

Launch Environment Ground Test Evaluation with Multi-axis Vibration and Shock for Pouch Solid-State-Ceramic Battery Advanced Energy Storage

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Abstract – Satellites must endure the hostile environment during their launching to space via rocket; therefore, they should be exposed to the real launch conditions for ground testing, including all subsystems and components which should be carefully tested. Several solid-state-ceramic batteries have been selected to be evaluated under the launch environment after been evaluated under the space environment, which has shown so far good results. This paper focuses on the physical degradation and the electrical performances of the batteries based on the discharge capacity, the open-circuit voltage, and charge/discharge modes. Batteries have been exposed to shock, then tested under vibration within different frequencies' levels with sinewave, sine burst, and random. Before and after the test, the physical properties of all batteries have been checked, several cycles of discharge and charge have been performed to check their performances and survivability after the evaluation test. With 95% of capacity, batteries could demonstrate their ability to withstand the launch conditions successfully, they could be able to operate during several cycles after the test, so far, showing no degradation on their performances within the limits. Also, the paper is providing the main requirements and criteria for batteries' launch ground testing for the small satellite project. **Copyright** © 2020 The Authors.

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Keywords: Solid-State Battery, Small satellite, Launch Environment, Low Earth Orbit, Vibration & Shock Test

I. Introduction

Even with the long history and large application of the Lithium-Ion batteries, since they have been the most used in large mobile applications: from ground such as cellphones and electrical vehicles, to space with spacecraft and space suits, they have been categorized as hazardous batteries [1], especially after a bad manipulation or working under extreme conditions [2].

The manufacturers and users have been required to cover several test conditions following different requirements such as vibration and shock to verify their ability to work safely at the nominal level and good performances. According to the mechanical design of the Lithium-Ion batteries, the vibration and shock conditions can have a significant effect on the batteries' performances. Concerning these effects, internal shorts may occur which can lead to venting the electrolyte with the possibility of firing and thermal runaway. It may lead to breaking the cells and leakage in the case of liquid or jelly batteries [3]. At the work was done by Lijun Zhang, it has been identified that the vibration may lead to a significant increase in discharge resistance [4].

Eventually, the vibration and shock test for batteries became necessary due to the effect which could affect

on the performances, like for the study done by Martin J. Brand, in which the effect of vibration and shock have been evaluated on two different battery structure: Cylindrical and Pouch, which the results have shown no degradation on the pouch batteries [5]. Or the work was done by James Michael Hooper on a multi-axis vibration test on the Li-Ion cylindric cells, for their electrical and physical evaluation [6], [7]. Then, the work was done by J-K Lee on the Pouch Lithium-Polymer battery in which the accelerated vibration and the charge-discharge cycling have been combined has shown good mechanical and electrical stability of the batteries [8]. However, Gunnar Kjell and Jenny Frodelius Lang have concluded with the comparison between different vibration test standard limits on the li-ion batteries and fatigue damage on the mechanical structure that the standards differ strongly and should be considered for the purpose which the battery will be used [9]. For the space applications, the primary objective is to ensure that the satellite and all components have passed the qualification test and free from workmanship defects. That why all kinds of energy storage including the batteries should be qualified for space used, otherwise, they should be evaluated and tested before launch to space. These are some examples

