Kyushu Institute of Technology
Department of Applied Science for Integrated System Engineering

Battery (Cells) Screening Procedures and its Verification Report

Laboratory of Spacecraft Environment Interaction Engineering

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1) Introduction

The battery (cells) charger/discharger system is used to select ideal electrochemical batteries. The selected batteries should have the best characteristics for them to qualify for space application. Battery (cells) screening and testing is done through a charger/discharger system.

The purpose of cells screening test aims to verify that individual battery (cells) used on satellites can satisfy requirements. Impedance and charge/discharge cycle checks before and after the environment test.

The process of approving the battery construction design requirements for a small satellite involves several steps, and the process may also depend on the launch provider and cell's chemistry.

LaSEINE, Kyushu Institute of Technology has developed the prototype charger discharger system for screening and testing of NiMH and Li Ion batteries(cells) used in nanosatellites and small satellites.

1. Cells Screening and Matching

To build batteries for use on satellites using Commercial Off-The-Shelf (COTS) cells, they must first be subjected to the screening process for approval. It is recommended to match similar cells from the screened cells before constructing the battery by using data obtained from the screening process.

An acceptable screening of battery (cells) mainly consists of physical and electrochemical tests (open-circuit voltage, internal DC resistance, power, load retention, measurement, mass) that are re-tested before and after the environmental test. This is the basis of cell screening and testing of the charger-discharger system. [1] Here, the cell matching process must be done before the battery is assembled. The system provides data when the screening process has taken place in the battery system. The cell matching process might be possible with the obtained data.[2]

The aim is to minimize the state of the charge imbalances that could adversely affect the efficiency and/or protection of the battery. Cells shall be matched based on open circuit voltage and mass (≤0.1%), capacity (≤5%) and DC resistance (≤10%). [3][5]

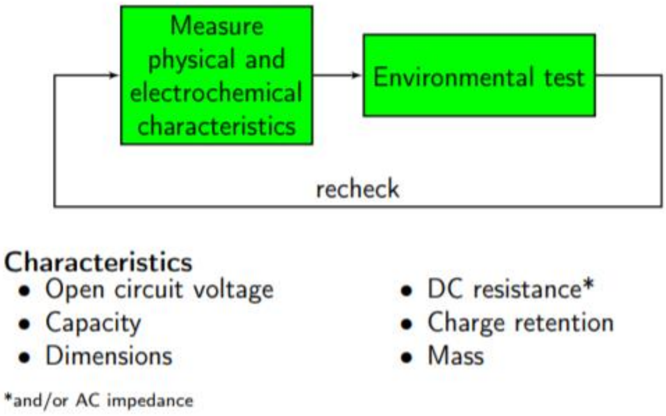


Fig 1: Battery (cell) screening process before and after the environmental test

2. Battey (Cell) Screening Overview

Since 2016 the system had been used to screen Ni-MH cells at (LaSEINE), Kyushu Institute of Technology and improved to perform DC resistance measurements, plus being more user-friendly [4].

Now the system can do screening of Li-ion electrochemical cells too. This system is more portable than the old system. It is an improved version of the screening process. The focus is on the acquisition of the data and an automated way to switch between the different states of the screening. In this system, a switching converter based multi-cell charger/discharger system that can make all the tests autonomously with high accuracy. The system consists of two sub-systems, a PI controlled DC-DC converter and a four-cells switcher.[5]

3. Kyutech-Charge/Discharge System

As shown in below Figure fig 2, The power source is connected to the converter input and the cell switcher is connected to the output, when the 4 DPST relay are set in charging position (NC). In this state, the converter work as a buck converter.

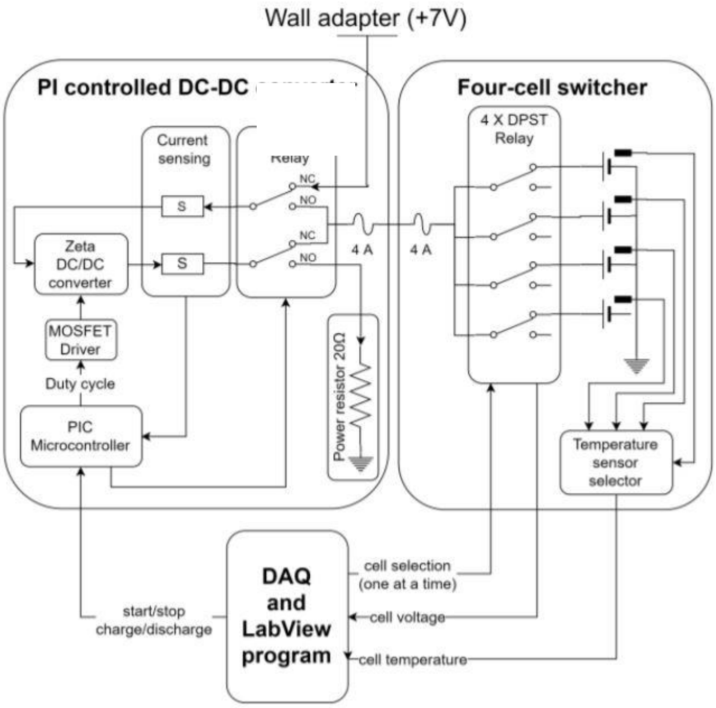


Fig 2: Block diagram of charger discharger system with cell switcher

The cell switch is connected to the input and the power resistor is connected to the output at that time when the relay is set in the discharge position (NO). In this state, the converter work as a boost converter. At Charge/discharge system block diagram, the maximum power of the device is set by the 4A fuse and varies between 10W and 17W depending on the SOC of the cell. This device will charge and discharge the cell, and this is performed by using a buck-boost topology known as Zeta. [5] [7]

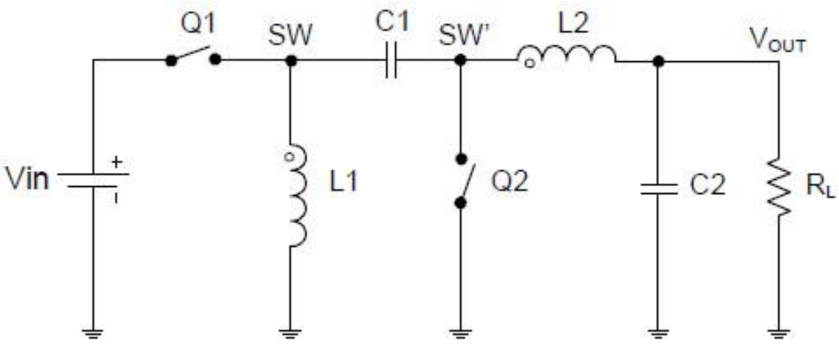


Fig 3: Zeta converter topology [7]

The value of the power resistor is 20 Ω, with this value we are going to get boost operation when it is discharged. The two options for converter operation and their related duty cycle equations are shown below in Figure 4. Assuming, for example, that a Li-Ion cell of 3250 mAh is discharged at 1C, the duty cycle will start at around 0.55 at 4.2V and will rise slowly until it reaches 0.61 at 2.5V.[5]

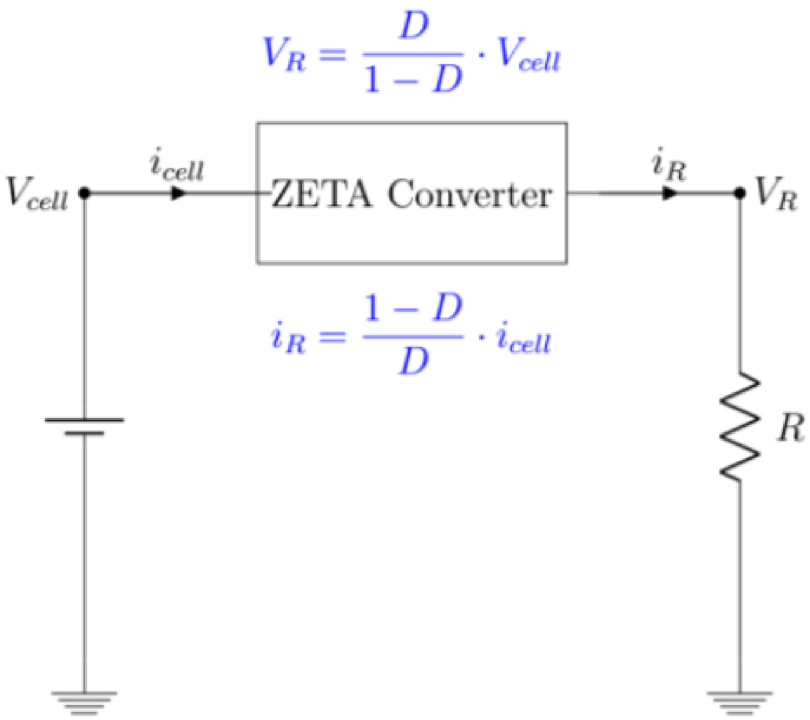


Fig: 4 Charge and discharge operation.[5]

4. Measurement State

The voltage measurement is performed on the four-cell switchboard to prevent voltage drop. In the system, the measurements are performed in the DC converter board using two Hall-effect current sensors, one for input and one for output. The detected potential levels will be interpreted by the ADC of the microcontroller. It uses constant current or constant voltage operation of the PI controller software. External serial ports link with LabView to both boards to perform data logging and to start or stop the device.

5. Microcontroller Controller

In the microcontroller chip, the PI controller is programmed. It automatically detects and switches from constant current (CC) mode to constant voltage (CV) mode when appropriate. It is a control loop that calculates voltage and current and adjusts the duty cycle accordingly to achieve the set value. Since the loop is run at a high frequency and the cell changes are very slow, the PI controller is not configured.[5]

6. DC Internal (Impedance) calculation

Below figure shows the DC resistance for each temperature. DC resistance was calculated by the two-point current-voltage relationship in the discharge curve. It is called the two-tier DC load method is showing the calculated concept for internal DC resistance. [8]

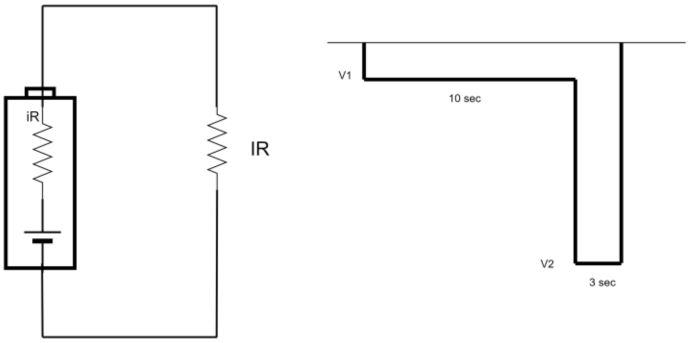


Figure Internal DC resistance derived method

Where,

$$Ri = \frac{(V1 - V2)}{(I2 - I1)}$$

V_1= Voltage is measured during low current with longer time

V_2= Voltage measured during the high current and shorter time

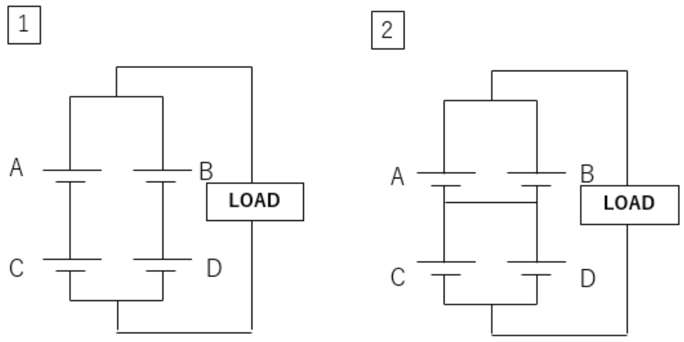
I_1= Current during for longer time

I_2= Current for short time

These methods are depending upon the battery (cell) charge, discharge, and the interruption the current flow in charge discharge.[5]

7. Cell Matching Criteria

The measurement of the DC resistance internal (Impedance) is one of the essential requirement tasks for selecting the battery (cell). For example, if the satellite has a two-series three (2S3P) parallel connection for the battery design. The most similar internal DC resistance is required in the series connection for the battery construction. If one cell has higher resistance in a series contnection, then there will be damage to the battery due the high resistance. The resistance creates heat in the battery. In series if one battery has issue then the voltage drops drastically and current cannot flow. This leads to overheating and overloading.



better condition in case,

1) A≠ B, C≠ D, A=C, B= D: The better option is the A=C, B=D for the cell balancing into the series connection. If the internal DC resistance is high, then current cannot flow properly in the circuit, hence the battery will overheat.

2) A=B, C=D, A≠ C : In this case, the battery is connected in parallel. If one battery has

higher internal DC resistance, then other battery can provide the power properly.

8. **NiMH Cells(battery) screening procedures**

1. First *carefully Insert the cells in the test bed of either for 1C or 0.5C, but this guide will show for 1C. Make sure you use the right testbed for the right batteries. If NiMH batteries, then use testbed for NiMH batteries.

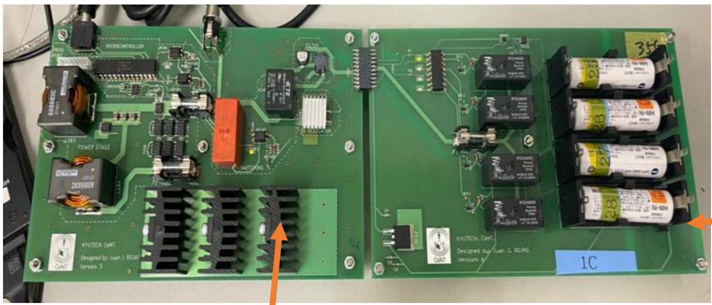
   Make sure the testbed is not yet connected to the Cell Switcher board.

   - Cells should be numbered as shown below.
   - Be careful of cell polarity, +Ve to +Ve and –Ve to -Ve.
   - The fan should be ON fulltime for cooling the batteries during testing.
   - *Rough handling of battery cells damages their internal properties and can cause an internal short-circuit (Thermal runaway).

Fan for cooling ON.

First Cell goes here.

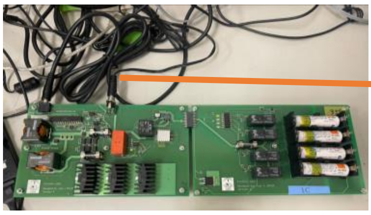
2. Then carefully connect the Cell switcher to the charger discharger via the port interface.

