Performance of Li-CF\textsubscript{x} Cells Installed in Earth Re-entry Capsule of Interplanetary Spacecraft ‘HAYABUSA’

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The period for beacon transmission / hours

20
19
18
17
16

Temperature / °C

-30 -20 -10 0 10 20 30

The capability of the battery is described as the period for the radio beacon transmission of the HAYABUSA Earth re-entry capsule. The duration of beacon transmission was estimated for the thermally degraded cells (●), flight-lot cells (○), and the cells recovered from asteroid journey (●).

Fig. Effect of the storage temperature to the discharge capability at 15°C after 12 years since the preparation of Li-CFx cells.
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The interplanetary spacecraft HAYABUSA returned to Earth on June 13, 2010, and a capsule containing an asteroid sample was released. The capsule deployed a parachute and transmitted a beacon signal indicating its position. The ground facilities successfully detected the beacon and determined the landing position of the capsule. For these actions, electricity was supplied by Li-CF₆ cells installed in the electric unit of the capsule. These cells had to work after storage for 12 years, including 7 years of space flight.

To confirm the performance of the flight cells, we prepared thermally degraded cells and tested their performance. We also discharged cells from the same lot as the flight cells. On the basis of the results, we expected proper performance of the cells up to landing of the capsule. These results were further compared with the discharge capability of the flight cells installed in the HAYABUSA capsule.

Comparison of all these data enabled a reliable prediction of the performance of the Li-CF₆ cells after an extended storage period, including a period in which the cells were subjected to space-flight conditions.

*Key Words: Lithium Primary Cell; Storage; Space Application; Thermally acceleration test*
1. Introduction

For space exploration missions, lightweight high-performance battery cells are important. Recently, numerous spacecraft for deep-space missions have used lithium-ion secondary cells,\textsuperscript{1-9} whereas lithium primary cells are sometimes used in equipment such as rovers, cameras, and capsules released from the main body of the spacecraft because of their high energy density and high storage capability. One example is the Rosetta lander, named Philae. The European Space Agency launched the comet orbiter Rosetta in 2004. It approached the comet 67P/Churyumov-Gerasimenko in August, 2014 and then released the lander Philae to observe the surface condition of the comet. The lander was equipped with both a lithium-ion secondary battery and a lithium primary battery. Its primary battery was based on LiSOCl\textsubscript{2} chemistry and was used for the landing operation on the comet.\textsuperscript{10,11} Deep-space missions require long-term operation for the journey, placing various performance requirements on the batteries of the spacecraft.

The interplanetary spacecraft HAYABUSA shown in Fig. 1 (a) was launched on May 8, 2003. The spacecraft approached the asteroid ITOKAWA and twice touched down on its surface. The final mission of the spacecraft was to return an asteroid sample to Earth. The asteroid sample was expected to be captured in a sample container in the ‘Earth Re-entry Capsule’ shown in Fig. 1 (b). However, a malfunction occurred after the touch-down operation. The spacecraft lost attitude control, and communication with HAYABUSA was terminated. Because the spacecraft lost sun acquisition, it could not generate electricity using its solar panels. Finally, the main bus battery using lithium-ion secondary
cells was over-discharged. Even after the malfunction, communication was reestablished with the spacecraft. The over-discharged battery was charged again by bypassing the damaged cells. The lid of the capsule container was finally closed using power from the battery. HAYABUSA finally returned to Earth and successfully released the Earth Re-entry Capsule shown in Fig. 2 on June 13, 2010. To pass through a severe aerodynamic heating corridor, the capsule was covered with forebody (front side) and the aftbody (back side) heatshields. Inside the ‘Instrument Module’, the On-board Electric Unit in Fig. 3 was installed to generate the beacon signal. Figure 4 shows the capsule flight procedure. After the capsule was released from HAYABUSA, it deployed heatshields and a parachute at an altitude of 5 km. The capsule then started to transmit a beacon signal that was subsequently used to determine the landing position. As a result of this process, the capsule was successfully recovered in the Woomera Prohibited Area of South Australia and was soon returned to Japan. When the container in the Instrument Module of the capsule was opened, dust grains recognized as the asteroid sample were detected.

When the capsule was released, it was necessary to be electrically powered using an internal primary battery based on Li-CF₃ shown in Fig. 5. This primary battery played a critical role by providing electricity to deploy the parachute, ignite the anchor of the heat shield, and transmit the beacon signal, which enabled the landing location of the capsule to be precisely tracked. Thus, understanding the capability of Li-CF₃ cells was important to the success of the capsule recovery operation. The cells were originally fabricated 12 years prior to their use in the capsule recovery mission, which included 7 years of
space flight.

