



Durability Analysis of the REIMEI Satellite Li-ion Batteries after more than 14 Years of Operation in Space

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ABSTRACT

The satellite REIMEI was launched in August 2005, this is one of the first satellites to use Li-ion batteries. REIMEI is a small scientific satellite designed for carrying out aurora observations using three different cameras. The main scientific mission of the satellite ended in 2013. More than 14 years have passed, and the batteries have experienced over 78,100 charge/discharge cycles. REIMEI remains in operation with a new mission dedicated to analyzing its Li-ion battery. In this work, we present a durability analysis for the REIMEI battery based on telemetry data.

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1. Introduction

Li-ion batteries have become the first choice to power a wide range of space exploration missions.¹⁻⁷ Due to their high energy density, performance and reliability, Li-ion batteries have replaced the use of Ni-Cd, Ni-MH and Ni-H₂ batteries, which were utilized to power many missions.

Li-ion batteries have shown to have a high reliability and very good performance to power a wide range of applications. Nevertheless, Li-ion batteries degrade over time and this degradation can be accelerated by certain operating conditions.⁸⁻¹¹ It has been reported that factors such as state of charge (SoC), temperature, electrolyte, electroactive material composition and cell engineering have an impact on the degradation mechanisms of Li-ion batteries.¹²⁻¹⁶ One of the main factors that has a huge impact on the degradation behavior of Li-ion batteries is the operating temperature. High operating temperatures in combination with a high SoC can accelerate the degradation of Li-ion cells. This combination promotes the growth of the solid electrolyte interphase (SEI) generated around the negative electroactive material, which leads to the capacity fade of the cells.¹¹ On the other hand, when a Li-ion cell is exposed to low temperatures, the occurrence of lithium plating can take place. This lithium plating phenomenon usually occurs when a cell is exposed to low temperatures and high currents during the charging process,¹⁷⁻¹⁹ which leads to the generation of metallic lithium around the negative active material. The metallic lithium reacts with the electrolyte,

which reduces the amount of cyclable lithium leading to a significant capacity fade.¹⁹ Additionally, metallic lithium deposited on the negative active material can grow dendritically and the lithium dendrites could cause internal short circuits, which can result in a catastrophic thermal runaway of the battery. In general, the operating temperature is an important parameter to control and consider in order to extend the lifetime of Li-ion batteries.

The Japan Aerospace Exploration Agency (JAXA) started using Li-ion batteries in 2003 with its Hayabusa spacecraft, which travelled to the asteroid Itokawa and was able to bring a sample from the asteroid back to earth.^{2,3} Since then, Li-ion batteries have been selected to power a wide range of missions. Another example of one of the first satellites to use Li-ion cells is REIMEI. This piggy-back satellite was launched from Baikonur, Kazakhstan on August 24, 2005 and injected into a nearly sun synchronous polar orbit. The main objective of REIMEI was the demonstration of the next-generation advanced satellite technologies, which included the use of Li-ion batteries. The scientific mission of REIMEI consisted of carrying out aurora observations by using three cameras with different wavelength filters. REIMEI's main scientific mission ended in 2013. Today, more than 14 years have passed, and the battery has experienced more than 78,100 charge/discharge cycles. The satellite remains in operation with a new mission dedicated to analyzing the performance of its Li-ion battery. In this work, we carry out a durability analysis for the REIMEI Li-ion battery after 14 years of operation.

