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Development and on-orbit operation of lithium-ion pouch battery for small scientific satellite "REIMEI"

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ABSTRACT

A lithium-ion battery was developed using off-the-shelf pouch cells and launched with a small scientific satellite "REIMEI." The cells were potted with polyurethane or epoxy resin to protect the battery from vacuum in space. Preliminary experimental test results of pouch cells potted in a soft aluminum cap suggested that the cells tended to swell in vacuum, although they had been reinforced with the resins. Bread board models (BBMs), in which pouch cells were potted with resins in a hard aluminum case, were fabricated for cycle life performance tests in the laboratory. The test results indicated that the performance of epoxy-potted BBM was superior to that of the polyurethane-potted BBM. The measured cell resistance implied that the electrolyte solution leaked through the polyurethane resin, resulting in premature deterioration. The epoxy resin was used for the flight battery. The end-of-discharge-voltage (EoDV) trend of the flight battery on orbit was compared with the laboratory test results corrected based on a post-launch cycle test using a fresh cell. The corrected EoDV trend in the laboratory was in good agreement with the on-orbit trend for the early cycle period, indicating that the on-orbit battery was not inadvertently affected by conditions in space.

1. Introduction

Lithium-ion cells and batteries are currently widely used for portable devices such as cellular phones, tablets, and laptops. In addition, they are the subject of extensive research and development for application in electric vehicles. Lithium-ion batteries offer a significant advantage in terms of specific energy over traditional alkaline batteries, such as Ni–Cd and Ni-MH batteries, especially for mobile applications. Thus, they are promising for not only terrestrial but also space applications where energy storage devices having high specific energies are strongly desired.

Lithium-ion batteries for space applications have already been developed [1], tested [2–9], and implemented [10–12]. In general, batteries for space applications, such as rockets, satellites, and spacecraft, are designed considering the harsh vibrations during lift-off and the vacuum in space. Robust metallic containers, which are not ideal from the viewpoint of specific energy, are used for batteries to withstand such conditions. On the other hand, for terrestrial applications, pouch casings, which allow a very thin and light cell design, have been developed and employed to achieve even higher specific energies. They are considered suitable not only for achieving high specific energies but also in high power applications, although the lack of rigidity of the casing cells makes them vulnerable to external mechanical damage, and they are prone to swell under improper conditions such as elevated temperature [13] and overcharging. Pouch cells are also attractive for space applications because of their high specific energy, but they need to be designed considering the harsh conditions in space. Lithium-ion polymer pouch cell batteries have already been developed and tested [14] for some space applications such as spacesuits.

We have addressed the above issues originating from pouch casing by using polyurethane- or epoxy-based resin for mechanical reinforcement. We developed a lithium-ion battery using off-the-shelf pouch cells for the small piggyback satellite "REIMEI" (Fig. 1). REIMEI (formerly known as INDEX) is a small scientific satellite designed for aurora observations and demonstration of advanced satellite technologies [15,16]. REIMEI was launched by the Dnepr rocket into a nearly sun synchronous polar orbit on August 23, 2005 from Baikonur, Kazakhstan, and is presently orbiting the Earth for its scientific observations. The REIMEI power system had three major advanced technologies to be demonstrated: (1) multi-junction photovoltaic cells, (2) solar concentrated paddles with thin

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Table 1
Specifications of the lithium-ion pouch cell used for REIMEI.

Electrode	
Positive	
Active material	$Li_xMn_2O_4$-based
Current collector	Al
Negative	
Active material	Graphite-based
Current collector	Cu
Electrolyte	1 M $LiPF_6$EC/DEC(3:7 by wt%) + additives
Rated capacity	3.0 Ah
Weight	75 g
Dimension	145 mm × 80 mm × 4 mm
Specific energy	158 Wh kg^{-1}
Charge voltage	4.1 V (4.2 V)
Lower voltage limit	3.0 V

film reflectors [17,18], and (3) a lithium-ion battery using off-the-shelf pouch cells.

Prior to launch, the tolerances of resin-potted pouch cells in vacuum were evaluated. Cycle life performance tests for bread board models (BBMs) using a combination of resin potting and a hard aluminum case for reinforcement were conducted in a vacuum chamber located in our laboratory. Based on experimental laboratory test results, a flight battery was designed and developed as one of the three major advanced technologies of the REIMEI power system.

Cycle life of non-potted lithium-ion pouch bare cell used for REIMEI was evaluated for 5000 charge–discharge cycles at atmospheric pressure [19]. Aged pouch cells were disassembled and the electrochemical performance of harvested electrodes was investigated using both two- and three-electrode pouch cells [20]. This paper describes the development process and presents the on-orbit operation data of the lithium-ion pouch battery for REIMEI.

The paper is organized as follows. First, preliminary experimental test results of pouch cells potted in a soft aluminum cap and cycled in vacuum are shown and discussed in Section 3. Long-term charge–discharge cycle tests were performed for two BBMs, and the influence of potting material on the life performance of the pouch cells is discussed in Section 4. Section 5 focuses on comparative analysis of battery performances in the laboratory and on-orbit in order to determine the on-orbit battery health.

2. Experimental

2.1. Cell specification

The specifications of off-the-shelf lithium-ion pouch cells (SH11-2626, NEC/TOKIN) are given in Table 1, and a photograph of one such cell is shown in Fig. 2. The cell design uses a mixture of active $Li_xMn_2O_4$-based material, carbon additives, and binder coated onto an aluminum current collector for the positive electrode, and a mixture of graphite and binder coated onto a copper current collector for the negative electrode (details of thicknesses, loading densities, and porosities are proprietary). The liquid electrolyte was 1 M $LiPF_6$EC/DEC (3:7 by wt%) with a few weight percent additives.