We were provided with flight-lot cells that had been stored in a ground facility as spares for HAYABUSA. They were helpful in understanding the performance of long-flight batteries in space; however, the number of cells available for parametric tests was limited. To confirm the performance of the flight battery, the Japan Aerospace Exploration Agency (JAXA) collaborated with Panasonic Corporation Ltd (Panasonic).

Our strategy was as follows. We decided to prepare two types of dummy batteries using flight-lot cells and thermally degraded cells. Using test conditions proposed by Panasonic, thermally degraded cells were prepared to simulate 12 years of storage. We first estimated the discharge capability parametrically using the dummy battery constructed with the thermally degraded cells. On the basis of the results from the thermally degraded cells, the candidate of the operational condition of the HAYABUSA capsule was then proposed. Finally, the dummy battery fabricated using the flight-lot cells was discharged to confirm the operational condition of the HAYABUSA capsule two months prior to Earth re-entry.

On the basis of the results, the temperature of the capsule before the release from HAYABUSA, the battery performance during the period of flight in space, and the battery performance during transmission of the beacon signal to indicate the capsule’s landing point were predicted after long-term storage of Li-CF₃ cells including space flight. Eventually, we identified the landing point of the capsule released from HAYABUSA on June 13, 2010.
2. Design of the Battery

Figure 3 shows the Onboard Electric Unit installed in the Instrument Module of the HAYABUSA Earth Re-entry Capsule. The capsule was covered by heatshields made of a carbon composite to protect the internal units from the high temperatures generated during Earth re-entry. The sample container and the Onboard Electric Unit were located inside the capsule. For identification of the landing point of the capsule, a beacon signal was generated by and transmitted from the electric unit. To supply electricity to the unit, BR-type Li-CF, primary cells produced by Panasonic were used.

For the battery, a 5 Ah-class BR-C cell and a 1.8 Ah-class BR-A cell were used as shown in Figs. 3 and 5. The specifications of the cells are shown in Table 1. Three BR-C cells were connected in series, and the two serial connections were connected in parallel. In addition, three BR-A cells were connected in series and the four serial connections were connected in parallel. Finally, all these units were connected in parallel to create the battery for the capsule electric unit. This complicated battery configuration was adopted because of the internal structure of the capsule. A column-shaped sample container was located in the central part of the electric unit. The BR-C cells surrounded the column, and the BR-A cells were located on the bottom of the electric unit, as shown in Fig. 5. All of the cells were covered with silicon resin to protect them from the heavy impact associated with Earth re-entry, descent, and landing.
3. Experimental

For the capsule recovery mission, the electric circuits of the capsule were first warmed by electricity supplied from the HAYABUSA main body. Immediately before the capsule was released, the internal battery started to be discharged.

The capsule was originally planned to make an hours-long flight in space with drawing 59.5 mA of discharge current to heat itself. After Earth re-entry, a sensor would measure the deceleration to confirm re-entry into the Earth’s atmosphere. When the capsule approached an altitude of 5 km above sea level, the parachute would be deployed. This action was predicted to require a 575.0 mA pulse current from the battery. Along with the parachute, an antenna would also be released to transmit the beacon signal to indicate the capsule’s position. The transmission of the signal was expected to use 972.7 mA, which was the largest discharge current demanded from the capsule battery. During all these actions, the battery would have to sustain a voltage of 4.8 V (or 1.6 V/cell) to maintain all of the electronics in their active condition.

We acquired the spare flight-lot cells prepared during development of HAYABUSA. Eleven BR-A and seven BR-C cells were stored at approximately 0–10°C in a ground facility.

Panasonic provided the thermal test conditions used to accelerate the degradation of the cells. Under the Panasonic experimental conditions, the fresh cells were stored at 60°C for 84 days to simulate storage at 23°C for 12 years. We used the thermally degraded cells to construct a dummy battery. Four BR-A cells and two BR-C cells were connected in parallel to simulate the flight battery.
We conducted parametric tests using a dummy battery composed of the thermally degraded cells. A half-sized dummy battery was also constructed using the flight-lot cells. In the designed experiment, the thermally degraded cells were used to establish the appropriate discharge conditions, and the flight-lot cells were used to confirm the validity of the discharge conditions.

4. Results and Discussion

Li-CF₃ cells are known to tolerate long-term storage, which is why JAXA decided to use them for the interplanetary mission. However, the original launch schedule for HAYABUSA was postponed for three years because of problems encountered with the launch rocket; in addition, a malfunction of HAYABUSA during space flight led to an additional three-year delay of the scheduled return to Earth. We therefore needed to understand the precise performance of the cells approximately 12 years after the injection of their electrolytic solution, including 7 years of space flight.

