Development of the Lightweight Li-ion battery with CFRP chassis.

MITSUBISHI ELECTRIC COPORATION

(MELCO)

Yosuke Osako, Takeshi Kiyokawa, Yoji Morinaga, Ken Araki,

INSTITUTE FOR UNMANNED SPACE EXPERIMENT FREE FLYER

(USEF)

Matsushi Miura

Development of the Lightweight Li-ion battery with CFRP chassis.

Contents:

1 Introduction
2 Development of CFRP chassis
3 Qualification test (QT) of Lightweight Li-ion battery with CFRP chassis.
3.1 configuration of Li-ion battery
3.2 Result of Qualification test (QT)
4 Conclusion

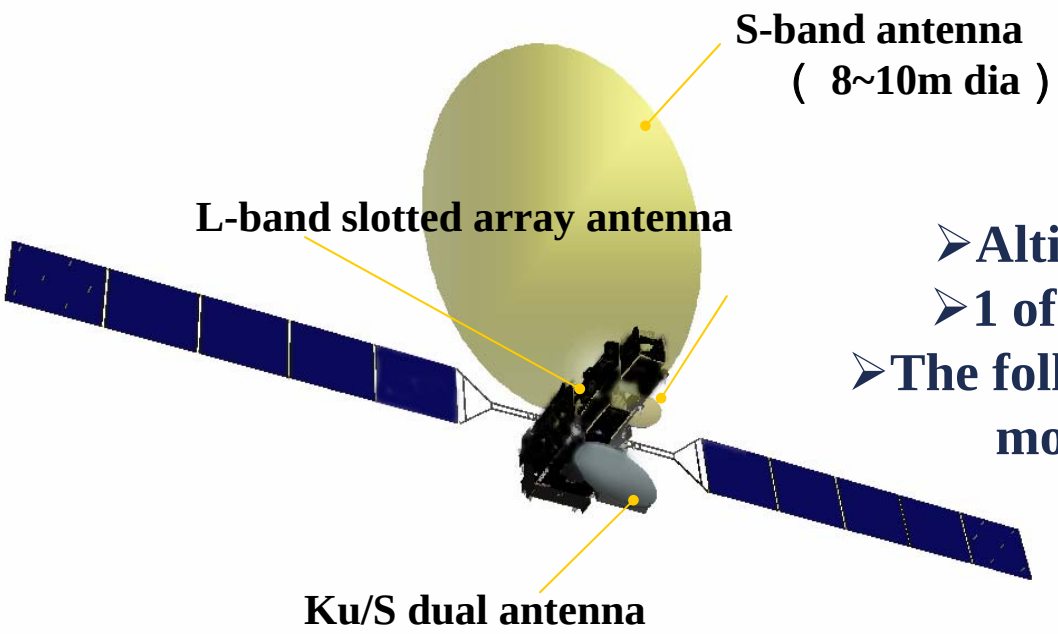
1 Introduction

Introduction

This presentation gives a development summary on large capacity Li-Ion battery with CFRP (Carbon Fiber Reinforced Plastic) chassis for the Quasi-zenith satellite.

The CFRP chassis material has both higher strength and better thermal conductance compared with those of Aluminum chassis, so that the weight reduction of the Li-ion battery was expected. The development results were satisfactory, and opened the way to provide more light Li-ion battery.