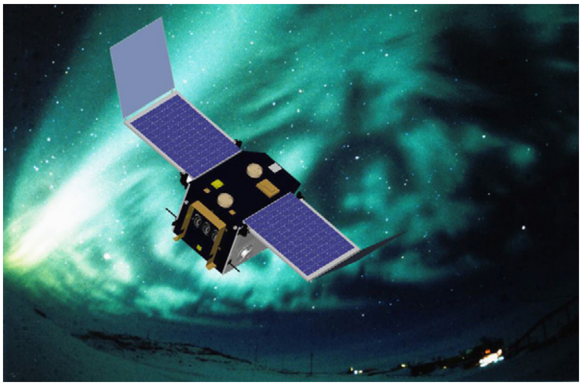

Fig. 1. Image of REIMEI.

Table 2
Charge–discharge cycle condition for the laboratory tests.

Mode	Charge	Discharge
Scheme	CC–CV	CC
Voltage	4.1 V (4.2 V)	–
Current	1.5 A	1.0 A
Time	65 min	35 min
Temperature	25 °C	

2.2. Potting materials

As mentioned in Section 1, swelling and mechanical damages because of the lack of rigidity are the major concerns about pouch cell designs. Thin aluminum laminated film was not sufficiently strong to retain the pouch cell in vacuum, where the cell tends to swell due to a difference between the vacuum pressure and the solution vapor pressure. Wang et al. reported that in vacuum, the swelling of pouch cells with liquid electrolyte causes a decrease in both capacity and voltage [21]. In addition, a bare pouch cell without any reinforcement could not withstand vibrations that occur during lift-off.

To reinforce the pouch cells to withstand sub-atmospheric pressure in space, polyurethane- or epoxy-based resins were used to improve their rigidity. Both resins were two-part adhesives; the polyurethane resin was a mixture of resin (Uralane 5753A, Ciba) and hardener (Uralane 5753B-LV, Ciba) (1:5 by wt%), and the epoxy resin was a mixture of resin (CY1005, Nagase ChemteX) and hardener (HY1006, Nagase ChemteX) (4:1 by wt%). Properties of the potting materials are shown in Table 3. Both resins are widely used in both terrestrial and space applications [14,22]. Tolerance against vacuum and cycle life performance of cells potted with resins are evaluated and discussed in Sections 3 and 4.

2.3. Charge–discharge cycle condition and cycle life requirement

The charge–discharge cycle condition specified prior to the launch is shown in Table 2. The charge and discharge periods of

Fig. 2. Lithium-ion pouch cell used for REIMEI.

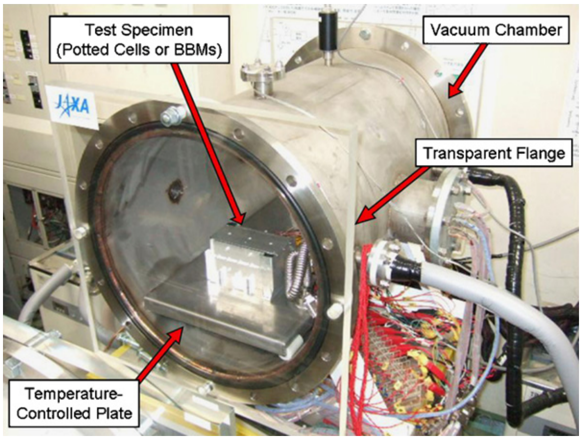

Fig. 3. Experimental setup for charge–discharge cycle tests in a vacuum chamber.

a single cycle are easily determined by the duration of sunlight and eclipse. During sunlight periods, solar arrays equipped to the satellite generate electricity to power the loads and charge the battery. On the other hand, during eclipse periods, the battery discharges to power the loads. Since REIMEI was to be launched into a nearly sun synchronous polar orbit with a 65-min sunlight period followed by a 35-min eclipse period, the laboratory tests included charge–discharge cycle with similar 65-min and 35-min charging and discharging periods, respectively. Although the cycle condition shown in Table 2 was a baseline condition specified from the satellite system design standpoint, the actual on-orbit cycle condition was expected to change depending on circumstances.

The experimental setup for cycle tests in a vacuum chamber is shown in Fig. 3. The cells were placed on a temperature-controlled plate in the vacuum chamber with transparent flanges for visual observations. The plate temperature was maintained at 25 °C using a coolant circulator (TGB120AA, Advantech). The cells were cycled using the battery charge–discharge testing system (TOSCAT3000, Toyo System) under the conditions given in Table 2.

For REIMEI's battery, the end of life is defined as the time when the end-of-discharge-voltage (EoDV) of the battery falls below an under-voltage-control (UVC) level of 26.25 V, or 3.75 V per cell, under which on-board devices and instruments may not able to function properly. The minimum life requirement for the battery was 3 months or approximately 1300 charge–discharge cycles.

In laboratory tests, the cells were cycled with constant current–constant voltage (CC–CV) charge and CC discharge schemes. To prolong the cycle life, two levels of charge voltage were provided. The charge voltage was set to 4.1 V per cell (28.7 V per battery) for an early period to suppress calendar degradations. When the EoDV decreases down to the UVC level due to degradation, the charge voltage is increased to 4.2 V per cell (29.4 V per battery) to increase the available cell capacities.

