SCREENING PROCESS AND IN-ORBIT PERFORMANCE OF HORYU-IV BATTERY

Mohamed Yahia Edries*, Erdenebaatar Dashdondog, Ichiro Omura, Mengu Cho

Kyushu Institute of Technology (KIT), Kitakyushu, Japan

*e-mail: n590906y@mail.kyutech.jp

Electrical Power Subsystem (EPS) is one of HORYU-IV satellite bus subsystems. The function of EPS is to provide uninterrupted power to all subsystems during the satellite's lifetime. Generally, EPS consists of Solar Arrays, a rechargeable Battery, and Power Control and Distribution Unit. The battery will store the extra energy which is generated during the sunlit period of the orbit; consequently, it will supply power to the satellite's subsystems during eclipse and overloading periods. Five main requirements should be fulfilled in the battery design, charge/discharge characteristics, storage life, cycle life and safety. Charge/discharge characteristics was verified extensively on each individual cell and for each pack. The storage life was verified by estimating the charge loss of different individual cells after storage in a full charge state for more than 3 months. The cycle life and safety requirements are proved by proper design of charge regulator and thermal control techniques during operation. The screening process of the battery includes the selection of the individual cells before packs and battery assembly, and the battery preparation procedures before launching. The individual cells were selected after going under extensive characterization process which includes, checking of charge/discharge characteristics and measuring of the internal impedance. The objective from that was to select the most identical cells to be assembled within the battery. Before sending HORYU-IV to launch site, the battery was fully charged and inspected from the safety point of view. The charging process was done under similar conditions to in-orbit operation. After Two weeks of in-orbit operation, we could analyze the battery performance to check its functionality. In this paper, we present the details of battery screening procedures and the in-orbit performance of the battery during two weeks of operation.

Key Words: HORYU-IV, Electrical Power Subsystem, Nickel Metal-Hydride battery, Commercial off-the-shelf (COTS)

1 INTRODUCTION

HORYU-IV is a 30x30x30 cm satellite developed in Kyushu Institute of Technology (KIT) and launched in February 17th of 2016. The primary mission of HORYU-IV is to investigate the effect of electrical arcing phenomena caused by space environment on high voltage solar panels. The in-orbit acquired satellite discharge data will promote the usage of high voltage space power systems. According to mass/size aspects, HORYU-IV is considered as a Nano scale satellite, but a new term has been suggested "Lean", which defines the satellites that utilize untraditional risk-accepting development methodology to achieve low-cost and fast-delivery. Electrical Power Subsystem (EPS) is one of the HORYU-IV bus subsystems. The function of EPS is to provide uninterrupted power to all subsystems during the satellite's lifetime. High reliability, high efficiency and simplicity are main requirements should be considered in the design of EPS. Generally, EPS consists of Solar Arrays, rechargeable batteries, and Power Control and Distribution Unit (PCDU). Block diagram of Electrical Power System is shown in Figure 1 [1].

The battery consists of series-parallel connected rechargeable cells. The overall battery voltage depends on the number of the connected cells in series. That voltage is varying according to the cells state of charge (SOC) and operating temperature. The battery capacity (ampere-hour) depends on the number of parallel cells strings.

Nickel-Cadmium (Ni-Cd), Nickel-Metal Hydride (Ni-MH) and Lithium-Ion (Li-Ion) are the commonly used types of rechargeable cells in satellites. Table 1shows the general characteristics of Ni-Cd, Ni-MH and Li-Ion cells. Although, Li-Ion cells are preferred from the aspects of individual cell's voltage and the rated capacity, they are intolerable against over charge or over discharge operation. On the contrary, Nickel based cells, are safer in operation, which make them preferable to be used in Piggy-Back satellites. To decrease the cost, commercial off-the-shelf (COTS) batteries can be

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used in satellite missions after conducting extra tests to proof the performance. For those reasons, NiMH cells have been used to compose HORYU-IV battery. It consists of three parallel packs, each consists of six series eneloop® NiMH cells. The rated capacity of one cell is 1900mAh, and for the battery will be 5700 mAh at 7.2V.

This paper is organized as follows; in Section 2, we presented the details of the screening process. Section 3 presents the test setup and method of measurements. Section 4 shows the results and In-Orbit data. Section 5 focuses on conclusion on it.

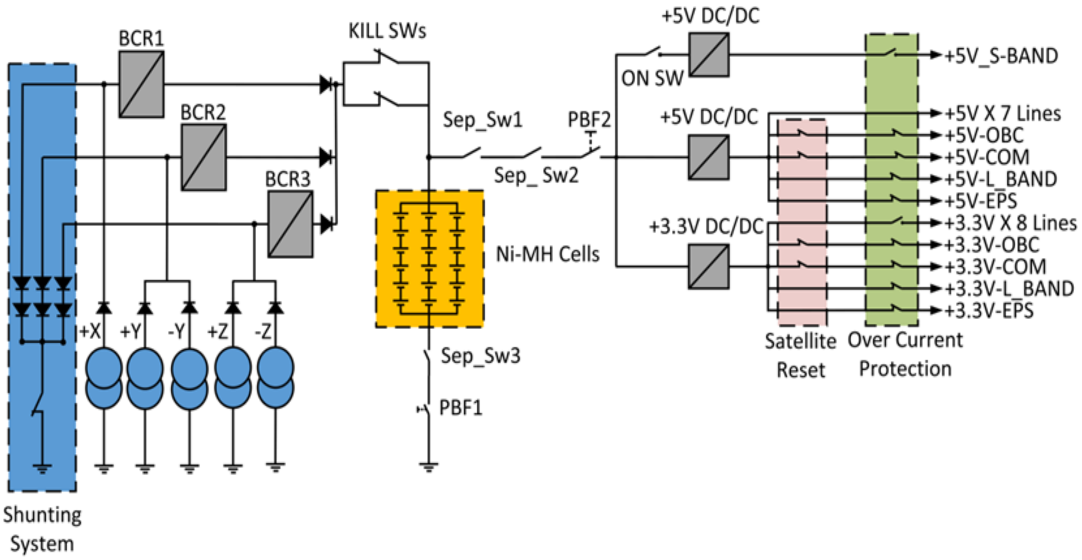

Figure 1 HORYU-IV Electrical Power Subsystem Block diagram [1]