We first needed to determine how long the beacon signal could be transmitted for. The beacon signal was intended to be transmitted when the capsule reached an altitude of 5 km above sea level. Our plan was to track the signal from different directions using four antennas and to then direct a helicopter to approach the landing position for recovery of the capsule.

Understanding the DC impedance of the Li-CF₃ cells was also very important. Figure 6 shows the temperature history of the capsule. The spacecraft was launched in May, 2003. During transit to the asteroid ITOKAWA (until November, 2005), the capsule’s temperature was maintained between −20°C
and −10°C. We lost communication with HAYABUSA at the end of 2005 as a result of a malfunction of the spacecraft. During the return to Earth, the temperature of the capsule was maintained at approximately −15°C.

The BR-A and BR-C cells were Li-CFe-type primary cells produced by Panasonic for residential applications such as controlling gas meters. In the case of discharge at high current, as required in the capsule application, an initial decrease of the discharge voltage should be observed, although the battery must sustain a voltage greater than 4.8 V (or 1.6 V/cell) to keep the electronics active. Otherwise, the electronics of the capsule would shut down, resulting in termination of the beacon signal.

To lower its DC impedance, the battery temperature should be increased. However, the spacecraft was under an important temperature-control protocol. In one instance, HAYABUSA experienced leakage of its hydrazine propellant, which has a boiling point of 2°C. To vaporize the leaking propellant, the heaters onboard HAYABUSA were used to “bake” or warm the spacecraft to 5°C. An important protocol establishing an upper limit on thermal control was thereafter established for HAYABUSA. The re-entry capsule consisted of a carbon composite that absorbed phenolic resin. The vaporization of the phenolic resin might exert a thrusting force on the spacecraft if it reaches a sufficiently high temperature. Especially in the case of near-Earth operation, the temperature must be kept less than 5°C.

Under the developed protocol, the target temperature selected for the capsule before separation from the HAYABUSA main body was less than 5°C. The capsule would make a flight in space for 3 h,
during which its temperature would decrease. The estimated lowest temperature was between $-15$ and $-20^\circ C$. In addition, the temperature in the Woomera Prohibited Area is typically greater than $15^\circ C$ in daytime. Thus, $-20$, $0$, and $+15^\circ C$ were selected as the test temperatures for the cells. The pattern for the discharge was estimated as follows: ① standby mode, $59.5$ mA for $3$ h; ② warming of the analog equipment, $575$ mA for $20$ min; ③ deployment of the parachute, $93.2$ mA for $0.5$ s; and ④ transmission of the beacon signal, $972.7$ mA.

Because the number of flight-lot cells was limited, the dummy battery fabricated using the thermally degraded cells was used to determine the suitable operating conditions. Figure 7 shows the discharge curves for the dummy battery fabricated using thermally degraded cells. The discharge voltage decreased to $1.8$ V at the beginning of the discharge in steps from ① to ④, even when the discharge was started at $-20^\circ C$. These results revealed that the operating temperature of the capsule should be increased to $5^\circ C$ prior to its release from HAYABUSA.

Figure 8 shows the discharge performance of the dummy battery fabricated using flight-lot cells. Because this battery was a half-sized dummy battery, its discharge performance in steps from ① to ④ was assumed to be one-half that of a full-sized battery. Despite a capacity loss of $1$ Ah estimated on the basis of leakage from the circuit, the beacon signal could be generated for more than $12$ h at $0^\circ C$ or $14$ h at $15^\circ C$.

Figure 9 shows the voltage when step ④ started, along with the discharge capability of the dummy batteries during the capsule’s beacon transmission period. When step ① started, the discharge
voltage initially decreased because of the high DC impedance of the LiCF$_x$. A large decrease of the discharge voltage was expected because the cells were originally developed for commercial applications involving long-term discharge at a low discharge current. An important objective of the tests was to determine the magnitude of the voltage drop; importantly, the voltage drop for the dummy battery constructed using the thermally degraded cells and that for the battery constructed using flight-lot cells were found to be similar. This suggests that the DC impedance of the Li-CF$_x$ cells was precisely simulated using the adopted thermal degradation test conditions. In addition, the capacities of the dummy batteries based on thermally degraded cells and flight-lot cells, which was estimated on the basis of the duration of the transmission of the beacon signal, were also similar.

