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Storage of a lithium-ion secondary battery under micro-gravity conditions

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ABSTRACT

'HAYABUSA' is a Japanese inter-planetary spacecraft built for the exploration of an asteroid named 'ITOKAWA.' The spacecraft is powered by a 13.2 Ah lithium-ion secondary battery. To realize maximum performance of the battery for long flight operation, the state-of-charge (SOC) of the battery was maintained at ca. 65% during storage, in case it is required for a loss of attitude control. The capacity of the battery was measured during flight operations. Along with the operation in orbit, a ground-test battery was discharged, and both results showed a good agreement. This result confirmed that the performance of the lithium-ion secondary battery stored under micro-gravity conditions is predictable using a ground-test battery.

1. Introduction

Lithium-ion secondary cells/batteries have received significant attention, due to their higher energy density compared with Ni–Cd, Ni–MH, and Ni–H_2 batteries. In the field of space technology, a number of current efforts have been focused on the application of lithium-ion secondary batteries in spacecraft [1–18].

One example is 'STENTOR', which attempted to demonstrate a SAFT 40 Ah lithium-ion battery system in geo-stationary orbit [6]. The European piggy-back satellite 'PROBA' uses lithium-ion batteries produced by ABSL Power Solutions Limited, using off-the-shelf lithium-ion cells manufactured by SONY [7]. The same technology was also applied to European planetary mission satellites such as the 'Rosetta' and the 'Mars-Express' [7].

The Japanese Aerospace Exploration Agency (JAXA) is also developing lithium-ion secondary batteries for spacecrafts used in earth orbit and for inter-planetary missions [10–18]. In the case of inter-planetary missions, lightweight and compact batteries are particularly critical. Thus, a lithium-ion battery is one of the most promising candidates for such applications [17,18].

For a spacecraft on an inter-planetary mission, it is covered with sunshine most of the time, and solar panels can be used to generate electricity. A battery requires storage with some amount of charge for long periods, and is only used in the case of a contingency, such as the loss of attitude control. However, lithium-ion secondary cells show decay in capacity if stored with a high state-of-charge (SOC). Therefore, appropriate control of the SOC is required to realize the best performance of the battery during a mission. An operational method for lithium-ion batteries needs to be developed to realize high performance systems [17,18].

The Japanese spacecraft 'HAYABUSA' (called 'MUSES-C' before launch) is an inter-planetary spacecraft that was launched in May 2003 for exploration of an asteroid named 'ITOKAWA' (1998SF36). The spacecraft mission was originally expected to last approximately 4 years [17]. In November 2005, HAYABUSA arrived at the asteroid, and after observing the surface, the spacecraft touched down. During these operations, some of the surface material of the ITOKAWA asteroid was most likely collected in the sampling container. However, after HAYABUSA had touched down on ITOKAWA in December 2005, the battery was over-discharged. The seven remaining healthy cells were slowly recharged using minimum current, and were used to seal the sample container with the asteroid surface sample [18].

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Fig. 1. Image of the HAYABUSA in space illustrated by Akihiro Ikeshita.

The battery used in the HAYABUSA spacecraft is a 13.2 Ah lithium-ion secondary battery [17,18]. In order to precisely understand the in-orbit performance of the lithium-ion secondary battery, the battery was discharged in a ground test as well during operation in orbit. In the present study, both of these results were compared and the storage performance of the lithium-ion secondary battery under micro-gravity conditions is discussed.

2. Experimental

Fig. 1 shows an image of the HAYABUSA spacecraft in proximity to the ITOKAWA asteroid. Table 1 shows the operational conditions of the battery. The battery was scheduled to be discharged for the launch, the earth swing-by, the ‘terminator operation’ at ITOKAWA, the touchdown operation for sample capture on the asteroid, and for re-entry into the earth’s atmosphere.

