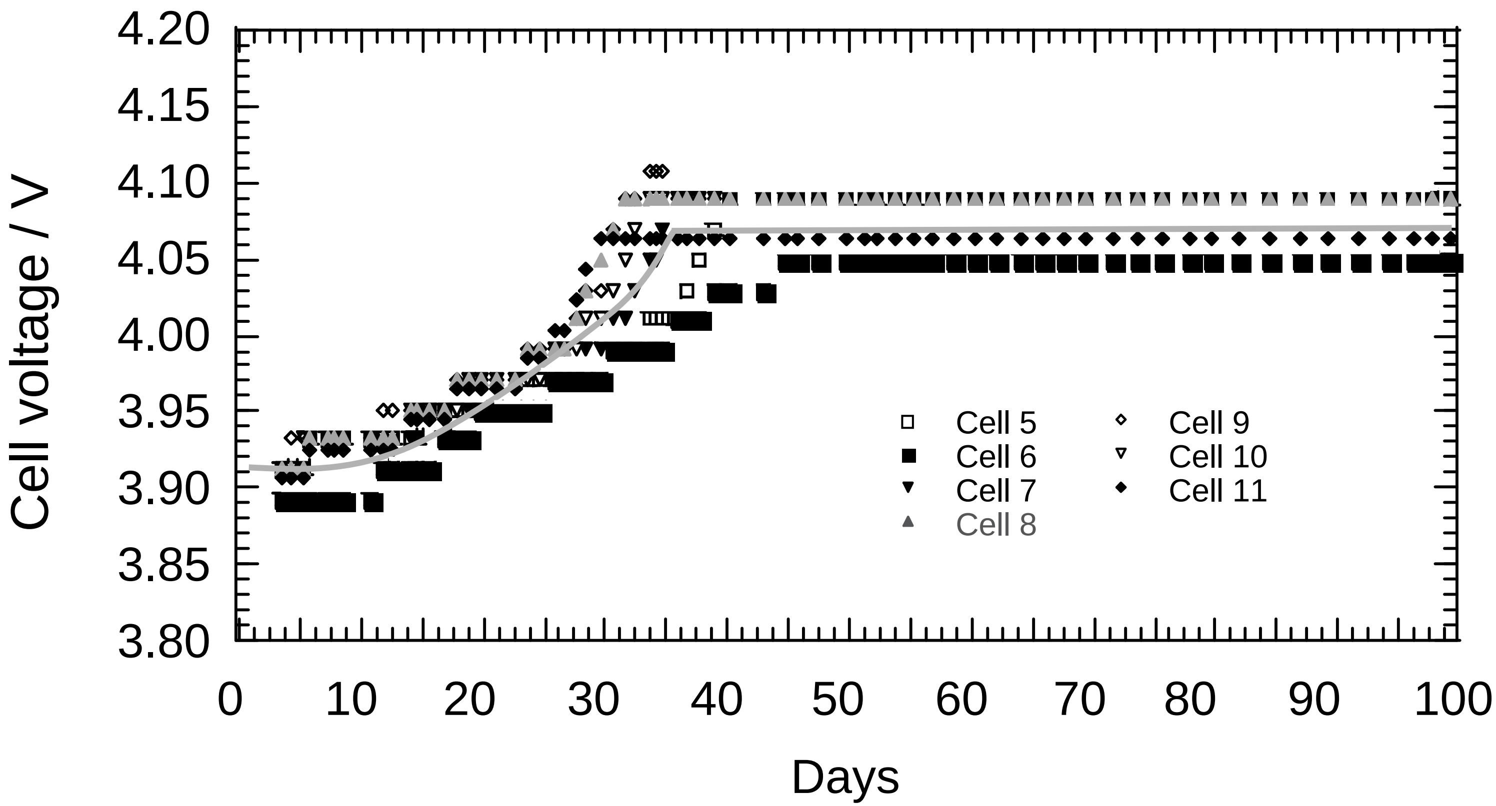

Fig. The day-to-day trend of the end-of-charge voltage (EoCV).
The voltage of cells 5-11 increased gradually and reached 4.05 - 4.10 V, after which the bypass circuit shunted the charging current.