The operable period of beacon transmission, as determined from the results shown in Figs. 7 and 8, is summarized in Table 2 and Table 3. To maintain operation of the capsule, 1.6 V/cell was necessary. The thermal analysis also indicated that the temperature of the capsule should remain above −20°C up to Earth reentry after the capsule was heated to 5°C. The circuit connected to the capsule battery drew a consistent leakage current after the battery was installed. The loss of capacity in the 12 years since the On-board Electric Unit was manufactured was 1.05 Ah. We therefore planned a strategy as follows: (1) The capsule should be warmed to 5°C. (2) The temperature should decrease to less than 0°C, but the electronics should remain operative. (3) After re-entry into the Earth’s atmosphere, the capsule should be warmed by the heat generated from the internal resistance of the battery. (4) When the capsule lands, the atmospheric temperature of the Woomera desert area is expected to be 15°C. Thus, the operable time of
the beacon signal should be ca. 14 h.

On June 13, 2010, the capsule transmitted its beacon signal in the Earth’s atmosphere and the signal was properly tracked. A helicopter determined the position of the capsule within 1 h, and the entire capsule was successfully recovered. When the capsule arrived in Japan, the battery in the On-board Electric Unit was discharged using the electric circuit of the on-board unit and the battery’s residual capacity was measured as shown in Fig. 10. The results showed that the beacon could be transmitted for an additional 7.6 h. The actual beacon was transmitted for 10.5 h, which meant that the total capability of the battery for beacon transmission was 18.1 h. This transmission time was far longer than that estimated on the basis of the ground tests.

The real current level was re-estimated using the recovered on-board unit, which revealed that the current for the beacon was 766.1 mA. The expected capacity was calculated again on the basis of the ground test results. All of the related results are shown in Fig. 11.

The flight-lot cells had been stored in a refrigerator at a temperature of between 0 and 10°C. The average temperature of the flight battery was about −15°C, but the capsule sometimes experienced temperature between −25 and 5°C. The temperature simulated by the thermal acceleration test was 23°C. Thus, the temperature was uncertain especially during the spaceflight, and the results did not exhibit an Arrhenius-type temperature dependence. However, Fig. 9 reveals that the beacon transmission period could be predicted to within an error of 30 min for 18 h discharge 12 years after fabrication of the Li-CF₃ cells, including interplanetary journey to the asteroid. In addition, a comparison of the ground test cells
with the flight battery indicated that cells intended for space exploration missions involving exposure to temperatures similar to those experienced by HAYABUSA can be stored at room temperature. All of the results obtained here were successfully reflected in the successive project, HAYABUSA-II.

5. Conclusion

For the HAYABUSA recovery mission, a battery based on Li-CFx cells was used for the Earth Re-entry Capsule. To estimate the operability of the battery, a dummy battery was constructed and used in a long-term storage simulation. By comparing the data from the thermal acceleration test, real-time storage experiments, and the flight experience, we obtained the following information:

1) The performance of the Li-CFx cells after long-term storage could be precisely estimated using appropriate thermal acceleration test conditions. The changes in the DC impedance and capacity were properly predicted on the basis of the thermal acceleration tests.

2) Space flight to a near-Earth-type asteroid did not affect the performance of the Li-CFx cells.

The information was not only applied for capsule recovery in the HAYABUSA mission but was also used in the development of HAYABUSA-II. We also expect the results obtained here not only to have implications for space exploration but also for future terrestrial applications of Li-CFx cells.

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dummy battery.

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Figure captions

Fig. 1  Artist’s image of interplanetary spacecraft HAYABUSA (a), and photograph of its Earth Re-entry Capsule (b).

Fig. 2  Internal structure of HAYABUSA Earth Re-entry Capsule.

Fig. 3  On-board Electric Unit of HAYABUSA Earth Re-entry Capsule.

A 3 series × 2 parallel connection of 5 Ah-class Li-CF, cells and a 3 series × 4 parallel connection of 1.8 Ah-class lithium primary cells were prepared. All serial connections were connected in parallel inside the electric unit.

Fig. 4  Flight procedure for capsule after separation from HAYABUSA.

Fig. 5  BR-A (a), and BR-C (b) cells used for On-board Electric Unit of HAYABUSA Earth Re-entry Capsule.

The cells were removed after the capsule was recovered. All cells were covered with resin to protect them against the impact associated with Earth re-entry, descent, and landing.

Fig. 6  Trend of temperature around battery for on-board electronics.

Temperatures at three different points (CPSL, CPSL Max, and CPSL Min) inside the capsule are shown.
Fig. 7  Discharge curves for thermally degraded cells simulating 12 years of storage (60°C for 84 days corresponds to about 23°C for 12 years)

Two 5 Ah-class Li-CF₃ cells and four 1.8 Ah-class Li-CF₃ cells were connected in parallel to prepare the dummy battery.