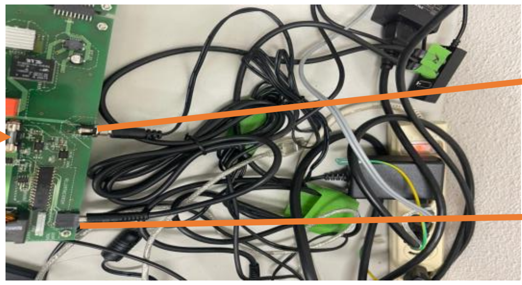


1C Testbed

Four Cell

3. Connect the switcher to power and confirm the UART Communication Interface channel for LabView (Ideally Channel 4).





Power connection

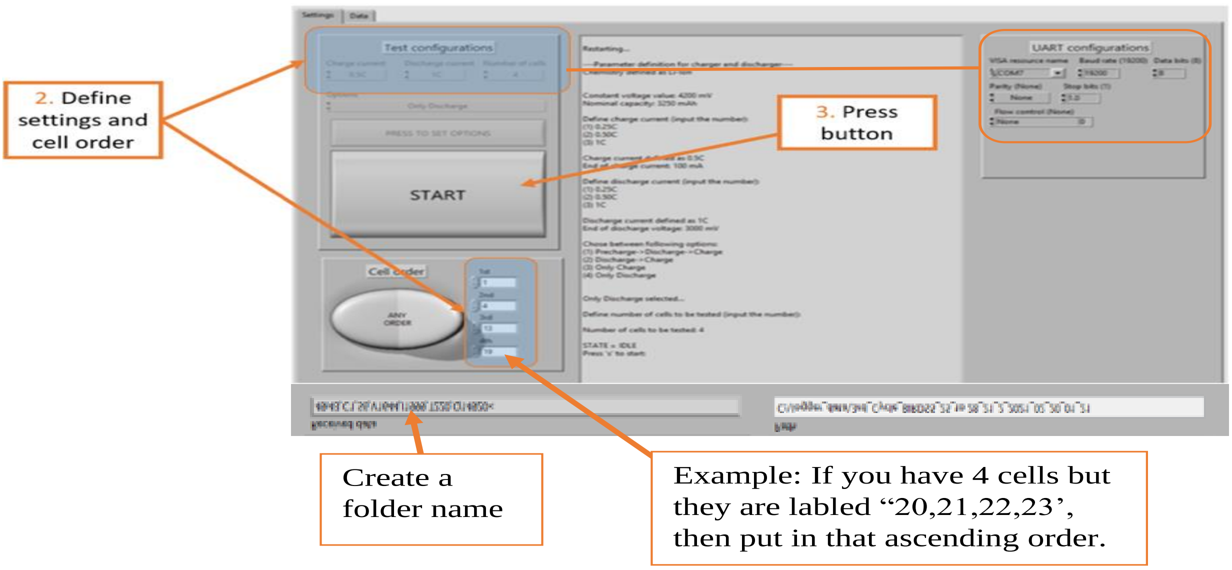
UART channel

4. Open LabView Battery Screening Program on Desktop and set the initial parameters as shown below. Put a folder name for storage of screening data (Example is: Cycle_BIRDS5_1_to_4_21_2_20). In that example

   Parameters to be initialized include:

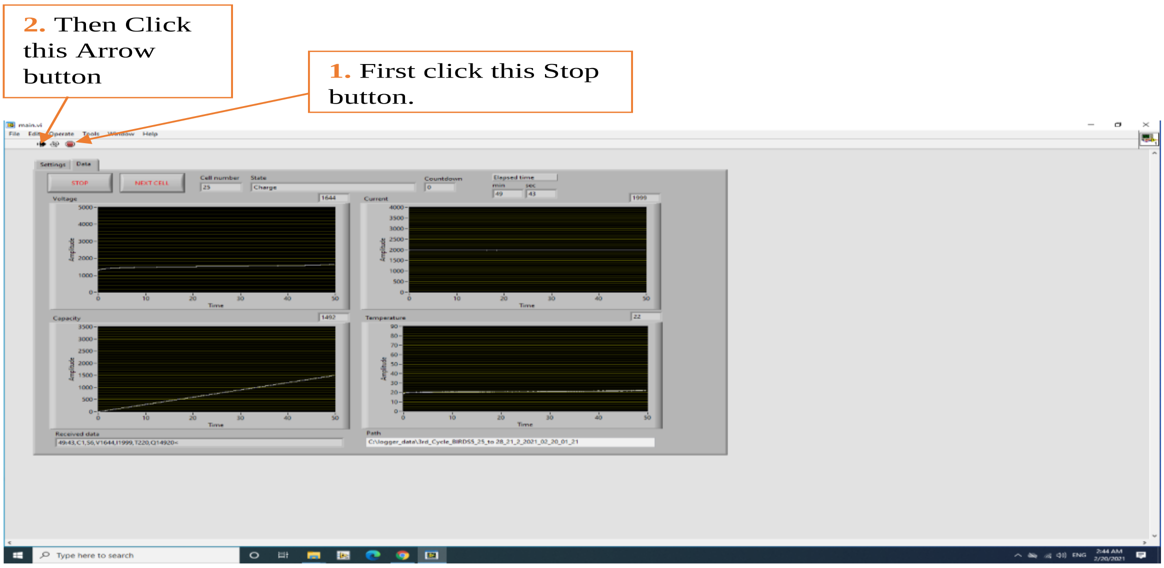
   - Charge current (C-rate). It should be the same as indicated on testbed (Example, if you chose 1C, put 1C)
   - Discharge current (C-rate). It should be the same as indicated on testbed. (same example as above)
   - Number of cells being screened. (Example, if 4, put 4)
   - COM channel (example, if you chose COM4 on UART output, Select COM4)

   Do not adjust the other settings from the default values.

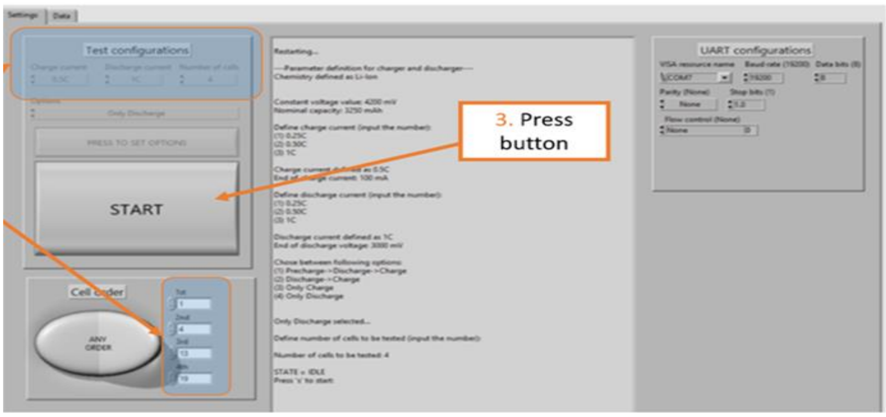


NOTE:

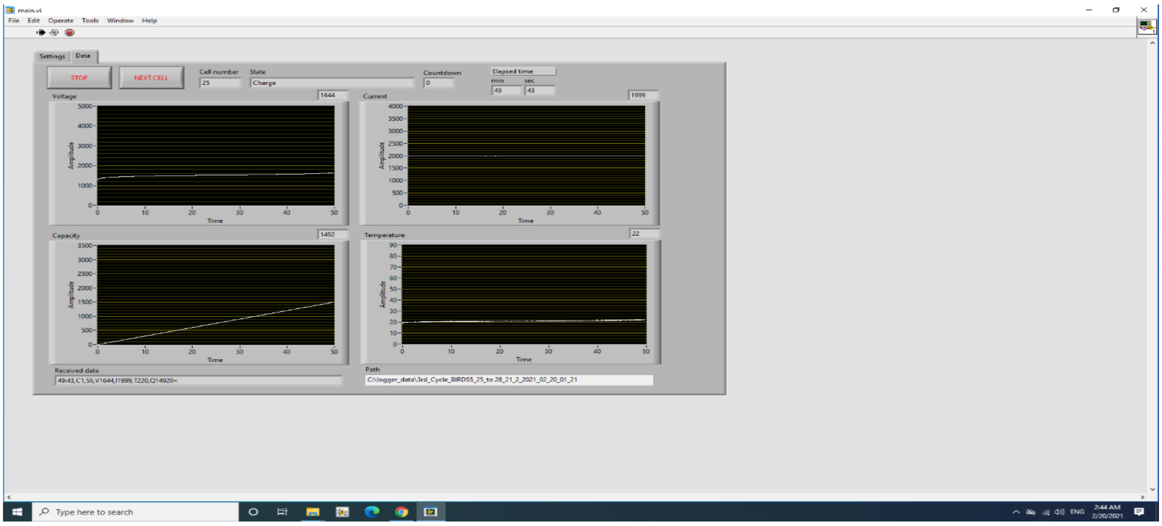
If after pressing START button, the system does not start instantly; then do the following.



Then click the START button, the system should be able to start now.



System running now.

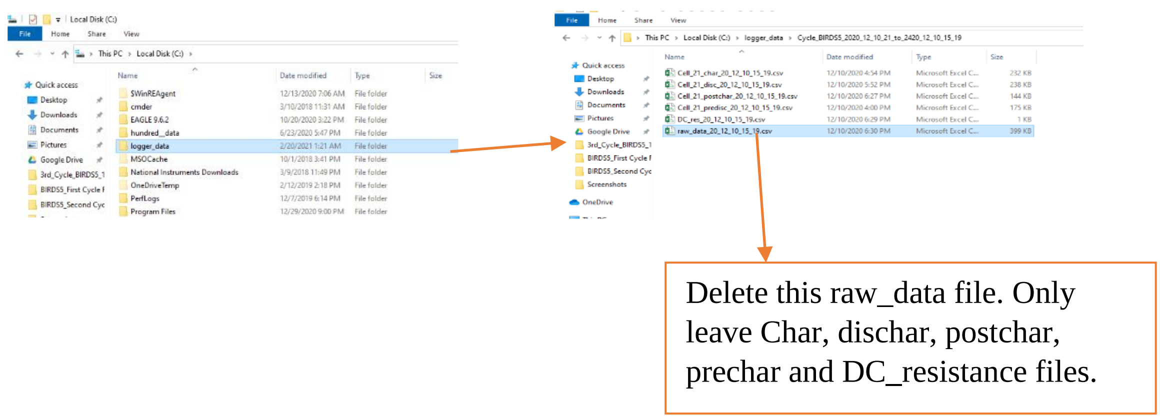


Note:

- For 1C, each battery cell takes around 4 hours to be screened for Predischarge, Charge, Discharge and Post charge.
- The battery charge-discharge automatically switches between cells, you just have to monitor the temperature change as you wait.
- If the temperature fluctuates to 80 degrees, stop the test and remove that battery cell.

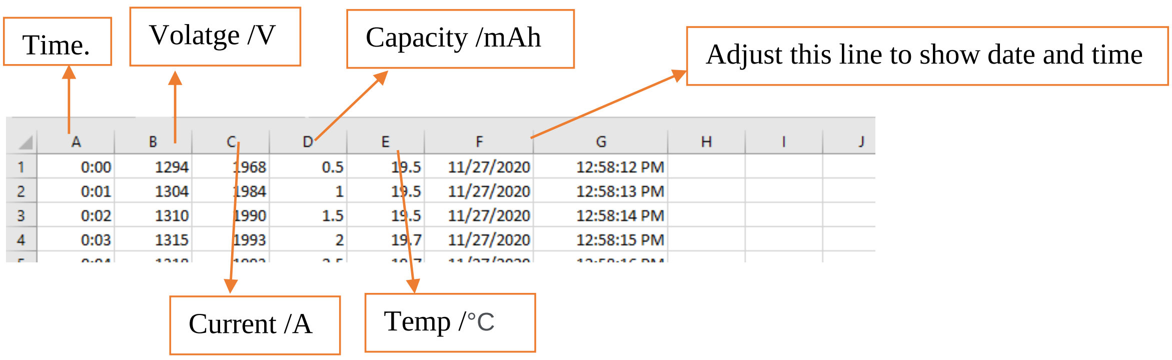
5. Interpretation of Data Collected after Screening:

After the screening of the batteries put in the testbed, data is stored in C folder:

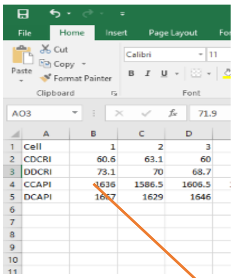


Char.csv, Prechar.csv, Dischar.csv and Postchar.csv Explanation;

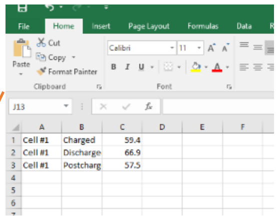
This is the Charge file, with same format as Prechar, Dischar and Postchar.



DC_res format in MATLAB Analysis results summary:



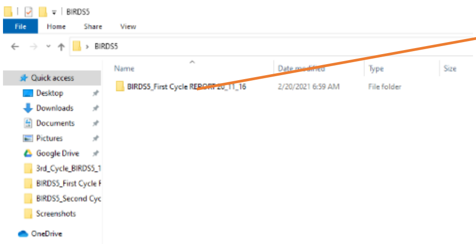
DC resistance in mΩ. **It should be to one decimal place, hence always correct it to one decimal place. Example is from 701 to 70.1**



DC_res format in DC_res raw of screened data for each cell.

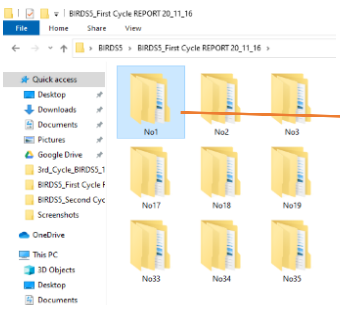
6. MATLAB Interpretation of Data:

➢ Create a folder for all the screened data.