Plan and study of the Quasi-zenith satellite



Case study image of
the Quasi-zenith satellite

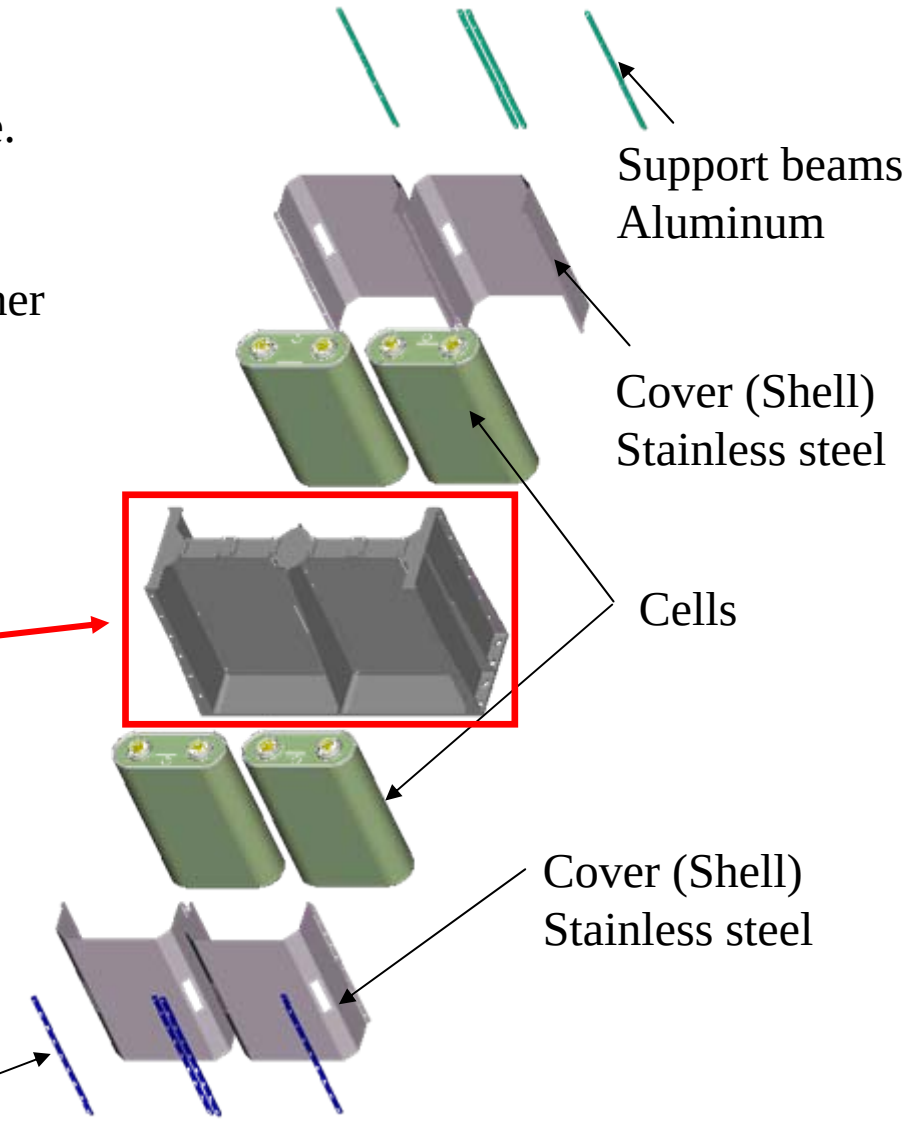
- Japan is located in the high latitude.
- Orbit inclination :High angle
- Altitude:Same as GEO (36,000km approx)
- 1 of 3 satellite always stay on Quasi-zenith.
- The following missions can be assumed for the mobile-use in the city surrounded by high buildings.
  - Communication
  - Broadcasting
  - High accurate global positioning
  - etc..

2 Development of CFRP chassis

Development of CFRP chassis

Following figure shows the 4cells scheme.

- Screws bolt for each cradle to fix the cover(shell) with the rib.
- Each packaged module is fixed to the other by screws.
- Cover (shell) is stainless steel sheet
- Cho-therm and epoxy coating are in between cells and rib.



<chassis>

Light weight mass is achieved by changing the chassis material from the aluminum to CFRP.

Development Flow of CFRP chassis

The development flow of the CFRP chassis is shown below.