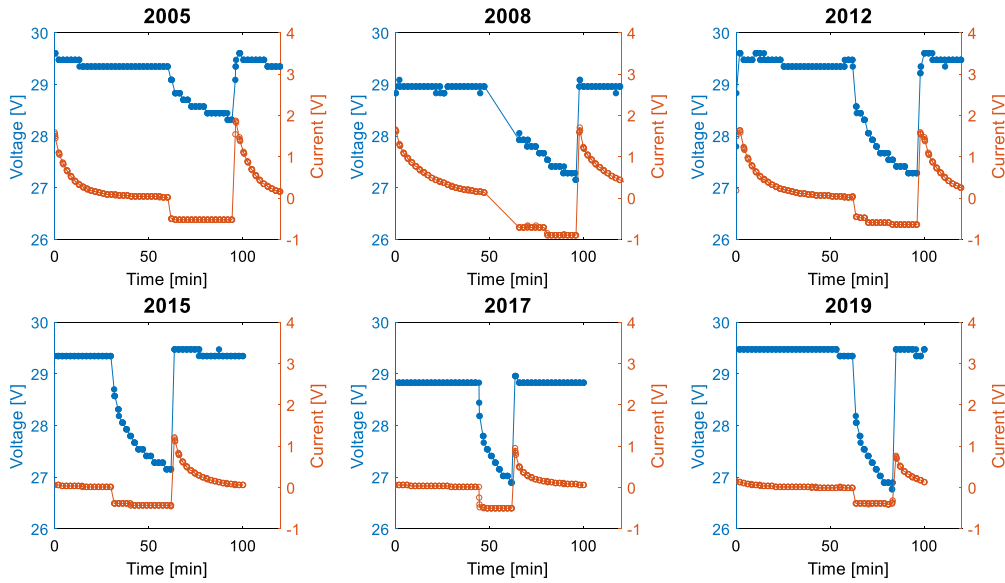


Figure 1. Charge-discharge telemetry data of the REIMEI Satellite Li-ion battery obtained in September 2005, 2008, 2012, 2015 and 2019.

2. Experimental

2.1 Lithium-ion cell

The REIMEI battery uses pouch Li-ion cells with a rated capacity of 3 Ah. The cell uses LiMn_2O_4 as the positive active material and graphitized carbon as the negative active material. The electrolyte composition is 1 M of LiPF_6 EC/DEC (3:7 by wt%) + additives.

2.2 Lithium-ion battery

The flight battery consists of two strings connected in parallel. The strings are labeled as battery 1 and battery 2. Each string has seven Li-ion cells connected in series to realize a bus-voltage of 28 V. The Li-ion cells were placed into an aluminum case and then potted with an epoxy resin, to avoid any possible expansion of the pouch cells when the battery exposed to vacuum. The specific energy density of the flight battery was 70 Wh kg^{-1} .

2.3 Battery operation

The Li-ion battery is charged and discharged according to a low earth orbit (LEO) satellite operation profile, where the charge and discharge time periods are constant. The satellite experiences 62 min of daytime and 35 min of nighttime. During the daytime the battery is charged following a constant current-constant voltage (CC-CV) protocol. Two maximum constant-voltage levels, V1 and V2 modes, are used during the charge process. V1-mode is set to 29.4 V, which corresponds to 4.2 V per Li-ion cell. V2-mode is set to 28.7 V, which corresponds to 4.1 V per Li-ion cell. During nighttime the battery is discharged within a depth of discharge (DoD) of 20%.

3. Results and Discussion

Figure 1 shows telemetry charge-discharge profiles for voltage and current of the REIMEI Li-ion battery obtained in September 2005, 2008, 2012, 2015, 2017 and 2019. A constant current of 1.5 A is applied during charging until the constant voltage limited is reached (V1 or V2), then the charging process continuous in the constant-voltage phase. During the discharging process, the battery is discharged within a depth of discharge (DoD) of 20% with a current-rate of 0.5C. The voltage telemetry data has an accuracy of 0.136 V, while the current has an accuracy of 23 mA.