3. Preliminary cycle tests of pouch cells potted with resin in soft aluminum cup

The pouch cells were potted with polyurethane or epoxy resins to improve the tolerance against vacuum in space. Fig. 4(a) and (b) shows photographs of two pouch cells potted with polyurethane and epoxy resin in soft aluminum cups, respectively. The thickness of the potted cells in an out-of-plane direction was approximately 16 mm. The cycle tests began at atmospheric pressure, and after several dozen cycles, the pressure of the vacuum chamber was reduced to sub-atmospheric pressures (approximately 20 Pa) using a rotary pump.

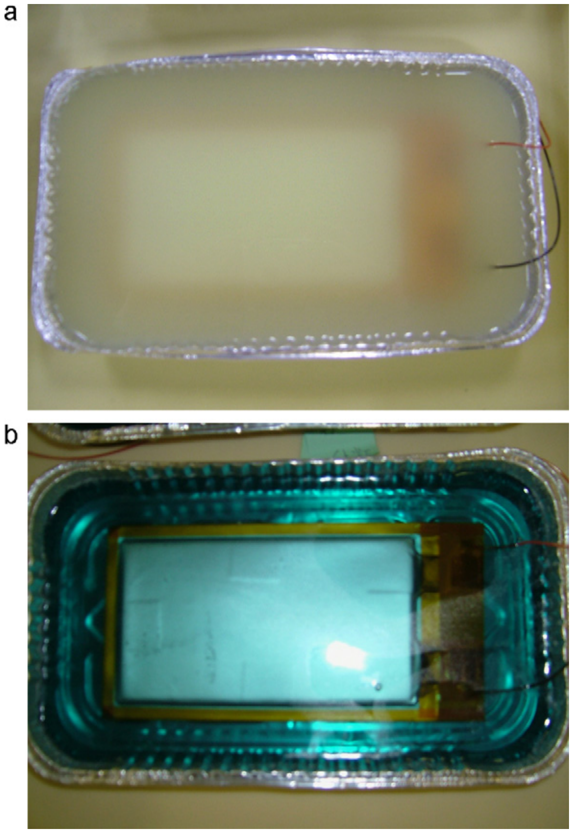

Fig. 4. Lithium-ion pouch cells potted with (a) polyurethane and (b) epoxy resin in a soft aluminum cup.

Resultant EoDV trends of the pouch cells potted with polyurethane and epoxy resins are shown in Fig. 5(a) and (b), respectively. The cell potted with the polyurethane resin swelled up as the chamber pressure decreased, as shown in Fig. 6, and its EoDV decreased. After the chamber pressure was restored to atmospheric pressure, the EoDV recovered as the swelling disappeared. However, the recovered voltage level (after the 160th cycle) was lower than that before the chamber evacuation (before the 60th cycle). The EoDV of the cell potted with epoxy resin gradually decreased in vacuum, although no swelling was observed visually. The EoDV of the epoxy-potted cell recovered slightly after the chamber pressure returned to atmospheric pressure.

Ohmic resistances (including resistance of electrolyte, tabs, and leads) of the potted cells at 1 kHz were measured at a cell voltage of 4.1 V at 20 °C both before and after the cycle tests. The measured ohmic resistances of the cells potted with polyurethane and epoxy resin were both 40 mΩ before the cycle tests, but after the tests, they increased to 43 and 42 mΩ, respectively. Capacity retentions were measured to be 93.6% and 95.8%, respectively. In comparison with cells in BBMs, which will be discussed in Section 4, the increase rates of resistance were rather higher, whereas the capacity retention ratios were comparable.

The decreases in EoDV in vacuum are deemed to originate from an increase in internal impedance and/or capacity losses due to swelling as the same tendency has been reported elsewhere [21]. The swelling leads to an increase in contact resistance not only between electrolyte and electrodes but also between electrode active materials and current collectors due to exfoliations. In addition to the increase in impedance, capacity loss is also expected because the swelling may have resulted in stress at the electrodes. However, since the cycle tests indicated that the capacity retentions were comparable to those of cells in BBMs (the results of

BBMs are presented in Section 4.2), the capacity loss in vacuum was considered unlikely or just recoverable.

Since detailed investigation, including measurement of AC impedance and capacity in vacuum, was not made during preliminary testing, a cause of the EoDV decrease in vacuum cannot be identified from the experimental results obtained in this section. However, these results are considered valuable, as they imply that swelling occurred to some extent even in the epoxy-potted cell, although it was not observed visually. Once the cell swelled in vacuum, internal conditions determining the internal resistance were deduced not to fully recover, and thus, the EoDVs did not recover completely. These results suggested that more reinforcement, in addition to resin, is required to retain the performance of pouch cells in vacuum.

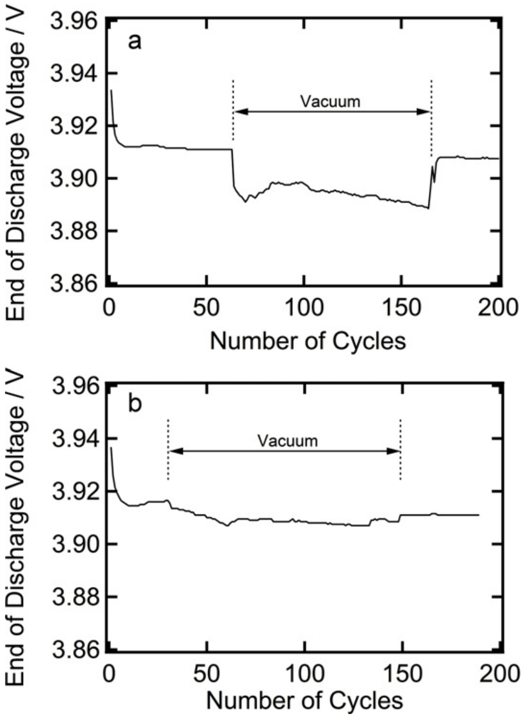

Fig. 5. Performances of pouch cells potted with (a) polyurethane and (b) epoxy resin in vacuum.