of the qualification test done on the batteries for small satellites including the launch environment, in which K-H. Park has presented the qualification test for the secured reliability of the Lithium-Ion batteries [10], moreover, the test was done by Saft and ESA for the qualification and life testing of the Saft Li-ion batteries [11]. Or the evaluation of variable cylindric cells by Jonghoon Kim, in which several batteries have been tested to evaluate their capacity and internal resistance [12], and another work for a battery certification for small satellite done by Zachary Cameron, for the Li-Ion cylindric cells test procedure [13]. Finally, the work was done by João P. Monteiro during the integration, and the verification approach of ISTSat-1 CubeSat is one of a good example for testing one kind of the solid-state-polymer battery for space use [14]. In this paper, for the first time, commercial solid-state-ceramic batteries have been tested under vibration and shock for the space application use. The same kind of batteries, in which have never been flown in space, have been previously evaluated under vacuum and thermal vacuum for the low earth orbit, which the results have been presented in different paper [15], the work has been done as part of the long evaluation process of the solid-state-ceramic batteries for the in-orbit demonstration mission onboard the future satellite. The feature of these kinds of batteries compared to other conventional batteries is having a solid ceramic electrolyte instead of liquid (LIB: Lithium-Ion battery) or gel (LPB: Lithium-Polymer Battery), which makes it very special for the safety issues with no risk for flammable liquid leakage. Compared to the other solid-state batteries, the solid ceramic electrolyte has a high elastic moduli makes it able to work at high temperatures [16], [17]. Since there are a few kinds of research and publications related to the vibration and the shock test for batteries for space use, this work is summarizing the main steps and procedure as a guideline for launch environment evaluation test which could be applied to not only solid-state-ceramic batteries but to all kind of energy storages and satellite's sub-systems.

The paper consists of five parts. Following the introduction in Section I, with the previous work have been discussing, Section II is about the description of the selected battery and the test preparation. Section III presents the inputs test condition required for launch environment, and the description in detail of the full test procedure and methodology. The reel test conditions applied on the batteries, the results and discussion are explained in Section IV. Finally, section V presents the conclusion and the future work plan.

II. Solid-State-Battery Selection and Test Preparation Description

During the launch environment test, a set of commercial solid-state-ceramic pouch batteries with two different capacities, the same kind of batteries that have been previously evaluated under the space environment, for vacuum and thermal vacuum [15], have been selected

for the shock and the vibration ground test. The approach for evaluating the performance and the effect of the test conditions on batteries has been done following several discharges and charges cycles using a test board designed for this purpose [15]. The discharge cycles have been used for the discharge capacity ratio calculation, and the capacity before the test has been used as a reference capacity for comparison with the capacity after the test.

To support the batteries during the vibration and shock test, a tailor-made jig has been designed, with a natural frequency of 2981 Hz. The performance of the jig has been checked with simulation for the three-axis and different modes using Solidworks software to confirm its ability to withstand the test conditions safely.



Figs. 1. Solid-state-ceramic battery ((a) LCB01, (b) LCB02) selected for evaluation test [15]

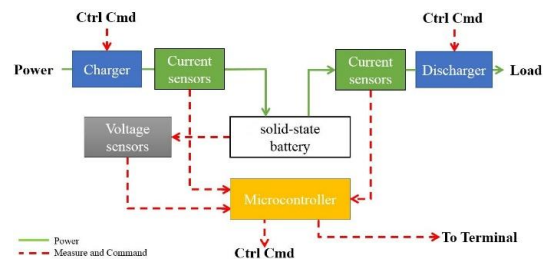


Fig. 2. Test board functional block diagram used for charge and discharge during the evolution test [15]

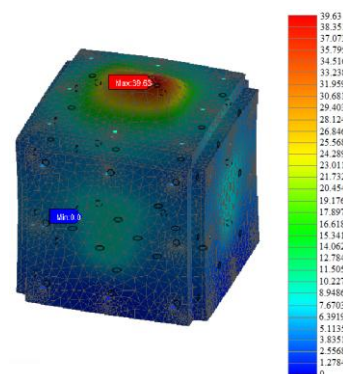


Fig. 3. Jig natural frequency and deformation simulation

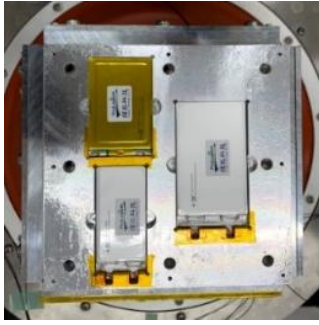


Fig. 4. Solid-state-ceramic batteries mounted on the jig before the vibration test