Figure 2 shows the end of discharge voltage (EoDV), end of charge voltage (EoCV) and battery operating temperature obtained

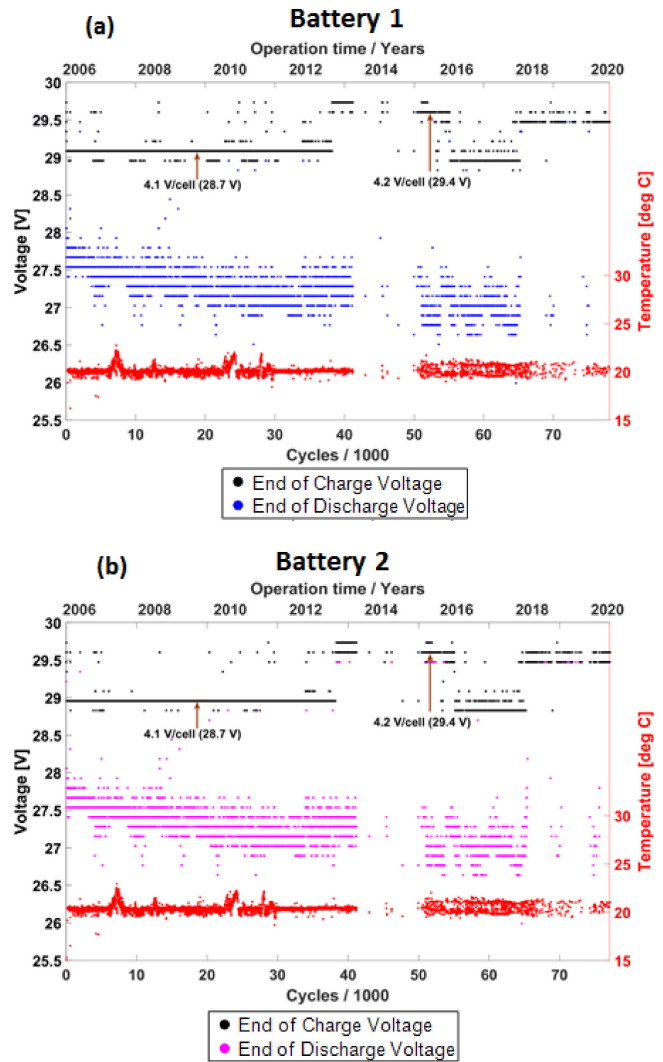


Figure 2. End of discharge voltage, end of charge voltage and battery operating temperature of the REIMEI Li-ion battery 1 (a) and 2 (b) as a function of charge-discharge cycles.

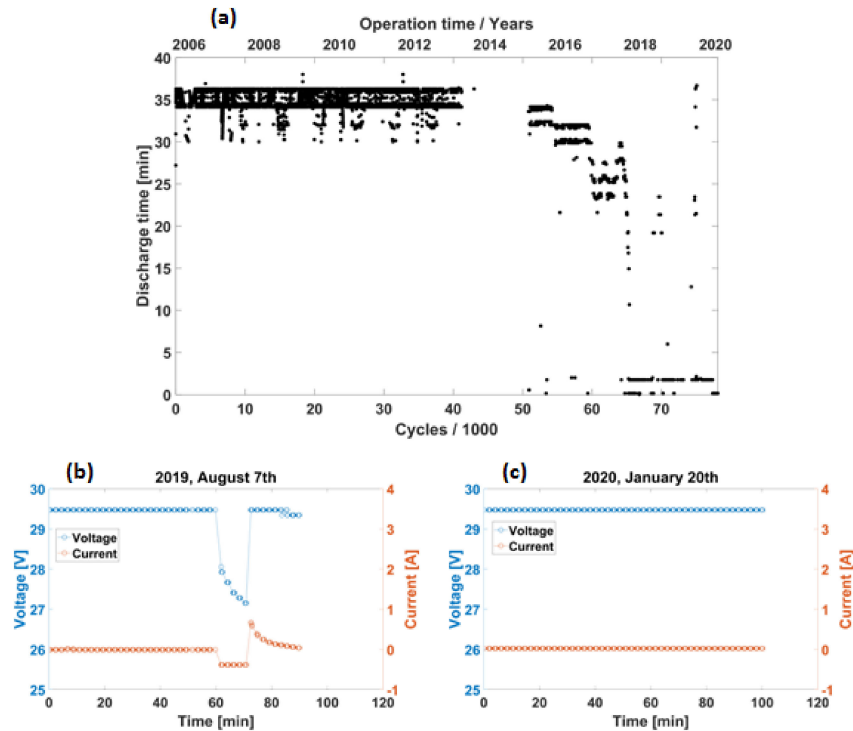


Figure 3. (a) Battery discharge time as a function of operation time and charge-discharge cycles. (b) Last time the REIMEI satellite experienced an eclipse period of time and its battery was discharged. (c) The REIMEI satellite only experiences sunlight and its battery remains fully charged.

