Certification of Lithium-ion Cells with Electrical Power Subsystem for CubeSat

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Abstract－The research in space technology and small satellite development is getting more prosperous in recent year. The 2U CubeSat project PHOENIX is being developed at NCKU as a part of the QB50 mission in collaboration with Von Karman Institute (VKI), which aimed to be launched in December 2016. Phoenix consists of several subsystems and one of the most critical one is Electrical Power Subsystem (EPS), which provides, stores, distributes, and controls the satellite's electrical power. A battery pack consisting of standard cylindrical 18650 lithium-ion cells has been chosen for PHOENIX-CubeSat missions. This paper will focus on the combination of EPS and lithium-ion cells for testing and certifying all criteria of NASA battery safety requirements. Lessons learned in this endeavor will be presented.

Key Words: CubeSat EPS, lithium-ion cell testbed, battery safety requirement

1. Introduction

CubeSats are giving rise to more interesting among academic, business, government for their low cost, short developmental duration, and the standardized architecture. Despite the small volume of CubeSats, they contain numerous subsystems which could be the use of off-the-shelf hardware and software. The Electrical Power Subsystem (EPS) could be regarded as the heart of CubeSat. It is in charge of powering several components of the CubeSat including the radio board, attitude control unit, payloads, etc. The EPS is only responsible for distribution, and management power, storage, regulation.

PHOENIX, one of the CubeSats in the QB50 project, which is the 2U CubeSat will be launched in the 2016. The EPS of PHOENIX is based on the GomSpace NanoPower P31u-9.0[1)] which consists the Power Distribution Modules (PDMs), Power Conditioning Modules (PCMs) and Battery Charge Regulators (BCR)[2)]. Fig. 1 shows the EPS architecture.

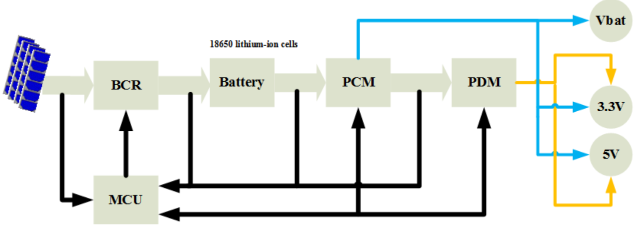

Fig. 1. EPS architecture

Many CubeSats planned to deploy from the International Space Station for their science projects are powered by the standard COTS 18650 lithium-ion battery. As the concerns about battery explosion emerge, the safety battery requirements become essentially important, especially in the ISS. If the CubeSat is planned to be deployed through the ISS, it should comply with the NASA battery safety requirements. In addition, NanoRack, the deployer of PHOENIX, made a few of different battery safety requirements[3)]. Since some batteries are mounted on the EPS board and they implement all the missions together, all the protection mechanisms and safety requirements shouldn't just consider either batteries or EPS board.

The pressure variation, the launch vehicle vibration, and the unsuitable design render direct and indirect damage to the battery. Also normal operation ages the battery, components of the circuit and producing the dendrites slowly. Dendrites are formed inside the cell that may cause the internal short[4)]. According to the aforementioned factors, certification procedures of safety battery are developed and executed in the following subjects: basic physical and electrochemical characteristics, electrical cycling characteristics, overcharge, overdischarge, external battery short, vibration and vacuum tests. Those tests simulate the adverse operation situations or environments.

The companies and academic organizations have developed many testbeds to verify the battery, but most of which don't focus on the applications of space field or NASA safety requirements. This paper focuses on the combination of EPS board and lithium-ion cells for testing and certifying all criteria of NASA battery safety requirements.

The rest of this article is composed of four sections: Section 2 introduces safety issue for CubeSat. Section 3 describes protection methods between the EPS board and batteries. Section 4 discusses the test setup, the experimental results and test procedures on PHOENIX. Finally, the paper ends with the conclusions and future work in Section 5.

2. Battery safety issue

Safety is the basic requirement for all the systems which are demanded to protect themselves and not to interfere others. The battery which is an energy storage device is the easiest to cause the damage for other components. Therefore, EPS board should be designed to facilitate battery safety so as to provide power to the components and isolate the adverse scenarios properly.

