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Cycle-life testing of large-capacity lithium-ion cells in simulated satellite operation

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Abstract

We are conducting cycle-life testing of 10–100 Ah-class lithium-ion cells in a simulated satellite operation at the Japan Aerospace Exploration Agency (JAXA). This paper reviews the latest test results of these lithium-ion cells. Thus far, we have verified impressive life performance exceeding 30,000 cycles in a simulated low-earth-orbit (LEO) mode and 1800 cycles in a simulated geostationary-earth-orbit (GEO) mode for some of these cells. We optimized the thickness of the electrode layer to suppress cell-internal impedance and found that a lithium-ion cell with a thin electrode layer exhibited promising cycling performance in a simulated LEO operation. Since the electrode material is an important factor affecting the charge–discharge behavior of a lithium-ion cell, we also compared the cycling performance of lithium-ion cells with different cathode materials.

Keywords: Lithium-ion cell; Satellite application; Cycle-life testing; Electrode surface area; Cathode material

1. Introduction

In a spacecraft, onboard rechargeable batteries serve as power storage devices. The cycle life and operation condition of these batteries rely rigorously on satellite orbit [1]. Typically, a spacecraft in low-earth-orbit (LEO, 500–1000 km above the earth) periodically experiences 60 min of sunshine and a 30-min eclipse. Therefore, the rechargeable batteries must store necessary power from solar cells during a 60-min interval, and generate enough power to meet electrical demands of bus and mission for a 30-min interval. A common 5-year LEO mission life corresponds to 30,000 cycles without interruption. However, a geostationary-earth-orbit (GEO, 36,000 km above the earth) spacecraft circulates around the earth once per day, and needs to store energy during only two equinox seasons per year. The orbit with an eclipse of no more than 72 min continues for 45 days in each season; thus, the rechargeable batteries are required to cycle 1400 times to meet a 15-year GEO mission life.

A rechargeable battery module, consisting of series-connected cells, is one of the most massive onboard components (7–10 wt.% of a spacecraft). Reducing onboard cell weight is always a primary challenge in developing a space power system. From this viewpoint, lithium-ion technology provides promising power storage devices for space applications, due to its high energy density and working voltage, compared with the conventional alkaline technologies [2,3].

Lithium-ion cells were first commercialized in Japan in the early 1990s. In 1994, we began a feasibility study of 1.0 Ah-class commercial lithium-ion cells for space applications at the Japan Aerospace Exploration Agency (JAXA). A few types of these cells were found to exhibit impressive performance [4]. Based on this knowledge, we commissioned some Japanese battery manufacturers to supply large-capacity lithium-ion cells and began conducting life testing of these cells in a simulated spacecraft operation in 1998 [5–8]. We set the development principles as: (1) develop lightweight lithium-ion cells with high energy density of above 100 Wh kg^{-1} at battery level; (2) produce prototypes of high-capacity lithium-ion cells with different designs and materials; (3) conduct cycle-life testing of high-capacity lithium-ion cells in simulated LEO and GEO operations; (4) find the optimum operation conditions (taper voltage, charge current,

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temperature, storage duration); and (5) improve safety and reliability in a space environment (vacuum, radiation, and vibration).

Thus far, some large-capacity cells have demonstrated excellent cycle life exceeding 30,000 cycles in the LEO simulation mode and 1800 cycles in the GEO simulation mode, corresponding to a 5-year LEO operation and a 20-year GEO operation [9]. These satisfactory results encouraged us to select large-capacity lithium-ion cells as power storage devices for some space programs. The flight data demonstrated normal operation of these lithium-ion cells in both LEO and GEO space environment without a single failure.

In this paper, we review the latest test results for large-capacity lithium-ion cells in a simulated satellite operation at JAXA. In addition to the progress in long-term cycle-life testing, our effort to develop lithium-ion cells with a thin electrode layer for LEO applications is also presented here. Furthermore, we compare the cycling performance of lithium-ion cells with different cathode materials.