The solid lines show the discharge voltage, and the dotted lines show the surface temperature of the dummy battery. The discharge was started inside a thermal chamber controlled at −20°C (green lines), 0°C (blue lines), and 15°C (red lines). The electrical currents for ① standby for monitoring, ② warming the analog line, ③ deploying the parachute and igniting the anchor, and ④ transmitting the radio beacon were simulated.

Fig. 8  Discharge curves for flight-lot cells stored for 12 years.

One 5 Ah-class Li-CF₃ cell and two 1.8 Ah-class Li-CF₃ cells were connected in parallel to prepare the dummy battery.

The solid lines show the discharge voltage, and the dotted lines show the surface temperature of the dummy battery. The discharge was started inside the thermal chamber controlled at −20°C (green lines), 0°C (blue lines), and 15°C (red lines). The currents for ① standby for monitoring, ② warming the analog line, ③ deploying the parachute and igniting the anchor, and ④ transmitting the radio beacon were simulated. The current was adjusted for the size of the dummy battery.

Fig. 9  Initial discharge and discharge period to a voltage of 1.6 V/cell for beacon transmission (step ④).

The data were adopted from Figs. 5 and 6.
○ : Voltage for dummy battery constructed using flight-lot cells.

● : Voltage for dummy battery constructed using thermally degraded cells.

△ : Beacon transmission period for dummy battery using flight-lot cells.

▲ : Beacon transmission period for dummy battery using thermally degraded cells.

Fig. 10 Residual discharge capacity of flight battery after recovery of HAYABUSA capsule.

The battery was discharged at the current level for beacon transmission. The temperature was maintained at 15°C using a thermal chamber.

Fig. 11 Effect of storage temperature on discharge capability at 15°C.

The capability of the battery represents the duration of radio beacon transmission.

The duration of beacon transmission was estimated for the thermally degraded cells (●), flight-lot cells (●), and the cells recovered after the asteroid journey (●).
Table 1  The specifications of the lithium primary cells used for the ‘On-Board Electric Unit’ of HAYABUSA Earth re-entry capsule.

| Type             | BR-A          | BR-C          |
|------------------|---------------|---------------|
| Nominal capacity /mAh | 1800          | 5000          |
| Diameter /mm     | 17            | 26            |
| Height /mm       | 45.5          | 50.5          |
| Mass /g          | 18            | 41            |
| Standard discharge /mA | 2.5          | 5.0           |
| Nominal voltage /V | 3             |               |
| Separator Material | Positive     | Graphite fluoride |
|                  | Negative     | Lithium metal  |
Table 2  The voltage of the dummy battery using thermally degraded cells simulating 12 years storage at 23℃ when the transmission of the beacon (Step ④) starts, and the estimated period for the beacon transmission.

*The leak current though the circuit of the On-board electric unit was estimated as 10 μA. The 1.05 Ah capacity (10 μA×12 years) was drawn from the experimental data for the calculation of the real operable period.

| Temperature /℃ | Initial voltage when the transmission started /V | Period for the transmission of the beacon signal as obtained by the experiment /h (Cut off voltage; 1.6V) | Period for the practical transmission of the beacon signal after 12 years /h* (Cut off voltage; 1.6V) |
|----------------|-----------------------------------------------|-------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|
| 15             | 2.238                                         | 14.8                                                                                              | 13.9                                                                                              |
| 0              | 2.062                                         | 12.6                                                                                              | 11.8                                                                                              |
| -20            | 1.848                                         | 10.1                                                                                              | Not applicable                                                                                   |
Table 3  The voltage of the dummy battery using the flight lot cells when the transmission of the beacon (Step ④) starts, and the estimated period for the beacon transmission.

| Temperature /℃ | Initial voltage when the transmission started /V | Period for the transmission of the beacon signal as obtained by the experiment /h (Cut off voltage; 1.6V) | Period for the practical transmission of the beacon signal after 12 years /h* (Cut off voltage; 1.6V) |
|----------------|-----------------------------------------------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| 15             | 2.298                                         | 15.6                                                                            | 14.6                                                                            |
| 0              | 2.152                                         | 14.3                                                                            | 13.4                                                                            |
| -20            | 1.916                                         | 9.4                                                                             | Not applicable                                                                 |

*The leak current though the circuit of the On-board electric unit was estimated as 10 μA. The 1.05 Ah capacity (10 μA×12 years) was drawn from the experimental data for the calculation of the real operable period.
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