There are many factors to affect the performances of the batteries. The main harmful elements are overcharge, overdischarge, external and internal short, high temperature, and structure issue.

One of the unfavorable conditions for battery is required to withstand prolonged exposure to the vacuum of space. During the shipment to the ISS, the pressure varying from 1atm to 0.0068atm may cause the electrolyte leakage and structural deformation. Electrolytic material is placed in the battery using the crimps in the outer metal shell of the batteries. Low quality crimp seals render electrolytic material leaking in low-pressure environments weakening battery performance and life. Besides, the electrolytic leakage of the acid property may corrode the surround circuit. CubeSats shall make sure that the crimps maintain the good condition in the low pressure environment.

Another adverse scenario for CubeSat rocket is suffered from vibratory loads over a substantial bandwidth of frequencies, which may pose the hazards to internal short, deformation and elements separation. Not only the battery safety requirements but also the QB50 project requires to implement the vibration test.

The internal short which is caused primarily by cumulating a large amount of dendrites swelling the battery that is the major factor of lithium-cell exploding. However, the dendrites are form when the battery is subjected to voltage, current and temperature beyond the tolerance itself. The secondary factor causing the internal short relates to the lax manufacturing process due to the impurity such as metal particle, burr, etc.

Another common mistake leading to failure is over charging/discharging accelerating the age and growing the dendrites. Especially, over charging spikes the temperature when the battery is full. Fig. 2 shows the temperature during the overcharge test. When the temperature rises, anode decomposes the electrolyte into the $LiCO^3$ that increases the film thickness and limiting ion anode access. This increases the impedance and reduces the capacity[5)]. In addition, the overdischarge may pose that the battery could not turn on again reducing the capacity due to the irreversible reaction[6)]:

$$LiCoO_2 + Li^+ + e^- \rightarrow Li_2O + CoO$$

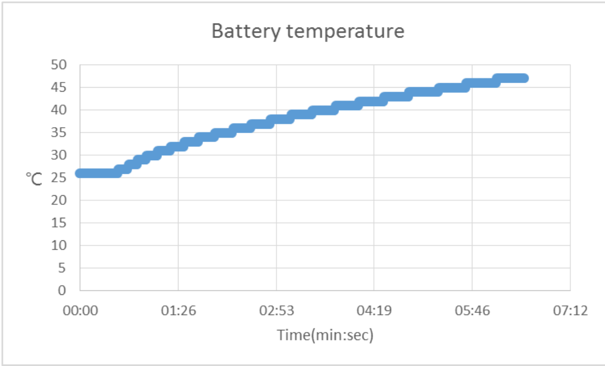

Fig. 2. Battery temperature during overcharge test

Moreover, the most severe scenario is an unintentional external short that will damage the circuit. In contrast the accident above, the external short raises the temperature and harms the battery and circuit instantaneously, though a PTC (Positive Temperature Coefficient) switch is used to prevent short-circuiting by inhibiting high current surges in the 18650 lithium-ion cell.

3. EPS protection mechanism

Most of the requirements test the protected action of EPS board when batteries meet the improper use. Since CubeSats don't only contain the batteries, it should coordinate with EPS board which controls, distributes and detects all the battery information. Therefore, the three major protection mechanisms are Over Voltage Protection (OVP), Over Current Protection (OCP) and Under Voltage Protection (UVP). Those mechanisms base on NanoPower P31u-9.0, but most of COTS EPS also provide those basic protected functionality. Fig. 3 shows the EPS protection mechanism.

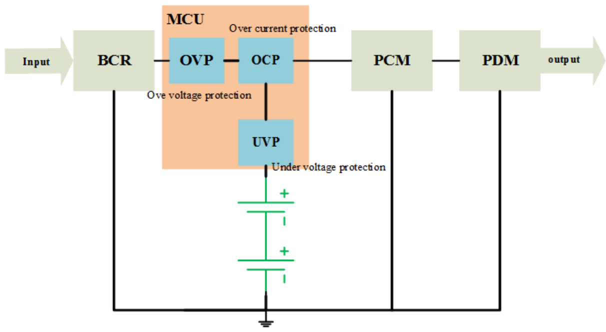

Fig. 3. EPS protection mechanism

OVP maintains the maximum voltage and diminishes the charged current when it detects that the battery voltage is higher than the threshold. EPS board is shunted down by OCP for 100ms when the current is more than the safe margin. The EPS board is turned off by the UVP until the voltage recovery to 6.4V.