2. Experimental

2.1. Cell description

Table 1 lists the specifications of typical large-capacity lithium-ion cells discussed in this paper [9].

GS-Yuasa Technology, Ltd. (GYT) manufactured 100-Ah standard cells, 40-Ah cells with a thin electrode layer, and 50-Ah cells with a $LiNi_{1-x-y}Co_xAl_yO_2$ cathode for space applications. Details of 100-Ah standard cells were described in the previous paper. The same type of cells, employed in a GEO satellite (ThaiCom-4), has been flying since August 2005. The 40-Ah cell has a thinner electrode layer design than the standard cell, causing a short diffusion distance of lithium ion and hence improving the charge–discharge performance even at a high charge (discharge) rate. As a penalty, the energy density may decrease due to a relative decrease in electrode active material. With the exception of the cathode, the 50-Ah cell has the same cell design and battery materials as the standard cell.

The 14.6-Ah Mn-based lithium-ion cell is manufactured by Mitsubishi Heavy Industries, Ltd. (MHI) for commercial applications. This type of cell has a prismatic shape and a common electrode-terminal seal with a polymer O-ring.

2.2. Cell setup

For cycle-life testing, the cells were fixed with end plates and tie rods, and connected in series. We did not activate the balancing circuit so as to facilitate evaluation of voltage dispersion during charging and discharging.

The cell stack was set in a thermostatic incubator with a control accuracy of 1 °C. The ambient temperature of the thermostatic incubator was remotely controlled at 15 °C by a thermal sensor near the cells. We monitored cell voltage, current, cell temperature, and incubator temperature during the testing.

2.3. Simulation conditions

Table 2 summarizes the charge–discharge conditions that simulate GEO operation.

The cells were managed by a constant current–constant voltage (CC–CV) charge mode and a CC discharge mode. The taper voltage of the standard cells was set at a low value of 3.95 V per

Table 1
Specifications of typical lithium-ion cells

Capacity (Ah)				
Rated	100	40	50	14.6
Nominal	110[a]	45[a]	53[a]	15.5[b]
Cell				
Sharp	Elliptic cylinder			Prismatic
Maker	GYT[c]			MHI[d]
Cathode	$LiCoO_2$		$LiNi_{1-x-y}Co_xAl_yO_2$	$LiMn_2O_4$
Anode	Graphite			
Nominal voltage (V)	3.7[a]		3.6[a]	3.87[b]
Weight (g)	2800	1480	1400	570
Dimensions (mm)				
Width	50	52		30.5
Length	130			73.5
Height	208	123		115
Energy density				
$Wh\,kg^{-1}$	145[a]	112[a]	136[a]	105[b]
$Wh\,l^{-1}$	328[a]	222[a]	254[a]	233[b]
Case				
Material	Aluminum alloy			
Terminal seal	Hermetical			Polymer

[a] Determined with a taper voltage of 4.1 V.
[b] Determined with a taper voltage of 4.15 V.
[c] GS-Yuasa Technology, Ltd.
[d] Mitsubishi Heavy Industries, Ltd.

Table 2
Operation conditions in the simulated satellite operations

	Discharge, CC mode			Charge, CC–CV mode		
	DOD (%)	Rate (C)	Time (h)	Rate (C)	Taper voltage (V)	Time (h)
LEO	25	0.5	0.5	0.3	3.95[a]	1.0
	40	0.8		0.5	4.15[b]	
GEO[c]	80	0.67	1.2	0.1		22.8

[a] Initial value for 100- , 40-, and 50-Ah cells.
[b] Initial value for 14.6-Ah cells.
[c] Accelerated simulation testing at a fixed DOD with no consideration of sunshine period.