Chassis design

↓

Forming of chassis （ method of RTM ）

RTM: Resin Transfer Molding

↓

Thermal Vacuum Test (chassis only)

↓

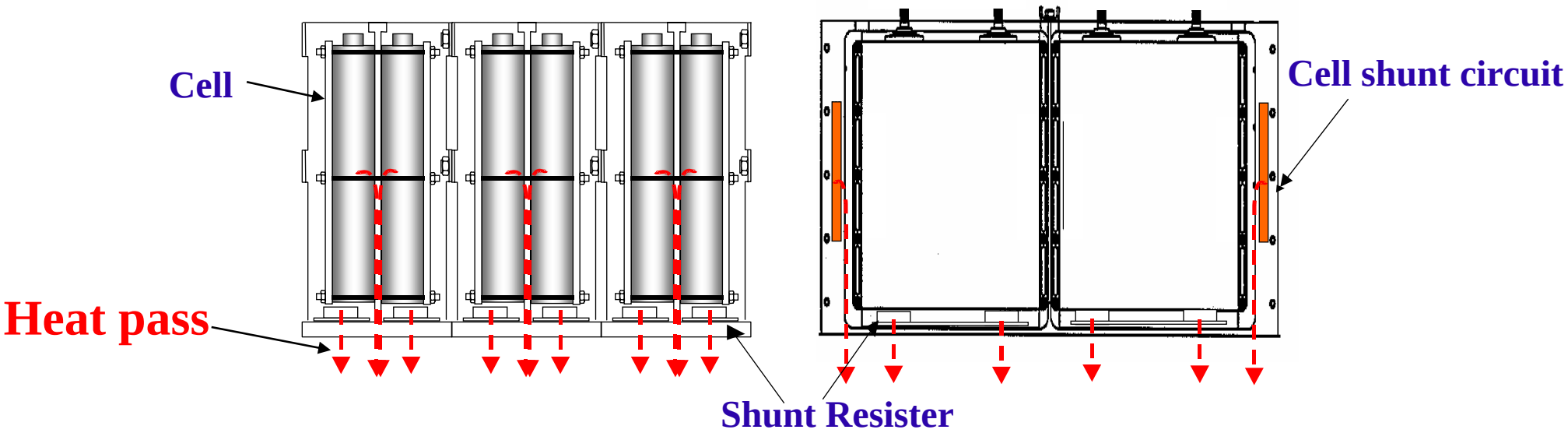
Charge and discharge test (Module of 4 cells)

↓

Vibration test (Module of 4 cells)

Design of CFRP chassis

The direction of the chassis's heat pass is indicated as follows. CFRP has very high specific heat conductivity compared with aluminum. Moreover, anisotropy can be given to the exhaust heat characteristic of the chassis by using CFRP with anisotropy, and there is a possibility of improving the exhaust heat characteristic .



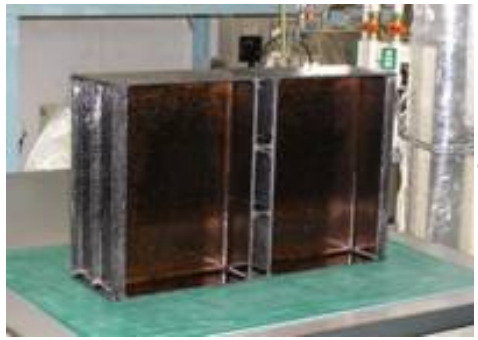
Design of CFRP chassis

As a result of the design of CFRP chassis, The first resonance frequency when 2 modules were connected exceeded 140Hz, thermal conductivities were about 4% higher than aluminum chassis, and the weight of the chassis was 20% lighter than aluminum chassis.

Development of CFRP chassis

Forming of chassis （ method of RTM ）

Material (only carbon fiber)



After forming

After machining

Method of RTM is more excellent than ‘Laminating Prepreg’ for complicate 3 dimension form.

Thermal balance test（ Thermal vacuum ）

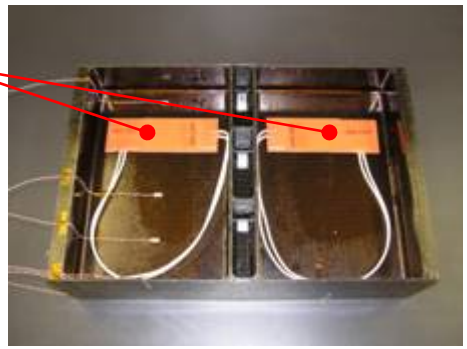
The evaluation test to confirm the thermal conductivity of manufactured CFRP chassis was executed.