TABLE I

SOLID-STATE-CERAMIC BATTERIES SPECIFICATION [14]

Lithium Ceramic Battery	LCB01	LCB02
Nominal Voltage (V)	3.75	3.75
Nominal Capacity (mAh)	1950	1450
Energy (Wh)	7.3125	5.4375
Operation voltage (V)	4.35~2.75	4.35~2.75
Size (mm)	4.5×60×105	6.3×42×88
Weight (g)	59.5	45
Operating temperature (°C)	-20~60	-20~60

Since the solid-state-ceramic batteries are planned to be launched on the same rocket as Ten-Koh satellite, the Japanese rocket H2A [18], [19], the same approach for the launch conditions previously adopted by Jesus Gonzalez for the solar modules integrated converters [20], as well as the Lithium-Ion battery pack for the Ten-Koh satellite and all its subsystems [21], [22], have been reproduced as the input's requirements for the launch environment ground test. Two different test facilities have been selected to satisfy the test conditions. Table II summarizes the specification for all the test equipment, first for the vibration machine which has the capability for testing under sine and random, and then the other machine used for the shock test.

III. Launch Environment Evaluation Test's Conditions and Procedure

The purpose of the launch environment evaluation test is to check the ability of the solid-state-ceramic batteries to withstand the conditions during launch and separation from the rocket. The hostile shock and vibration conditions are applied according to the defined H2A rocket requirements. During the launch environment test, a group of the six solid-state-ceramic batteries P1X, P1Y, and P1Z for LCB01, P2X, P2Y, and P3Z for LCB02 have been tested during two steps: once the group has been exposed to shock condition, and then it has been tested under several vibration environments.

TABLE II

LIST OF THE EQUIPMENT USED DURING THE EVALUATION TEST

Name	Type	Range
Vibration machine	A30 (TBD-A30)	5 Hz to 2600 Hz
Shock machine	CeNT	4000 G
Cubed jig	TCJ-B200-A30-A	DC ~ 2000 Hz
SSB Jig	Jig for SSB (Original)	2981 Hz

The robustness of the solid-state-ceramic batteries has been evaluated carefully. Before and after each test, the solid-state batteries have been inspected with a visual check, measurement of physical property: weight, length, width, and thickness, then the electrical measurement of the open-circuit voltage and the discharge capacity, finally charged and discharged during several cycles.

III.1. Shock Test

For the high frequency from 100 to 5000 Hz, the shock test is needed to simulate the conditions during the rocket stage, fairing, and satellite separation. The six solid-state-ceramic batteries have been distributed in three different groups and then exposed to a short shock duration with more than 1000 G. The accelerometers have not been attached to the test article directly but to the support jig, because the battery survival is the main concern for the test. Thus, only the input shock spectrum has to be measured.



Fig. 5. Solid-state-ceramic batteries selected for the launch environment ground evaluation



Fig. 6. Solid-state-ceramic battery charged and discharged before and after each test. Discharge condition: constant current (CC): DC: 0.5C, EOD: 2.8V. Charge condition: constant-current constant-voltage (CC/CV): CC: 0.5C, CV: 4.35V, LCB01 EOC: 97.5mA, LCB02 EOC: 72.5mA [15]



Fig. 7. The shock test's pickup sensors configuration for the solid-state-ceramic batteries mounted on the shock machine