Table 3
Capacity-check condition during cycle-life testing

Charge, CC–CV mode			Discharge, CC mode	
Rate (C)	Initial taper voltage (V)	Time (h)	Rate (C)	Cut-off voltage (V)
0.1	3.95	16	0.5	2.75

cell at the beginning of life (BOL) phase. We raised the taper voltage with a step of 50 mV to compensate the capacity loss when the cell voltage at the end of the discharge declined to 2.75 V. The maximum taper voltage was 4.1 V per cell for the standard cells. The charge–discharge current was calculated here by using the rated capacity. We determined the cycle life based on the cycle at which voltage in the discharge phase dropped to 2.75 V.

We checked the cell capacity at fixed points during the cycle-life testing. Table 3 lists the charge–discharge condition for capacity check.

3. Results and discussion

Since high cell voltage is needed for long-term satellite operation, voltage at the end of the discharge is an important parameter for comparing cycling performance of cells. Here, we mainly depict the cell voltages at the end of the charge and discharge as a function of cycle number to evaluate the voltage trend.

3.1. Typical life performance of 100-Ah standard cells

Cycle-life testing of 100-Ah standard cells began in 1998. The operation conditions were set by simulating LEO (DOD 25%), LEO (DOD 40%), and GEO (80%) operations. Five cells in series were tested under each operation condition.

Fig. 1 depicts the voltage trend of each cell at the end of the charge and discharge with a simulated condition of LEO (DOD 25%). So far, we have accumulated more than 30,000 cycles, corresponding to a 5-year LEO operation. Overall, the cell voltage at the end of the discharge maintained a high level of almost 3.5 V, indicating excellent life performance under this operation condition. Cell-voltage dispersion at the end of the charge and discharge was also sufficiently small and increased with cycling. The maximum cell-voltage dispersion was 44 mV at the end of the charge and 58 mV at the end of the discharge. At the 17,637th cycle, we temporarily changed the operation condition by simulating an LEO operation (DOD 40%) to verify the cell operation in the case of one-cell failure. A small voltage drop of 0.23 V was observed at the end of the discharge when DOD increased from 25 to 40%, suggesting these cells were sufficiently robust to meet the unexpected power demand. After the DOD was changed back to 25%, the voltage at the end of the discharge again moved normally along the original locus.

The cycle-life testing of 100-Ah standard cells in a simulated LEO operation (DOD 40%) accumulated 23,000 cycles, corresponding to a 4-year LEO operation (Fig. 2). The cells exhibited a relatively severe voltage decline at the end of the discharge, compared with those operating at a 25% DOD. This result may be attributed to the large charge and discharge currents, which cause a serious *iR* drop effect. At the 21,390th cycle, the voltage at the end of the discharge declined to the lower voltage limit of 2.75 V. We then raised the cell taper voltage from 3.95 to 4.0 V to increase cell capacity. As a result, the voltage at the end of the discharge increased to 3.4 V and maintained a high level of 3.2 V after 23,000 cycles. The maximum taper voltage for these cells is 4.1 V; therefore, we can reasonably expect these cells to exhibit excellent life performance exceeding 25,000 cycles

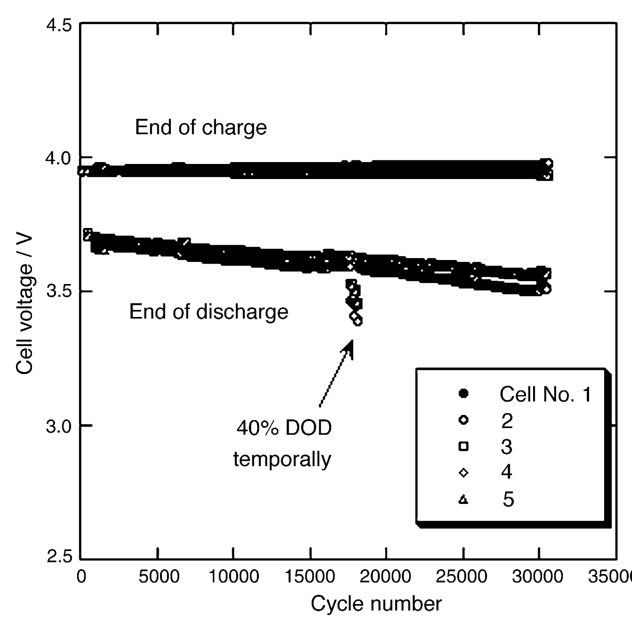

Fig. 1. Voltage trend of 100-Ah standard lithium-ion cells in simulated LEO operation (DOD 25%).