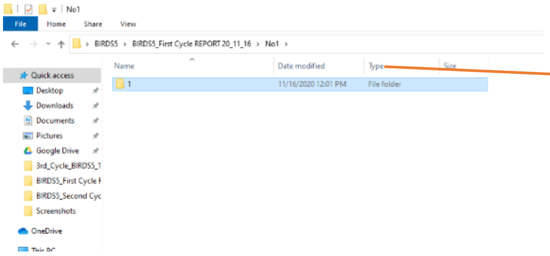
Created Folder for MATLAB

➢ Inside that folder, create a folder label ‘No.Battery number), Example is No.1



Created Battery number folder.

- Inside the Battery number folder, create another folder label ‘Number of screening done’, Example is ‘1’.



Folder indicating number of screening done. Here it is 1 because it is the first

- Inside ‘Number of screening done’ folder, copy and paste the screened data for that very batter. E.g. Char.csv, Dischar.csv, Postchar.csv, Prechar.csv and DC_resis data. This data is got from the screening folder you created above.

Note:

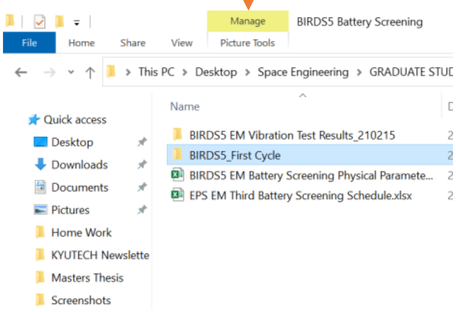
- **If you do a second session of screening on the same batteries (for example after Vacuum tests), create a folder for that data too, e.g., label ‘2’, for the second version of that data. Put that folder in ‘Number of cells’ folder (For example ‘No.1’ for our examples above. If you do a third screening test (for example after vibration test), put that data in a new folder inside that cell’s folder, for example create and put in folder ‘3’, inside folder No.1.**

7. Copy this MATLAB code file found here: https://drive.google.com/file/d/1GIZ8r8-RbGU4Sp_FmrLknQjQBdHXmYxB/view?usp=sharing

And paste it inside the main folder you created for MATLAB analysis. For example, the folder created in ‘no.6’ explanation here.

Further example:

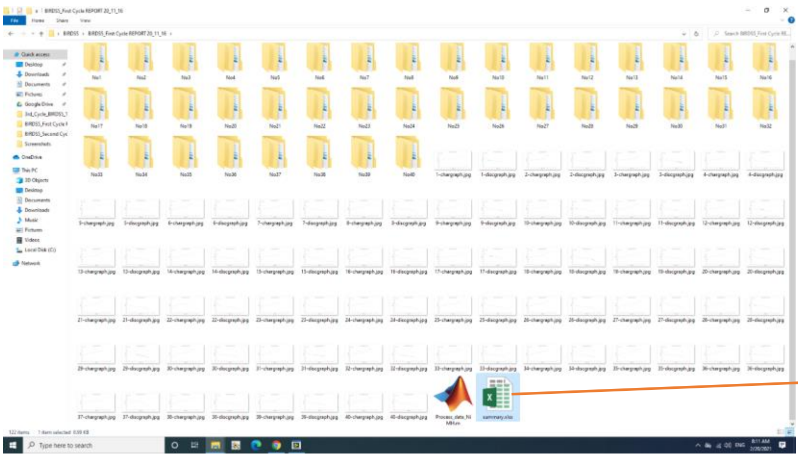
If this is the Folder created for MATLAB analysis,
Then put the MATLAB file (.m) in here.



8. Run MATLAB and obtain graphs for data analysis, **plus a Summery of the data.**
9. The MATLAB analysis results graphs will be saved automatically in the same folder you created for MATLAB analysis of the screened data.

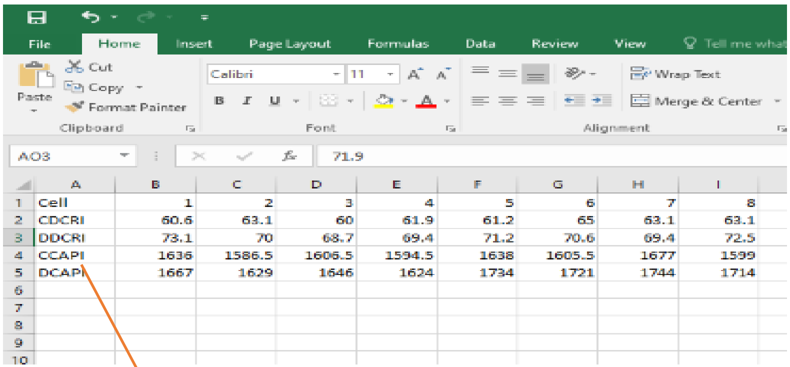
Also the Summery excel sheet of the MATLAB analysis will be saved in this same folder.

The saved MATLAB analysis excel sheet contains DCAP where we get our battery capacity in mAh



Saved Matlab Analysis Summery excel sheet. Plus charge and discharge profile graphs for each cell.

Saved MATLAB analysis summery contents:



	A	B	C	D	E	F	G	H	I
1	Cell	1	2	3	4	5	6	7	8
2	CDCRI	60.6	63.1	60	61.9	61.2	65	63.1	63.1
3	DDCRI	73.1	70	68.7	69.4	71.2	70.6	69.4	72.5
4	CCAPI	1636	1586.5	1606.5	1594.5	1638	1605.5	1677	1599
5	DCAPI	1667	1629	1646	1624	1734	1721	1744	1714

The DCAPI (Discharge Capacity Internal) gives us the mAh of that battery cell. For example, Cell No.1 has 1667

Acronyms:

CDRI	Charge Internal DC _Resistance
DDRI	Discharge Internal DC_ Resistance
CCAPI	Charge Internal_ Capacity
DCAPI	Discharge Internal _ Capacity
Char	Charge
Dischar	Discharge
Disc	Discharge
Predisc	Predischarge

References,

[1] N. J. S. Center, JSC 20793. Crewed Space Vehicle Battery Safety Requirements., Houston, Texas, 2014.

[2] ISO, ISO 17546. Space systems - Lithium ion battery for space vehicles - Design and verification requirements, 2016.

[3] N. J. S. Center, JSC 66548. Requirements fro Fligth Certification and Acceptance of Commercial Off the Shelf Lithium Ion Batteries., Houston, Texas, 2013.

[4] T. Motohata, T. Shimizu, H. Masui and M. Cho, "Development of a Testing Standard of COTS Lithium-Ion Batteries for Nano-Satellites," in 65th International Astronautical Congress, Toronto, Canada, 2014.

[5] Juan J. Rojas, Jesus Gonzalez-Llorente, Yamauchi Takashi and Mengu Cho, Development of a charger/discharger system for electrochemical cell screening and testing. 2I04.

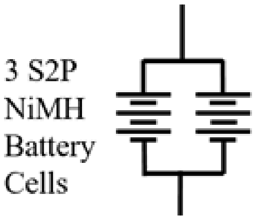
[6] M. Yahia, Design and Testing of a Lean Satellite Electrical Power Subsystem, HORYU-IV, Kyushu Institute of Technology (Doctoral Thesis), 2016.

[7] https://www.electronicsweekly.com/blogs/engineer-in-wonderland/zeta-that-other-dc-dc-topology-2016-05/

[8] https://batteryuniversity.com/learn/article/how_to_measure_internal_resistance

Introduction

This test was aimed to verify that individual battery cells used for three satellites (GuaraniSat-1, Maya-2 and Tsuru) can satisfy requirements. Impedance and charge/discharge cycles were checked before and after the environment test. The purpose of cells verification was for selecting identical cells for packaging battery. Batteries construction and specification are shown in Figure 1-1.



Type:	Nickel-Metal Hydride Battery
Size:	AA Consumer Type
Capacity:	3800-4000mAh
Nominal Voltage:	1.2V * 3 = 3.6V
Weight:	27g * 6 = 162g
Size :(Diameter) x (Height):	14.35(D) x 50.4(H) mm

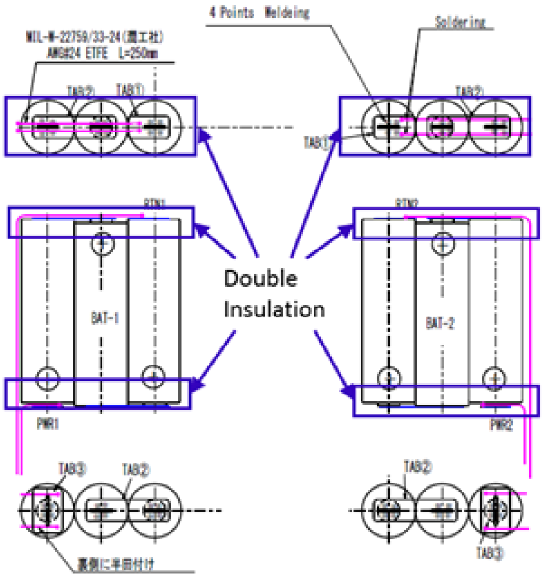


Figure 1-1 Batteries construction and specification

2) Referenced Documentation

[1] JX-ESPC-101133-C: JEM Payload Accommodation Handbook Vol.8 Small Satellite Deployment Interface Control Document

[2] 01_EP-J-19-001: Battery Description HR Attachment

[3] 「きぼう」放出超小型衛星のバッテリ安全に関する設計・検証ガイドライン

3) Test Purpose

a) Overall test description

To satisfy BIRDS-4 battery requirements, verifications shall be performed throughout this test. It includes the following steps:

- **Charge and discharge cycles shall be normal, i.e., abnormal situations shall not be accepted. Abnormal situations include over-heating; packing internal impedance over-range, etc.**
- **Structure of batteries box shall not be modified during the test.**
- **Test shall be carried out at constant room temperature since batteries properties are temperature sensitive.**
- **The impedance verification shall be performed after charge and discharge.**

- **During the vacuum leak test, the pressure should be less than in pressure to 0.1 [psi] or less for 6 hours.**
- **For the random vibration test, the level shown by Figure 3-1 shall be followed.**

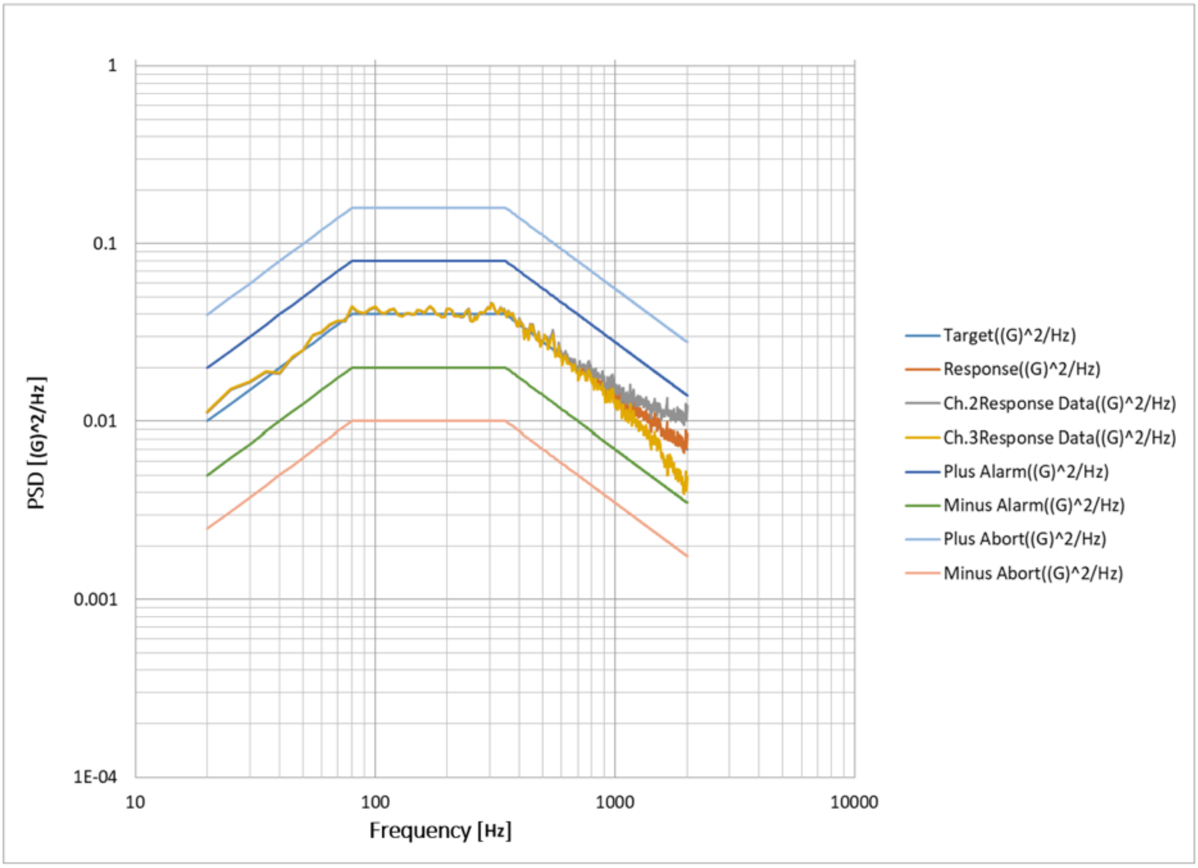


Figure 3-1 Random vibration test level (Minimum Screening Level)

b) Deviation

The test shall comply with the following conditions. If any non-compliance occurs, a non-compliance report shall be written.

- **Abnormality of sensors or testing article component part.**
- **Aborting test due to control malfunctioning.**
- **Change any of hardware, software setup, or configuration during test. If a problem occurs and requires trouble shooting involving a configuration change (for example sensors change, component removal, etc.), then the test shall be iterated.**
- **Any other test anomalies shall be reported.**

c) Success Criteria of cell screening

- The change of capacity before and after each environmental test should be less than 5%.

- The change of mass and open circuit voltage during before and after vacuum leak test should be less than 0.1%.
- The change of mass and open circuit voltage during before and after random vibration test should be less than 0.1%.
- Internal impedance of cell should be equal as much as possible.
- Battery temperature will not reach the 45 degree (analysis).

Selection Methodology

- Excluding all cells with discharged capacity less than 0.88 rated value
- Select 18 cells with the most equal internal impedance for six packs

4) Test article(s)

Test article is shown in Table 4-1.