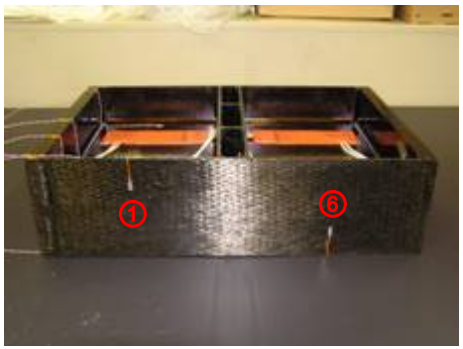
<evaluation method>
The temperature distribution was made in CFRP chassis by the heater heating. The temperature at each thermo-couple position were measured, and a measurement result and an analytical result are compared.

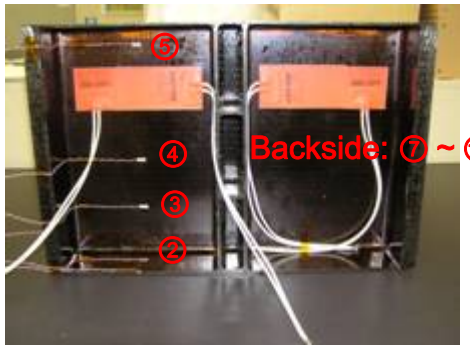
Thermal balance test （ Thermal vacuum ）

Thermocouple and heater

heater

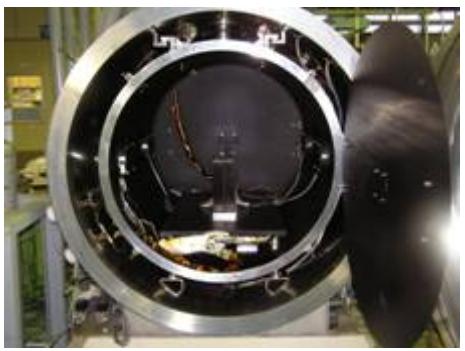




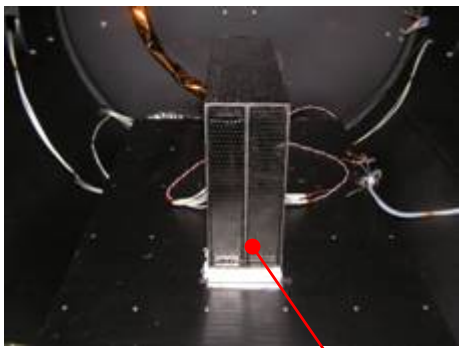


① ~ ⑩ ： Thermocouple

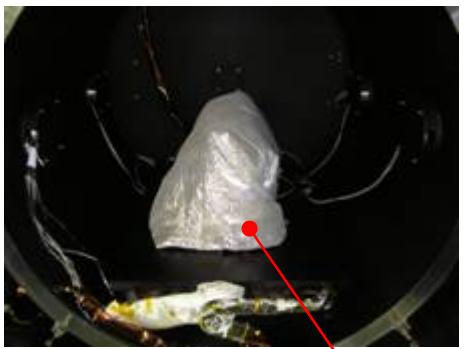
Thermal balance test



Vacuum chamber



CFRP chassis

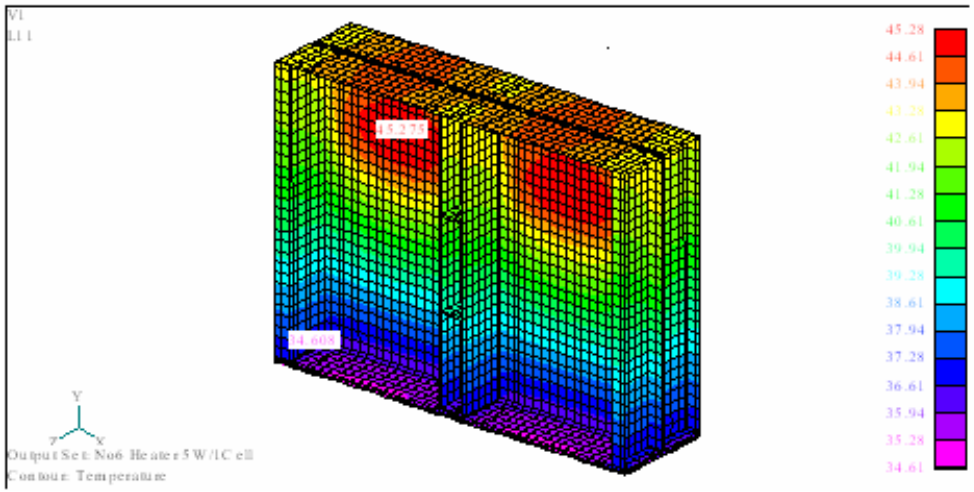


MLI cover

Thermal balance test （ Thermal vacuum ）

Thermocouple	Measurement temperature (deg C)	Difference with base plate (deg C)	Measurement temperature (Convertion from No1to 35℃.)	thermal analysis
No.1	32.7		35.0	35.0
No.2	34.3	1.6	36.4	35.3