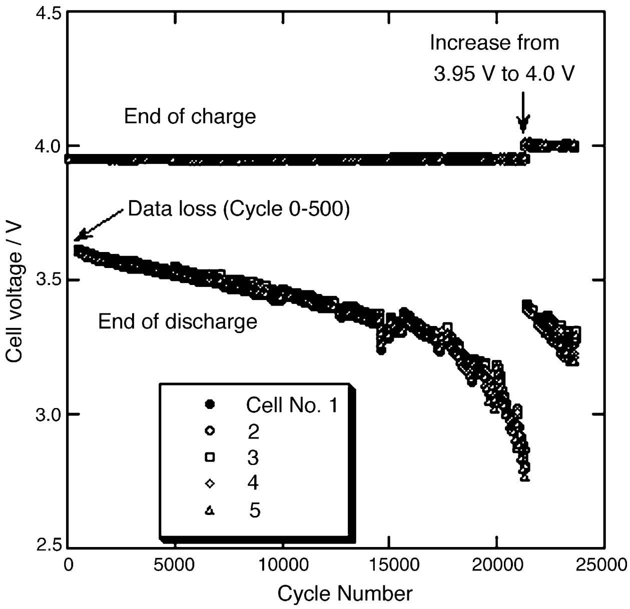

Fig. 2. Voltage trend of 100-Ah standard cells in simulated LEO operation (DOD 40%).

even at a high DOD of 40%. The cell voltage had a much larger dispersion at the end of the discharge than that at the end of the charge, reflecting both a cell-internal impedance increase during life testing and a discharge characteristic of a large voltage slope at low SOC. Maximum cell-voltage dispersion was 120 mV at the end of the discharge.

The GEO simulation of 100-Ah standard cells was accelerated testing by considering only a 45-day eclipse period at each equinox season and using a maximum DOD of 80% (Fig. 3). During the testing, the taper voltage increased from 3.95 to 4.1 V with an interval of 50 mV after the discharge voltage declined to the lower voltage limit of 2.75 V. Obviously, the capacity-increase effect decreased with increasing taper voltage. Only a slight improvement was observed at a taper voltage of 4.1 V. This testing was finished after 1800 cycles since the taper voltage of 4.1 V is the upper limit for these cells. This cycle life corresponds to a 20-year GEO operation. A maximum voltage dispersion of 160 mV was observed at the end of the discharge before the testing was finished. Voltage dispersion at the end of the charge was relatively small and occurred only after using a taper voltage of above 4.05 V. This result suggests that the examined cells are promising power storage devices for GEO applications. Indeed, a GEO satellite employing cells of this type was launched in August 2005; the flight data at the first eclipse period indicated normal charge–discharge behavior of these cells.

3.2. High-rate designed 40-Ah cells with a thin electrode layer

The onboard rechargeable cells in a spacecraft must exhibit good cycling performance at high charge and discharge rates. In a previous study, we found that the thin electrode layer design effectively improved the charge–discharge performance of large-capacity lithium-ion cells even at a high charge (discharge) rate due to the short diffusion distance [10,11]. As a penalty, the cell capacity was reduced due to the relative decrease in electrode active material. Based on this knowledge, we prepared 40-Ah lithium-ion cells with an optimum electrode layer that was thinner than that of 100-Ah standard cells and began evaluating them in a cycle-life testing simulated LEO operation (DOD 40%). Five cells were connected in series for the testing.