Table 4-1 Test articles

	Article name	Model Number	Manufacturer	Range	Quantity
1	Battery cells	Eneloop BK-3MCC	Panasonic	1.2 V	80
2	FM batteries box	-	HMD	-	3
3	Cell switcher system	V.5	KyuTech	-	1
4	Charger/Discharger system	V.5	KyuTech	-	1
5	LabVIEW	2015	National Instruments	-	1
6	Vibration machine	35000BD/LA36AP	EMIC	28kN 5～2200 Hz	1
7	Square chamber	-	-	>1x10^{-4} Pa	1
8	Jig	C-2	-	-	1

5) Test method

We conducted each test according to flowchart which is shown in Figure 5-1.

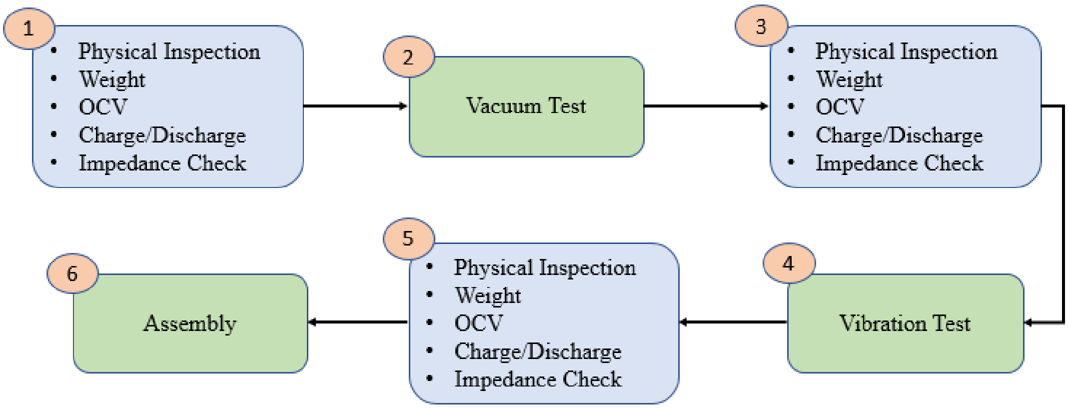


Figure 5-1 Flowchart for screening test (Ref. [3])

a) Cell screening

i. Procedure

Procedural checklist (given in Figure 5-2) was written during test for each battery cell. It includes necessary steps for the test performed. The table shall be filled out during the test. As-run test consists of 5 steps described below.

- **1st impedance measurement**

  At the first, each battery cell's impedance is measured and is automatically recorded. See Annex for the principle of impedance measurement.

- **Pre discharge and charge**

  In this step, the battery is firstly pre-discharged to 1 V, in case the batteries have any remaining charge and then fully charged until its full capacity.

- **2nd impedance measurement**

  After first pre-discharge and charge cycle, each battery cell's impedance is measured and is automatically recorded.

- **Discharge**

  In this step, discharge test was conducted after each cell fully charged at the first cycle. In this case, the voltage was approximately 1.6 V for all of the battery cells. The battery is discharged until 1 V.

- **3rd impedance measurement**

  After last discharge, each battery cell's impedance is measured and is automatically recorded.

- **Post Charge**

  After full discharge, each cell was charged until 1.4 V for keeping the battery at a good capacity level.

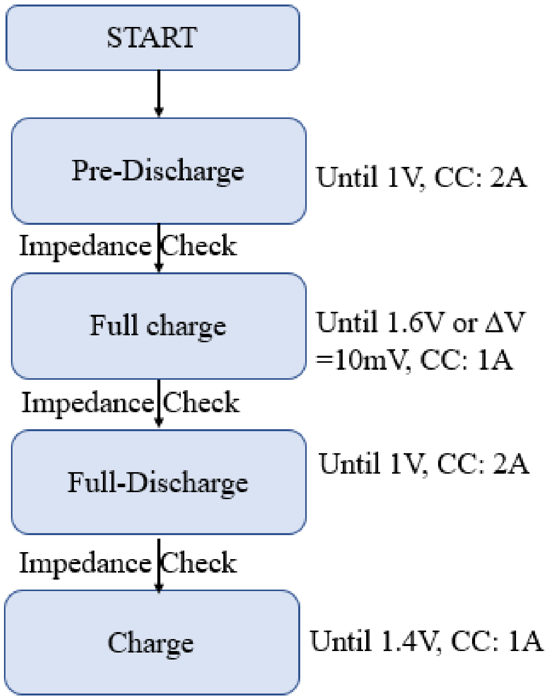


Figure 5-2 Procedural checklist of Battery Cell screening

ii. Hardware configuration

Testing setup consists of 5 main items: a wall adapter DC power supply (1), a charger/discharger (2), cell switcher system (3), a computer running a LabVIEW based program for testing control (4), and battery cells (5). Block diagram of measurement setup is shown in Figure 5-3 and real appearance of measurement setup is shown in Figure 5-4.

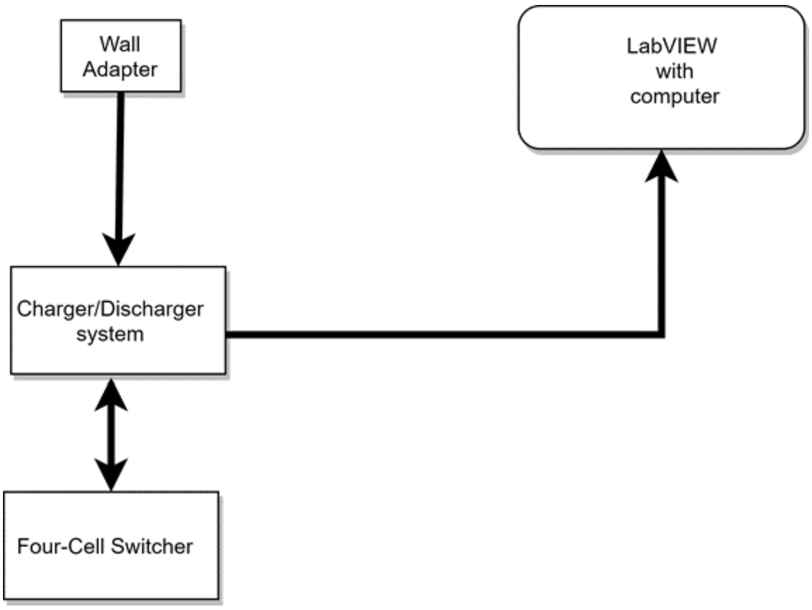


Figure 5-3 Block diagram of hardware configuration of battery screening setup

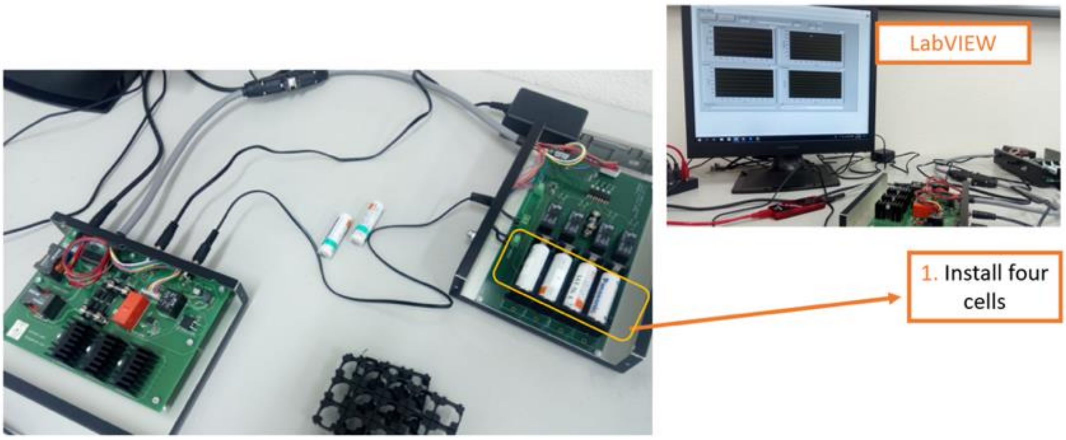


Figure 5-4 Real appearance of hardware configuration

iii. Software configuration

To run the test, a LabVIEW program was used to perform charge/discharge cycles and for battery cell impedance measurement. Interface of LabVIEW program is shown in Figure 5-4. The time was also recorded during the test. Figure 5-5 shows the testing setup as required in the LabVIEW program.

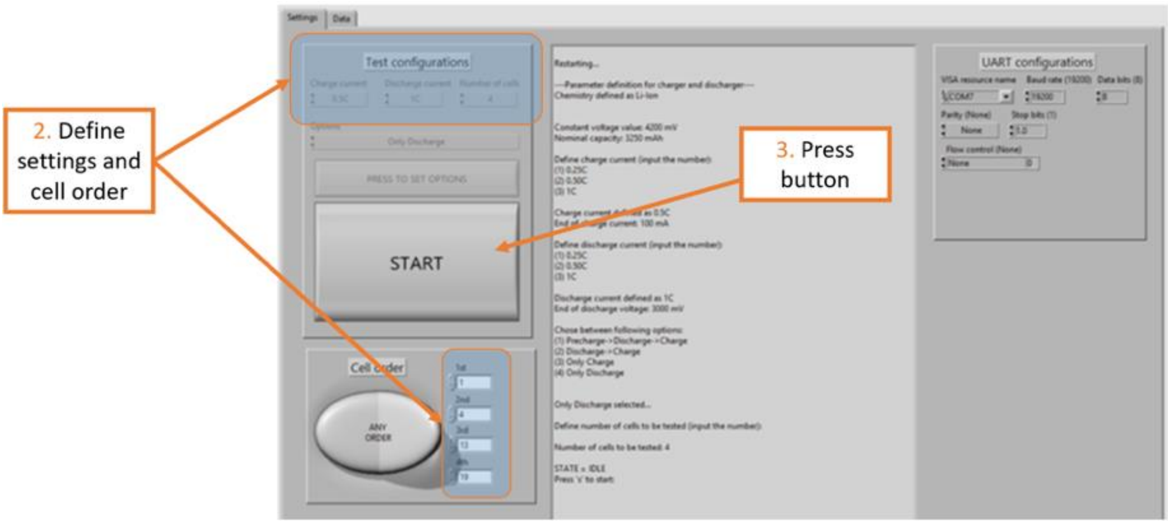


Figure 5-5 Software configuration

iv. Safety

b) Vacuum Leak Test for Battery Cells

i. Procedure

Battery cells were left in a chamber reduced in pressure to 1x10^{-3} Pa or less for 6 hours. Battery cells' mass, open circuit voltage and capacity were measured before and after the vacuum test.

ii. Configuration

Figure 5-6 and 5-7 show the configuration of vacuum test and battery cells.

Figure 5-6 Battery cells configuration

Figure 5-7 Chamber configuration

c) Random Vibration test for Battery Cells

i. Procedure

Random vibration test of battery cells utilizes the conditions shown by Table 5-1. The vibration level covers Minimum Screening Level (MSL) and battery cells' mass, open circuit voltage and capacity were measured after the vibration test.

Table 5-1 Random Vibration Condition (Ref. [3])

Frequency [Hz]	PSD [g^2/Hz]
20	0.010
80	0.040

350	0.040
2000	0.007
Overall [Grms]	6.1
Duration (sec)	60

ii. Configuration of the vibration test

Figure 5-8 show the configuration of vibration test.

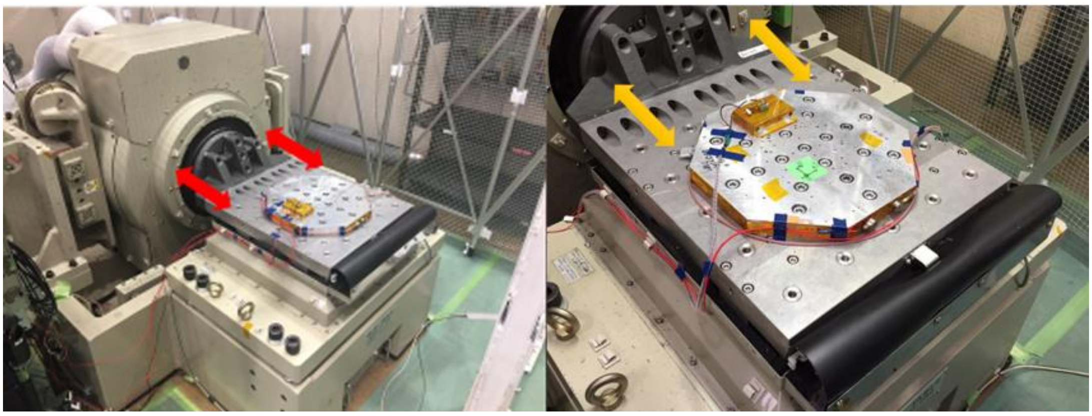


Figure 5-8 Test Configuration

6) Test Result

a) Cell Screening

i. Example of Battery Cell profiles

Tested cells' charging and discharging profiles were similar which are shown in Figure 6-1 and 6-2.

