Research on Ground Storage Scheme of Li-ion Battery Based on Rapid Satellite Launch

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Abstract. With the rapid development of society, satellites play an irreplaceable role in human production and life. Space has become the commanding strategic point of the world's scientific and technological competition and the core area of the scientific and technological revolution. The competition for space among the space powers is becoming increasingly fierce. In order to adapt the requirements of rapid and emergency satellite launches, the mode of satellite long-term storage, regular testing, and selective launch is maturing. Lithium-ion battery has a limited lifespan, and its storage options need to be fully demonstrated. In this paper, the performance degradation of space-use lithium-ion batteries under different ground storage conditions is verified by experiments, and based on this, ground storage strategies and plans for lithium-ion battery are formulated.

1. Introduction

Lithium-ion battery has a limited lifespan, which is affected by environment temperature, state of charge, and storage time. Therefore, Lithium-ion battery storage should be fully proved to be reasonable and operational, in order to minimize performance degradation in the requirement of satellite launch project.

On account of the actual situation, lithium-ion battery currently has the following two storage solutions.

Option 1: Lithium-ion battery is assembled in satellite, stored with the satellite.

The life of the battery includes cycle life and storage life. During the storage period, the battery is hardly charged and discharged, and most of the time is in a shelved state. The performance degradation rate of a battery during storage is affected by the battery's state of charge (SOC) and storage temperature\([1-2]\). In order to reduce the storage performance degradation of the battery, it is necessary to control the temperature and battery state of charge during storage. At the same time, due to the self-discharge of the battery and the leakage of the PCU, the voltage will gradually decrease during the storage of the battery, which is prone to over-discharge. Long-term storage in the over-discharged state will cause the battery's performance degradation rapidly and seriously affect its lifespan. Therefore, during the storage period of the battery, it is necessary to conduct regular voltage detection and supplementary charging to keep the battery voltage within a reasonable range.

During storage with the satellite, since battery can only be stored at room temperature and the temperature is relatively high, state of charge of the battery should be controlled to be low to prevent large capacity degradation under high state of charge. At the same time, in order to avoid...
over-discharge of the battery, the state of charge of the battery cannot be too low. Therefore, the state of charge of the battery is controlled between 30% and 50%. If the state of charge of the battery is lower than 30%, it needs to be supplemented to 50%.

The advantage of this solution is that the battery is always stored with the satellite, without disassembly and installation operations. Satellite can be launched into orbit according to procedures when required by the mission. The disadvantage is that the storage temperature and state of charge of the battery are higher, and the battery performance degradation will be greater.

Option 2: Lithium-ion battery stored separately.

The battery is removed from the satellite, packed into a dedicated packing case, and transported back to the manufacturer for storage. The battery is stored in a cold storage, where the environment temperature is 0°C ~ 10°C, the state of charge is 20% ~ 30%. During storage time, the environment temperature and battery voltage are checked regularly.

The advantage of this solution is that the storage temperature and state of charge of the battery are lower, so the battery performance degradation is smaller when stored for the same time. The disadvantage is that the battery needs to be disassembled and installed once (about one day each time), which affects the physical state of the satellite, and the battery needs to be transported long distance two times (about three days each time).

2. Experimental

The experimental sample is a lithium-ion battery for space use. The positive electrode uses NCA material, the negative electrode uses graphite material, and the electrolyte uses lithium hexafluorophosphate carbonate-based multi-organic solvents[3]. Since the performance degradation rate of lithium-ion batteries during storage is mainly affected by the battery's state of charge (SOC) and storage temperature[4], the sample battery is set to 20% SOC, 50% SOC, and 80% SOC, stored in an environment of 0°C, 10°C, 20°C, and 30°C separately. The number of batteries in each state is three, the storage time is four years, and the performance of the battery is tested every six months to compare the performance degradation of the battery under different storage conditions.