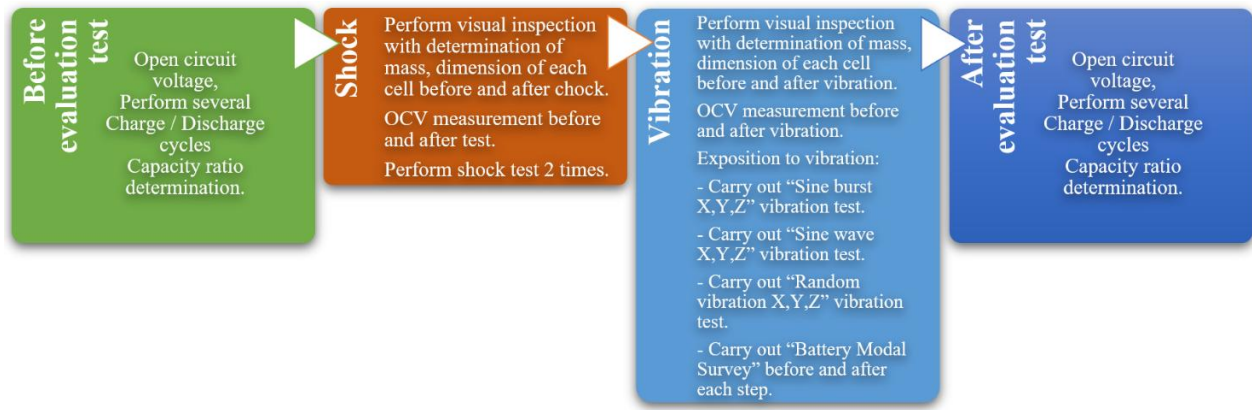


Fig. 8. Launch environment test flowchart summarized in fourth parts: before the test, shock, vibration, and after the test.
The quasi-static acceleration test is carried out by replacing it with a sine burst test

The inputs shock spectrums conditions for the shock evaluation test are the qualification level (QT) of the H2A rocket which is represented in Table III. Typically, the required shock level is between 1000 to 4000 G within the frequency range from 100 to 5000 Hz [23].

III.2. Vibration Test

The purpose of the vibration test is to check the compliance of the solid-state-ceramic batteries with the vibration that may occur during the launch, they should be able to keep at least the same performances without degradation or malfunctions for the next operation in orbit. During the vibration test, the launch environment conditions defined as the qualification test level for batteries required by JAXA for the H2A rocket, have been reproduced as the input required for the test. The solid-state-ceramic batteries have been tested under low and high frequencies:

- Quasi-static or sine-burst: Demonstration against the static acceleration in the longitudinal and lateral direction. The maximum quasi-static acceleration is a combination of the static acceleration and the low-frequency dynamic acceleration [18]. Typically, the number of cycles is 3 to 5. A sine-burst is often selected reason for the difficulty to get the static acceleration in one direction. The test's frequency should be lower than the item's natural frequency;
- Sinusoidal: It is often standardized rather than quasi-static acceleration conditions with a low frequency (from 5 to 100 Hz) within 2 minutes in the longitudinal and lateral direction;
- Random: For the high frequency (from 20 to 2000 Hz), it is caused by the acoustic noise [18].

The solid-state-ceramic batteries have been divided into three jigs, each jig contained one battery from each sample, and it has been tested three times following three configurations. The following distribution allowed us to test the three axes for all batteries sequentially. During the first configuration, the solid-state-ceramic batteries have been mounted into the three jigs (1, 2, and 3) where the tested axes for batteries (x, y, and z) have followed

respectively the vibration machine axes (X, Y, Z) in which the vibration will be applied (X for jig 1, Y for jig 2, and then Z for jig 3). Then after each test's sequence (sine burst, sinewave, and random), the three jigs are rotated, which the following tested axis for the battery should be respectively (Y for jig1, Z for jig2, and X for jig3); finally, the last rotation. Figs. 9 and Table 7 summarize all the three configurations with the three rotations for each test's sequence.