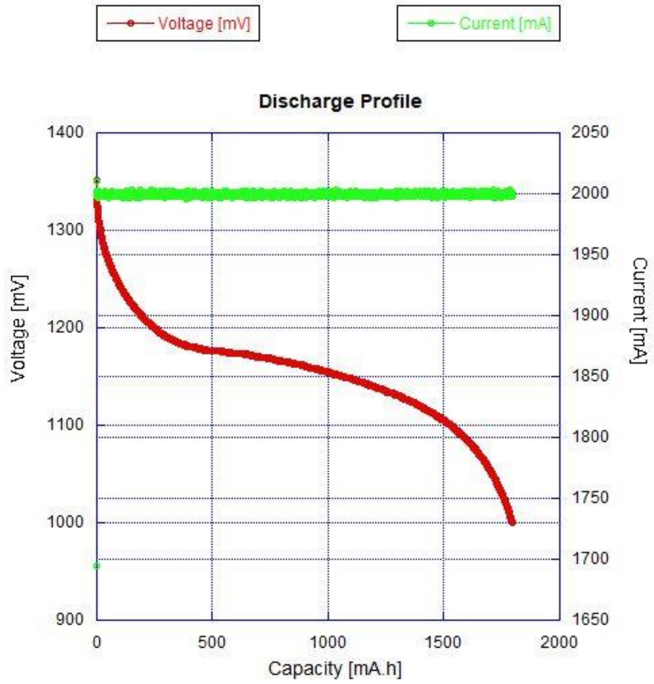


Figure 6-1 Discharging profile for cell

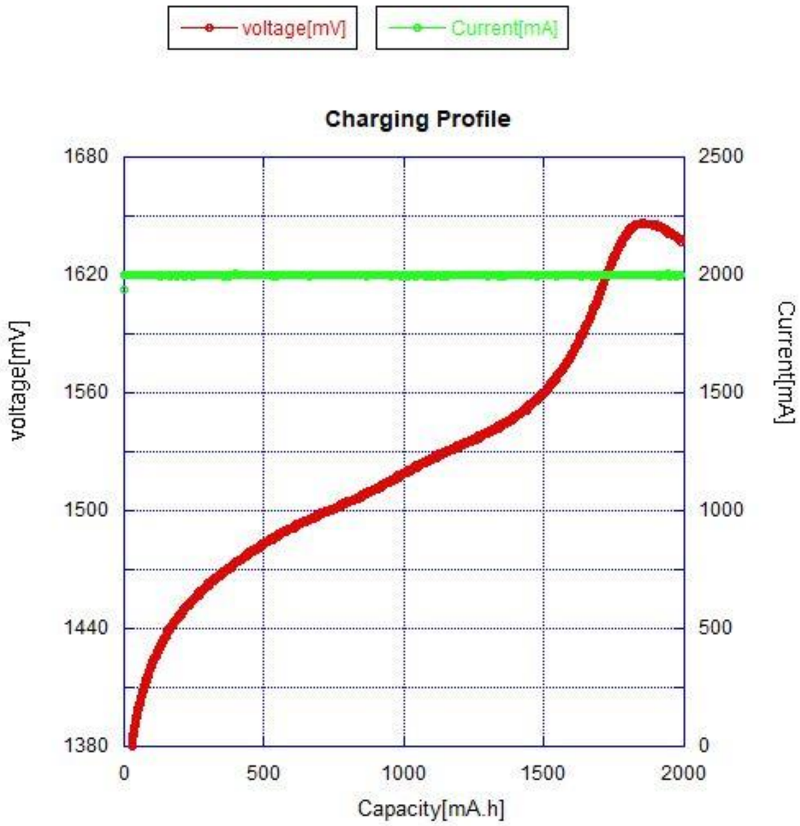


Figure 6-2 Charging profile for cell

b) Vacuum Leak Test for Battery Cells

Table 6-1 shows the data of cells.

Table 6-1 Comparison of Mass, OCV and capacity before and after vacuum test

Battery No	Mass			OCV			Capacity		
	Before Vacuum [g]	After Vacuum [g]	Change [%]* (<0.1)	Before Vacuum [V]	After Vacuum [V]	Change [%]* (<0.1)	Before Vacuum [Ah]	After Vacuum [Ah]	Change [%]* (< 5)
#3	26.55	26.56	0.04	1.36	1.36	0.00	1.771	1.785	-0.79
#8	26.31	26.30	0.04	1.36	1.36	0.00	1.783	1.795	-0.67
#10	26.60	26.59	0.04	1.36	1.36	0.00	1.757	1.773	-0.91
#11	26.54	26.52	0.08	1.36	1.36	0.00	1.772	1.788	-0.90
#13	26.40	26.40	0.00	1.36	1.36	0.00	1.754	1.778	-1.37
#15	26.31	26.31	0.00	1.36	1.36	0.00	1.764	1.786	-1.25
#22	26.60	26.60	0.00	1.36	1.36	0.00	1.795	1.801	-0.33
#31	26.24	26.25	0.04	1.36	1.36	0.00	1.765	1.766	-0.06
#39	26.41	26.39	0.08	1.36	1.36	0.00	1.805	1.804	0.06
#46	26.31	26.31	0.00	1.36	1.36	0.00	1.791	1.787	0.22
#49	26.27	26.28	0.04	1.36	1.36	0.00	1.801	1.797	0.22
#50	26.36	26.36	0.00	1.36	1.36	0.00	1.811	1.797	0.77
#53	26.38	26.37	0.04	1.36	1.36	0.00	1.784	1.778	0.34
#55	26.27	26.26	0.04	1.36	1.36	0.00	1.787	1.790	-0.17
#58	26.34	26.32	0.08	1.36	1.36	0.00	1.784	1.773	0.62
#61	26.39	26.39	0.00	1.36	1.36	0.00	1.802	1.787	0.83
#65	26.33	26.33	0.00	1.36	1.36	0.00	1.811	1.807	0.22
#78	26.35	26.35	0.00	1.36	1.36	0.00	1.786	1.784	0.11

*percentage shows the difference before and after the environment test

c) Random Vibration Test for Battery Cells

Table 6-2 shows the data of mass, open circuit voltage and capacity for each battery cell.

Table 6-2 Comparison of Mass, OCV and capacity before and after vibration test

Battery No	Mass			OCV			Capacity		
	Before Vibration [g]	After Vibration [g]	Change [%]* (<0.1)	Before Vibration [V]	After Vibration [V]	Change [%]* (<0.1)	Before Vibration [Ah]	After Vibration [Ah]	Change [%]* (< 5)
#3	26.56	26.54	0.08	1.36	1.36	0.00	1.785	1.788	-0.17
#8	26.30	26.31	0.04	1.36	1.36	0.00	1.795	1.813	-1.00
#10	26.59	26.61	0.08	1.36	1.36	0.00	1.773	1.784	-0.62
#11	26.52	26.54	0.08	1.36	1.36	0.00	1.788	1.791	-0.17
#13	26.40	26.42	0.08	1.36	1.36	0.00	1.778	1.781	-0.17
#15	26.31	26.31	0.00	1.36	1.36	0.00	1.786	1.783	0.17
#22	26.60	26.59	0.04	1.36	1.36	0.00	1.801	1.796	0.28
#31	26.25	26.23	0.08	1.36	1.36	0.00	1.766	1.774	-0.45
#39	26.39	26.39	0.00	1.36	1.36	0.00	1.804	1.799	0.28
#46	26.31	26.31	0.00	1.36	1.36	0.00	1.787	1.781	0.34
#49	26.28	26.28	0.00	1.36	1.36	0.00	1.797	1.796	0.06
#50	26.36	26.37	0.04	1.36	1.36	0.00	1.797	1.799	-0.11
#53	26.37	26.37	0.00	1.36	1.36	0.00	1.778	1.774	0.22
#55	26.26	26.28	0.07	1.36	1.36	0.00	1.790	1.784	0.34
#58	26.32	26.34	0.07	1.36	1.36	0.00	1.773	1.781	-0.45
#61	26.39	26.38	0.04	1.36	1.36	0.00	1.787	1.787	0.00
#65	26.33	26.35	0.08	1.36	1.36	0.00	1.807	1.801	0.33
#78	26.35	26.36	0.04	1.36	1.36	0.00	1.784	1.776	0.45

*percentage shows the difference before and after the environment test

7) Selected Batteries

Based on the selection procedure, impedance check was carried out to verify that self-discharge would be as minimal as possible before assembly of the battery box. Cells were divided into 3 groups. Battery boxes were charged after the assembly. Table 7-1 shows packaging through selection procedure. 3 sets of batteries have been spread to each country as set-1 for Japan, set-2 for Paraguay, and set-3 for Philippines. The assembled battery cells were chosen so that the requirement of having the change of mass and open circuit voltage less than 0.1%, and the change of capacity less than 5% before and after each environment test was met.

Table 7-1 Package of cells after the Vibration Test

SET 1					
	Cell #	OCV [V]	Mass [g]	Capacity [Ah]	Impedance [mΩ]
Series 1	22	1.36	26.59	1.796	65.9
	65	1.36	26.35	1.801	65.9
	55	1.36	26.28	1.784	66.0
Series 2	3	1.36	26.54	1.788	66.0
	11	1.36	26.54	1.791	66.0
	8	1.36	26.31	1.813	66.0
SET 2					
	Cell #	OCV [V]	Mass [g]	Capacity [Ah]	Impedance [mΩ]
Series 1	31	1.36	26.23	1.774	66.5
	46	1.36	26.31	1.781	66.5
	50	1.36	26.37	1.799	66.5
Series 2	49	1.36	26.28	1.796	66.6
	53	1.36	26.37	1.774	66.7
	39	1.36	26.39	1.779	66.7

SET 3					
	Cell #	OCV [V]	Mass [g]	Capacity [Ah]	Impedance [mΩ]
Series 1	58	1.36	26.34	1.781	65.3
	10	1.36	26.61	1.784	65.3
	61	1.36	26.38	1.787	65.3
Series 2	78	1.36	26.36	1.786	65.4
	13	1.36	26.42	1.781	65.4
	15	1.36	26.31	1.783	65.4

Following figures are provided to indicate the discharge characteristics of the cells. While 1st cycle shows the test result before the cells are exerted into the vacuum in the test (blue plot), the 2nd cycle gives the result after the test (red plot). Once the 2nd cycle tests are finalized, vibration test was conducted and the results after the test are shown as 3rd cycle (green plot).