Table 1 General characteristics of Ni-Cd, Ni-MH and Li-Ion cell [2]

CELL TYPE	NI-MH	NI-CD	LI-ION
GRAVIMETRIC DENSITY (W-HR/KG)	55	50	90
VOLUMETRIC DENSITY (W-HR/L)	180	140	210
SELF-DISCHARGE @ 20°C (%/MONTH)	20-30	15-20	5-10
NOMINAL CELL VOLTAGE (V)	1.25	1.25	3.6
OPERATIONAL TEMPERATURE (°C)	10-40	0-50	0-45

2 SCREENING PROCESS

In this section, the batteries screening test is described. The aims of test is to select the most identical cells to make three packs of six series cells among 86 eneloop® NiMH cells, which is shown Figure 2.

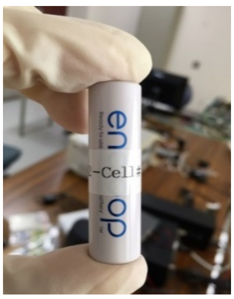

Figure 2 Eneloop® NiMH cells

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In requirement of EPS designer, battery selection and made of battery box shall follow procedure which is shown in Figure 3.

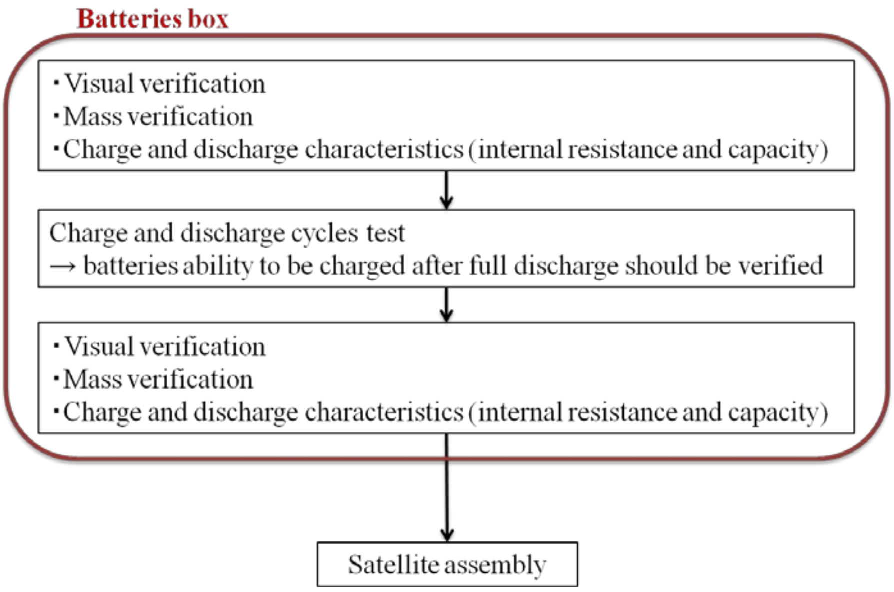

Figure 3 Battery Box assembly requirements

Test is in three folds first, each battery cell is inspected and screened to determine the cells to be mounted together for each pack. Second, after batteries pack assembly and mounting with the batteries box, charge/discharge cycles are carried out and batteries packs characteristics are evaluated prior and after charge/discharge cycles. Third, after batteries box soundness is proven, the batteries box is mounted to the satellite for integration testing that include mechanical and thermal testing. The three packs will be connected in parallel to work as EPS Battery. The characterization process included two tests. The first test was Discharge/Charge test, and the second test was internal impedance estimation test. Eventually battery packs shall be constructed based on test result. Figure 4 shows CAD design of battery box and Figure 5 shows real assembled battery box that based on result of testing.

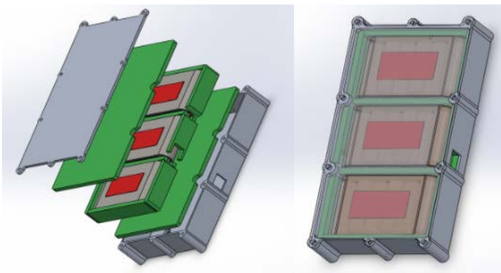

Figure 4 CAD design of battery box

Figure 5 Assembled battery box

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One of the tests is to estimate cells impedance, which is a characteristic of battery self-discharge, just before and after the charge/discharge cycles in case of without environment test. Because HORYU-IV EM battery test result gave a conclusion that environment test doesn't affect to battery performance. Hence, HORYU-IV FM battery test was carried out only before environment test.