TABLE III
INPUTS TEST CONDITION FOR THE SHOCK TEST [20]

Axis	Frequency range (Hz)	Shock Response Spectrum (SRS)	Number of tests
X (longitude)	100~2600	+6dB/octave	2 times
Y and Z (lateral)	2600~5000	2000G	

TABLE IV
SINE BURST INPUTS TESTING PARAMETERS [20], [24]

Direction	Frequency [Hz]	Acceleration	Excitation time [s]
X axis	20	58.8 m/s _{0-p} ²	1
		7.5 G _{0-p}	
Y, Z axis		49 m/s _{0-p} ²	
		6.25 G _{0-p}	

TABLE V
SINUSOIDAL VIBRATION INPUTS TESTING PARAMETERS [20], [24]

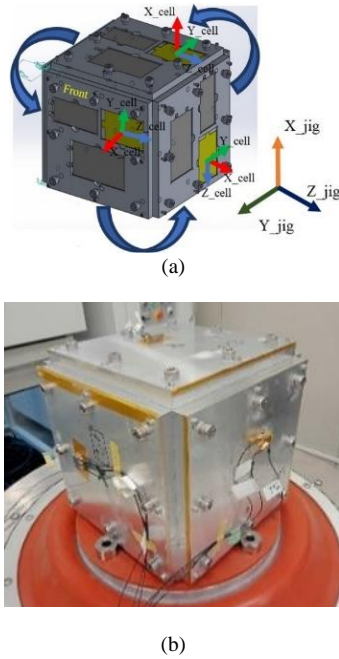
Direction	Frequency [Hz]	Level	Excitation time [oct/min]
X axis	5-7.1	0.02 m _{0-p}	2 (UP and DOWN)
	7.1-100	30.7 m/s _{0-p} ²	
		3.13 G _{0-p}	
Y, Z axis	5-6.3	0.02 m _{0-p}	
	6.3-100	24.5 m/s _{0-p} ²	
		2.5 G _{0-p}	

TABLE VI
RANDOM VIBRATION INPUTS TESTING PARAMETERS [20], [24]

Direction	Frequency [Hz]	Level	Excitation time [s]	RMS value
3 Axis	20-200	+3 dB/oct	120	11 Grms
	200-2000	0.064 G ² /Hz		

TABLE VII
SOLID-STATE-CERAMIC BATTERIES DISTRIBUTION FOR THE THREE CONFIGURATIONS DURING THE THREE TEST'S SEQUENCE: SINE BURST, SINEWAVE AND RANDOM

Configuration	Jig 1		Jig 2		Jig 3	
#1	P1x	P2x	P1y	P2y	P1z	P2z
#2	P1y	P2y	P1z	P2z	P1x	P2x
#3	P1z	P2z	P1x	P2x	P1y	P2y



Figs. 9. Solid-state-ceramic batteries' configuration during the vibration test: (a) Solid-state-ceramic batteries' configuration inside the jig during the three axes rotations, (b) The pickup sensors' configuration for the three jigs

III.2.1. Vibration Test Sequence

The following test sequence should be carried out during all the three rotations for the vibration test:

1. Solid-state-ceramic batteries should be mounted according to the first configuration (Table VII);
2. Starting the first sequence for the x-axis:
 - ✓ Performing x-axis Sine burst vibration;
 - ✓ Performing x-axis Sine wave vibration;
 - ✓ Performing x-axis Random vibration.
3. Changing to the second configuration (Table VII), then the sequence at step 2 should be repeated for the y-axis;
4. Finally, repeating the sequence at step 2 for the last configuration for the z-axis.

IV. Test Result and Discussion

Considering the vibration and shock as a circumstance that may happen simultaneously or consecutively, the results of the two evaluation tests are discussed in the same section. However, during the launch environment evaluation test, the two groups have been tested separately under vibration and shock. During the launch ground test's result evaluation, the criteria used during the space evaluation for the vacuum and the thermal vacuum test have been used [15]. The criteria (#3 in Table 8) have been adopted, which are a combination of the two following criteria for the change in values after each environmental test: Such as some projects at NASA used the first criteria (#1 in Table VIII), others used the second criteria (#2 in Table VIII) for the qualification test for the COTS battery.