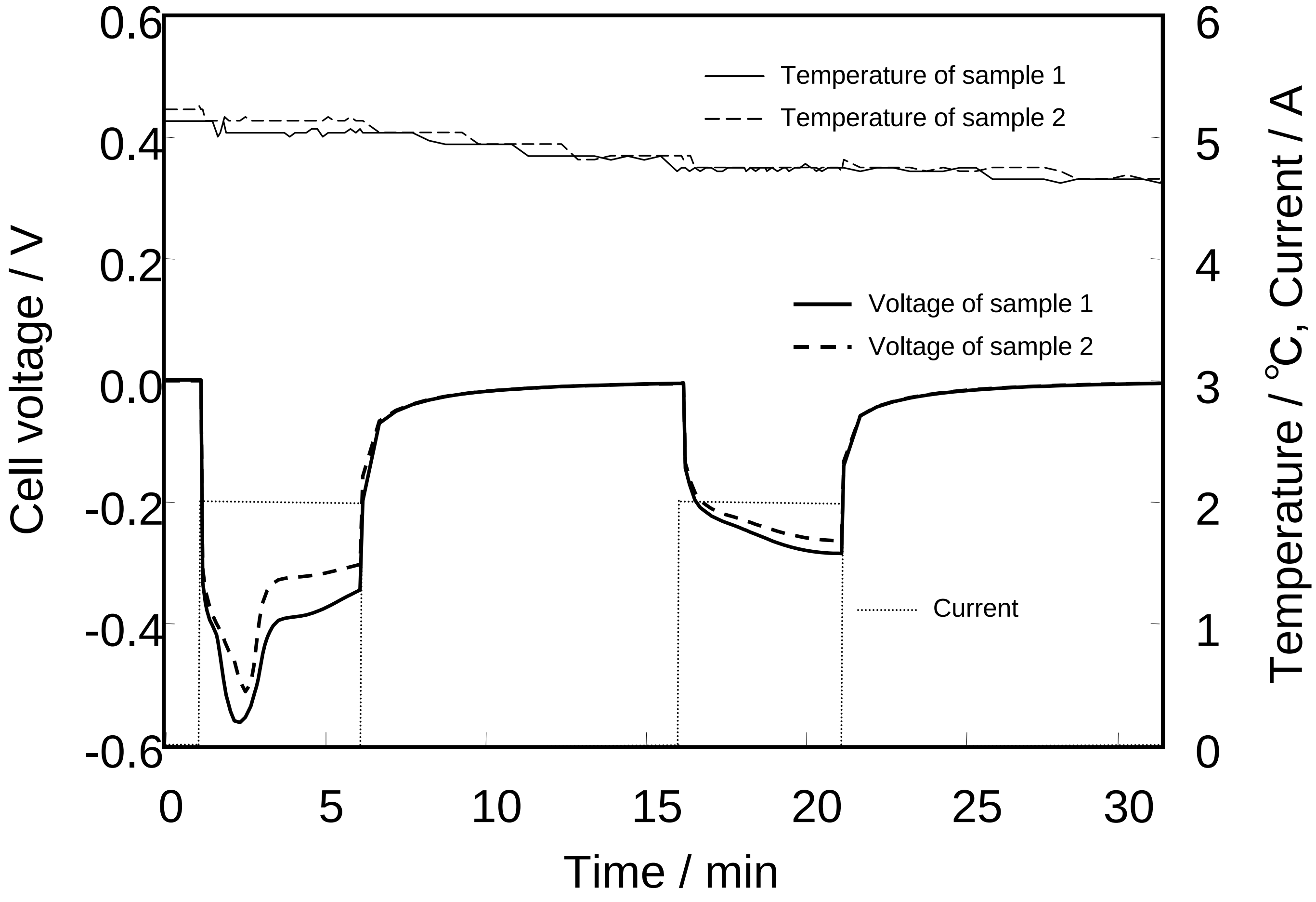

Fig. Discharge performance of the lithium-ion secondary cells. Two cells were discharged to 0 V. Current was drawn from the cells twice.