3 TEST SETUP AND METHOD

In this section, three sections were included. One is the hardware configuration, second is a software configuration, another is as-run detailed procedural checklist. Hardware and Software development is based those equipment and software manuals [3] [4]. Method of charge and discharge cycling is based on Ni-MH battery user manual, which is from manufacturer [5]

Three sets of batteries have been prepared for HORYU-IV. Two sets for engineering model and one set for flight model. Each set was consisting of 18 cells.

36 cells have been screened for the engineering model's sets. One set was the main and the other was the backup. However, 48 cells have been screened to produce the flight model's set.

To match the tight schedule, two identical setups -setup1 and setup2- prepared for testing to perform the screening process faster. By that we were able to test two cells at the same time. Each setup's hardware was illustrated as in Figure 8. It took 6 hours for the screening process of one cell. To complete the screening process for all cells, it took more than 500 hours. Setup 1 denoted as S1 and setup2 denoted as S2. The screened cells denoted as C1 to C18 for each setup in case of engineering model and C1 to C24 in case of flight model.

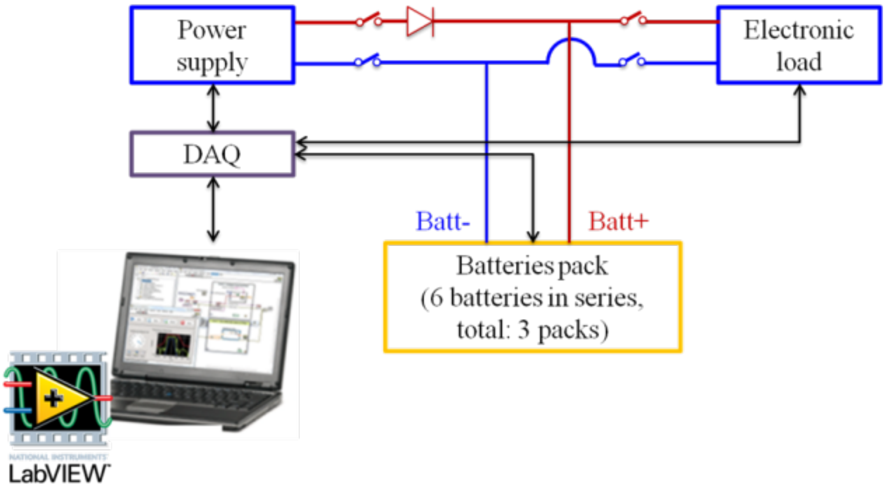

Figure 6 Block diagram of measurement setup (setup1 and setup2)

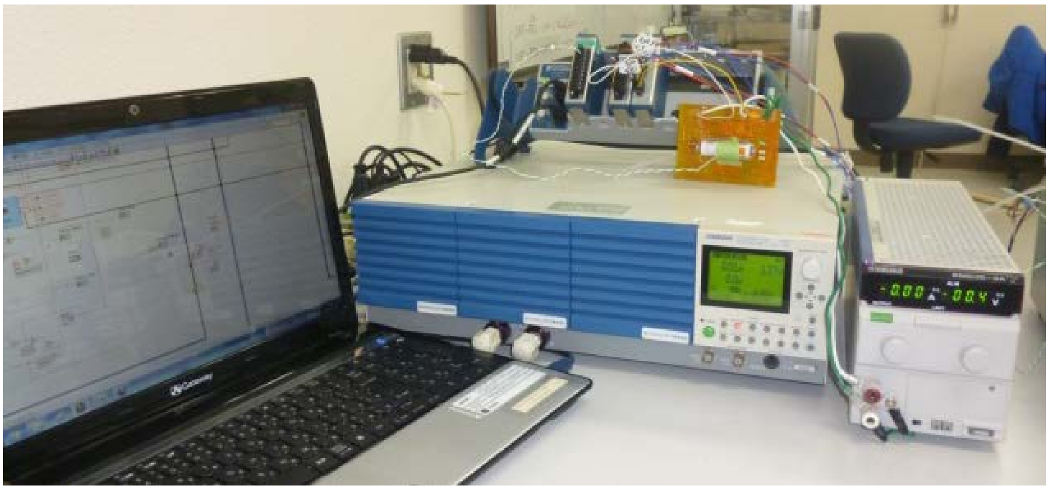

Figure 7 Real appearance of measurement setup (setup1 and setup2)

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3.1 Hardware configuration

Block diagram of measurement setup is shown in Figure 5 and real appearance of measurement setup is shown in Figure 6. Testing setup consists of five main items: an electronic load, a multi-range DC power supply, data acquisitions system, computer running a LabView based program for testing control, and the cell under test. Electronic load is used for C.C mode during the discharge and makes easy to controlling of the load by LabView based program. Multi-range DC power supply makes measurement to be able to work on various range of DC current during the charge. DC power supply is possible to be controlled by LabView based program as well. To control all equipment, National instrument's tool which named Data acquisition was used. All this equipment and tools has been controlled by LabView based program.

3.2 Software configuration

To run the test, LabView program is required to perform charge/discharge cycles along with for batteries impedance estimation. Algorithm of LabView based program was matched to the procedure of Ni-MH batteries charge and discharge. Program starts discharge stage, because any charging shall be start from empty charge of battery. During the charge and discharge test, internal impedance of battery shall be estimated by program. Impedance estimation shall be carried out three times, before first discharge, after charge and after last discharge. During the testing all data shall be saved on the data base. Moreover, date and time shall also be recorded before and after testing.

Procedural Checklist was written during test for each pack testing. The procedure list was filled out for each cell during the test. It includes necessary steps for the test performed. Figure 8 and Table 2 show the flow chart and the description of the screening process steps as implanted by the program.

