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Charge/discharge performance of lithium-ion secondary cells under microgravity conditions: Lessons learned from operation of interplanetary spacecraft Hayabusa

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ABSTRACT

The Japan Aerospace Exploration Agency (JAXA) is developing a lithium-ion secondary battery for deep space missions. Lithium-ion secondary battery was first used for the interplanetary spacecraft, Hayabusa. With a view to future long-term operations on the moon and interplanetary travel, the in-orbit performance of the lithium-ion battery of Hayabusa was examined. The battery cells maintained a constant performance over 2.7 years of operation as Hayabusa travelled to the asteroid Itokawa. To maintain cell conditions. The state of charge was fixed by using a balance circuit. The cell voltages differed by less than 60 mV during the operation, which is within the error expected based on the circuit design and the telemetry conditions.

1. Introduction

Research and development of energy-storage devices with high energy densities has recently received significant attention. Lithium-ion secondary cells/batteries have received special attention as they have higher energy densities than Ni–Cd, Ni–MH, and Ni–H_2 batteries. In the field of space technology, many studies have focused on using lithium-ion battery systems on spacecraft [1–20].

One example is Stentor, which attempted to demonstrate the use of a SAFT 40 Ah lithium-ion battery system in a geostationary orbit [6]. Unfortunately, the demonstration failed because the spacecraft could not be injected into the orbit due to a problem with its launcher. The European piggy-back satellite *Proba* employs lithium-ion batteries produced by ABSL (formerly AEA) that uses off-the-shelf lithium-ion cells from Sony [7]. The same technology was also applied to European planetary missions such as the satellite *Rosetta*, the Mars Express, and the Mercury Planetary Orbiter [7]. Today, many satellites use lithium-ion secondary cells for the bus battery.

The Japan Aerospace Exploration Agency (JAXA) has also been developing lithium-ion secondary cells for aerospace applications [10–20]. One example is the *Hayabusa* spacecraft, which used 13.2 Ah lithium-ion secondary cells [17–19]. *Hayabusa* travelled to the asteroid *Itokawa* and brought a sample of the asteroid back to the Earth. It was launched in May 2003 and returned to Earth on June 2010. The battery should be lightweight to conserve the propellant of the launcher and spacecraft, especially for interplanetary missions. When *Hayabusa* was being designed, a lithium-ion secondary battery was ultimately adopted for the main bus battery to reduce the spacecraft mass.

Hayabusa used 13.2 Ah lithium-ion secondary cells [17–19]. To maximize the battery performance for long-term operation, the state-of-charge (SOC) of the battery was maintained at ca. 65% during storage in case it was needed for contingency operations. The battery was used during the Earth swing-by and touch down on *Itokawa* and it was used to close the lid of the sample container [18].

After the launch of *Hayabusa*, we used 3 Ah lithium-ion pouch cells on the satellite *Reimei*. The cells were off-the-shelf lithium-ion secondary cells that used spinel manganese oxide for the positive electrode. The satellite was in a low Earth orbit and the lithium-ion secondary cells need to be charged and discharged 15 times per day. This satellite remains operational after 6 years in space and its battery has been charged and discharged over 30,000 times.

Another example of an application of lithium-ion batteries is the H-II Transfer Vehicle (HTV), which supplies materials to the International Space Station. The JAXA HTV project developed 100 Ah and 200-Ah-class lithium-ion secondary cells that have a high energy density. We performed simulations to evaluate the performance of

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Fig. 1. Artist's impression of *Hayabusa* touching down on the asteroid.

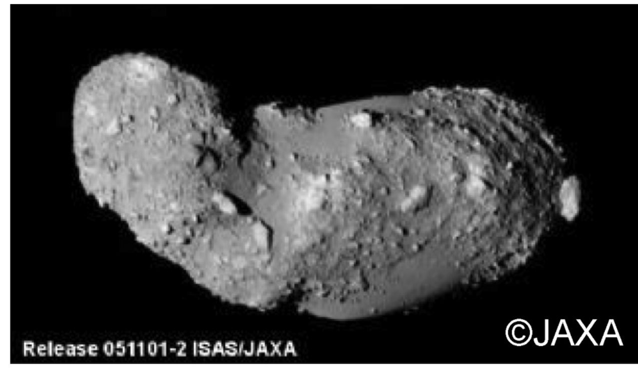

Fig. 2. Photograph of the asteroid *Itokawa*. The distance between *Hayabusa* and the Earth was 300×10^6 km when the spacecraft approached *Itokawa*.

this cell for lunar missions. This cell was repeatedly charged at 50 °C and discharged at −20 °C to simulate energy management on the Moon at night [20].