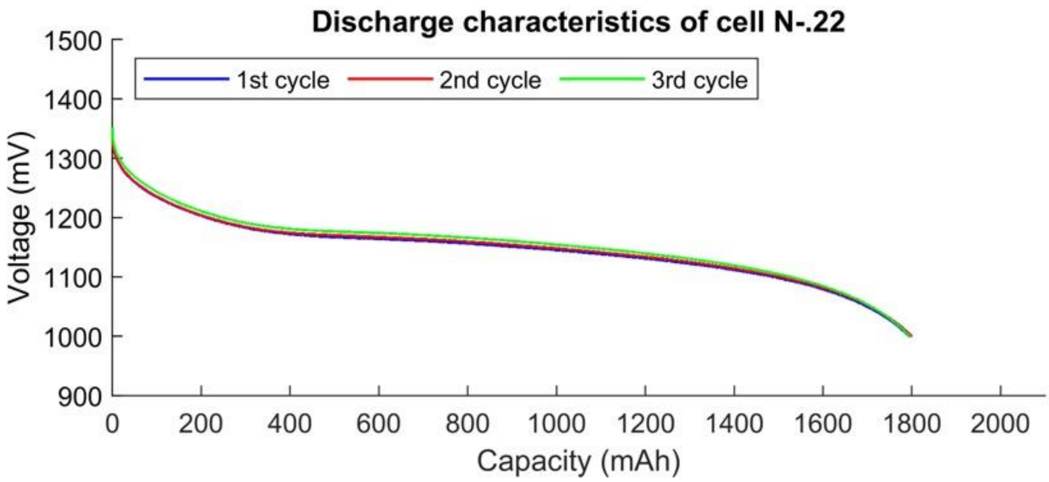


Figure 7-1 Results of discharging cell #22

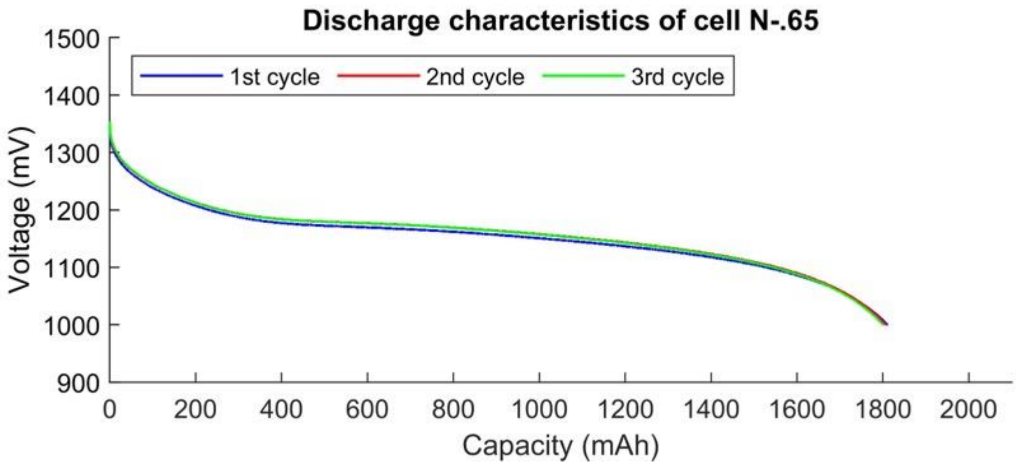


Figure 7-2 Results of discharging cell #65

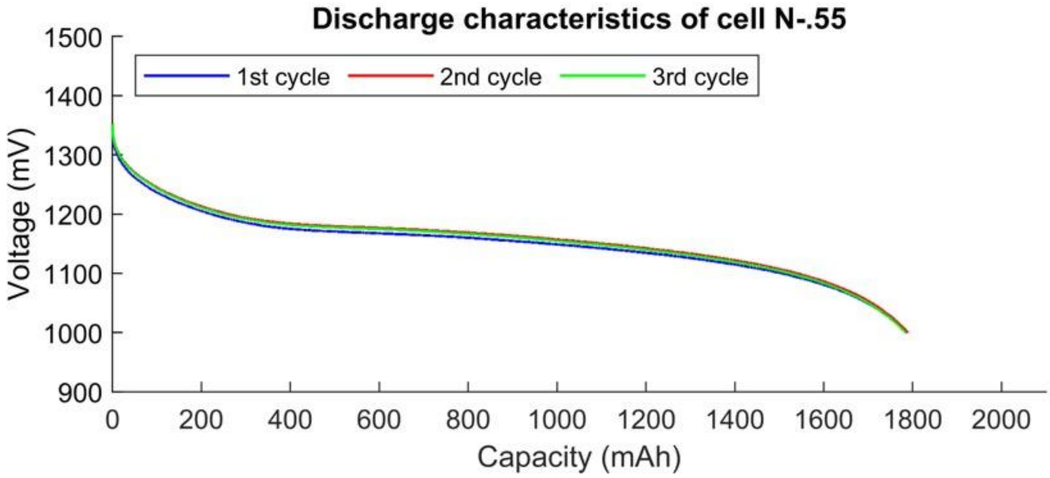


Figure 7-3 Results of discharging cell #55

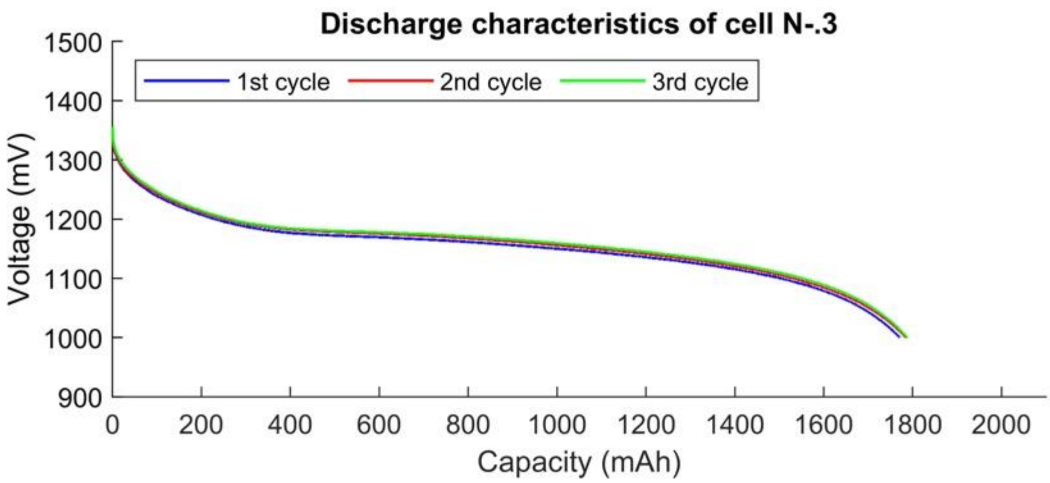


Figure 7-4 Results of discharging cell #3

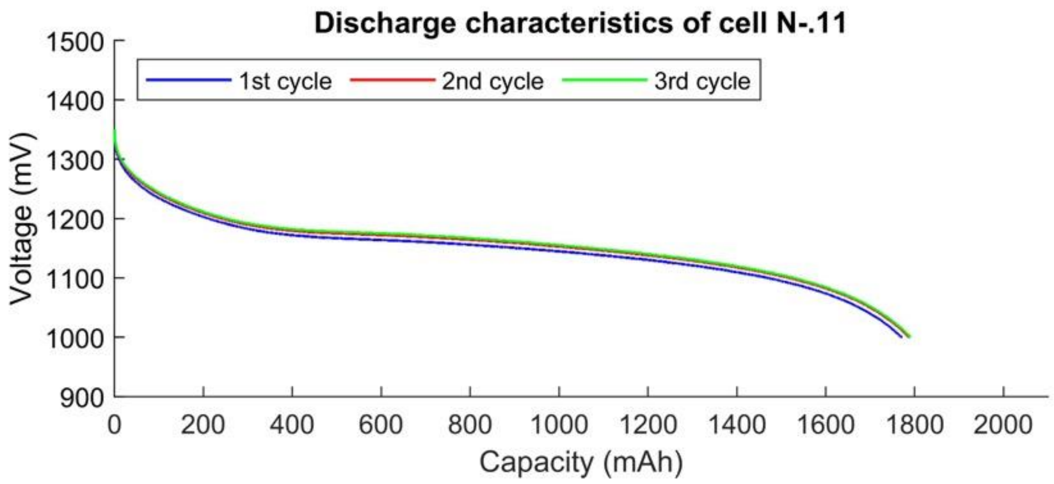


Figure 7-5 Results of discharging cell #11

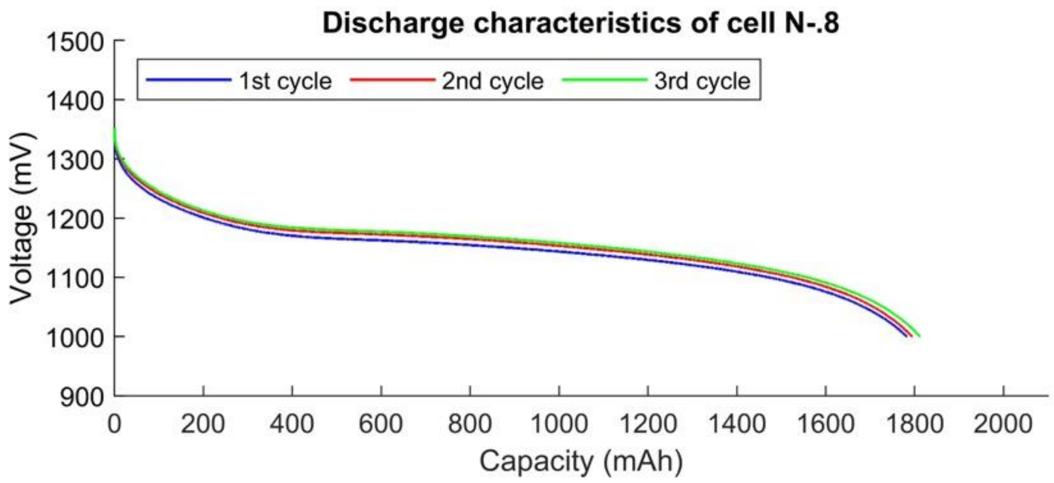


Figure 7-6 Results of discharging cell #8

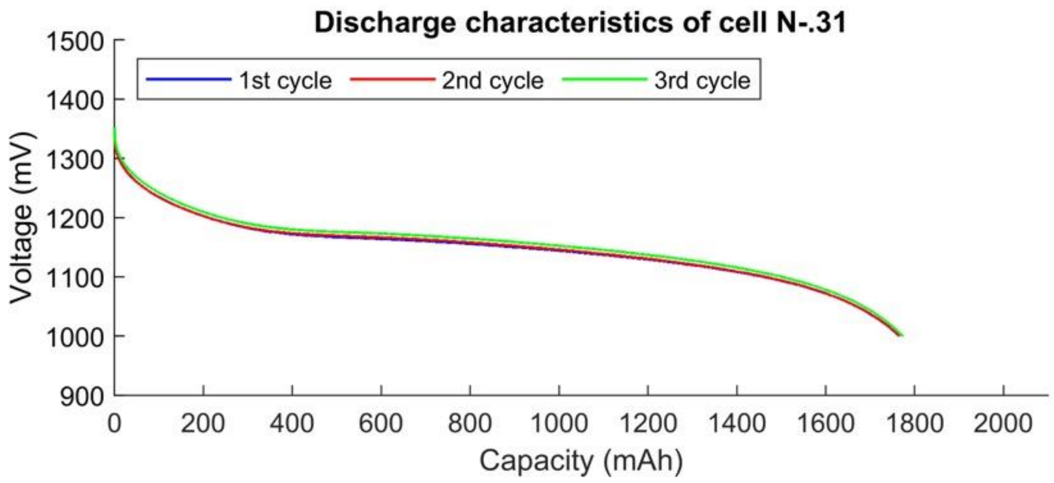


Figure 7-7 Results of discharging cell #31

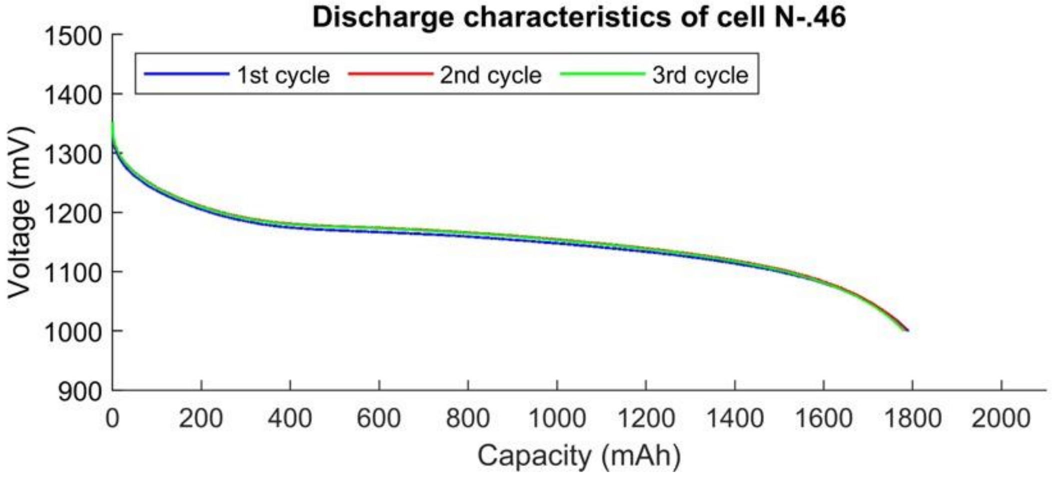


Figure 7-8 Results of discharging cell #46

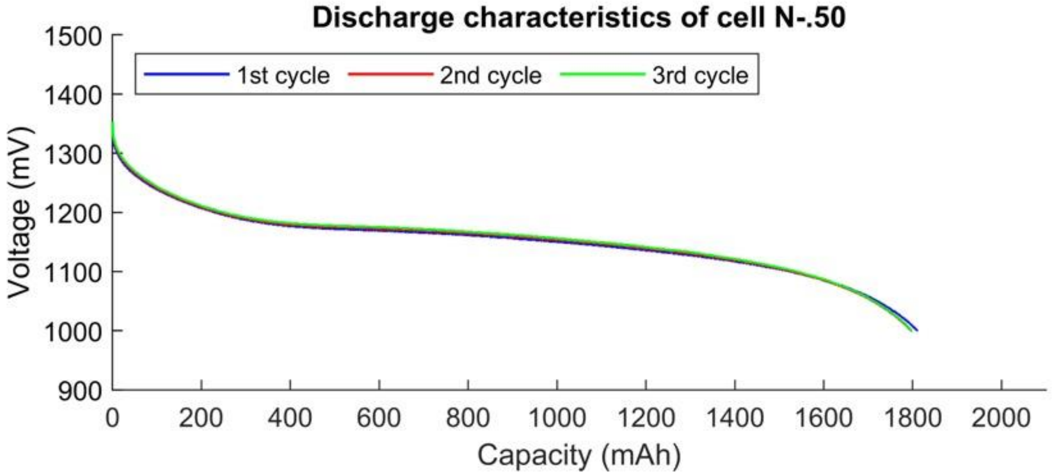


Figure 7-9 Results of discharging cell #50

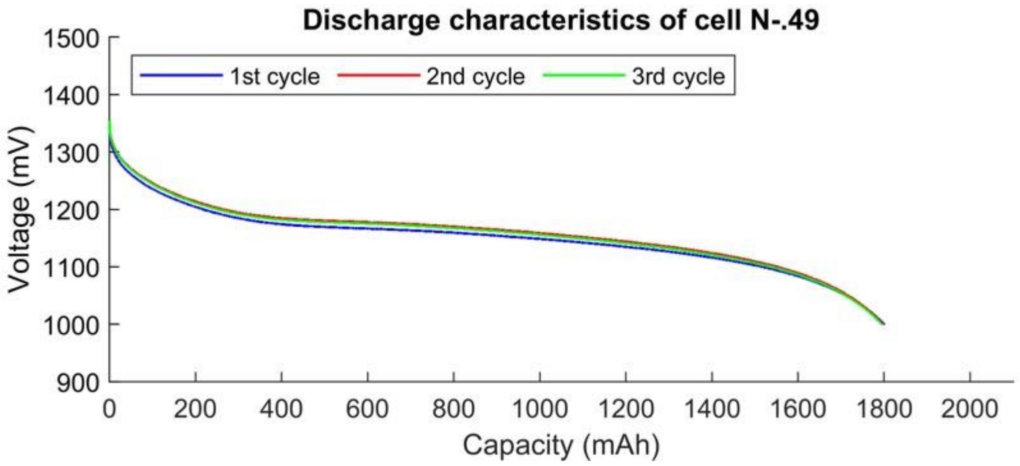


Figure 7-10 Results of discharging cell #49

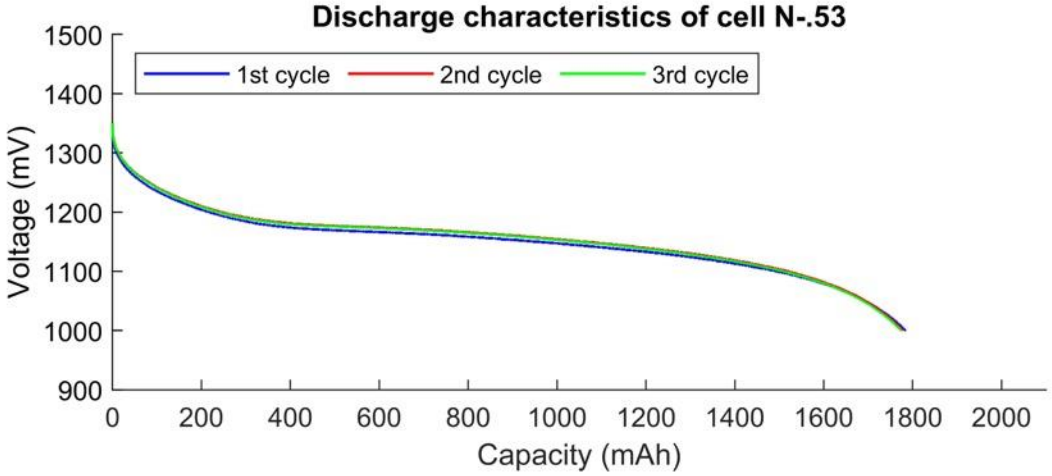


Figure 7-11 Results of discharging cell #53

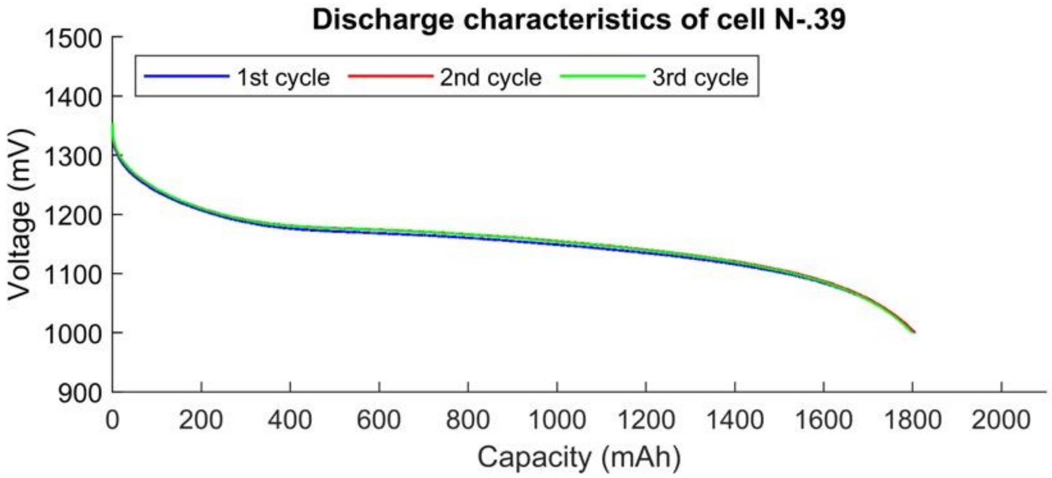


Figure 7-12 Results of discharging cell #39

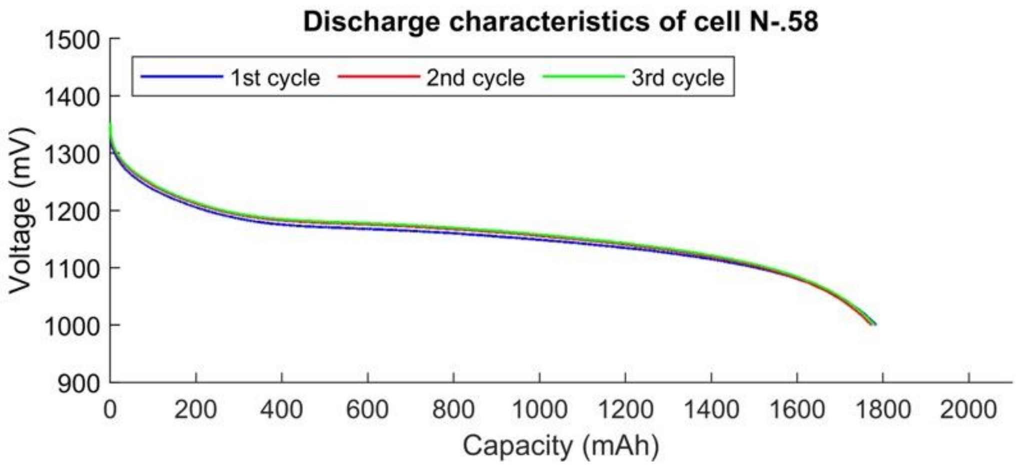


Figure 7-13 Results of discharging cell #58

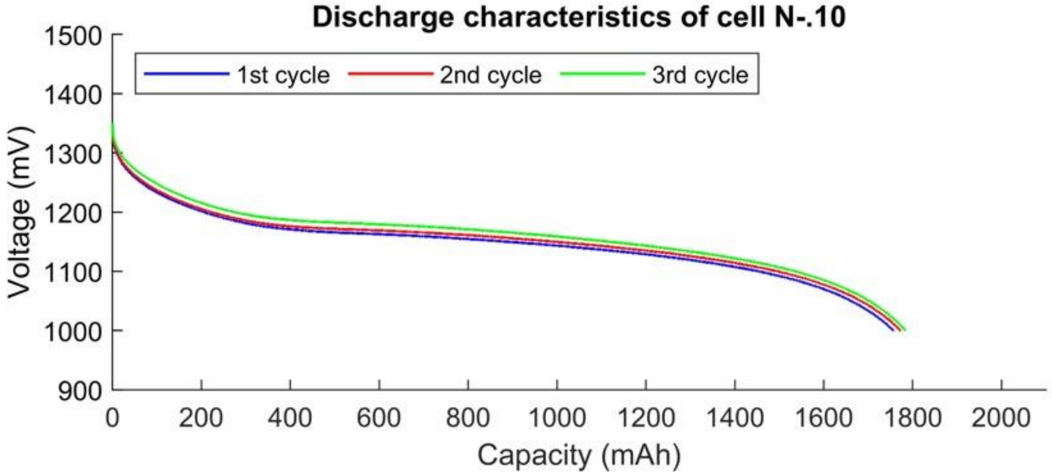


Figure 7-14 Results of discharging cell #10

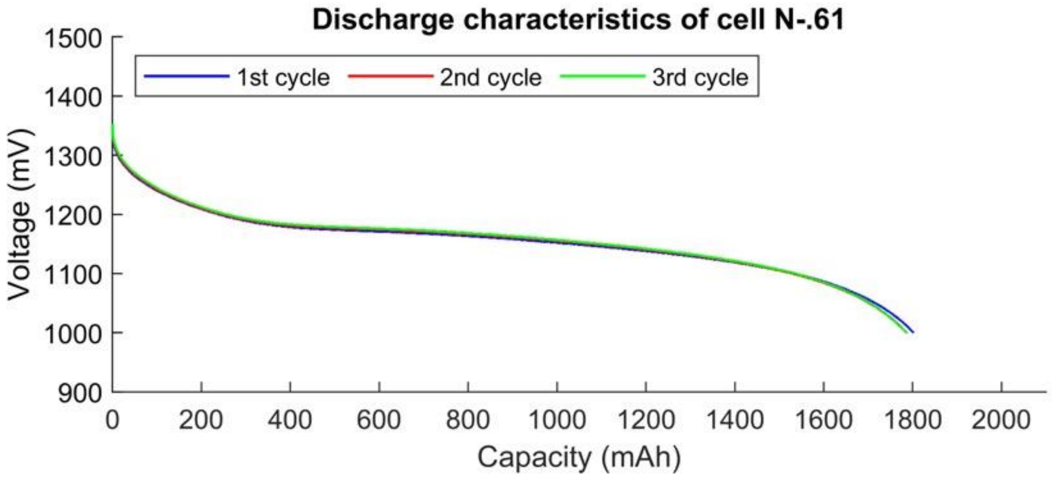


Figure 7-15 Results of discharging cell #61

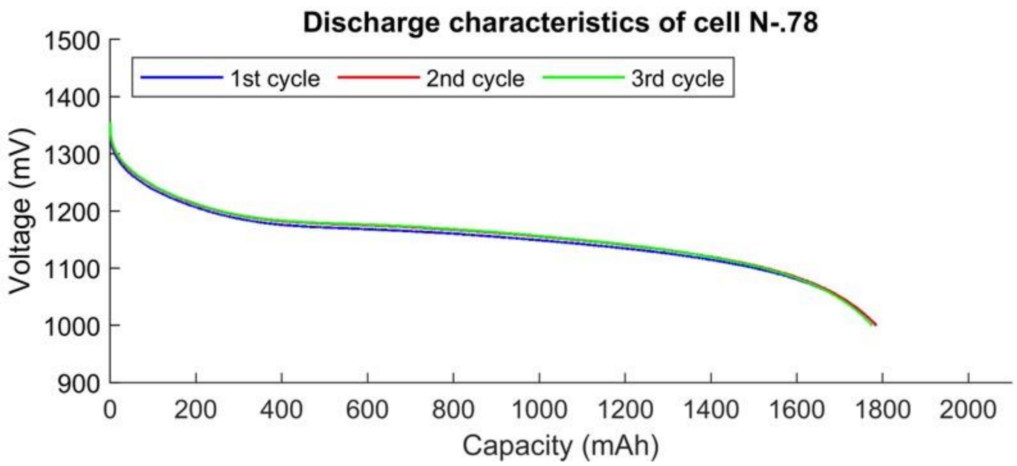


Figure 7-16 Results of discharging cell #78

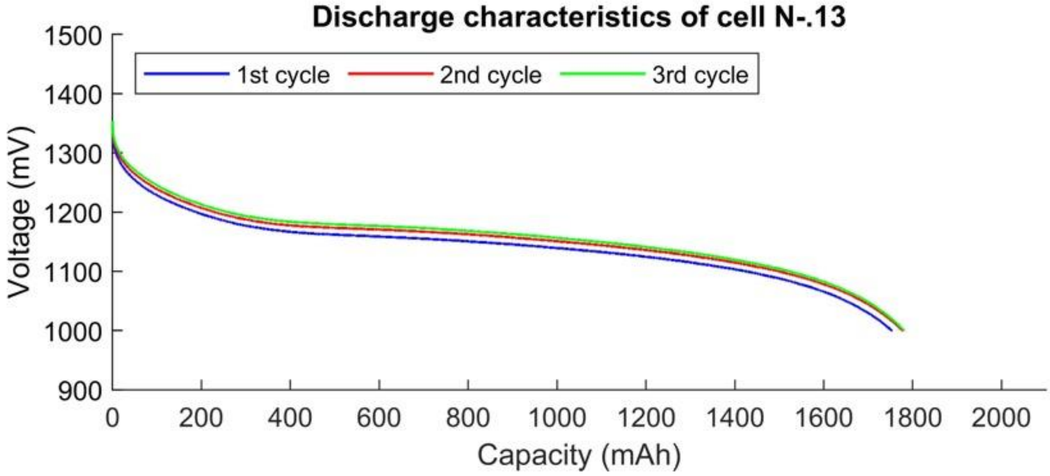


Figure 7-17 Results of discharging cell #13

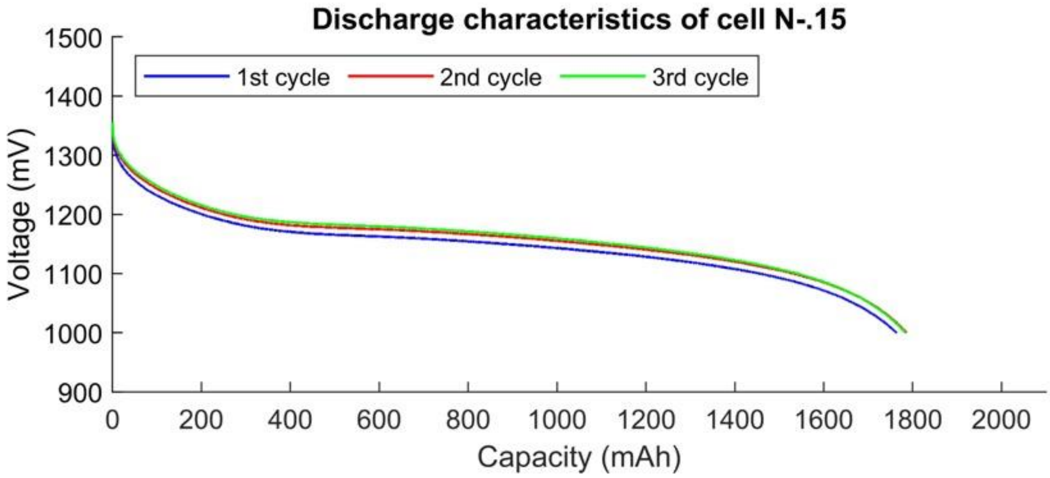