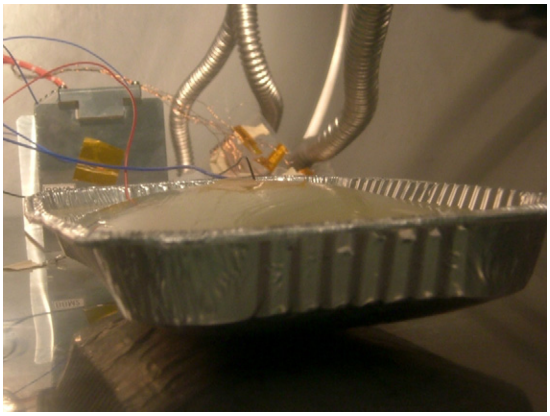

Fig. 6. Swelling of pouch cell potted with polyurethane resin in vacuum.

4. Cycle life performance tests for bread board models

4.1. Bread board models

Hard aluminum cases were used to improve the rigidity of resin-potted pouch cells, and two BBMs were fabricated using polyurethane or epoxy resin for cycle life performance tests in vacuum. Seven bare cells, Cells 1–7, were physically stacked (not connected electrically), and then placed in the aluminum case having geometry similar to that of a flight battery (see Fig. 12). The aluminum case had two separate compartments because the flight battery consisted of two strings in parallel (details of the flight battery will be described in Section 5.1). Physically stacked cells were potted with polyurethane or epoxy resin in one of the compartments, and the other compartment was filled with only resin.

A decrease in liquid electrolyte is considered to increase electrolyte resistance by decreasing the amount of ion-conductive electrolyte solution [23]. In vacuum environment, leakage of the electrolyte solution along the tabs, through the adhesive areas of the pouch cell and the potting materials, was expected to cause a premature increase in electrolyte resistance. Before starting the charge–discharge cycle tests, leakage of the BBM's electrolyte solution in vacuum was examined by gas chromatography. The BBMs were separately left in a vacuum vessel (approximately 50 Pa) at 40 °C for 6 h.

Diethyl carbonate, a solution material of the pouch cell, was detected at 0.588 ppm from the BBM using polyurethane resin. On the other hand, no leakage was detected from the BBM using epoxy. The results imply that the electrolyte solution leaked through the pouch seal and the polyurethane resin in vacuum, whereas the epoxy resin protected the solution from leaking. In the former case, the leak was attributed to the high permeability of polyurethane, which is almost 100 times greater than that of epoxy as shown in Table 3. However, it should be noted that the permeabilities shown in Table 3 were measured using CO_2, which is one of the standard gases for permeability measurements, because of technical difficulty of using diethyl carbonate for the measurements. Although these values cannot be directly fitted to diethyl carbonate, the detected leakage amounts support that the tendency shown in Table 3 is also true for diethyl carbonate; the polyurethane resin is more permeable than the epoxy resin for diethyl carbonate. Since no leakage was detected from the epoxy-potted BBM, the permeability of the epoxy resin for diethyl carbonate is considered sufficiently low enough to prevent solution leakage. Even though the leakage amount of 0.588 ppm for the polyurethane-potted BBM was very low, cumulative leakage over a long time period may cause premature deterioration resulting in increased electrolyte resistance. The long-term influence of the solution leakage on cycle life performance is discussed in Section 4.4.

4.2. Charge–discharge cycle life performance in vacuum

The charge–discharge cycle life performance tests of BBMs in vacuum were conducted. The cells in each BBM were individually cycled under the conditions presented in Table 2. The cycle tests were performed at atmospheric pressure for several dozen cycles, after which the chamber pressure was decreased to approximately 20 Pa using a rotary pump once stable EoDV trends were obtained. The retention capacities of the cells were periodically measured to evaluate the capacity fade trends of both BBMs. For capacity measurements in the vacuum chamber, the cells were charged with CC–CV charging of 1.5 A–4.1 V for 5 h and discharged with a CC of 1.0 A at 20 °C.

Short-term EoDV trends of BBMs using polyurethane and epoxy resin at the beginning of the cycle tests are shown in Figs. 7(a) and 8(a), respectively. Declines in the EoDV due to the vac-

Table 3
Properties of polyurethane and epoxy resin.

	Polyurethane	Epoxy	Remarks
Weight density (g cm^{-3})	0.966	1.144	
Permeability (cm^3 mm (m^2 24 h atm)$^{-1}$)	10,600	105	JIS K7126-2 (23 °C, CO_2)

uum were not observed. In contrast to the results shown in Fig. 5(a) and (b), the hard aluminum cases appeared to adequately prevent the cells from swelling in vacuum.

Figs. 7(b) and 8(b) show the long-term EoDV trends of BBMs using polyurethane and epoxy resin, respectively. Both BBMs fulfilled the minimum cycle life requirement of 1300 charge–discharge cycles or 3 months. Even after it was verified that the cycle life performance of BBMs satisfies the minimum life requirement, the cycle tests were continued until their EoDVs attained the UVC level of 3.75 V. For each BBM, all the cells showed similar trends until approximately the 15,000th cycle. However, as the number of cycles increased, deviations in EoDV gradually became apparent. The voltage deviations were considered to originate from nonuniform individual degradations due to nonuniform cell properties and/or temperature gradients in the BBMs.