Thus far, 3000 cycles have been completed for this testing. Fig. 4 compares the cell voltages at the end of the discharge of five 40-Ah cells with a thin electrode layer and five 100-Ah standard cells in the same simulated LEO operation (DOD 40%). Obviously, 40-Ah cells exhibited a relatively high volt-

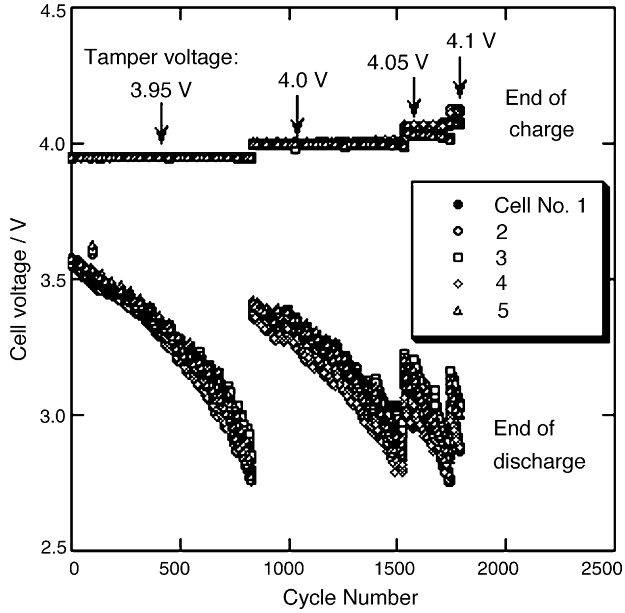

Fig. 3. Voltage trend of 100-Ah standard cells in simulated GEO operation (DOD 80%).

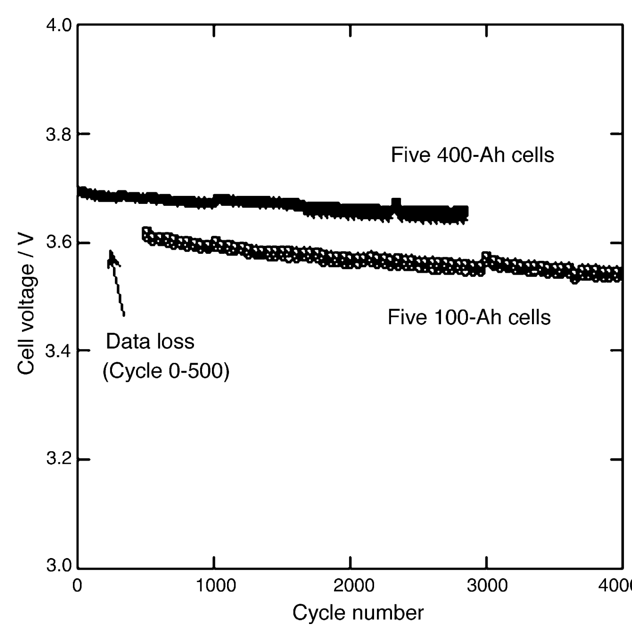

Fig. 4. Voltage comparison of 40-Ah lithium-ion cells with thin electrode layer design and 100-Ah standard cells in simulated LEO operation (DOD 40%).