TABLE VIII
PASS/FAIL CRITERIA FOR THE LAUNCH ENVIRONMENT TEST

Criteria	OCV	IR	Mass	Capacity
#1 [25]	< 0.1%	< 0.1%	0.1 to 1%	< 5%
#2 [26]	< 0.5%	/	< 0.5%	< 3%
#3	0.1 to 0.5%	< 0.1%	0.1 to 0.5%	3 to 5%

IV.1. Output Test's Conditions

For each group, Fig. 10 shows the reel spectrum for the applied shock during the test, following the same test condition in Table III. The pickup sensors show that the acceleration during the test has exceeded the upper limit, because of the difficulty of tuning, while it is still higher than the lower limit which is more important for the credibility of the test. However, we could say that the batteries were exposed to an accepted shock level test even if the upper limit was exceeded. During the vibration test for the sine burst, the pickup sensors' records for CH2, CH6, and CH7; could reach the required limit at 7.5G with more than 10 cycles (typically only 3 to 5 are required), as represented in Fig. 10. CH2, CH6, and CH7 are respectively the records for the axes that have been exposed to the same sine burst excitation's direction during the second configuration. For the sinewave, Fig. 12 shows the real condition during the test where all the solid-state-ceramic batteries' jigs have been exposed during the low frequencies from 5 to 100 Hz.

Finally, with the high frequencies, during the random vibration, Fig. 13 shows the real test spectrum generated during the test, following the inputs parameter required in Table VI, in which the batteries have been exposed to the random vibration between 20 and 2000 Hz within 2 minutes.

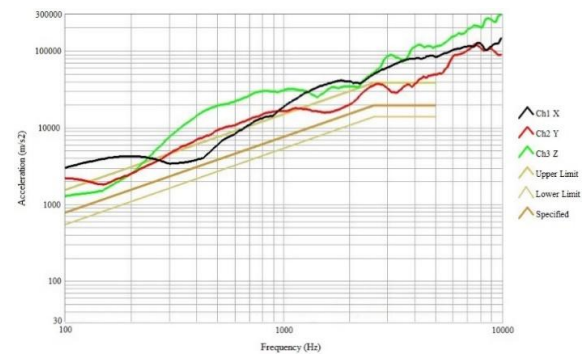


Fig. 10. Shock test pickup sensors' outputs spectrum

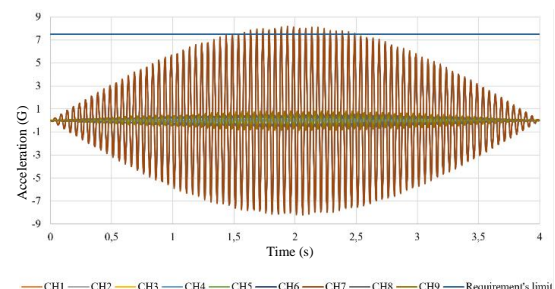


Fig. 11. Sine burst test pickup sensors' outputs, Jig 1 (CH:1,2,3), Jig 2 (CH:4,5,6), and Jig 3 (CH:7,8,9)

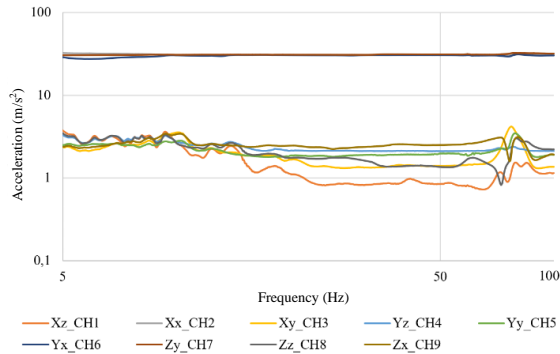


Fig. 12. Sinewave test pickup sensors' outputs recorded for the solid-state-ceramic batteries following the inputs' condition