The EoDVs of BBMs using polyurethane and epoxy resin reached the UVC at approximately the 22,000th and 24,000th cycle, respectively, under the cycle condition with a charge voltage of 4.1 V. The cycle tests were restarted by increasing the charge voltage to 4.2 V. After increasing the charge voltage, the EoDVs decreased more rapidly due to a higher degradation ratio caused by a higher charge voltage, and then decreased to the UVC level again at approximately the 24,500th and 27,000th cycles, which correspond to 4.66 and 5.14 years, respectively.

Trends of discharge curves and capacity retentions of BBMs using polyurethane and epoxy resin are shown in Figs. 9(a) and (b) and 10(a) and (b), respectively. Discharge curves of Cell 4 of each BBM are shown as representative results. All the cells in each BBM deteriorated almost uniformly in terms of discharge curve and capacity retention. The voltage decline at the beginning of discharge became significant with increase in the number of cycles, indicating a significant increase in the cell impedance. The capacities of both BBMs consistently decreased and their retention ratios at the end of life were approximately 48%. The degradation was attributed mainly to the positive electrode because the harvested positive electrodes of aged pouch cells in the previous study were identified as having a larger capacity fade in comparison with the negative electrodes [20].

4.3. Cell temperatures during cycling in vacuum

Since the polyurethane and epoxy resins are thermally insulating materials, a temperature increase of the cells in the BBMs due to thermal insulation is anticipated. Cell temperatures in the polyurethane potted BBM were measured using T-type thin thermocouples which were also potted in the BBM.

Fig. 11 shows the temperature profiles during cycling in vacuum. Since the charging and discharging processes of lithium-ion cells are endothermic and exothermic, respectively, the temperatures decreased during charging and increased during discharging. The temperature difference between the cells and the aluminum case was less than 0.4 °C. The temperature deviation among the cells was found to be less than 0.3 °C. These temperature behaviors are attributed that the thickness of the resin layer between the cells

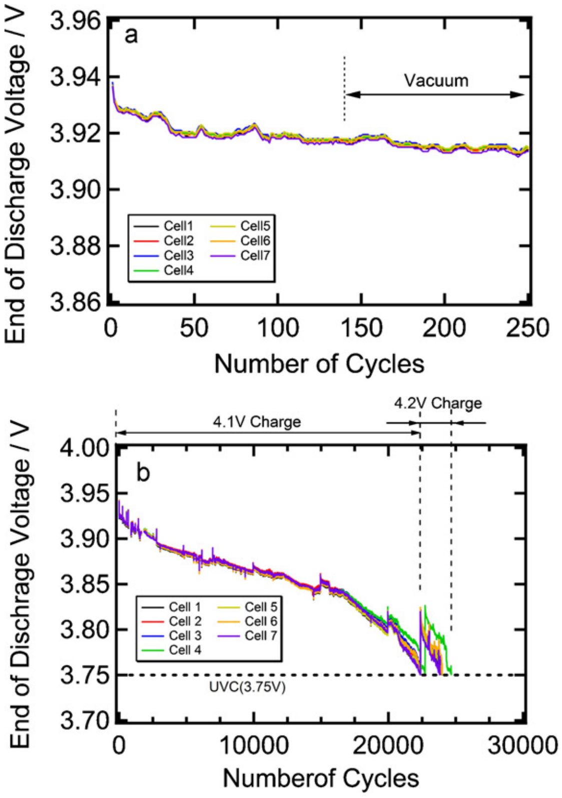

Fig. 7. (a) Short-term and (b) long-term trends of end-of-discharge-voltage of cells in the bread board model using polyurethane resin in vacuum.

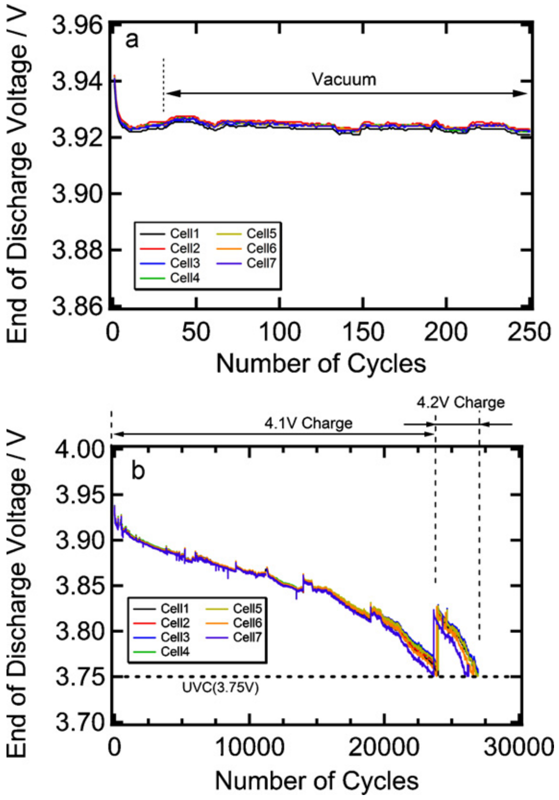

Fig. 8. (a) Short-term and (b) long-term trends of end-of-discharge-voltage of cells in the bread board model using epoxy resin in vacuum.