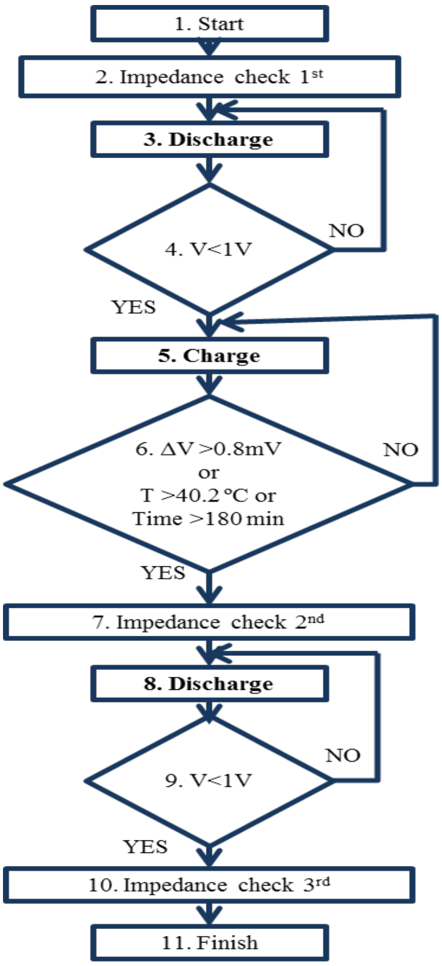

Figure 8 screening process steps

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Table 2 Screening process steps description

1.	Charge/discharge program start
2.	1st impedance measurement (I=500mA, 100mA)
3.	Discharge (C.C mode Current 1C=1900mA, EOD=1V)
4.	Check EOD until 1V
5.	Charge (preparation mode I=500mA, Rapid charge mode I=1000mA, Trickle charge I=100mA)
6.	Three parallel conditions were checked
7.	2nd impedance measurement (I=500mA, 100mA)
8.	Discharge (C.C mode Current 1C=1900mA, EOD=1V)
9.	Check EOD until 1V
10.	3rd impedance measurement (I=500mA, 100mA)
11.	Cycling process finish

4 RESULTS AND IN-ORBIT DATA

4.1 Battery screening result

In general, the selection criteria of the cells were indicated as:

- Charge/Discharge profile per cell as typical Ni-MH cells
- Discharged capacity per cell is at least 0.85 the rated capacity (rated capacity of eneloop Ni-MH is approximately 1900mAh)
- Internal impedance per Cell is less than 0.09 ohm

For the engineering model main set, the all screened cells sorted according to their impedance -regardless how much were the discharged capacity of each-. The most identical cells have been selected for the main set, and the rest have been selected for the back-up set. Figure 9 shows the selected cells for the engineering model sets and their individual impedance. as shown in figure the average impedance was about 79 mΩ, which is close to the value indicated by the manufacture (75mΩ [5]).

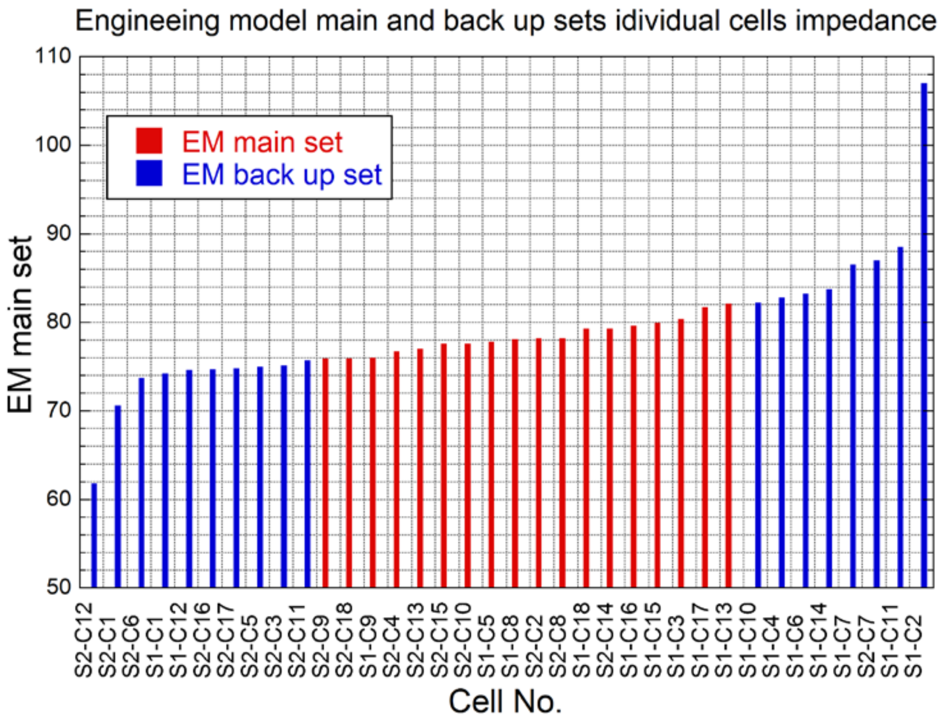

Figure 9 Engineering model main and back-up sets individual cells impedance

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For the flight model set, the selection of 18 cells among all 48 screened cells were done in two steps; first, we excluded 16 cells which had the discharged capacity less than 0.85 rated, second, we selected 18 cells out of the remaining 32 which have nearly equal internal impedance.

The summarized measurement of testing is shown in Table 3. Test result includes charged capacity and its ratio with rated capacity by manufacturer. Identical cells shall be selected based on success criteria and selection method which mentioned above.