The deepest discharge was required for the ‘terminator operation’ on ITOKAWA. The operation was to observe the surface of the asteroid using the contrast near the boundary between day and night on the asteroid. Discharge of the battery was required down to 45% depth-of-discharge (DOD). Furthermore, it took 3.7 years after preparation of the cell to eventually approach ITOKAWA. Therefore, there was a requirement to protect the cell from decay in capacity during the mission.

Table 1
Expected performance of the battery

Event	Years[a]	Discharge performance	
		Current (A)	Capacity (Ah)
Launch	1.34	–	7.03
Earth swing-by	2.40	14.27	4.76
Touchdown on ITOKAWA	3.71	16.70	2.51
Terminator observation	3.79	17.61	5.95
Capsule re-entry to earth	5.44	15.23	3.43

[a] ‘Years’ was counted starting after preparation of the flight cells.

In general, the storage of the lithium-ion cells at a high SOC accelerates the decay of cell performance. A high SOC enhances the formation of a solid electrolyte interface (SEI) film. The formation of a SEI is thought to consume lithium-ions inside the negative electrode, resulting in degradation of the cell capacity. Furthermore, a SEI has a lower conductivity than the other materials used in the cell; therefore, it is thought that the cell impedance is increased by formation of a SEI [19–24].

Considering the performance of the HAYABUSA battery, for which a high DOD with a high discharge current is required after storage for over 3 years, the best method to maintain cell performance is storage at a lower temperature with a low SOC. However, in the case of a contingency, the battery must be appropriately discharged. Thus, it was decided that the temperature of the battery should be maintained at approximately 5 °C, and that the SOC level of the battery should be kept around 65%.

During the storage operation, the voltage in each cell was monitored, and this monitoring discharged the battery. The discharged capacity was recovered by a slight charge up to around 65% SOC once a week. For precise control of the SOC, 256 levels of charge voltage were prepared between 35.0 V/40 °C and 47.5 V/0 °C. If the charge current started to taper, the timer would cut-off the current in the case of over-charging. The period for the taper charge could be alternated from 0 to 9.1 h.

The battery charge condition was raised once a week; however, the temperature variation inside the battery and differences in performance of the monitoring circuit for each cell resulted in different SOC levels among the battery cells. For compensation of the SOC levels, the battery was charged using a balance circuit which bypasses the current when the cell voltage reaches 4.1 V. By spending time, the SOC level of each cell reaches the same level stepwise. After being completely charged, the battery was discharged to ca. 50% SOC using the heater-resistance of the spacecraft. The battery was then charged again to 65%, in order to be ready for any contingency operation. This operation was repeated every 4 months.

In order to understand the detailed performance of the flight battery, the capacity of the battery was measured in space. Firstly, the battery was charged up to 4.1 V cell^{-1}, and then discharged to 3.3 V cell^{-1}. Fig. 2 shows a block diagram of the electrical power subsystem (EPS) and the battery. The electric power generated by the solar array was regulated to 50 V using a series-switching regulator. To charge the battery, 500 mA of current was supplied to the battery through the battery charge regulator (BCR). The resistance of the heater used for the discharge was 8 Ω.

In addition to preparation of the flight battery, cells and a battery were also prepared for ground tests. Using these cells and battery, the operation of the battery on HAYABUSA was simulated. Following the operations in orbit, the ground-test battery was also charged and discharged under the same conditions as those used in orbit, so that the flight data could be compared with the ground-test results. These simulation tests were also used to determine the charge conditions after the balance operation.

Table 2 shows the cell specifications. The rated capacity of the cell is 13.2 Ah when the cell is discharged with 2.64 A (0.2 C) at 20 °C. The positive electrode is lithium cobalt dioxide ($LiCoO_2$) and the negative electrode is graphite. The energy density is 85 Wh kg^{-1}, which is smaller than that of commercial lithium-ion secondary cells. This design is based on the discharge performance requirements of the battery. The largest discharge current would be 17.61 A. Based on the discharge, the HAYABUSA mission would require a capacity of over 11.9 Ah at 0 °C. Considering the high discharge current rate and the decay of capacity during the long journey to ITOKAWA, a 13.2 Ah/570 g lithium-ion secondary cell was designed.