3. Results and Discussion

3.1. Capacity test

3.1.1. The tendency of capacity with storage time. The capacity of the sample battery decreases with the increase of storage time. This capacity decline can be attributed to the loss of active lithium in the battery. It is theorized that active lithium is mainly lost through electrolytic reduction on the anode surface, and at the same time, the thickness of the SEI film (solid electrolyte interface film) increases. Julius Schmitt believes that the capacity decay rate during storage is linearly related to the square root of time[5], which conforms to the following formula:

$$\frac{C_t}{C_0} = a - b(t)^{1/2}$$  

(1)

Where

- C_t: Storage capacity after t time
- C_0: Storage capacity before t time
- a: Offset aging parameters
- b: Square root aging parameters
- t: Storage time

According to the experimental data of sample battery storage, the relationship curve between the relative capacity value and the square root of the time function is shown in Figure 1. Table 1 lists the fitting parameter values of the model function of each curve fitted by the linear regression method according to formula (1), describing the capacity reduction caused by aging, and the table is all dimensionless parameters. Because the model function describes the relative capacity, a is close to the value of 1. The fitting parameters show that the values of the correlation coefficient R^2 are all greater than 0.94, indicating that the capacity decay of the battery has a good linear relationship with the square root of the time function.
Figure 1. The relationship between relative capacity value and time under different storage temperature and state of charge.

Table 1. Fitting parameter values of model function.

| SOC (%) | Temperature (°C) | a     | b     | c     |
|---------|------------------|-------|-------|-------|
| 20      | 10               | 1.0005| 0.0036| 0.9494|
| 20      | 10               | 1.0011| 0.0056| 0.9481|
| 20      | 20               | 1.0007| 0.0079| 0.9625|
| 20      | 30               | 1.0022| 0.0132| 0.9742|
| 50      | 0                | 0.9992| 0.0037| 0.9467|
| 50      | 10               | 0.9992| 0.0083| 0.9654|
| 50      | 20               | 0.9995| 0.0109| 0.9702|
| 50      | 30               | 1.0016| 0.0184| 0.9891|
| 80      | 0                | 1.0000| 0.0206| 0.9787|
| 80      | 10               | 0.9994| 0.0232| 0.9882|
| 80      | 20               | 0.9980| 0.0269| 0.9899|
| 80      | 30               | 0.9962| 0.0365| 0.9901|

3.1.2. Change trend of capacity with temperature. According to the experimental data under different storage temperatures of the experimental sample batteries, capacity decay rates are shown in Figure 2 to Figure 4. The figures indicated that under the same state of charge, the capacity decay rate rises with the increase of storage temperature[6]. Due to the temperature increases, side reaction of active material and electrolyte is intensified, which results in Li+ loss mounting and capacity degradation increased.
Figure 2. Variation curve of battery storage capacity at different temperatures at 20% SOC.

Figure 3. Variation curve of battery storage capacity at different temperatures at 50% SOC.

Figure 4. Variation curve of battery storage capacity at different temperatures at 80% SOC

The decay of capacity has obvious correlation with temperature, which accords with the description of Arrhenius equation.

\[ k = A \exp\left(\frac{-E}{RT}\right) \]  

(2)

Where \( k \) is the reaction rate, \( A \) is the exponential factor, \( E \) is the activation energy, \( R \) is the gas constant, and \( T \) is the absolute temperature[7]. Table 2 shows the parameters of the Arrhenius equation.
for the capacity decay rate b at different temperatures. The correlation coefficient \( R^2 \) is higher than 0.95, indicating that the capacity decay rate is consistent with the Arrhenius equation.

Table 2. Fitting parameter values of Arrhenius equation

| SOC (%) | A    | E    | \( R^2 \) |
|---------|------|------|------------|
| 20      | 1327.2 | 29149 | 0.9915     |
| 50      | 21058  | 35119 | 0.9687     |
| 80      | 7.2247 | 13465 | 0.9536     |

3.1.3. Change trend of capacity with state of charge. It can be realized from Figure 1 that at the same temperature, as the state of charge increases, the capacity decay rate also shows an upward trend[8]. This is because the active material of the positive electrode is in a high oxidation state under a high charge state and is more likely to react with the electrolyte. Studies have also shown that the anode potential in the high-charge state contributes to electrolyte reduction and SEI growth, leading to accelerated loss of Li+ during storage.