Even if the manufacturers declare that the circuit and battery could deal with most of the accident, it still needs to verify all the functions and gets the data to analyze the EPS's behavior.

For example, the cycle of charging and discharging could get the approximate ratio of the Depth of Discharge (DoD)[7] and State of Charge (SoC)[8] which help to determine when the CubeSat should go into the safe mode turned off the non-essential subsystem.

4. Experimental results and test procedures

This paper presents the test procedures and results for the certification of PHOENI. The results are applicable to other CubeSats with a little adjustment. In order to execute the tests, several different testbeds were developed. Due to the EPS board limitation, that some of the regulations are different with NanoRack are still acceptable. Fig.4 shows the basic architecture of the test setup. The battery is charged/discharged via the EPS board by sensing the temperature, voltage, and current information on the EPS board. The I^2C protocol is used as an interface between the EPS board and the STM32 or On Board Computer (OBC) which serves as the auxiliary device to assist the storage of data and the logic decision.

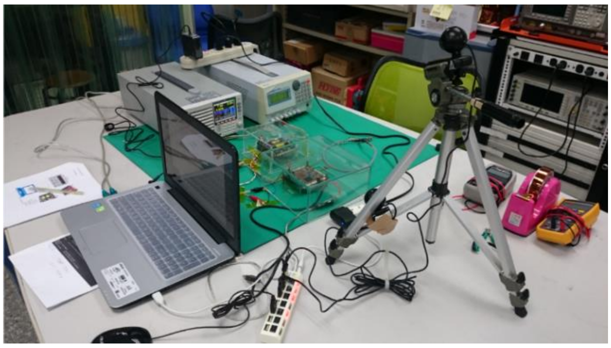

Fig. 4. Basic architecture of the test setup

4.1. Physical and electrochemical characteristics

Prior to simulate any adverse scenario, the parameters including the dimension, weight and capacity ought to be checked in order to build the basic aspect. Nevertheless, only the width and length of the batteries could be measured, since the batteries are mounted on the EPS board. For this reason, the weight including the circuit board is measured. The mass of NanoPower P31u-9.0 is shown in the Fig.5. The test procedures are as follows:

- Visual Inspection; record all findings such as scrapes, bulge or dents, etc.
- Measure the physical properties such as dimension with 1mm precision and weight with 0.1g precision.
- Record the Open Circuit Voltage (OCV) with 0.1V precision.
- Ensure that the cell/ battery is at least charged to 8V before proceeding. After setting up the programmable load to a constant current of 1.875A, load the battery and wait for 30 seconds before recording the Closed Circuit Voltage (CCV).

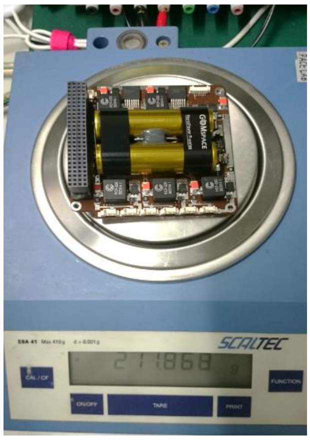

Fig. 5. The mass of NanoPower P31u-9.0

4.2. Electrical cycling characteristics

In addition to the OCV and CCV, the cycles of charge and discharge are also very important to measure the capacity which is compared with the rest of the tests. The charge cycling data and procedures include the following cycles in this order: charge, discharge, charge, discharge, and charge. Record relevant data for all of these cycles and a 10 minute rest period should be provided between charge and discharge. The purpose of the rest period is to cool the battery, especially after the charge. The C-rate defines the discharge rate that is equal to the capacity of the battery in amp-hours divided by 1 hour. For example, the PHOENIX'S battery rated at 2600mA so the discharged rate of C/2 means the battery dissipates the 1300mA. The cycles show in the Fig.6. The test procedures are as follows:

- Charge the cells/ batteries to 8.4V using the EPS input current of C/2. Then hold the batteries at a constant 8.4V until the current drops below 100mA.
- Discharge the battery pack at a rate of C/2 until the UVP switches off the EPS board.
- Repeat charge cycling procedures until cycling is complete.