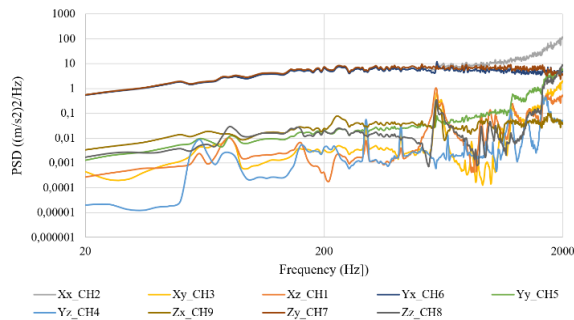


Fig. 13. Random test pickup sensors' outputs for the three jigs during the first configuration

IV.2. Visual Inspection, Weight, and Open-Circuit Voltage Measurement

At the end of the test with the non-functional check, no physical damage has been observed related to the fatigue, none of the batteries have shown a change in dimensions or weight, Table IX summarizes the weight measurement before and after all the launch environment test. Otherwise, the change of value for the OCV measurements shows a variation exceeding the criteria's limits for some batteries (LCB02) with 0.2% excess as shown in Table X. After comparing the measurements between after the shock; which the results have shown no significant variation in value at the order of 10^{-3} ; and after the vibration, it has been concluded that the change of the value has been induced by the vibration and not the shock. However, the exceeding could not be used for judgment until the function test has been done which will give the more significant interpretation.

TABLE IX

WEIGHT MEASUREMENT BEFORE AND AFTER TEST

LCB	01#1	01#2	01#3	02#1	02#2	02#3
Before (g)	58,32	58,38	58,18	45,44	45,56	45,46
After (g)	58,33	58,37	58,17	45,43	45,56	45,45
Difference (%)	0,02	0,02	0,02	0,02	0,00	0,02

TABLE X

OCV MEASUREMENT BEFORE AND AFTER TEST

LCB	01#1	01#2	01#3	02#1	02#2	02#3
Before (V)	4,21	4,21	4,23	4,28	4,28	4,28
After (V)	4,19	4,21	4,21	4,25	4,25	4,25
Difference (%)	0,48	0,00	0,47	0,70	0,70	0,70

IV.3. Functional Test Results

After the batteries have been exposed to the shock and vibration test, several charges and discharges cycles have been performed showing that batteries have been able to operate several cycles in normal conditions which means that the hostile environment did not affect the charge mode of batteries.

As shown in Fig. 14 and Fig. 15, the constant-current constant-voltage (CC-CV) mode has been perfectly followed, starting charging with a Constant-Current (CC) at ~ 1.3 A and a voltage at ~ 3.4 V for LCB01, and ~ 0.8 A and ~ 3.3 V for LCB02, the constant-current has been switched to the Constant-Voltage (CV) at ~ 4.1 to 4.2 V, then the charge stopped when the batteries have been fully charged. However, for the discharge mode and the capacity evaluation, Fig. 16 and Fig. 17 represent the result of the discharge capacity after the shock only, and after all the test compared to the before test discharge capacity.

All batteries have been discharged at the required discharge current, ~ 0.92 A for LCB01, and ~ 0.72 A for LCB02, with the same discharge rate 0.5C. It has been noticed that the LCB01 batteries show a decrease in capacity so far not exceeding the limit of 3% after the shock and vibration only, and between 3% to 5% after all the test. While the only exception is for one LCB02 battery which has shown a decrease of more than 5% after all the test, it may due that the battery was already in bad condition or manufacturing defect, the others LCB02 show no significant loose in capacity, less than 3% after the shock, between 3% to 5% after the vibration and all the test.