A photograph of the cell is shown in Fig. 3. The cell case is fabricated from stainless steel with dimensions of

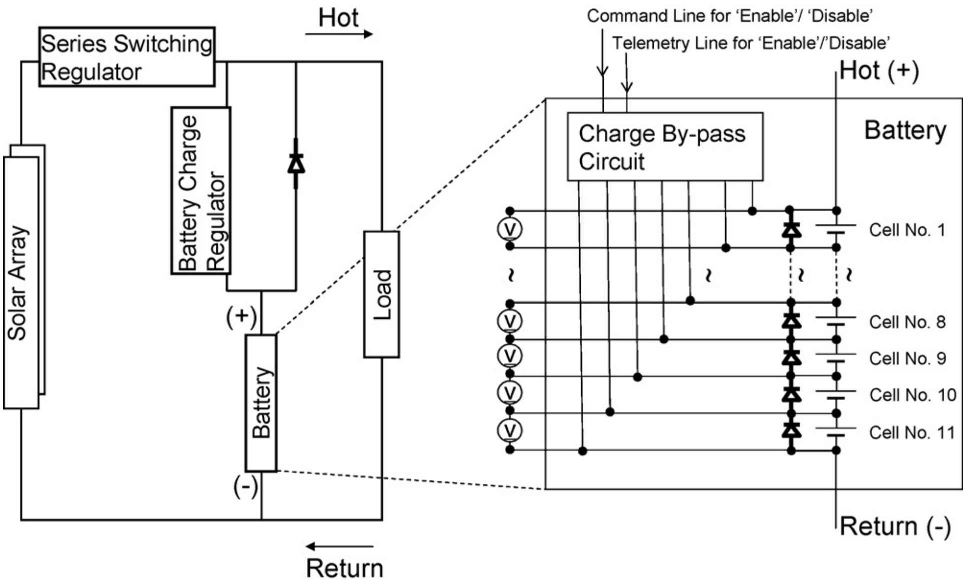

Fig. 2. Block diagram of the electrical power sub-system (EPS) used for HAYABUSA.

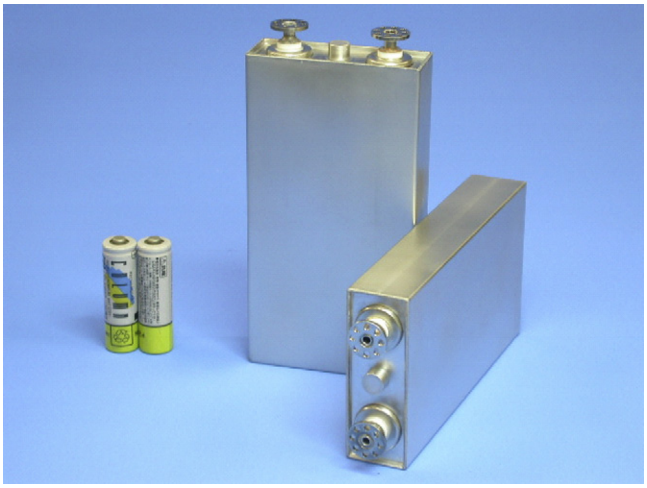

Fig. 3. Lithium-ion secondary cell used in the HAYABUSA battery. The lithium-ion cell is compared with an AA-size cell.