Table 3 Detailed measurement of Charge and Discharge cycling

Total 48 Cells	Charge (C %)	Discharge (C %)	R_internal (mOhm)
Minimum	83.79	66.97	66.8
Maximum	113.26	91.01	87
Average	99.19	86.68	72.47

The results of the 48 screened cells which performed equally by setup1 and setup2 followed the normal distribution. Figure 10 shows the range of variation of the measured parameters of all the 24 cells which have been screened by setup1. In the figure, all measured parameters for each cell were are presented. The X-axis is divided into 3 sections; the percentage of charged capacity, the percentage of discharged capacity, and the impedance. Y-axis shows the range of values variation for each of the 24 screened cells. Each cell is presented as a dot. Red dots shows the percentage of charged capacity, the blue dots shows the percentage of discharged capacity, and the green dots shows the impedance. As shown, all the 24 cells were distributed around the average (continuous line). Figure 11 show plotted results of the individual cells. Similarly, Figure 12 and Figure 13 show plotted results which measured by Setup2.

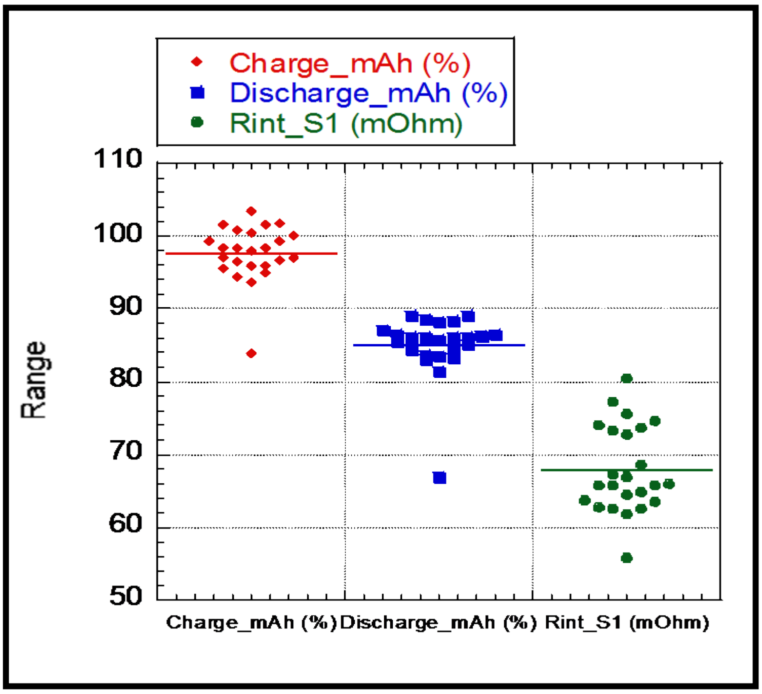

Figure 10 Range of variation of the Charged /discharged capacity and internal impedance of the cells screened by setup1

Distributing the selected cells to the three packs performed to provide equal impedance for each as much as possible. Based on this method three packs of battery were selected to the battery box. To calculate the internal impedance we used DC method the following procedures were done:

- Fully discharge the cells at current equal to 1C (1.9A).
- Turn OFF the Electronic Load and measure the cells' open circuit voltage.
- Adjust the E-Load at CC mode of 100mA.
- Turn ON the discharge switch and measure the new value of the cell's voltage.
- Repeat the test many times and calculate the average value.
- The internal impedance calculated as in Eq (1).

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$$R_{internal} = (V_{off} - V_{on})/0.1 \qquad (1)$$

Figure 14 shows the impedance of the selected 18 cells which vary between 0.076 Ω and 0.082 Ω. Table 4 shows the total impedance of each pack.

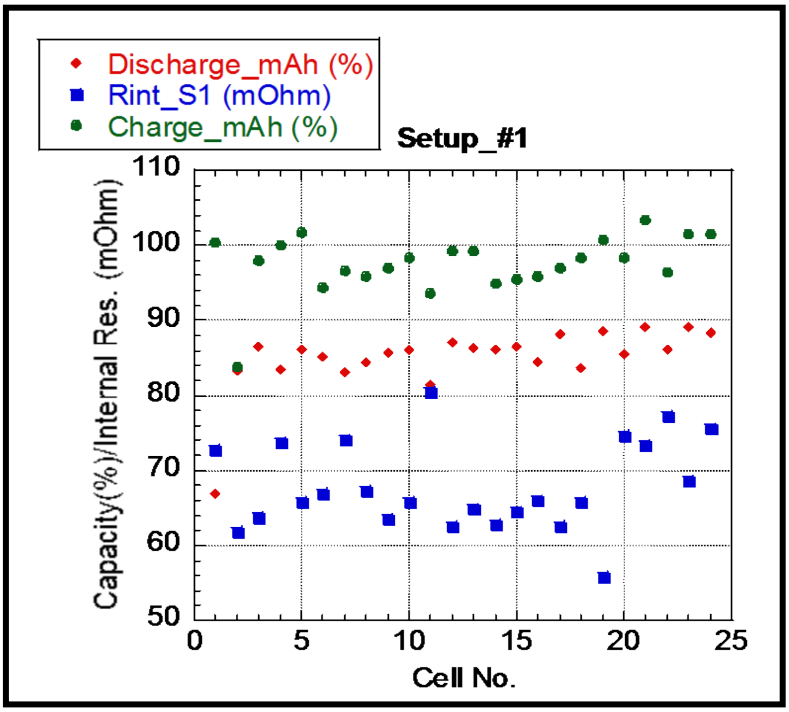

Figure 11 Charged /discharged capacity and internal impedance versus cell numbers screened by setup1