3.2. Internal resistance test

The internal resistance of the sample battery is tested once every six months during the 4-year storage. The changes in the internal resistance of the battery under different state of charge and storage temperatures are shown in Figures 5 to 7.

It can be seen from the figures that as the temperature and the state of charge increase, the internal resistance of the battery shows an increasing trend, and the higher the temperature, the higher the state of charge, and the more obvious the increase in internal resistance. This is due to the side reaction between the electrode active material and the electrolyte, which not only causes the loss of the electrolyte, but also causes the passivation film on the positive and negative electrodes of the battery to thicken and the internal resistance increases[9-10].

![Figure 5. Variation curve of internal resistance at different temperatures at 20%SOC.](image)
3.3. **AC impedance test**

Comparing the 50% SOC, 20°C of environment temperature, the AC impedance data of battery before storage and four years after storage, the results are shown in Figure 8. The high frequency stage mainly reflects the electronic contact impedance of lithium-ion batteries and the diffusion impedance of Li+ in the electrolyte. The intermediate frequency stage mainly reflects the charge exchange impedance of the electrode/electrolyte interface. The low frequency stage mainly reflects the diffusion impedance of Li+ in the active material and SEI. It can be seen from the figure that as time increases, the intersection of the AC impedance curve and the horizontal axis shifts to the right, indicating that the ohmic impedance of the battery has increased slightly, which is the same as the ohmic impedance value measured by the internal resistance meter during storage. Basically the same; the semicircle in the high-frequency region of the battery reflects that the charge transfer between the SEI and the electrode occupies a major position in the impedance, which is caused by the characteristics of resistance and capacitance. After storage, the semicircle diameter of the high frequency part of the curve increases: on the one hand, due to the occurrence of side reactions, the thickness and composition of the passivation film on the surface of the positive and negative electrodes change, which increases the impedance of the passivation film; on the other hand, due to the loss of electrolyte and the change of some components also affect the charge transfer speed of the electrochemical reaction inside the battery to a certain extent, thus causing the increase of the impedance in the middle and high frequency region.

**Figure 6.** Variation curve of internal resistance at different temperatures at 50%SOC.

**Figure 7.** Variation curve of internal resistance at different temperatures at 80%SOC.

![Figure 6. Variation curve of internal resistance at different temperatures at 50%SOC.](image1)

![Figure 7. Variation curve of internal resistance at different temperatures at 80%SOC.](image2)
Figure 8. AC impedance data of the battery at 50% SOC at 20℃.

4. Conclusion
This paper selects lithium-ion batteries for space use, and experimentally verifies the degradation of its ground life, and draws the following conclusions.
(1) The higher the state of charge and storage temperature, the faster the battery performance decays. Therefore, the battery should be stored at a low state of charge and lower temperature as much as possible.
(2) According to the experimental data of satellite storage, if the storage time is no more than 1 year, option 1 should be selected for storage. And the capacity decay of the battery is no more than 1.5%; If the storage time is more than 1 year, in order to reduce the performance degradation of the battery and affect the service life of the satellite in orbit, option 2 should be used for storage.
(3) The detailed storage method of option 1 is as follows.
The battery is stored with satellite, storage environment temperature is 0℃~25℃, and storage environment humidity is 20%~60%. The environment temperature and humidity are recorded once a day. The battery voltage is between 24.5V and 25.5V, check the battery voltage every three months, and perform activation treatment every six months.
(4) The detailed storage method of option 2 is as follows.
The storage battery is assembled into a dedicated packing case and stored separately. Storage environment temperature is 0℃~10℃, and storage environment humidity is 20%~60%. The environment temperature and humidity are recorded once a day. The battery voltage is between 23.8V and 24.5V, check the battery voltage every three months, and perform activation treatment every six months.

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