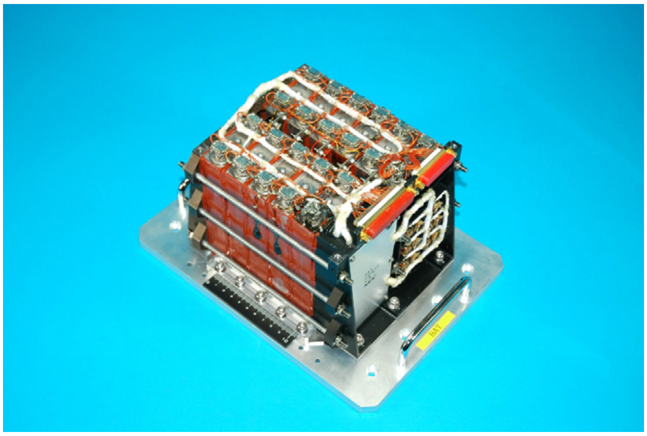

Fig. 4. The lithium-ion battery used on HAYABUSA, consisting of 11 cells connected in series. A by-pass circuit was installed in this battery stack.

69.3 mm × 132 mm × 24.4 mm. The terminal was sealed with a ceramic material. Fig. 4 shows a photograph of the battery, consisting of 11 cells connected in series. An electric circuit was designed to by-pass excess current. When the cell voltage reached 4.1 V, the charge current was by-passed through the circuit in order to finally realize the same full charge condition of all the cells. The balance circuit for 11 cells was packed and installed with the battery. For the charging operation, 500 mA was supplied to the battery.

3. Results and discussion

Fig. 5 shows the operations scheduled prior to launch. The SOC level was fixed at ca. 65% and every cell voltage was monitored. Self-discharge was compensated by charging once a week. Flight operation had been simulated using the ground-test cells and battery. The ground-test battery was maintained in the same way as the battery for orbit, using the same level of SOC. For the charge, it took 12 h for the cell voltages to reach 4.1 V, after which the balance circuit started to by-pass excess current. The current passing through the circuit generates heat; therefore, the temperature must be carefully monitored to avoid excessive heating of the cells due to the balance circuit. The difference in the cell voltages during the operation was monitored so as to be within 50 mV, which meant that the cells maintained a good balance.

Table 2
Specifications of the lithium-ion secondary cell used in HAYABUSA

Rated capacity[a]	13.2 Ah
Discharge voltage (average)[a]	3.6 V
Size	
Width	69.3 mm
Height	132 mm
Thickness	24.4 mm
Electrode material	$LiCoO_2$
Positive	Graphite
Negative	
Weight	<570 g
Energy density/mass	>85 Wh kg^{-1}
Energy density/volume	>215 Wh L^{-1}

[a] The rated capacity assumed charging at 6.60 A (0.5 C) and discharging at 2.64 A (0.2 C) at 20 °C.

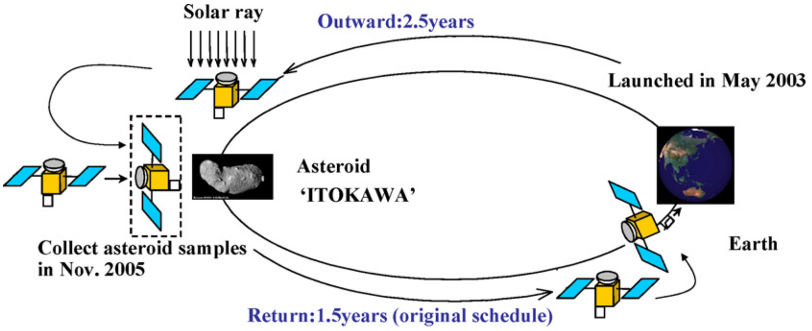

Fig. 5. Flight of HAYABUSA showing scheduled operations.

Fig. 6 shows the trend of the battery voltage in orbit after the launch. Firstly, the battery was charged to 100% SOC for the launch, and then discharged. The monitored battery voltage slightly increased with the elevated charge conditions, in order to fix the SOC level at ca. 65%. For compensation of the SOC levels, the battery was charged at 500 mA with the by-pass circuit enabled; when enabled, this circuit was designed to shunt the charge current at 4.1 V.