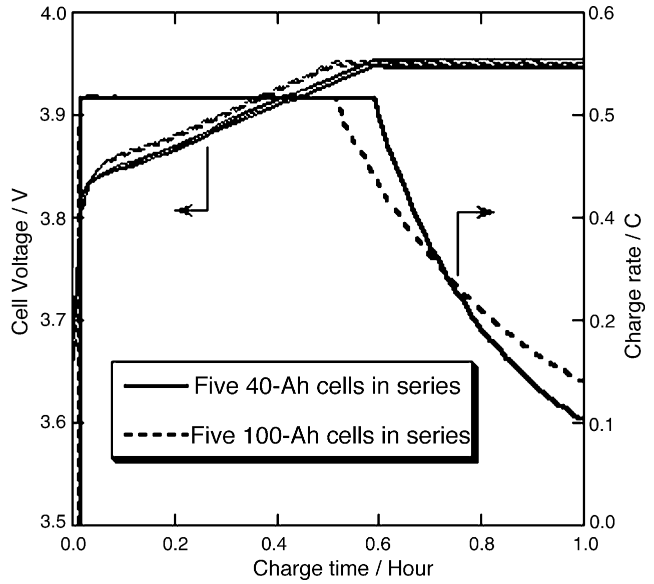

Fig. 5. Charge–discharge curves at the 500th cycle of 40-Ah lithium-ion cells with thin electrode layer design and 100-Ah standard cells in simulated LEO operation (DOD 40%).

age compared with the 100-Ah standard cells at the end of the discharge. This result provides evidence that the thin electrode layer design effectively improves cycling performance at a high charge (discharge) rate.

To explain this phenomenon, we checked the charge curves at the 500th cycle of these two types of cells. Generally, the CC charge time and the current at the end of the charge are two important parameters for evaluating cell-internal impedance. Low cell-internal impedance may result in both a long CC charge time and a low CC charge current at the end of the charge. From Fig. 5, we can deduce that the 40-Ah cell with a thin electrode layer has relatively low internal impedance, and therefore is promising for LEO applications.

3.3. Alternative cathode materials to $LiCoO_2$

One characteristic of lithium-ion cells is the diversity of the cathode materials, which are generally constructed from the transition metal as a center atom. In addition to the Co-based cathode, Ni-based and Mn-based cathode materials have also been developed. Since these cathode materials cause lithium-ion cells to exhibit different charge–discharge performance, it is important to investigate the correlation of cathode type with cycling performance.

A good example is the space lithium-ion cell with an Ni-based cathode developed by SAFT, which was used in a few GEO satellites launched in March 2004 [12]. This encouraged us to conduct the cycle-life testing of 50-Ah lithium-ion cells with Ni-based cathodes in a simulated GEO operation (DOD 80%). We connected five cells in series for this testing. So far, six eclipse periods have been completed, corresponding to a 3-year GEO operation.

Fig. 6 compares the cell voltages at the end of the discharge of five 50-Ah cells with Ni-based cathodes and five 100-Ah standard cells in the same simulated GEO operation (DOD 80%). The 50-Ah cells exhibited a relatively low discharge voltage at the beginning of the testing. However, voltage retention was maintained at a high level, indicating less performance degradation of these cells than 100-Ah standard cells.

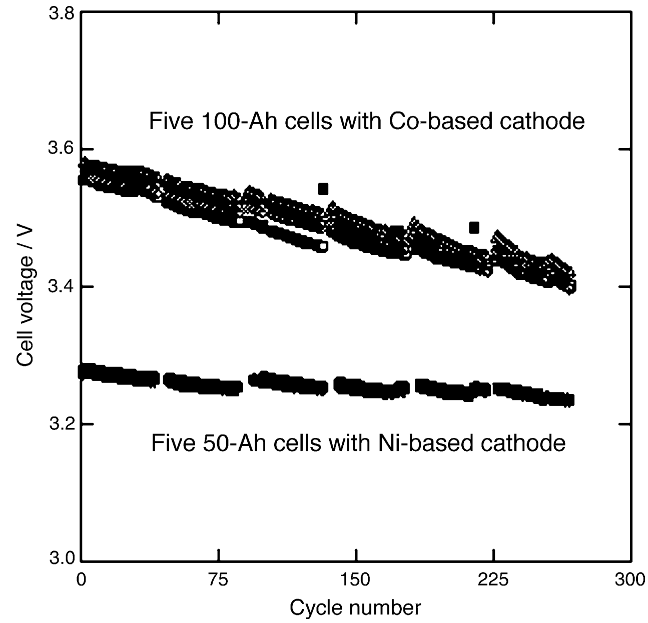

Fig. 6. Voltage comparison of 50-Ah lithium-ion cells with Ni-based cathode and 100-Ah standard cells in simulated GEO operation (DOD 80%).