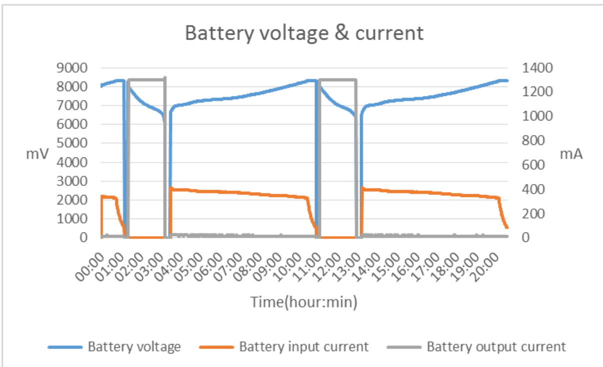

Fig. 6. Batteries voltage and current

4.3. Overcharge and overdischarge

Sometimes news report the battery explosion when charging. The reason is the charger doesn't cut off the power at the proper moment. To prevent the overcharge circumstance, EPS board coordinates the OVP to restrain the growing voltage and to lessen the charging current. Overdischarge dwindles the capacity and then couldn't reboot EPS anymore. Therefore, EPS board should work with UVP system to avoid the hostile situation. The purpose of the over-charge/discharge test is to verify the performance of the OVP and UVP. The test should record the capacity, then the capacity is calculated by equation (1)

$$Q = I * t \quad (1)$$

Where Q is the battery capacity (amp-hour), I is the constant current of discharge current (A), t is the discharge period (hour). For example the Fig.6, the capacity (2.38 amp-hour) equal the constant current (1.3A) multiply the period (1.83 hour).

The OVP and UVP action are shown in the Fig.7 and Fig.8, respectively. The following steps are as follows:

- Overcharge cells/ batteries to 10.0V with the EPS input current of 1C. The OVP should active protection when the voltage is more than the threshold which sets 8.3V.
- Record the voltage at which the protection activates.
- Discharge the cells/ batteries a rate of C/5 until the decreasing voltage lulls. The purpose verifies the reversion of the EPS.
- Complete a charge/ discharge cycle as specified in Section 4.2 and record the capacity.

Similarly, the over-discharge test verifies the UVP and the recoverable ability.

- Overdischarge the cells/ batteries at a rate of 1C to 0V. The UVP should be triggered when the voltage is lower than the threshold which sets 8.3V.
- Record the voltage at which the protection activates.
- Charge the board at a rate of C/5 and until the charging current is below 100mA. The purpose checks that EPS board could be reset again.
- Complete a discharge/ charge cycle as specified in Section 4 and record the capacity.