By spending time, the battery voltage reached 45 V (4.1 V cell^{-1}). After being charged, the battery was then discharged to ca. 50% SOC. The battery was then charged again to 65% for contingency operation readiness. In order to understand the exact performance of the flight battery, the capacity of the HAYABUSA on-board battery was also measured under micro-gravity.

Fig. 7 shows the discharge curve of the flight battery during the capacity measurements. The flight battery was discharged to 36 V (3.3 V cell^{-1}). After 1.2 years following the launch of the spacecraft, the battery capacity was directly measured using the flight battery under low gravity in orbit. The discharge load was 200 W, which could flow ca. 5 A from the battery. In this case, the cut-off voltage for the measurement was 36 V in the case of over-discharge, while the battery design permitted discharge down to 30.25 V (2.75 V cell^{-1}). The discharge curve for the battery in orbit was approximated, and the capacity of the flight battery was revealed to be 13.3 Ah.

In the case of lithium-ion secondary cells, the separator does not strongly absorb the organic solvent. If the solvent migrates from the separator to the free volume inside the cell under micro-gravity conditions, then the cell/battery loses its capacity. This fading capacity is unpredictable without measurement of the capacity of the battery in orbit.

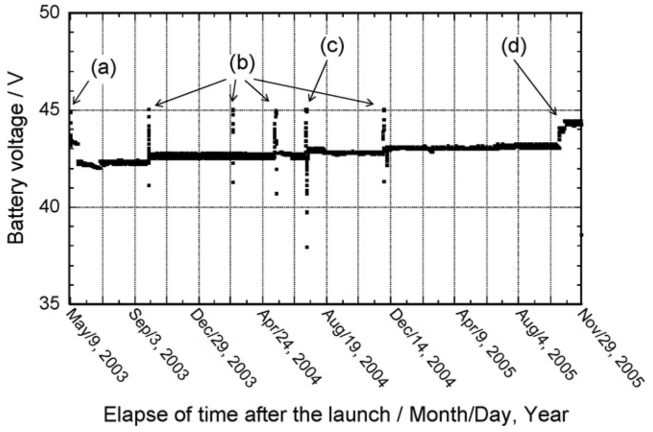

Fig. 6. Battery voltage trends during flight. (a) The battery was charged to 100% SOC for the launch. (b) For compensation of the SOC levels, the battery was charged using a balance circuit that by-passes the current when the cell voltage reaches 4.1 V. After being charged, the battery was discharged to ca. 50% SOC. (c) The capacity of the battery was measured in space. (d) Before HAYABUSA touched down on the asteroid, the battery was charged to 44 V (4.0 V cell^{-1}), so that the spacecraft could be operated for 40 min using battery power.

Fig. 8 shows the capacity decay since the battery cells were prepared. Prior to the launch of the spacecraft, the battery cells were stored at 5% SOC, and were stored inside a temperature controlled chamber at 0 °C. When the battery was required for the flight test, the battery was installed to the spacecraft and the temperature outside was controlled to approximately 25 °C. After the launch, the battery condition was maintained at 65% SOC, and the temperature was kept around 5 °C. The capacity measurements shown in Fig. 8 indicate that the capacity decay seems to be accelerated after the launch.

The capacity decay of the battery in space was compared to that obtained from the ground tests. Using the ground-test battery, the capacity decay was monitored to confirm whether the results would be identical to the flight capacity data. The ground-test cells and battery were stored since the flight operation of HAYABUSA started. The SOC condition for the ground-test battery was also maintained at approximately 65% during storage, in order to simulate the cruise phase of the flight battery. The cells and battery were stored inside a chamber to simulate the thermal conditions expe-