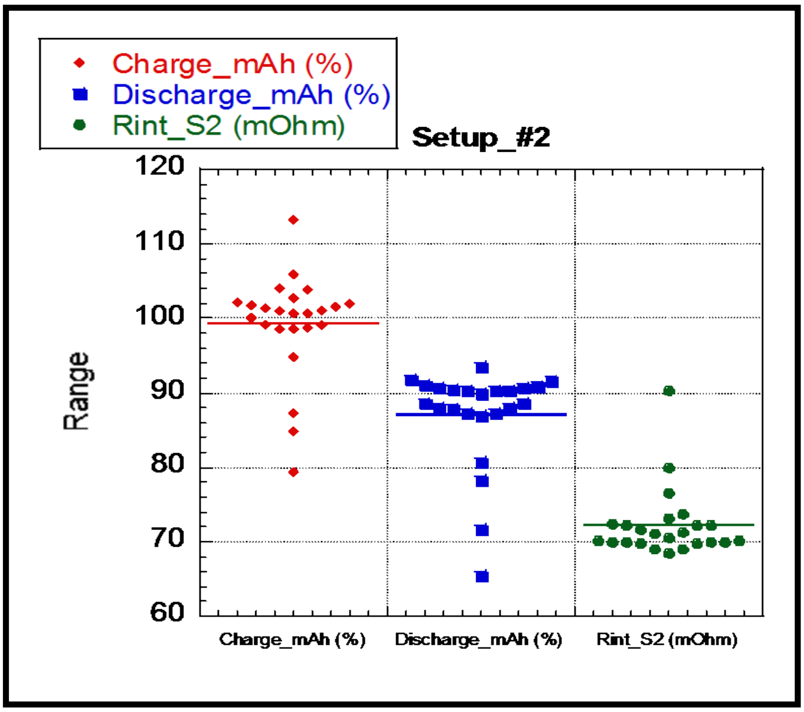

Figure 12 Range of variation of the Charged /discharged capacity and internal impedance of the cells screened by setup2

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Table 4 Total Impedance of each pack

Pack No.	1	2	3
Total Impedance (Ω)	0..4704	0.4704	0.4705

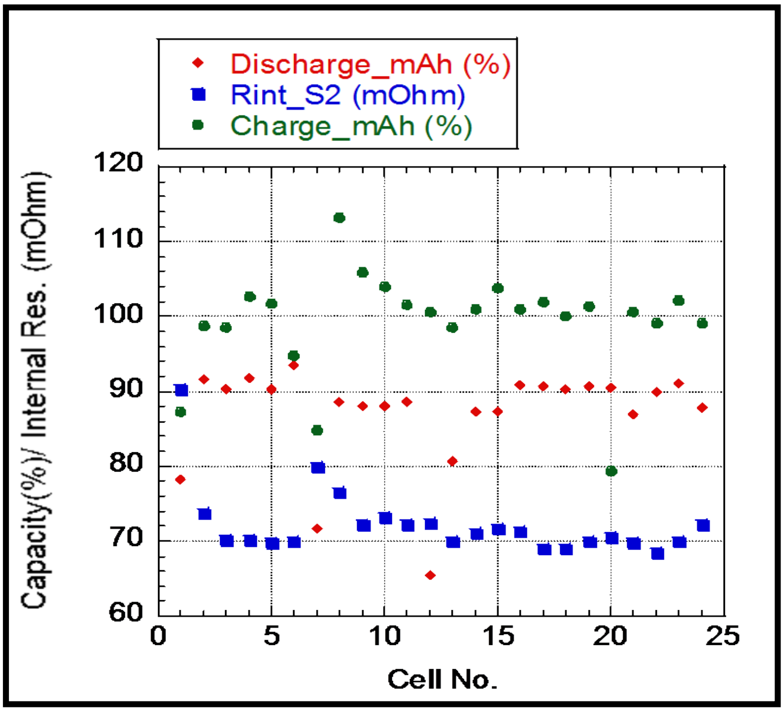

Figure 13 Charged /discharged capacity and internal impedance versus cell numbers screened by setup2