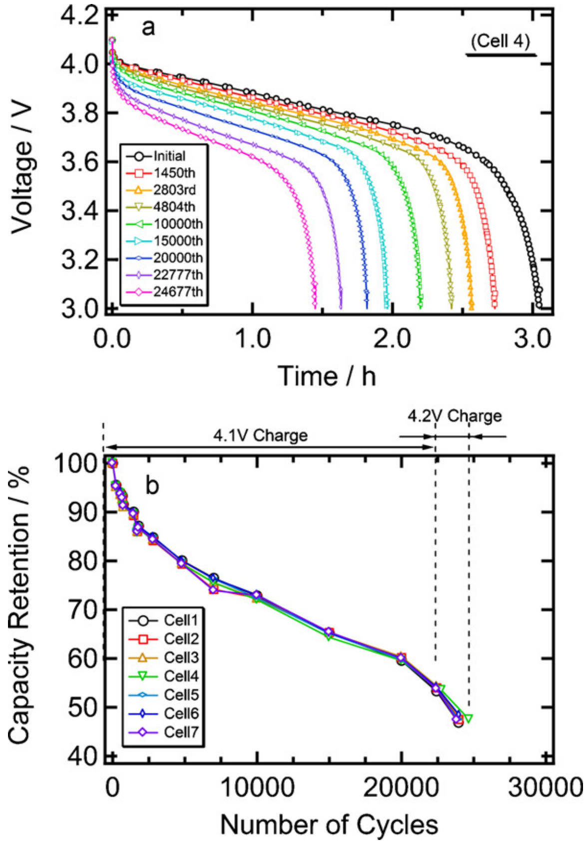

Fig. 9. (a) Discharge curves and (b) capacity retention of the cell(s) in the bread board model using polyurethane resin.

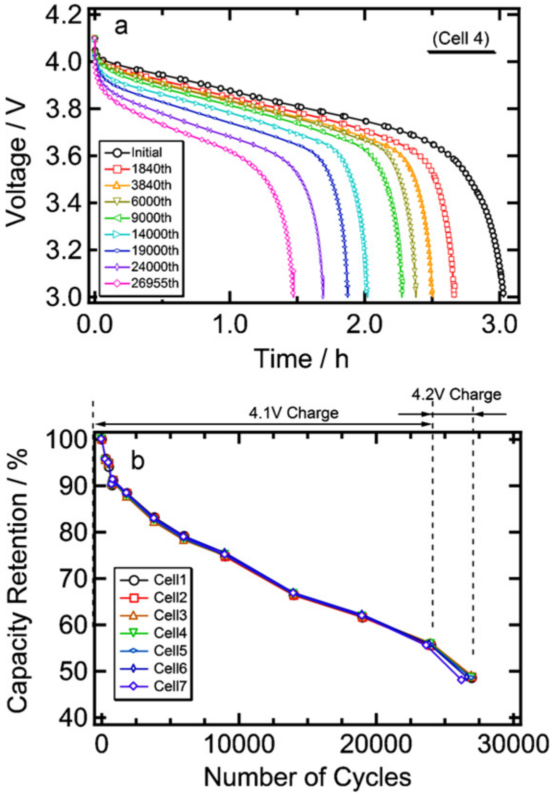

Fig. 10. (a) Discharge curves and (b) capacity retention of the cell(s) in the bread board model using epoxy resin.

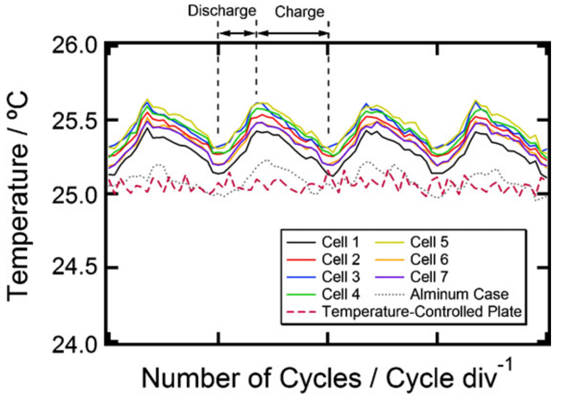

Fig. 11. Temperature profiles of cells in the bread board model using polyurethane resin during cycling in vacuum.

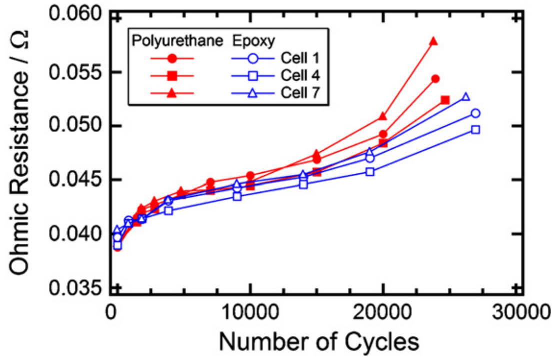

Fig. 12. Ohmic resistance of cells in the bread board models using polyurethane or epoxy resin.

and the aluminum case was thin, approximately 1–2 mm, so that the temperature difference due to thermal insulation of the resin was low enough.

The thermal conductivity of the epoxy resin differs from that of the polyurethane. Although temperatures of the cells in the epoxy-potted BBM were not measured, the temperature tendency of the epoxy-potted BBM is deemed similar to that of the polyurethane-potted BBM because both the BBMs have the identical dimension having thin resin layer that makes thermal insulation effect low enough. Therefore, the influence of temperature increase due to thermal insulation of potting materials on cycle life performance of the BBMs is conjectured not significant.

4.4. Ohmic resistance trend in vacuum

The BBM using epoxy resin showed better cycle life performance and capacity retention trends than the BBM using polyurethane resin. The most likely cause of the worse performance of the BBM using polyurethane resin is conjectured to be a degradation induced by the solution leakage, as mentioned in Section 4.1. Although the detected amount of solution from the BBM using polyurethane resin was infinitesimal (0.588 ppm), since it was cycled in vacuum for 4.66 years, the cumulative leakage may have been sufficiently large to cause premature deterioration.