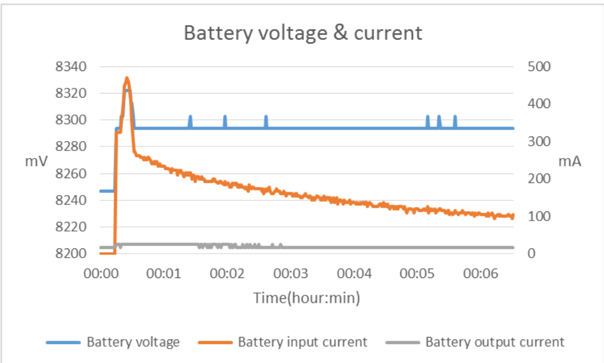

Fig. 7. Battery voltage and current when OVP active

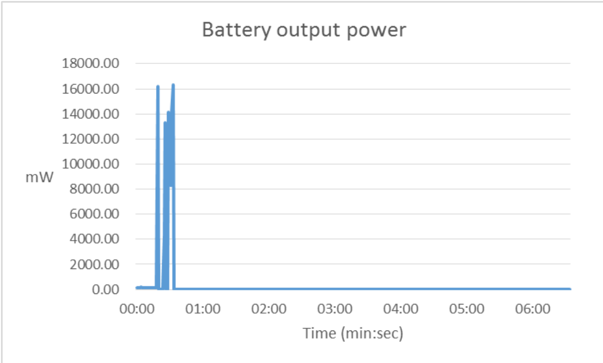

Fig. 8. The output power of overdischarge

4.4. External battery short

External short that is the most dangerous test must prepare stricter security measures. Due to the instantaneous heat and current, the board or battery may be explosion, flame or smoke. Though the battery build-in a PTC to protect itself, the high temperature and current make the pernicious harm of CubeSat. Therefore, the test configuration includes the explosion-proof housing, extinguisher powder, and the wider gage wiring. Fig.9 presents the testbed of external short. Also, the electronic load turns on the OCP function protected those facilities and sets the constant resistance mode as the load of the battery. Nevertheless, some EPS boards don't provide the OCP function. It must pay attention prudently before execution. The short current triggers the OCP shown in the Fig.10. The enormous current generate through calculating the Ohm law:

$$I = V/R \quad (2)$$

Where R is the 40mΩ short circuit resistor, V is the battery voltage around 6.4 ~ 8.3V, I is the short current. The equation (2) describes the reason why the current spike. The steps are following:

- Short the battery using the 40mΩ load for 10 secs. The OCP should active and shunt down the EPS board for 100ms.
- Record the current at least rate greater than 10 Hz.
- After the external short, charge the board at C/5 current to verify whether the OCP can reset itself.
- Complete a discharge/ charge cycle as specified in Section 4 and record the capacity.

Fig. 9. External short testbed, EPS board in the explosion-proof housing

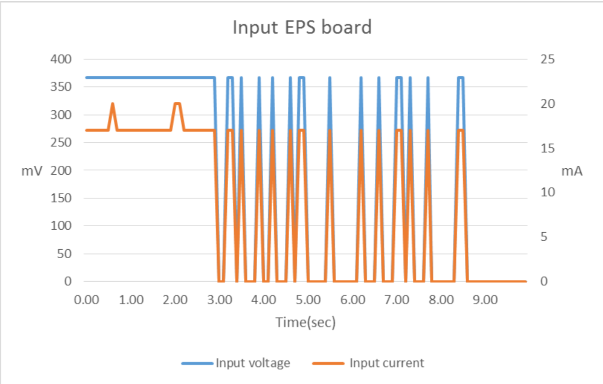

Fig. 10. OCP switch off the EPS board

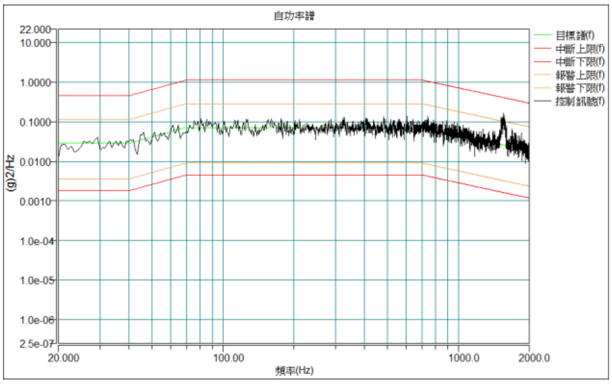

Fig. 12. X-axis spectrum

4.5. Vibration test

The vibration test is regarded as the basic test, no matter how to deploy the CubeSat into space. During CubeSat launched to the space, it will subject to the violent vibration created by the many stages of the transportation rocket and launcher. The vibration level of CubeSats partially depends upon the weight and material, and then NanoRack defines a set of testing spectrum of frequencies and corresponding acceleration in the Table1. The spectrum covers an extensive range of frequencies at diverse accelerationa that may trigger any possible resonance. Fig.11 displays the testbed of vibration test. Fig.12 shows the spectrum of x axis. The following procedures are as follows:

- Record the OCV before vibration test and after each axis of vibration
- Each axis of vibration continues 1 min.
- Discharge/ charge/ discharge cycle each battery after the vibration tests and record the capacity.
- The pass/ fail criteria requires that there shall be less than 0.1% change in the OCV and less than 5% change in capacity before and after vibration test

Table 1. Vibration Testing Spectrum

Frequency (Hz)		ASD (G2/Hz)	dB/OCT	Grms
20		0.0288	*	*
40	0.0288	0	0.76	
70	0.072	4.93	1.43	
700	0.072	0	6.89	
2000	0.01872	-3.86	9.65	

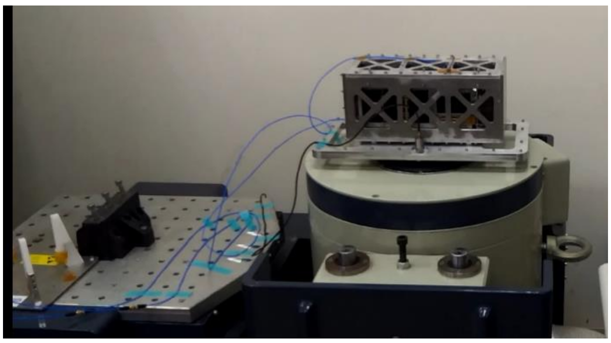

Fig. 11. Vibration test facility

4.6. Vacuum test

CubeSats launch to the ISS at an altitude of 400 km. It means the pressure varies from 14.7 psi to 0.1 psi approximately. The changing pressure usually causes the deformation issue, while the battery of CubeSats should maintain the completeness of structure and capacity. EPS board is placed in the chamber to test the sealing level of the battery structure for electrolyte leaks. The test simulates the environment via the vacuum chamber in the constant temperature. Fig.13 presents the testbed of vacuum test. The procedures are as follows:

- Implement the test of section 4.1 again before and after the vacuum test except the CCV test.
- Place fully charged batteries into the vacuum chamber at atmospheric pressure and pull vacuum at approximately 8 psi/minute. Maintain vacuum (approximately 0.1 psi) for 6 hours. Re-pressurize the chamber to ambient at a rate of 9 psi/minute.
- The pass/ fail criteria requires that there is less than 0.1% change in mass.
- Discharge/ charge/ discharge cycle the cells/ batteries and record the capacity.
- The pass/ fail criteria requires that there shall be less than 0.1% change in the OCV and less than 5% change in the capacity before and after vacuum testing.

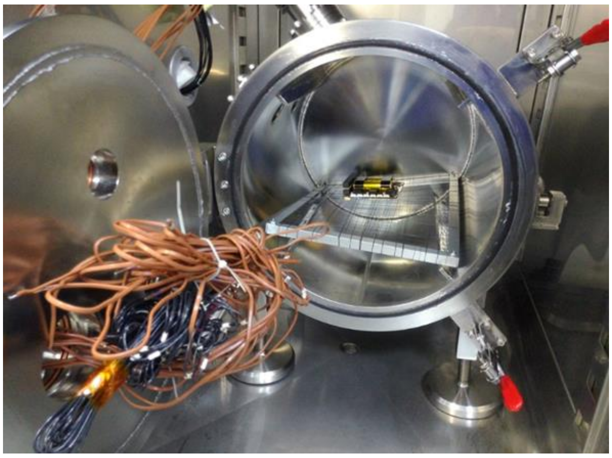

Fig. 13. Vacuum chamber

5. Conclusion

Each test simulates the different scenario which may pose the battery failed during the mission. It is very essential from the safety aspect to verify the functionality and limitation of EPS to avoid impacting the mission or hurting the people. In those experiments, charge/discharge cycles could be utilized to determine DoD, SoC and other parameters, those data could predict the behavior of EPS. Through the serious of test, the PHOENIX battery has been certified to meet the safety requirements as established by NASA and Nanorack.

In the future, the testbeds will be more general and reliable for different EPS board and battery. And the test configuraions should be considered the EMC and ESD issue. The goal is to build up the standard process and testbed for any battery test of CubeSats, even though the feature or characteristic of EPS board and battery is usually different.

Acknowledgments

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