from telemetry data as a function of charge-discharge cycles for the REIMEI battery 1 and 2. Note that the operating temperature has been maintained within the range of 19–21°C during the satellite operation. EoDV values were picked up just before the satellite’s power control unit (PCU) switched from discharge to charge modes, while EoCV values were picked up when the PCU switched from charge to discharge modes. It can be observed that the EoDV tends to decrease with cycles, due to an increase in the internal resistance of battery which is probably caused by cycling degradation. The satellite has a special control system consisted of contingency strategies and measures which consider “satellite survivability” in case of unexpected malfunctions. One of those measures is the under voltage control hardware/software (UVC) system. For REIMEI, the UVC level is set to 26.5 V, this value corresponds to the minimum voltage required by the satellite to recover sunlight acquisition for its solar panels using the energy of the battery in the event of any malfunction. Therefore, it is very important to monitor the EoDV trend during the satellite operation. Parallel to the satellite operation, the same type of Li-ion cells were tested on ground under charging/discharging condition similar to those of the satellite operation.³ The only differences were the operating temperature, which was 25°C, and the reinforcement of the flight battery. In case of the Li-ion cells tested on ground, the trend of the end of discharge voltage reached the under voltage control level of 26.5 V after 27,000 charge-discharge cycles. This indicates that a small difference in the operating temperature can have a huge impact on the performance on the Li-ion cells. Additionally, the reinforcement of the flight battery and the in-orbit operation in space seem to prolong the utilization of the battery.

In addition, two levels of EoCV can be observed in Fig. 2, 29.4 V and 28.7 V, which respectively correspond the V1 and V2 maximum voltage levels. Usually, the voltage level V2 is utilized in most of the operation, while V1 is used in the case of any contingency and with the aim of increasing the EoDV level. Furthermore, it can be seen

that approximately from cycle 65,000 the level of EoDV and EoCV are the same. This indicates that the battery is not been discharged and it remains fully charged.

Figure 3a shows the battery discharge time as a function of cycles and operation time. A discharge time of 35 min remains almost constant for most of the operation time. This discharge time depends on the orbit into which REIMEI was originally injected. However, from approximately cycle 55,000 the discharge time begins to decrease until zero around cycle 65,000. This coincides with the point at which the EoDV and EoCV have the same value. Since the discharge time depends on the satellite eclipse time-period, the observed decrease in discharge time indicates that the orbit of REIMEI has been altered so that there are periods of time in which the solar panels of the satellite are always facing to the sunlight, and therefore during this periods the battery remains fully charged. Figure 3b shows the last time REIMEI experienced eclipse time and the battery was discharged. Figure 3c shows the voltage and current profiles when the satellite only faces sunlight and the battery remains fully charged.

Figure 4 shows voltage discharge curves filtered from battery telemetry data for different operation dates. In the case of the discharge curve of 2013/03/01 a kink, which appears to be similar to a voltage plateau, is observed at the beginning of the discharging process. The appearance of this voltage kink suggests the occurrence of lithium plating during the previous battery charging process. Usually, lithium plating takes place when a Li-ion cell is exposed to low temperatures and high currents during charging.^{17–19} Since the battery temperature of REIMEI has been maintained within the range of 19–21°C during its operation, the occurrence of lithium plating due to low temperature exposure can be discarded. However, the generation of lithium plating can also be a consequence of a shift in the capacity of the battery positive and negative electroactive materials due to charge-discharge cycling degradation.¹⁹ As the occurrence of lithium plating can compromise