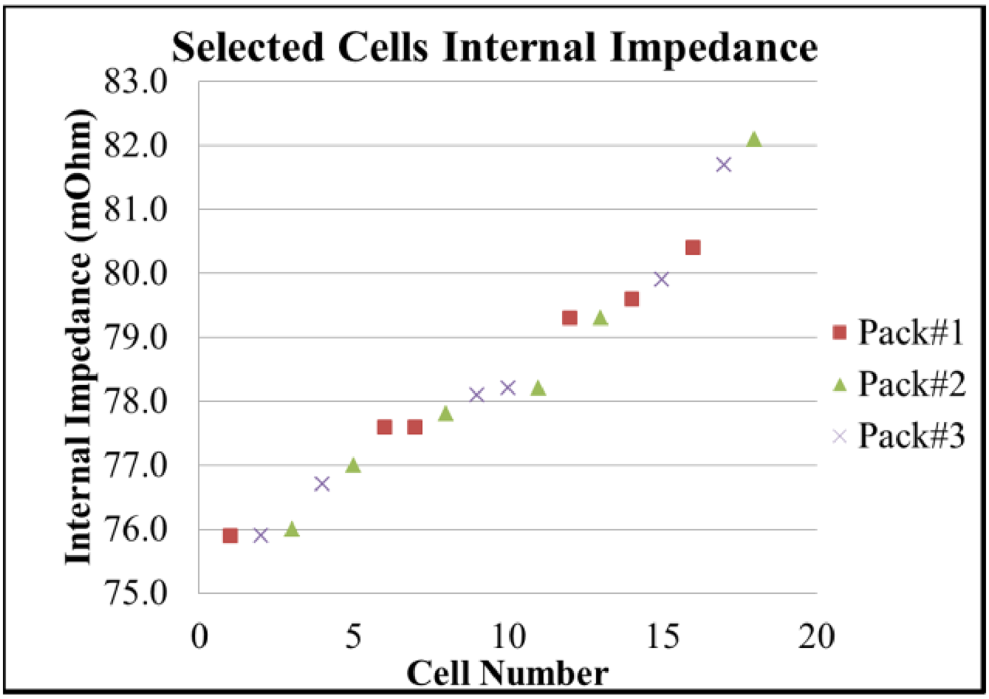

Figure 14 Selection cells internal impedance for corresponding packs

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4.2 Discharging and Charging before launch

After selection, battery box was assembled and just before launch it was fully charged. Before charging battery shall be fully discharged. Measurement result during discharge is shown in Figure 15. After discharging battery shall be fully charged and measurement result during charge is shown in Figure 16. Here, we can see that charging and discharging was properly cycled and capacity was good enough to satisfy requirement.

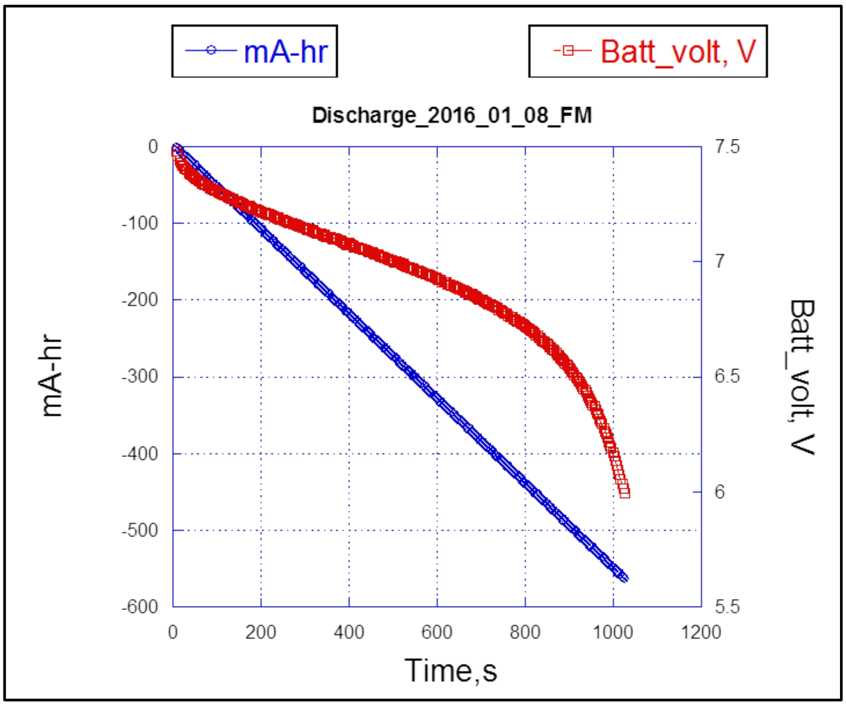

Figure 15 Measurement result during discharge

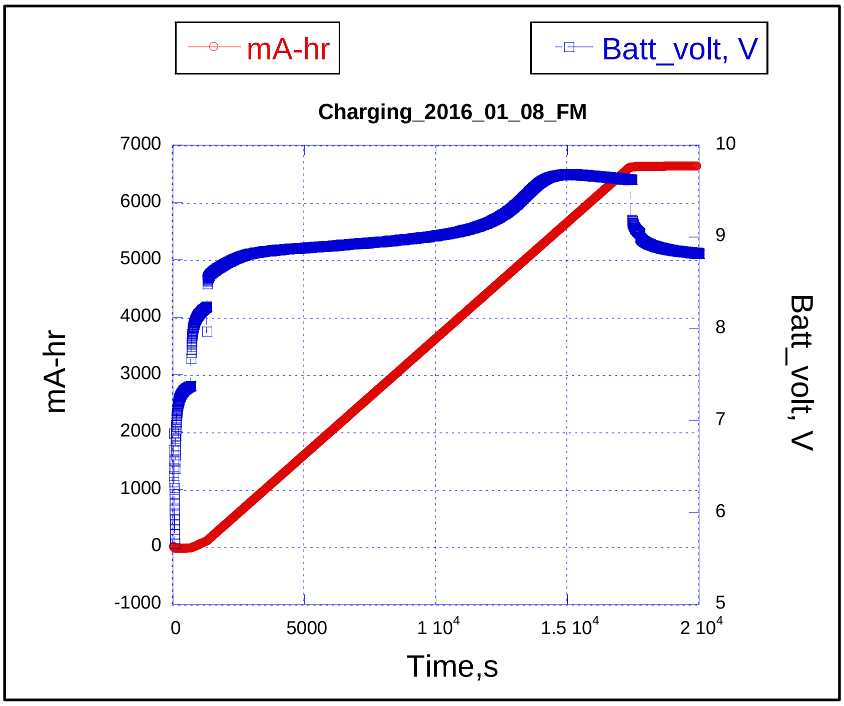

Figure 16 Measurement result during last charge

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4.3 In-Orbit data

After Two weeks of in-orbit operation, battery voltage, current and temperature data was analyzed. Voltage was between 8V and 9V, battery was still had a fully charge. Current was looked normal as well. Voltage and current data is shown in Figure 17. Regarding temperature of battery, it is shown lower than normal during the launch and after while it has gradually increased and reached to the considerable normal value. The temperature data is shown in Figure 18 with board and panel temperature data. Hence we can assume that data demonstrate battery performance was as well as its functionality.