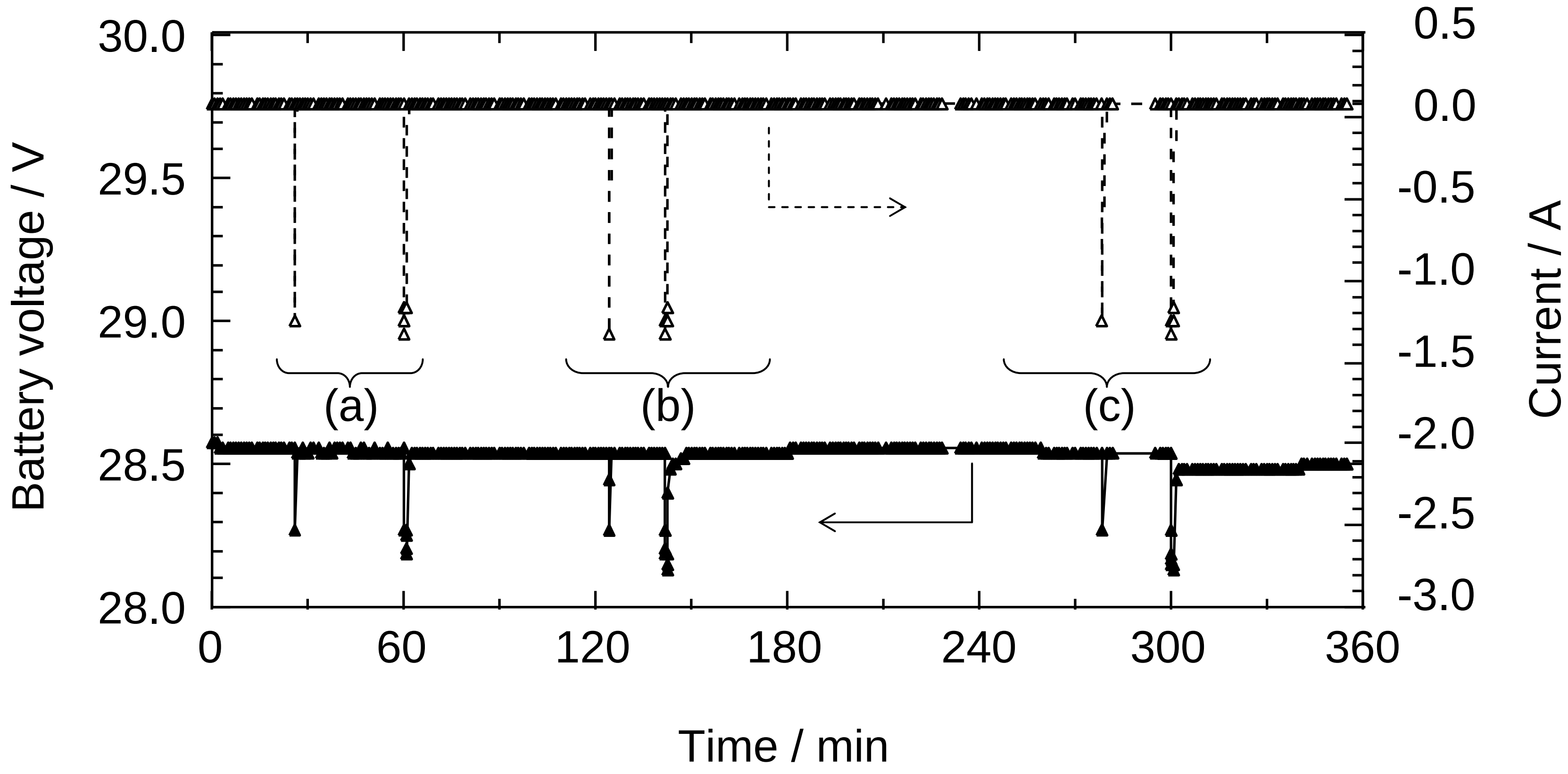

Fig. Telemetry data during HAYABUSA's lid-closure operation.
(a): The lid of the asteroid sample container was closed, and the tube to guide the sample into the sample container was pulled down.
(b): The sample container was injected into the Earth re-entry capsule.
(c): The spring was released to latch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

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 ー Lessons Learned from the Operation of the Interplanetary Spacecraft HAYABUSA’, Electrochemistry, pp. 950-957, Vol. 75 No. 12 (2007).

Y. Sone, et. al., ‘Storage of a lithium-ion secondary battery under micro-gravity conditions’, Journal of Power Sources, in press.

Summery

- Large lithium-ion secondary cells designed for space applications were used in the Japanese interplanetary spacecraft, HAYABUSA.
- When HAYABUSA attempted to leave the asteroid, the attitude control of the spacecraft malfunctioned.
- Four of the 11 series-connected cells had over-discharged during the malfunction.
- The lid of the asteroid sample container was still open. To close the lid and to inject the container into the Earth reentry capsule, power from the battery was required.
- The seven healthy battery cells were then slowly charged at minimum current using current leaked from the charge bypass circuit.
- Ground tests and simulations were conducted using similarly-built and intentionally over-discharged cells to evaluate the operational safety of this procedure.
- After the safety of the lithium-ion secondary cells was confirmed, the lid of the sample container could be closed. The asteroid sample was then transferred into the Earth re-entry capsule, and latching and sealing of capsule was completed successfully using power from the over-discharged lithium-ion secondary battery.