A capacity check further verified this tendency. We checked cell capacity after each eclipse period and plotted capacity retention against cycle number (Fig. 7). After six eclipse periods, the 50-Ah cells with Ni-based cathodes exhibited an extremely high

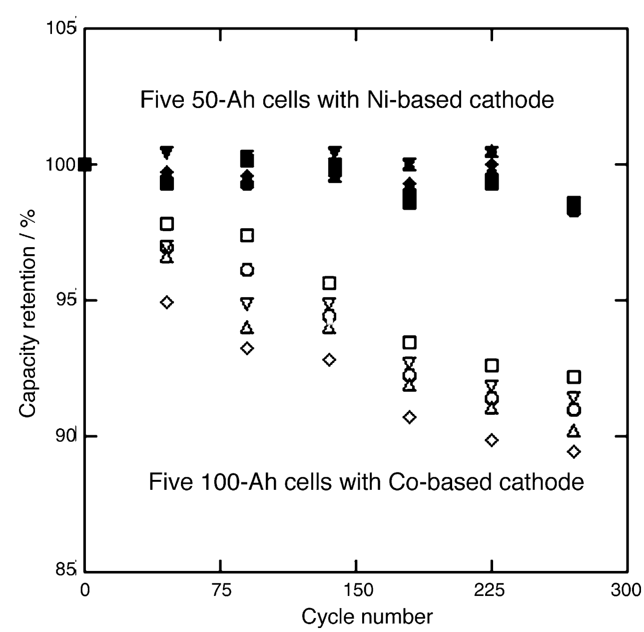

Fig. 7. Plot of capacity retention against cycle number of 50-Ah lithium-ion cells with Ni-based cathode and 100-Ah standard cells in simulated GEO operation (DOD 80%).

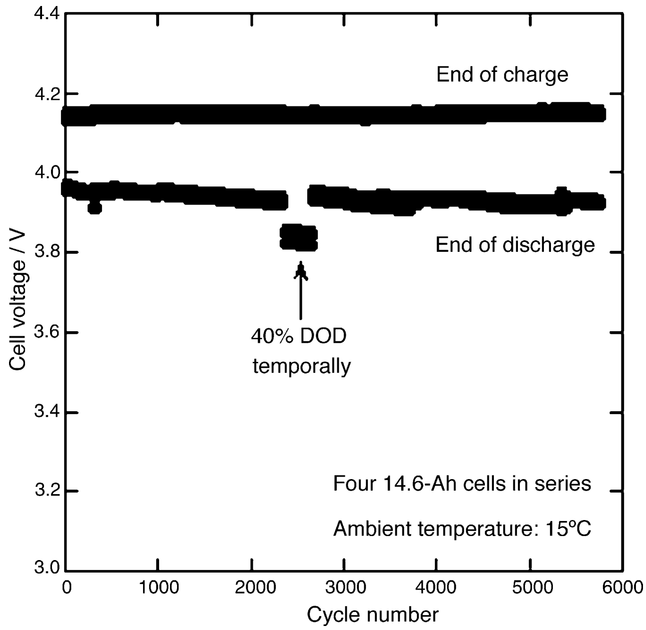

Fig. 8. Voltage trend of 14.6-Ah lithium-ion cells with Mn-based cathode in simulated LEO operation (DOD 25%).

capacity retention of 98%, compared with the 100-Ah standard cells' retention of 90%.

$LiMn_2O_4$ is another cathode material used in commercial lithium-ion cells. The main disadvantage of this material is Mn dissolution at an elevated temperature of 60 °C, which may cause poor cycling performance. For space applications, the ambient temperature is controlled in an optimum range near 15 °C. The advantages of high safety and low cost may make the Mn-based cathode promising.