Ohmic resistances of the cells in each BBM were also measured for a cell voltage of 4.1 V at 20 °C and an amplitude of 5 mV at 1 kHz in vacuum. Fig. 12 shows trends of the ohmic resistance of cells 1, 4, and 7 in each BBM. The ohmic resistances, which comprise of resistance of electrolyte, tabs, and leads, consistently increased as the same tendency has been reported elsewhere [23–25]. Although both BBMs showed almost identical values 39–40 mΩ at the begin-

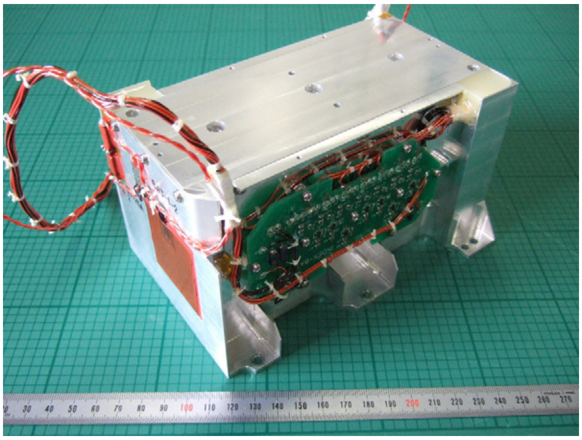

Fig. 13. Flight model of lithium-ion pouch battery with shunting equalization circuits.

ning of the cycle tests, the ohmic resistances of the BBM using polyurethane resin were prone to increase more than those using epoxy resin. Since the leakage contributes to the dry up of solution that in turn decreases the electrolyte conductivity as mentioned in Section 4.1, this result implied that the significant increase in ohmic resistance of the BBM using polyurethane resin was likely due to the cumulative leakage of the solution.

The experimental results obtained in this section imply that the hermeticality of the electrolyte solution plays an important role in maximizing the long-term cycle life performance of the cells in vacuum. The epoxy-resin-potting was considered preferable over the polyurethane resin for the pouch cells to achieve longer life performance.

5. On-orbit cycle life performance of flight model battery

5.1. Specification of flight model battery

Based on experimental results obtained in the previous sections, epoxy resin was used as the potting material for reinforcing the pouch cells for the flight battery. Two strings, each consisting of seven cells connected in series, were potted with epoxy resin in the two separate compartments of the aluminum case, and connected in parallel outside the battery. Each cell was connected to shunting equalization circuits, which are commonly used to protect lithium-ion cells from overcharging in case of cell voltage imbalance [26,27]. When a cell voltage equal to or exceeding a shunt voltage level of 4.25 V is detected, the charge current is bypassed through the equalization circuit to prevent overcharging.

Specifications for the flight battery are given in Table 4, and a photograph of the battery is shown in Fig. 13. The dimension of the aluminum case as well as the amount of epoxy resin poured in the case were not well optimized, and thus the specific energy of the flight battery were rather lower than that of the bare cell shown in Table 1. Because the primary benefit of using pouch cells is the high specific energy compared with that using metal casing, further efforts and optimization are necessary to improve specific energy for future applications.

Table 4
Specifications of the flight battery.

Configuration	14 Cells (7 series, 2 parallel)
Potting material	Epoxy resin
Case material	Al
Dimension	168 mm × 102 mm × 99 mm
Weight	2.42 kg (including equalization circuits)
Specific energy	70 Wh kg^{-1}

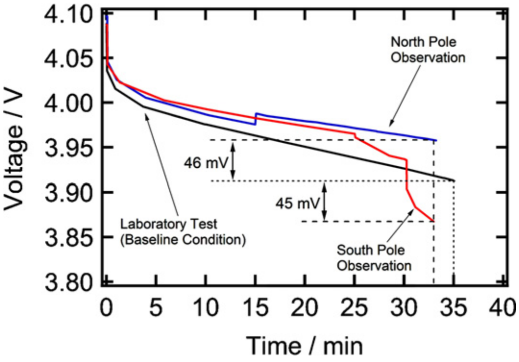

Fig. 14. Discharge curves of a fresh cell cycle with on-orbit and laboratory conditions.

Vibration tests simulating lift-off were performed for the flight battery before the launch. The charge–discharge curves were measured before and after the vibration tests. Any anomalous performance after the vibration tests were not observed verifying that the potted battery was tolerant against the vibration during lift-off.

5.2. On-orbit cycle life performance

The cycle tests in the laboratory were performed with 65-min charge and 35-min discharge intervals at 25 °C as shown in Table 2. However, the actual cycle conditions in orbit (63-min charge and 33-min discharge at 20 °C) were different, as mentioned in Section 2.2. In addition, there were significant seasonal variations in the discharging profile due to aurora observations using an on-board aurora camera, which consumes a relatively large amount of power. The aurora observations can be divided into two seasonal operations: South Pole and North Pole. A comparison of the typical charge–discharge cycle conditions in orbit with those in the laboratory tests is shown in Table 5. These different cycle conditions result in different EoDV trends, so it is not possible to use the comparisons with laboratory test results (shown in Fig. 8) to determine the accuracy of telemetry data and the health of the flight battery while in orbit. Therefore, the EoDV differences between laboratory and on-orbit conditions need to be corrected for comparisons.

To correct the EoDV trends, a post-launch cycle test was conducted in the laboratory; a fresh cell was cycled with the cycle conditions shown in Table 5 to determine the EoDV differences due to the different cycle conditions. Discharge curves of the fresh cell during the cycle tests are shown in Fig. 14. The EoDV at the South Pole observation condition was lower than that obtained with the baseline condition because of the large discharge current at the end of discharge, although the depth of discharge (DoD) for the South Pole observation condition was lower. The EoDV at the conditions simulating South/North Pole observations was 45 mV lower/46 mV higher, respectively, than the corresponding value obtained with the baseline condition. These values were added to or subtracted from the laboratory test results shown in Fig. 8 (i.e., the trends for the cell in the BBM using epoxy resin) in order to offset the difference of the EoDV values, and were compared with the flight data.