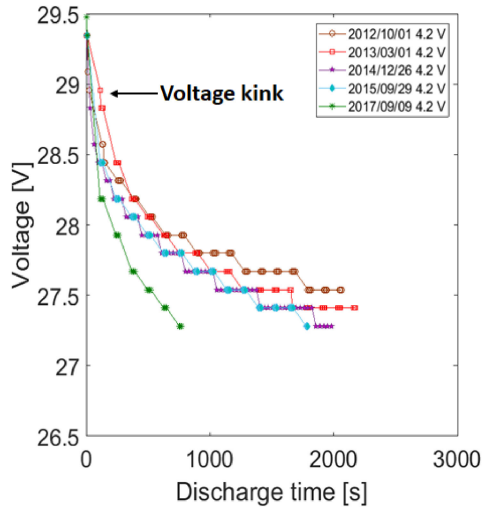


Figure 4. Discharge curves profiles for the REIMEI Li-ion battery filtered from telemetry data.

the safety and reliability of Li-ion batteries, its detection is very important.

To detect the occurrence of lithium plating from REIMEI battery telemetry data, discharge voltage profiles were scanned to identify the occurrence of a voltage plateau at the beginning of the discharging process. Figure 5 shows flowcharts of the algorithms used to detect voltage kinks from battery telemetry data. The algorithms were implemented in Matlab R2017b. The scanning process mainly consists of reading csv battery telemetry files, identifying discharge voltage and current profiles, and calculating the change of voltage with respect to time (dV/dt). Then, the calculated rate of change of the points 1 and 3 is compared with an identification factor. In the first algorithm (Fig. 5a), variable and constant current during the discharging process of the battery are considered. The variable discharge current is caused by the use of the satellite observation cameras. In the second algorithm (Fig. 5b), only constant current during the discharging process is considered.

Figure 6 shows the results of the kink detection frequency distribution obtained by applying the algorithms shown in Fig. 5. This detection distribution was calculated using the following equation:

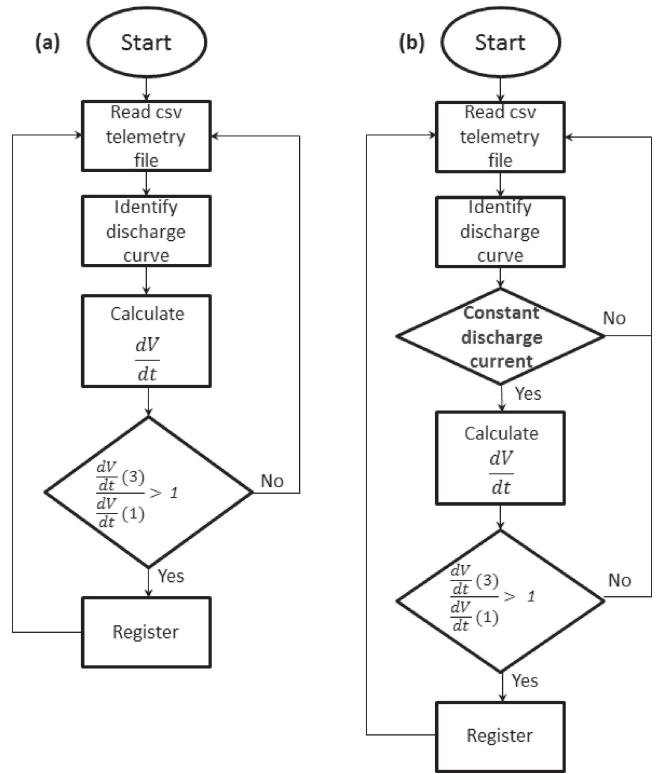


Figure 5. Flowcharts of the algorithms that were used to identify voltage kinks at the beginning of the discharge process from the telemetry data of the REIMEI satellite Li-ion battery.