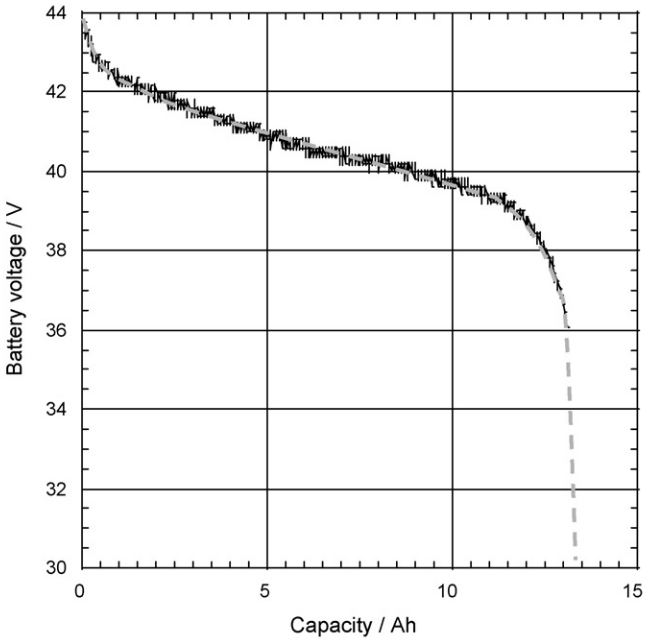

Fig. 7. Discharge curves of the lithium-ion battery during the in-orbit capacity measurement.

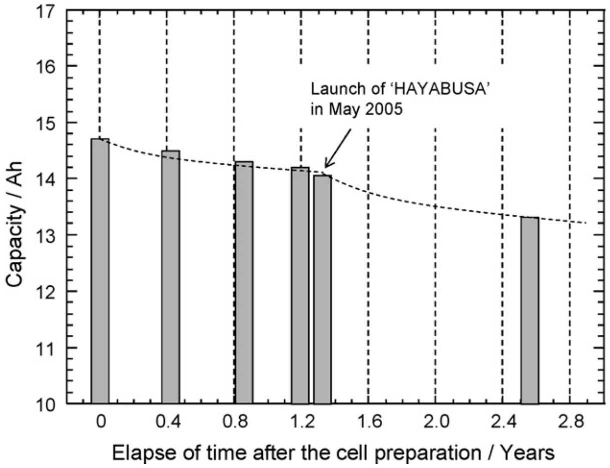

Fig. 8. Capacity decay of the battery before and after the launch of the spacecraft. The battery was stored at 0 °C prior to launch. After the launch of the spacecraft, the temperature of the battery was maintained at 5 °C.

rienced in space. Along with the balance operation and capacity measurements of the flight battery, the ground-test battery capacity was also measured at a charge of 500 mA up to 4.1 V cell^{-1}. When the battery was discharged, a 200 W discharge load was connected to the ground-test battery in order to simulate the discharge condition of the HAYABUSA battery.

Fig. 9 depicts the tendency of capacity decay for the lithium-ion secondary cells and battery since the start of the HAYABUSA flight. The capacity of the lithium-ion battery faded, which is usual, due to the calendar effect and charge and discharge cycling [24]. The HAYABUSA battery was hardly used, because the spacecraft received sunshine during the cruise phase and could generate electricity using solar cells. Since the battery was stored in space with a constant SOC, this fading capacity seems to be due to the calendar effect. With the formation of a SEI layer, lithium-ions in the electrode are consumed. Even though the SOC was maintained at approximately 65% during storage, the capacity of the lithium-ion secondary cells and battery was gradually degraded. The results obtained from the ground tests show good agreement with the capacity decay in space, as shown in Fig. 9. This confirms that the degradation of lithium-ion secondary batteries under micro-gravity conditions is predictable based on ground tests of the same batteries.