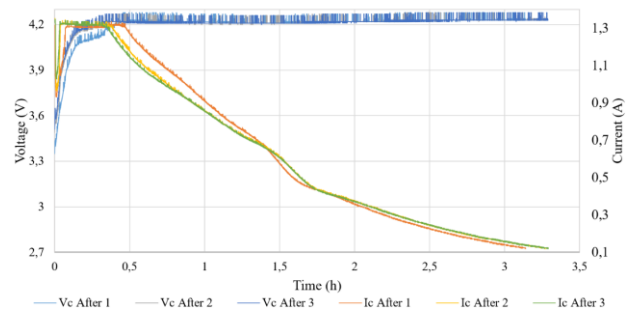


Fig. 14. Charge cycles for LCB01 1950 mAh, group's samples for one jig after the launch evaluation test

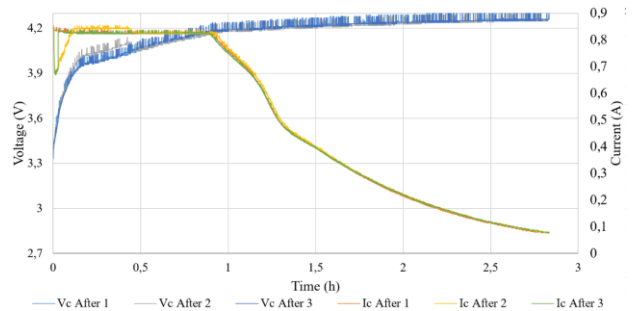


Fig. 15. Charge cycles for LCB02 1450 mAh, group's samples for one jig after the launch evaluation test

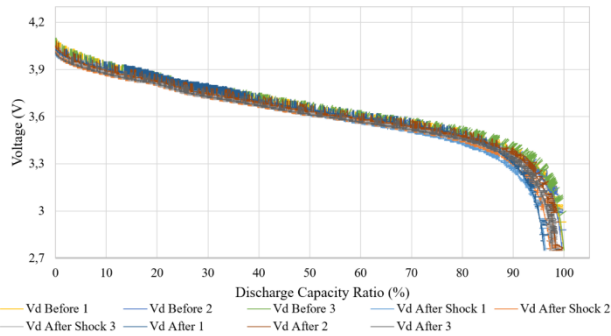


Fig. 16. Discharge voltage vs discharge capacity ratio for LCB01 1950 mAh. Group's samples for one jig: before, after the shock tests, and after the 3 axis vibration tests

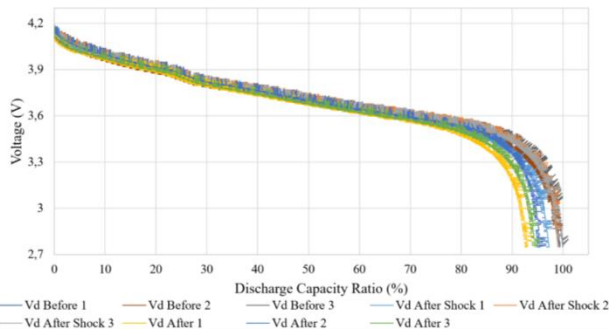


Fig. 17. Discharge voltage vs discharge capacity ratio for LCB02 1450 mAh. Group's samples for one jig: before, after the shock tests, and after the 3 axis vibration tests

V. Conclusion

So far, the results from the evaluation within the launch environment conditions for the solid-state-ceramic batteries show that all batteries have not been affected by the high vibration and the high shock level.

The batteries could withstand the launch environment successfully; it can be noticed on the comparison between the capacity before and after the test that the batteries do not show any significant degradation: 83% of the solid-state-ceramic batteries tested could be able to keep their capacity with 95%, which means that all LCB01 and two LCB02 have passed the launch environment evaluation, so far within the limits. Additionally, they have not shown any physical degradation.

The paper also summarizes the main steps for the battery's ground testing under the launch environment and some criteria which may be used for evaluation after the environment test.

After the space and the launch environment ground evaluation test have been done successfully, the next step is to design a mission board for orbit demonstration of the solid-state-ceramic battery on a real application onboard a low earth orbit small re-entry satellite, in which the battery will be able to be tested at the real conditions during more than one year in orbit, and then recovered after re-entry for further analysis.

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