$$f_d = \frac{n}{N_{tlm,year}} \quad (1)$$

where f_d is the kink detection frequency distribution, n is the number of times a voltage kink is detected and $N_{tlm,year}$ is the number of battery cycles obtained by telemetry per year. It can be observed that the intensity of the kink detection distribution increases with operation time. In case of the variable discharge current, the frequency distribution intensity is higher than that of the constant discharge current. This is likely due to some discharge pulses caused by the use of REIMEI cameras and these discharge pulses have an

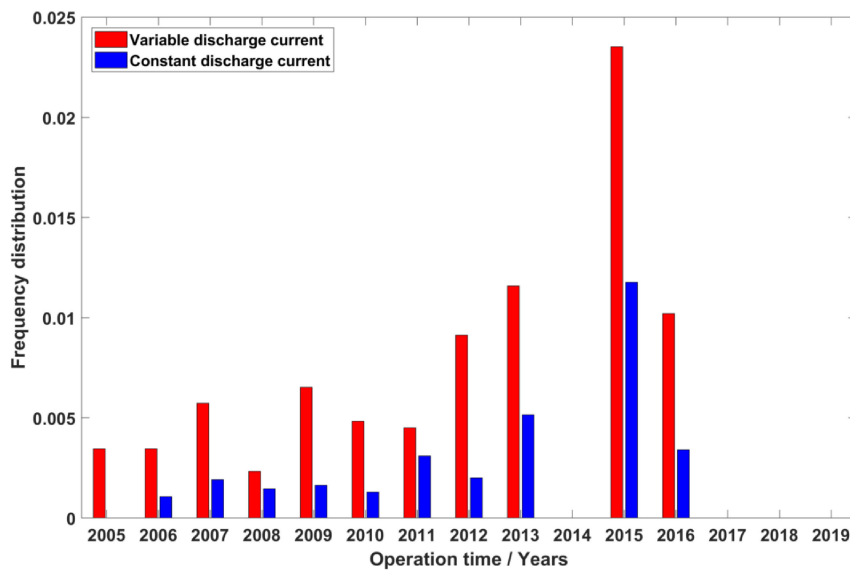


Figure 6. Annual voltage kink detection frequency distribution results for the REIMEI satellite Li-ion battery.

effect on the discharge voltage profiles which could generate some voltage kinks. In addition, it can be seen that voltage kinks are not detected in the years 2017, 2018 and 2019. This due to the fact that the satellite started experiencing a few eclipse periods of time in those years and the battery remains fully charged most of the time, and therefore voltage kinks are not detected. In general, the results of Fig. 6 show that the appearance of a high voltage plateau at the beginning of the battery discharging process, which could be related to the occurrence of lithium plating, is increasing with operation time. We will continue to track the appearance of this high voltage plateau during the satellite operation.

4. Conclusions

The REIMEI satellite was launched on August 23rd, 2005 and after more than 78,100 charge-discharge cycles of its battery, REIMEI is still in operation. REIMEI uses a battery which is composed of LiMn_2O_4 -Graphite pouch Li-ion cells. The main scientific mission of the satellite ended in 2013, since then, REIMEI remains in operation with a new mission dedicated to analyzing its Li-ion battery performance. A durability analysis of the Li-ion battery has been carried out. The end of discharge voltage for battery 1 and 2 has been monitored as a function of operating cycles and the obtained trend was similar for the two battery strings, indicating that the current distribution between these strings has been the same during the satellite operation. The temperature of the battery has been maintained within the range of 19–21°C. This proper control in temperature has allowed the battery to prevent any premature degradation, which is reflected in its long operation performance. In addition, the appearance of a voltage plateau at the beginning of the discharging process from the battery telemetry data was analyzed. The results showed that the appearance of this voltage plateau has increased with operation time. The operation of the satellite will continue, and we will keep tracking the end of discharge voltage trend and the appearance of a high voltage kink at the beginning of the discharging process of the REIMEI Li-ion battery.

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