No.3	36.3	3.6	38.4	38.5
No.4	38.4	5.7	40.7	41.1
No.5	41.6	8.9	43.8	44.6
			-	-
No.6	32.3		-	-
No.7	33.5	1.2	-	-
No.8	35.5	3.2	-	-
No.9	37.9	5.6	-	-
No.10	41.0	8.7	-	-

Comparison between Measurement temperature and thermal analysis

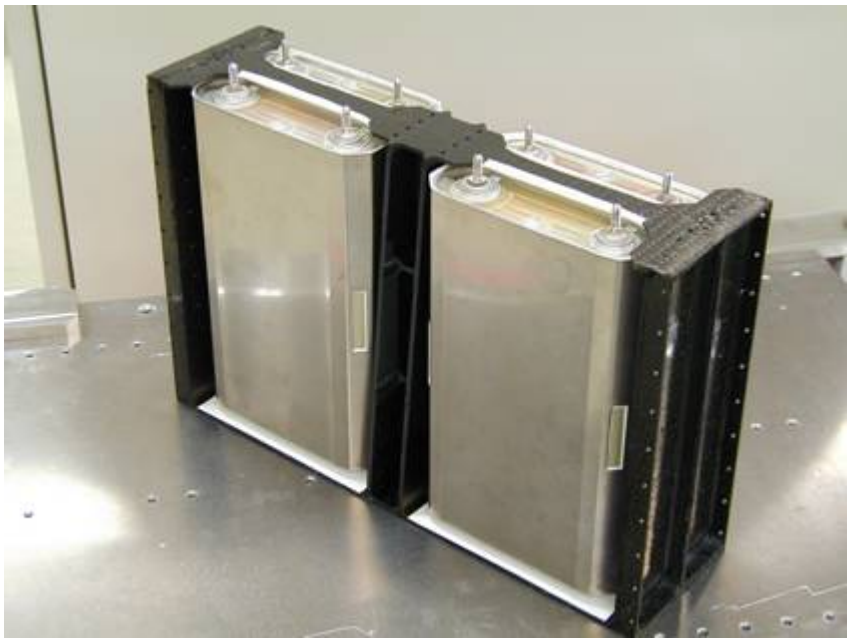


Thermal analysis (Boundary temperature:35degC,heater:5W

A measurement result and an thermal analysis result agreed almost, and were able to confirm the validity of the heat design. The thermal conductivity in the direction of the heat pass improved by 19% compared with the aluminum chassis , and was 214W/m･K.

Charge and discharge test（ Thermal vacuum ）

The battery cell was mounted on the CFRP chassis, and the electrical charge and discharge was executed in the vacuum chamber. At that time, the temperature distribution was measured, and the exhaust heat characteristic of the chassis was evaluated.