Fig. 8 reveals the voltage trend of 14.6-Ah lithium-ion cells with Mn-based cathodes in a simulated LEO operation (DOD 80%). Four cells were connected in series for testing. So far,

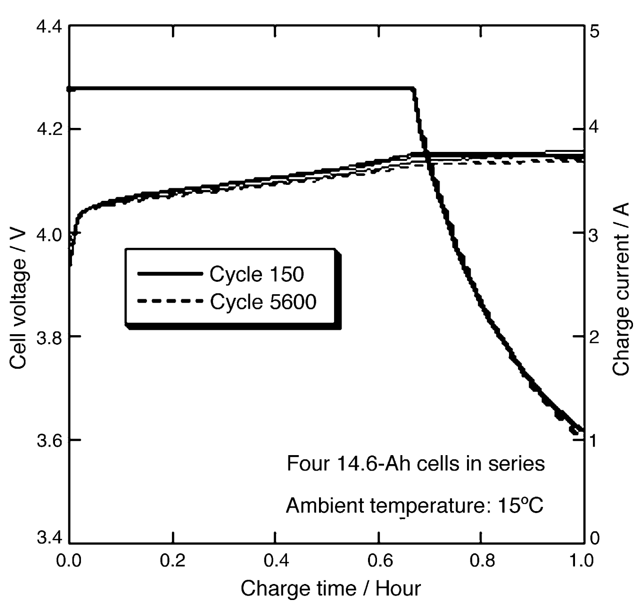

Fig. 9. Comparison of charge–discharge curves of 14.6-Ah lithium-ion cells with Mn-based cathode at Cycles 150 and 5600.

we have accumulated 6000 cycles, corresponding to a 1-year LEO operation. By using a taper voltage of 4.15 V, we obtained a high discharge voltage near 4.0 V at the beginning of testing. After 6000 cycles, the voltage at the end of the discharge still remained at a high level of 3.9 V, suggesting excellent cycling performance of this type of cell.

We compared the charge curves of the 14.6-Ah cells with Mn-based cathodes at cycles 150 and 5600 (Fig. 9). Focusing on the CC charge time and the current at the end of the charge, we found only a slight change in these parameters. This result indicates that these cells experienced little performance degradation even after 1-year LEO operation.

4. Conclusions

We are conducting cycle-life testing of large-capacity lithium-ion cells in simulated satellite operation. The purpose of this program is to assess the life performance of these cells in both LEO and GEO regimes, to optimize the operation condition, to improve the electrode design in order to suppress cell-internal impedance, and to investigate the correlation of cathode type with cycle life.

This paper presents the test results of 100-Ah lithium-ion cells with $LiCoO_2$ cathodes and graphite anodes as an example. We set the initial taper voltage at a low level of 3.95 V and raised it to 4.1 V to increase cell capacity after the discharge voltage declined to a designated value. Thus far, we have verified impressive life performance exceeding 30,000 cycles in a simulated LEO mode and 1800 cycles in a simulated GEO mode, which correspond to a 5-year LEO operation and a 20-year GEO operation. The same type of cell has been employed in a launched GEO satellite as a power storage device.

We prepared 40-Ah lithium-ion cells with thin electrode layers to reduce cell-internal impedance. These cells were used for life testing in a simulated LEO operation (DOD 40%). The testing results indicated improved life performance compared with that of 100-Ah standard cells. We believe that this type of cell with the optimum electrode design is promising for LEO applications.

Additionally, we compared the cycling performance of lithium-ion cells with different cathode materials. The 50-Ah lithium-ion cells with Ni-based cathodes exhibited excellent capacity retention in a simulated GEO operation. The 14.6-Ah lithium-ion cells with Mn-based cathodes were found to maintain a high voltage level at the end of the discharge in a simulated LEO operation.

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