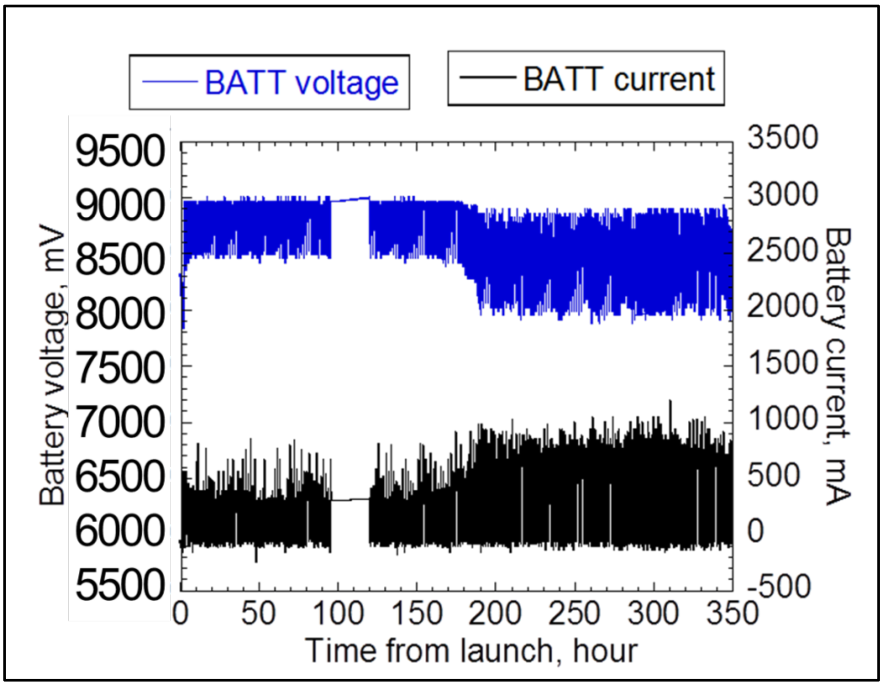

Figure 17 Battery current and voltage on orbit

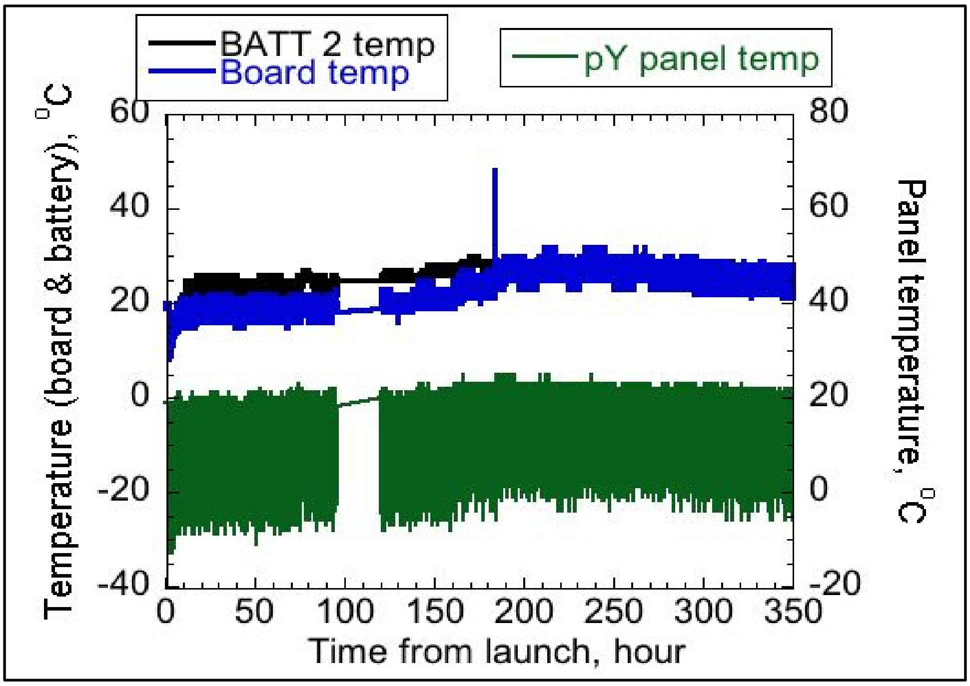

Figure 18 Battery temperatures on orbit, °C

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5 CONCLUSION

We used screening test method to the battery cell selection for the lean satellite electrical power systems battery box. The screening test of battery is assumed a method which can help to select identical batteries for corresponding packs of battery box based on test result and data evaluation. The screening procedure basically consists of a two sections, one is a charge and discharge cycling which is for checking of functionality. Another one is an internal impedance estimation which is for identical packing of the battery box. It has a benefit that lowest self-discharge and voltage drop on the battery. After all, we can say that our method was successfully demonstrated by properly operation of HORYU-IV in the low earth orbit.

6 ACKNOWLEDGEMENT

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