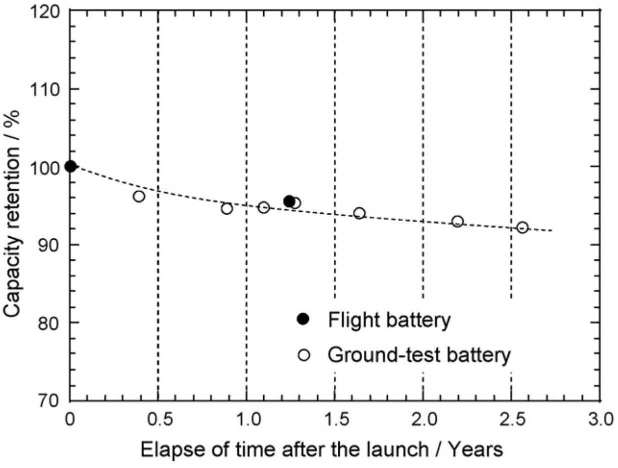

Fig. 9. Capacity decay trend of the battery over time.

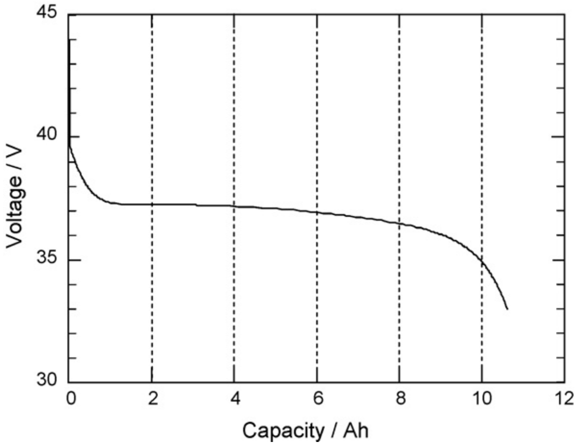

Fig. 10. Discharge curve of the ground-test battery during the capacity measurement. The battery was charged to 44 V at 5 °C.

When HAYABUSA arrived at ITOKAWA in November 2005, the battery was charged to the highest possible SOC. The original intention was to achieve this by charging the cells at 500 mA with the by-pass circuit enabled. However, the shunted current produces heat due to the resistance of semiconductors inside the circuit. When the HAYABUSA positioned near ITOKAWA, the communications delay between HAYABUSA and the earth was approximately 40 min. Although the temperature was monitored, and an increase in temperature had been detected, cutting the charge current would not have been possible. Therefore, the battery was charged without use of the by-pass circuit. The HAYABUSA battery had 256 levels of charge voltage between 35.0 V at 40 °C and 47.5 V at 0 °C. Once tapering of the charge current begins, a timer cuts off the current to avoid over-charging, and the period for this taper charging was varied from 0 to 9.1 h. A period of 2 h and a voltage of 44 V (4.0 V cell^{-1}) were selected as parameters for the taper charging. In addition to operation in space, the ground-test battery was also charged under the same conditions used in orbit. Fig. 10 shows the discharge curve of the ground-test battery after it was charged to 47.5 V at 0 °C. Based on the results shown in Fig. 9, the capacity of the flight battery was calculated. It was confirmed that the flight battery had a 10.5 Ah capacity, which meant that the HAYABUSA could be operated using battery power for 40 min.

On December 20 and 26 in 2005, HAYABUSA touched down on ITOKAWA. It is likely that the surface material from ITOKAWA entered the sample container.

4. Conclusions

In order to simulate the performance of lithium-ion secondary cells in space, the operation of the HAYABUSA flight battery was simulated using ground-test cells and a battery. The battery on the HAYABUSA spacecraft is a 13.2 Ah lithium-ion secondary battery. To realize maximum performance of the battery for a long period, the battery was stored in space with ca. 65% SOC.

The ground-test battery and cells were prepared and managed in the same way as those used on the HAYABUSA. The capacity of the flight battery in space was measured during the cruise phase of the spacecraft after storage under micro-gravity conditions for 1.2 years. The decay in the capacity during flight was compared to that obtained from the ground-test battery, and both results were in good agreement. This confirmed that battery storage performance in orbit is predictable using the evaluation of ground-test batteries.

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