New missions and projects use lithium-ion technology. In most cases, long-term operation of the spacecraft is critical so that the ongoing operability of lithium-ion secondary cells over many years is very important. However, very little is known about the long-term operability of lithium-ion secondary cells under micro-gravity conditions.

In Ni–Cd, Ni–MH, and Ni–H_2 cells used for space missions, the electrolyte solvent was contained in a nylon/polypropylene separator. The electrolyte solvent was an aqueous solution of KOH, which can be contained in the separator even under microgravity conditions. In contrast, lithium-ion secondary cells use an organic solvent and a polypropylene separator. When we started using lithium-ion secondary cells in space, we had no specific information regarding how well the solvent would perform in space. Furthermore, we did not have any information about cell capacity degradation or the increase in the impedance under microgravity conditions.

Dendrite growth has been reported to be accelerated under microgravity conditions due to reduced convection [21]. If this is true, lithium-ion secondary cells may rapidly degrade during space missions. Since the performance of lithium-ion secondary cells in space is unknown, it is important to discuss their performance in space based on their electrochemistry. To confirm the operability of the cells in space, we investigated the performance of lithium-ion secondary cells that had already been used in space. In this paper, we discuss the charge/discharge performance of the lithium-ion secondary cells used for *Hayabusa* that had been stored for many years under micro-gravity conditions.

2. Experimental

Fig. 1 shows an artist's impression of *Hayabusa*. It was launched on 9 May 2003, and its destination was the asteroid *Itokawa*, which is shown in Fig. 2. The distance from the asteroid to the Earth was 300×10^6 km (2 au). The ultimate mission of the spacecraft was to bring a sample from the asteroid to Earth. The spacecraft spent over 2.5 years travelling to the asteroid. The most important aspect of the battery operation was to minimize degradation of the cell performance.

The spacecraft used the lithium-ion secondary cells are shown in Fig. 3. The cells were fabricated by Furukawa Battery Co. Ltd. The rated capacity of the cell was 13.2 Ah when the cell was discharged with 2.64 A (0.2 C) at 20 °C. The positive and negative electrodes were $LiCoO_2$ and graphite, respectively. The electrolyte was $LiPF_6$ dissolved in a mixture of ethylene carbonate and diethyl carbonate. The cells had an energy density of 85 Wh/kg, which is lower than that of commercial lithium-ion secondary cells. The cell was designed based on the discharge requirements of the battery. The maximum discharge current was 17.61 A. Based on this discharge, the *Hayabusa* mission would require a capacity of over 11.9 Ah at 0 °C. A 13.2 Ah/570 g lithium-ion secondary cell was designed by considering the high discharge current and the decay of the capacity. The cell case was made from stainless steel and was 69.3 mm wide, 132 mm high, and 24.4 mm thick. The terminal was sealed with a ceramic [19].

Fig. 4 shows the battery fabricated from the cells, while Fig. 5 shows a block diagram of the electrical power subsystem of the spacecraft. Electricity was generated by the solar panels. The electrical power from the solar panels was regulated to 50 V by the series-switching regulator and was then supplied to the bus systems. The battery consisted of 11 cells connected in series. The battery was charged by supplying it with a charge current of 500 mA through the battery charge regulator [19].

To prevent overcharging the lithium-ion secondary battery, it was initially charged using a constant current and it was then continuously controlled to maintain a constant voltage after the battery voltage reached the upper limit of the voltage. The charge current started to decrease when a constant charge voltage was provided.

The same charging method is also suitable for controlling the battery SOC. The SOC under the open-circuit condition should be determined from the voltage of the battery/cell when the

Fig. 3. Lithium-ion secondary cell used in *Hayabusa*. The cell capacity was 13.2 Ah when it was charged by 0.2 C and discharged by 0.5 C. The AA cells indicate the size of the *Hayabusa* cell.