Figure 7-18 Results of discharging cell #15

8) Other Qualification Tests

a) Thermal Test

Thermal test of the battery cell is performed for the confirmation of temperature tolerance. The test has been conducted for the temperatures between 60 °C to 65 °C for 2.5 hours (ref. Figure 8-1). The experiment set-up is given as Figure 8-2. Before and after the thermal test, the results of functionality test were different as it could be seen from Table 8-1 showing the results of the test. The discharge test results are also given in Figure 8-3. A visual inspection has been also performed and the battery had no sign of a damage (no scratches, misaligned seals or an electrolyte leakage).

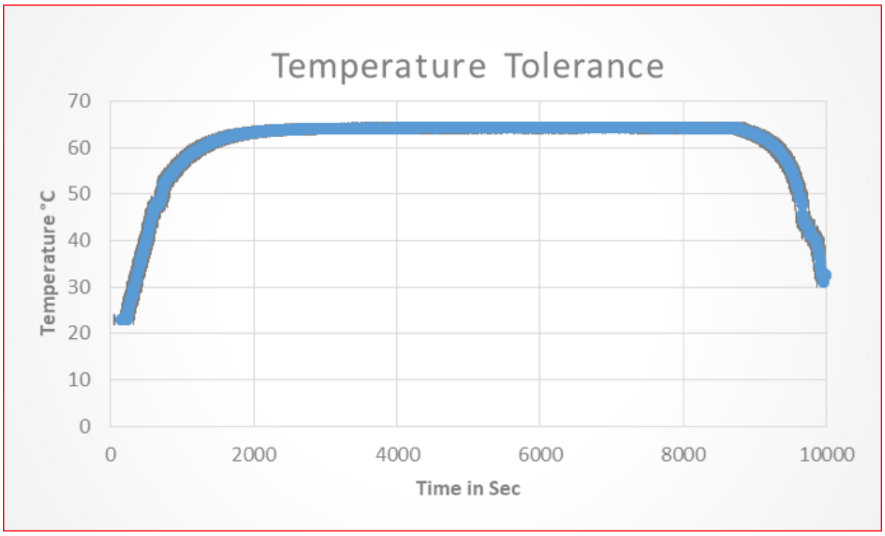


Figure 8-1 Thermal profile applied in the test

Table 8-1 Test results before and after the thermal tolerance test

Battery No	Mass			OCV			Capacity		
	Before [g]	After [g]	Change [%]* (<0.1)	Before [V]	After [V]	Change [%]* (<0.1)	Before [Ah]	After [Ah]	Change [%]* (< 5)
#71	25.93	25.92	0.04	1.34	1.33	0.07	1.801	1.771	1.70

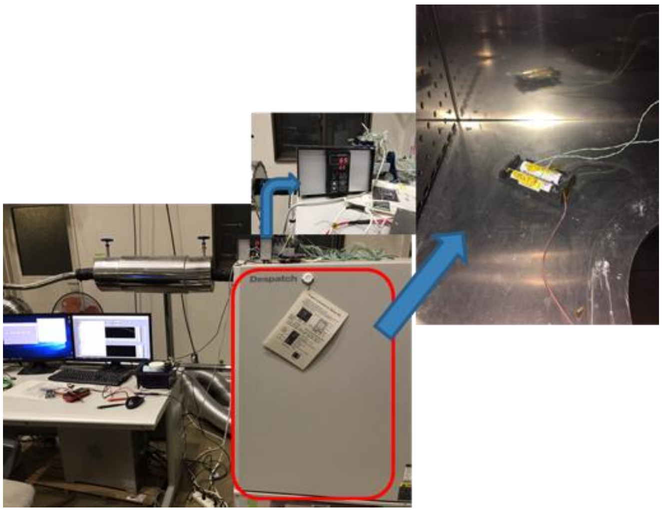


Figure 8-2 The experimental set up thermal tolerance set up at thermostatic chamber

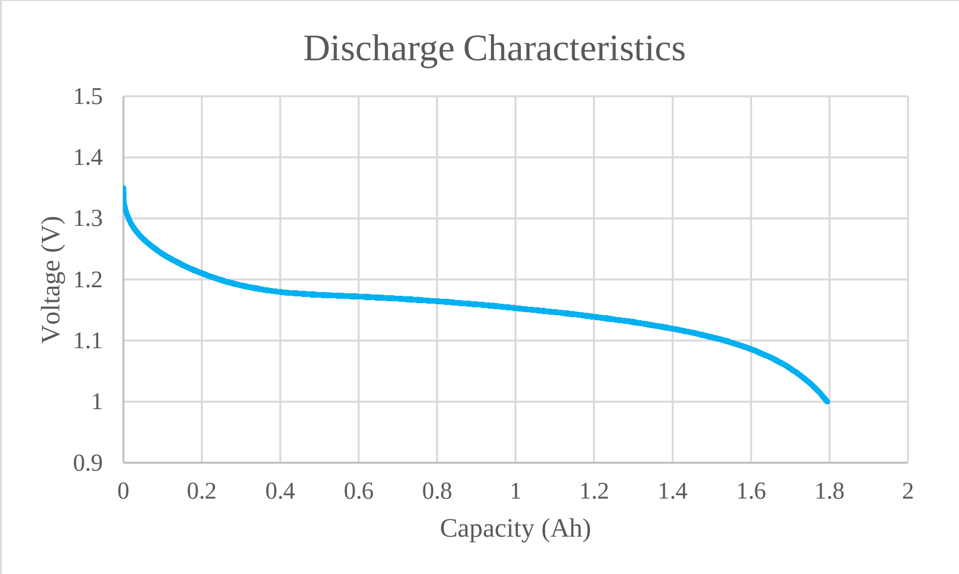


Figure 8-3 Result of discharging after thermal test

b) Battery box self-discharge test

Self-discharge is an inherent feature of batteries. It occurs in batteries due to various reasons. Here the batteries are placed at room temperature while inside the satellites. This test was done when the batteries are assembled with the satellites.