Fig. 15 shows the on-orbit EoDV trend for the flight battery. The trends of Cell 4 in Fig. 8(b) before and after the correction using offset values obtained in Fig. 14 are also depicted (indicated as “Ground Cell”). Those trends are multiplied by 7 to compare with trends for the flight battery, which consists of 7 cells in series. There were fluctuations in the EoDV of the flight battery because load current profiles in orbit were not constant, depend-

Table 5
Differences in charge–discharge cycle conditions in orbit and in laboratory.

	Laboratory test (baseline)	On orbit	
		North Pole observation	South Pole observation
Charge (CC–CV)	1.5 A–4.1 V for 65 min	1.5 A–4.1 V for 63 min	
Discharge (CC)	1.0 A for 35 min	0.88 A for 15 min 0.74 A for 18 min	0.78 A for 25 min 0.96 A for 5 min 1.63 A for 3 min
Depth of discharge	19.4%	14.7%	16.2%
Temperature	25 °C	20 °C	

ing on operation states of on-board instruments. In addition, the EoDV changed significantly due to the seasonal aurora observations mentioned above. During the South Pole observation period in the 20,000–22,000th and 26,000–28,000th cycles, the length and frequency of observation were intentionally curtailed because of the concern that the EoDV would fall below the UVC level of 26.25 V.

The corrected trend of the ground cell (Cell 4 in the BBM using epoxy resin) was in good agreement with that of the flight battery for the early period (approximately up to the 12,000th cycle). A comparison of the results indicated that the flight battery in orbit was not inadvertently affected by the conditions in space. The trends of the flight battery and ground cell gradually differed from each other as the number of cycles increased; the trend of the flight battery showed the tendency of a higher EoDV. The degradation ratio of the flight battery was considered to be lower than that of the ground cell because both the operating temperature and the average DoD of the on-orbit condition were lower than their corresponding values in the laboratory test. In addition, the correction values obtained in Fig. 14 were of the fresh cell, and did not reflect degradations. Thus, the corrected EoDV trend cannot be used for life prediction of the on-orbit flight battery because of different degradation ratios resulting from different cycle conditions and operating temperatures. However, this correction is considered useful from the viewpoint of ascertaining the accuracy of telemetry data and health of the flight battery in orbit for the early period.

The on-orbit flight battery achieved a longer cycle life performance than the cells of the BBMs in the laboratory owing to the lower operating temperature and average DoD. The lithium-ion pouch battery is still operating properly above the UVC level of 26.25 V with a charge voltage of 4.1 V per cell (28.7 V per battery), and REIMEI is presently orbiting the Earth for its scientific observation as of this writing.

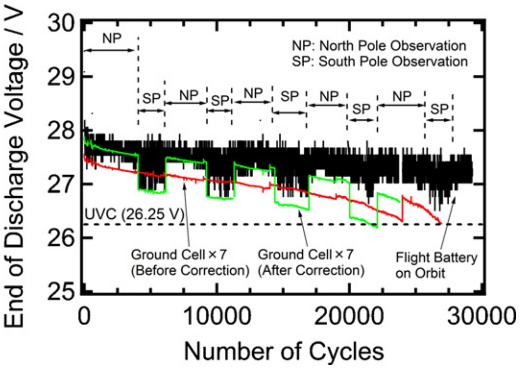

Fig. 15. End-of-discharge-voltage trend of the flight battery compared with a cell in the bread board model using epoxy resin. The trend of the cell in the bread board model is corrected based on the differences in charge–discharge cycle conditions between on-orbit and laboratory.

6. Conclusions

A lithium-ion battery using off-the-shelf pouch cells was developed for a small scientific satellite "REIMEI" that was launched on August 23, 2005. The pouch cells were reinforced by potting with polyurethane or epoxy resin to withstand vacuum in space. The course of the development, experimental results in the laboratory, and on-orbit data of the flight battery were presented in this paper.

In preliminary experimental tests, pouch cells potted with polyurethane or epoxy resin in a soft aluminum cup were cycled in vacuum. The cell potted with polyurethane resin swelled up in vacuum and its EoDV decreased significantly. Swelling of the epoxy-potted cell was not observed visually, but its EoDV decreased gradual.

The BBMs, in which the cells were potted with polyurethane or epoxy resin in a hard aluminum case, were fabricated for cycle life performance tests in the laboratory. The cells in the BBM using epoxy resin showed better cycle life performance than those using polyurethane resin. In addition, the electrolyte resistances of the cells using polyurethane resin were prone to increase more than those using epoxy resin. The inferior life performance of the polyurethane-potted BBM was attributed to a cumulative leakage of the electrolyte solution over a long time period because the solution leakage was detected only from the BBM using polyurethane resin.

Based on the laboratory test results, epoxy resin was employed as the potting material for the flight battery. The EoDV trends in the laboratory tests and in orbit were different due to different charge–discharge profiles and temperatures. The EoDV differences due to different cycle conditions were corrected based on a post-launch cycle test using a fresh cell. The corrected EoDV trend in the laboratory test was in good agreement with that of the flight battery for the early cycle period. A comparison of the results indicated that the on-orbit flight battery was not inadvertently affected by the conditions of space.

At the time of this writing, REIMEI is conducting scientific observations and the lithium-ion pouch battery is still operating properly.

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