Date	Satellite	Battery voltage	Capacity(mAh)
September 9, 2020	Guaranisat	4.153	3783.4
	Tsuru	4.167	3779.5
	Maya-2	4.142	3785
September 11, 2020	Guaranisat	4.132	3772.2
	Tsuru	4.145	3767.3
	Maya-2	4.121	3775

Satellite	Self-discharge (mAh)	Percent Self-discharge per day
Guaranisat	11.2	0.15%
Tsuru	12.2	0.16%
Maya-2	10	0.13%

Based on the result, it can be seen that the battery pack of all the satellites has self-discharged by less than 0.16% per day. A similar test done by [Vorkoetter, 2007] obtained 0.2% self-discharge. This shows that the assembled battery of BIRDS-4 is the expected amount of self-discharge.

c) DC-DC Converter Test

The function of the DC/DC converter used as a battery overcharge protection device was confirmed. The DC/DC converter is a power electronics device which accepts variable DC input power and provide a stable DC output voltage. BIRDS-4 uses LTC3119 DC/DC converter chip with a wide input range from 2.5V to 18V. The test set-up is shown in Figure 8-4. For this test, the battery is charged through the external charging port using a power supply. The battery overcharge voltage is 4.8V or higher. Therefore, if the DC/DC input voltage was applied by 4.8V or more, it was confirmed whether the DC/DC output voltage was 4.8V or less. Table 8-2 shows the test results. Even if a voltage higher than the overcharge of the battery is input to DC/DC, the output voltage of DC/DC is about 4.2V, which protects overcharge of the battery.

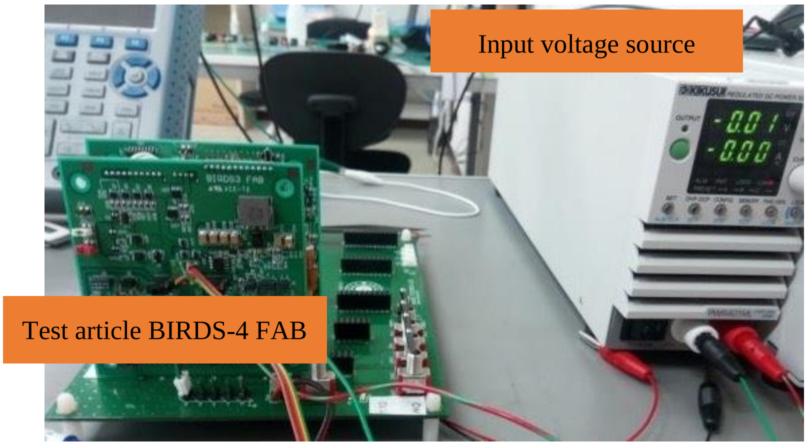


Figure 8-4 shows the DC/DC converter test set up due to requires voltage and current

Table 8-2 Result of the DC/DC test

DC/DC Input(V)	Input Current (A)	DC/DC Output (V)	Condition
4.654	0.604	4.229	*CV
5.000	0.460	4.219	
6.000	0.383	4.219	
7.000	0.330	4.219	
8.000	0.289	4.219	

*CV: Constant Voltage

d) Diode Test

The purpose of the diode test is to verify that no current flows through the diode and into the solar cells. In order to check if current flows in the reverse direction of the diode, an electronic load is connected in place of the solar panels. The anode side of the diode under test is connected to the electronic load and a power supply is connected to the cathode side of the diode under test, as shown in Figure 8-5. When the electronic load is activated to draw current, the diode should prevent it from doing so. Shown in Table 8-3 are the test results and based on the measurement on the electronic load side, there is no current flowing. This proves that the diode works in blocking the reverse current that could come from the battery or DC/DC converter. The test setup is shown in Figure 8-6.

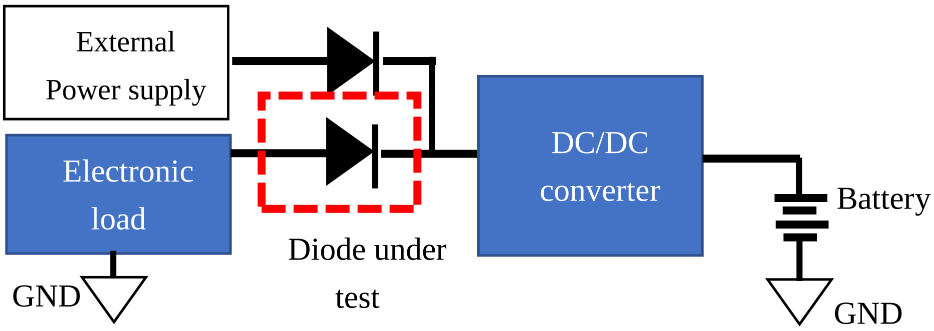


Figure 8-5 Shows the during Diode test set up with configuration

Solar Panel connection	Power supply setting	Electronic load current setting	Electronic load current measurement
+Y	5.2V, 0.8A	0.8A	0V, 0A
+Z	5.2V, 0.8A	0.8A	0V, 0A
+X	5.2V, 0.8A	0.8A	0V, 0A
-Y	5.2V, 0.8A	0.8A	0V, 0A
-Z	5.2V, 0.8A	0.8A	0V, 0A

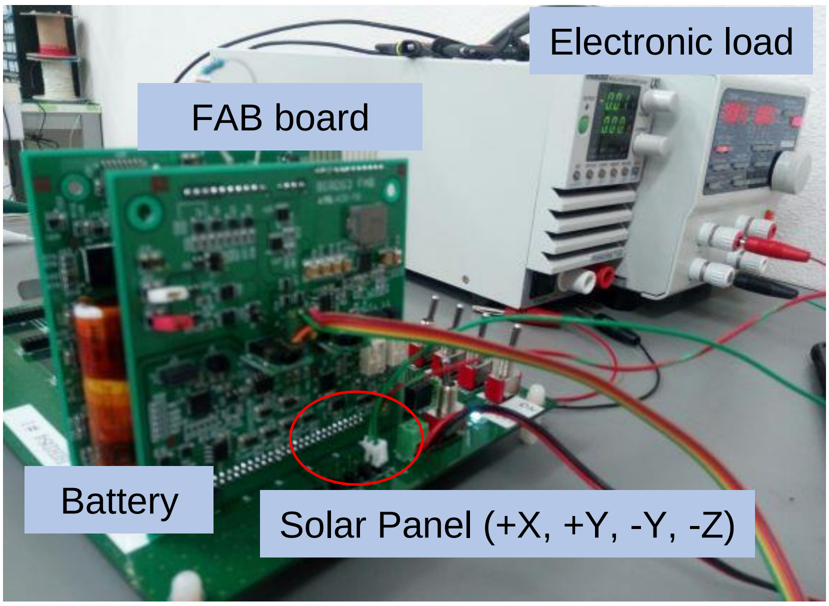


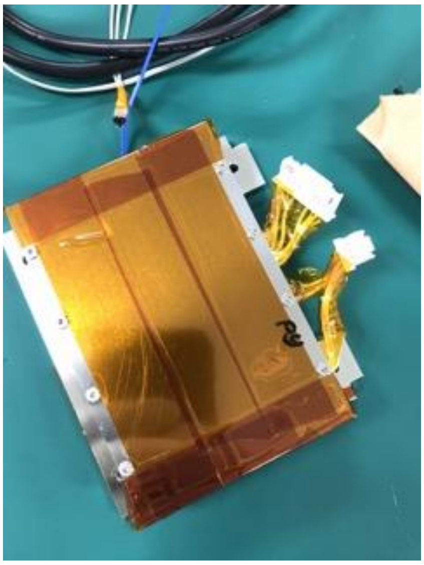
Figure 8-6 Shows the during Diode test set up with configuration

9) Insulation Process

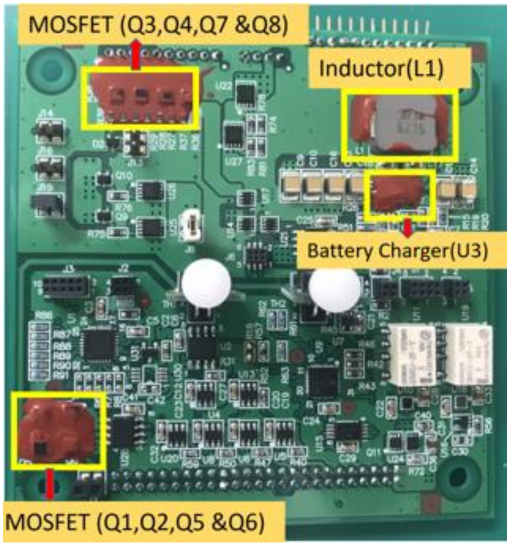
After the tests are completed and the final assembly comes, before inserting the components/parts having the way from battery to inhibits are covered with insulator materials to ensure the insulation. For this purpose, following instructions are followed:

- The MOSFETs, DCDC converters, and diodes are covered by RTV.
- Deployment switch cables are covered by shrinkable tube and Kapton tape twice.
- The batteries, the aluminum box used as the battery case and the battery cables are covered by Kapton tape twice.

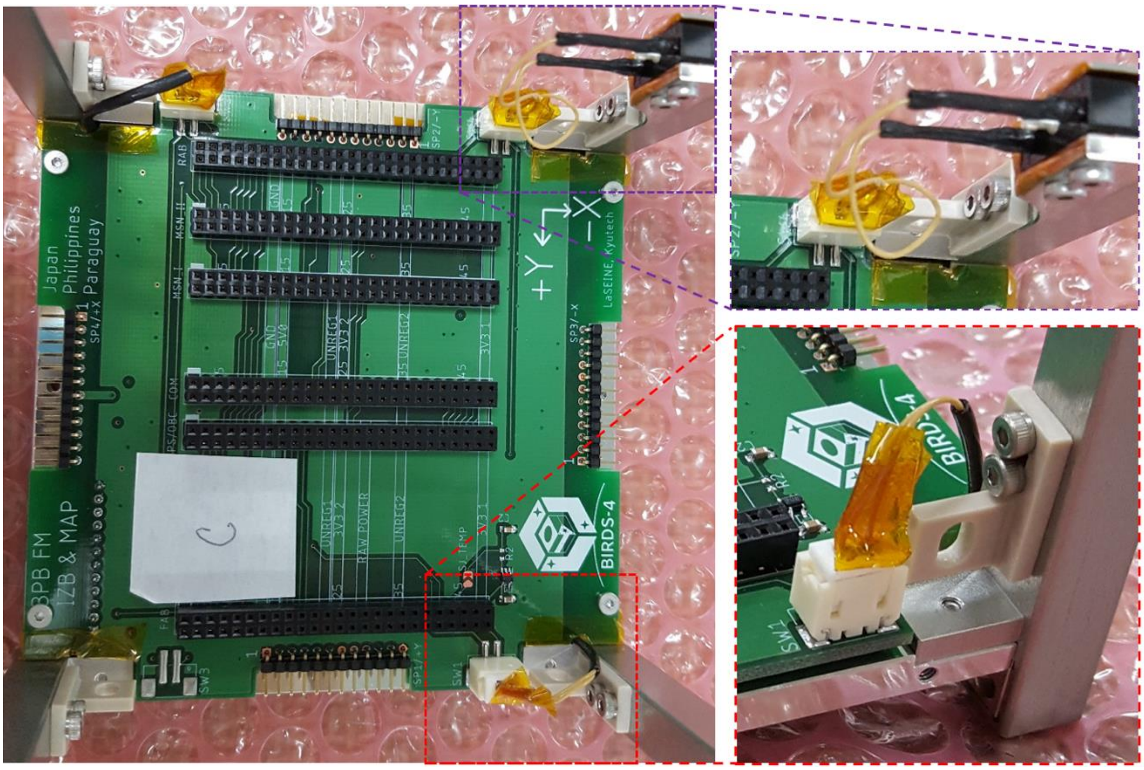
Following figures indicate the aforementioned insulation methods applied on FM components.



(a)



(b)



(c)

Figure 9-1 The insulated location images: (a) Kapton tape used on battery box, (b) MOSFETs, diodes, inductor and the battery charger covered by RTV, and (c) deployment switches covered by shrinkable tube and Kapton tape

Annex Principle of battery impedance measurement

In principle, the battery cell i**m**pedance can be measured from ****