<4cell module>

Width：118 mm

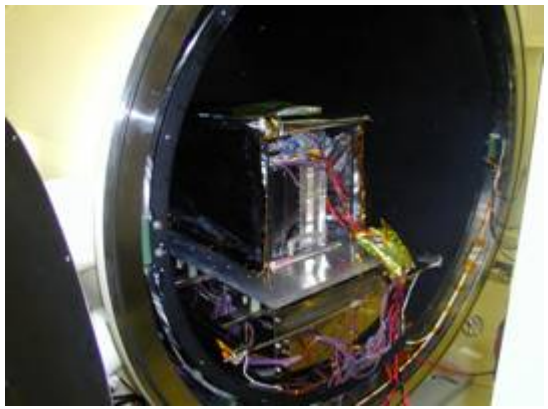
Length：435mm

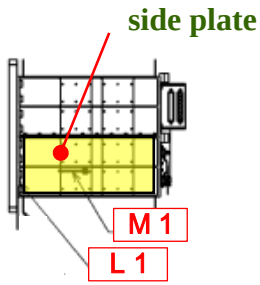
Height ：344.6mm

Mass ：22.8 kg

Module of 4 cell (Charge and discharge test)

Charge and discharge test (Thermal vacuum)





M2: Cell surface

M5: Cell surface

M3: Cell surface

M4:CFRP chassis/ center of center plate

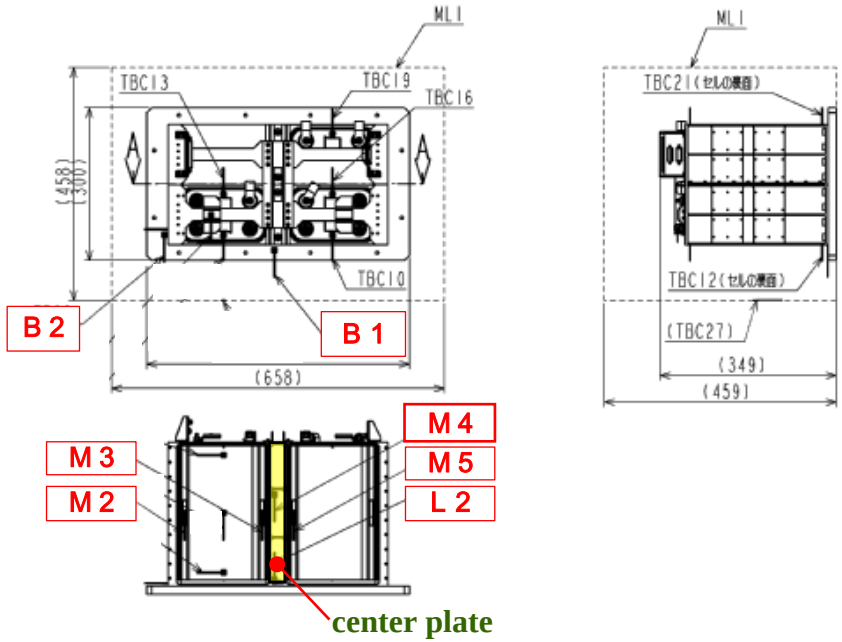
M1:CFRP chassis/ center of side plate

L2:CFRP chassis/ mounting of center plate

L1:CFRP chassis/ mounting of side plate

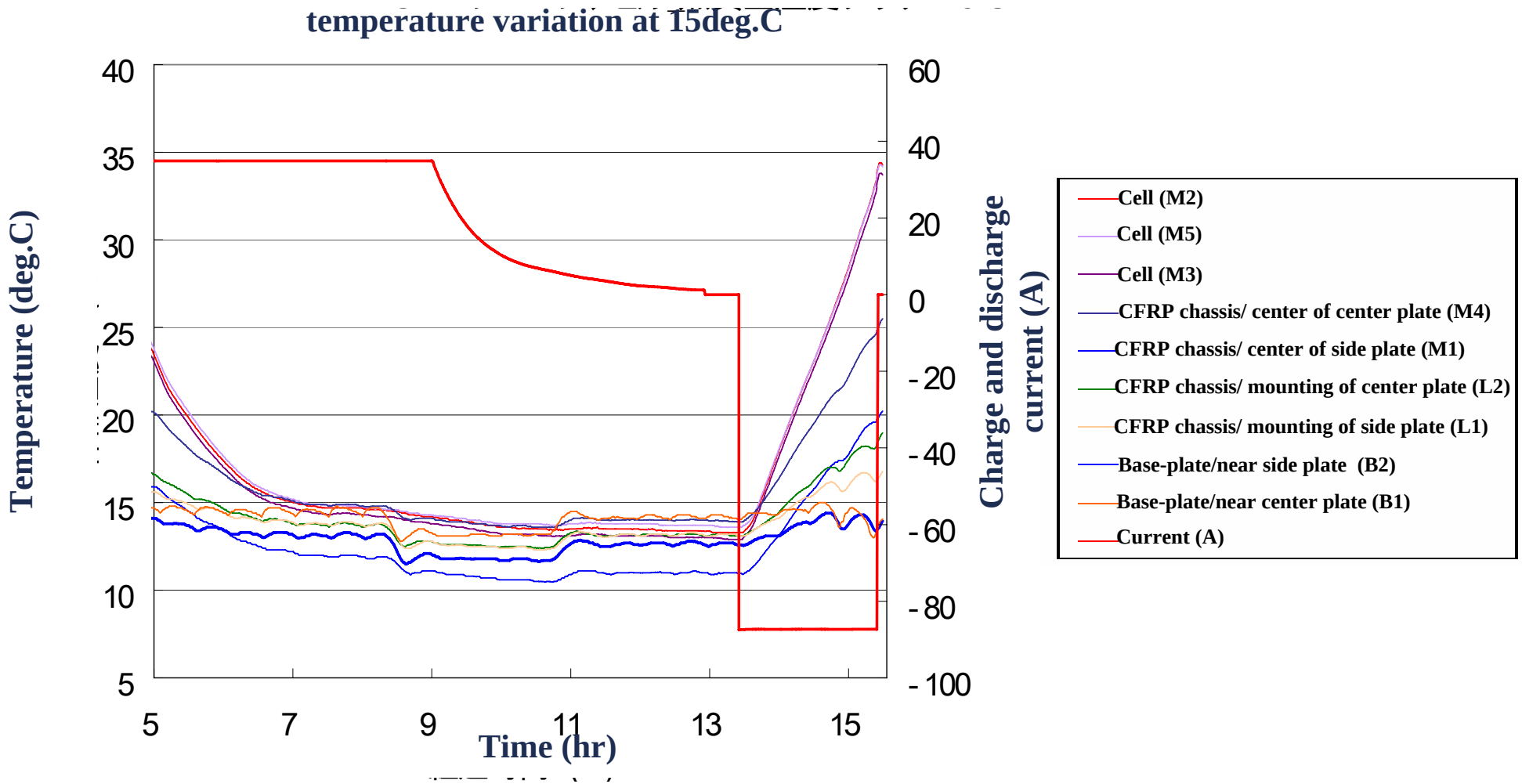
B1: Base-plate/near center plate

B2: Base-plate/near side plate



Location of thermocouple

Charge and discharge test (Thermal vacuum)



Result of Charge and discharge test

Charge and discharge test (Thermal vacuum)

chassis's material	between chassis's center and base-plate △ T1[℃]	direction of thermal pass in center plate of chassis △ T2[℃]	between chassis's side mounting and base-plate △ T3[℃]	direction of thermal pass in side plate of chassis △ T4[℃]	between chassis and cell △ T5[℃]	
	L2-B1	M4-L2	L1-B2	M1-L1	M3-M4	M5-M4
alminum	3.4	8.3	1.3	9.8	8.0	7.6
CFRP	3.4	6.5	2.9	3.4	8.5	8.7

Result of Charge and discharge test

Charge and discharge test（ Thermal vacuum ）

-Temperature difference inside CFRP chassis is smaller than aluminum chassis

-Temperature difference between CFRP chassis and cell, CFRP chassis and base-plate are bigger than aluminum chassis.

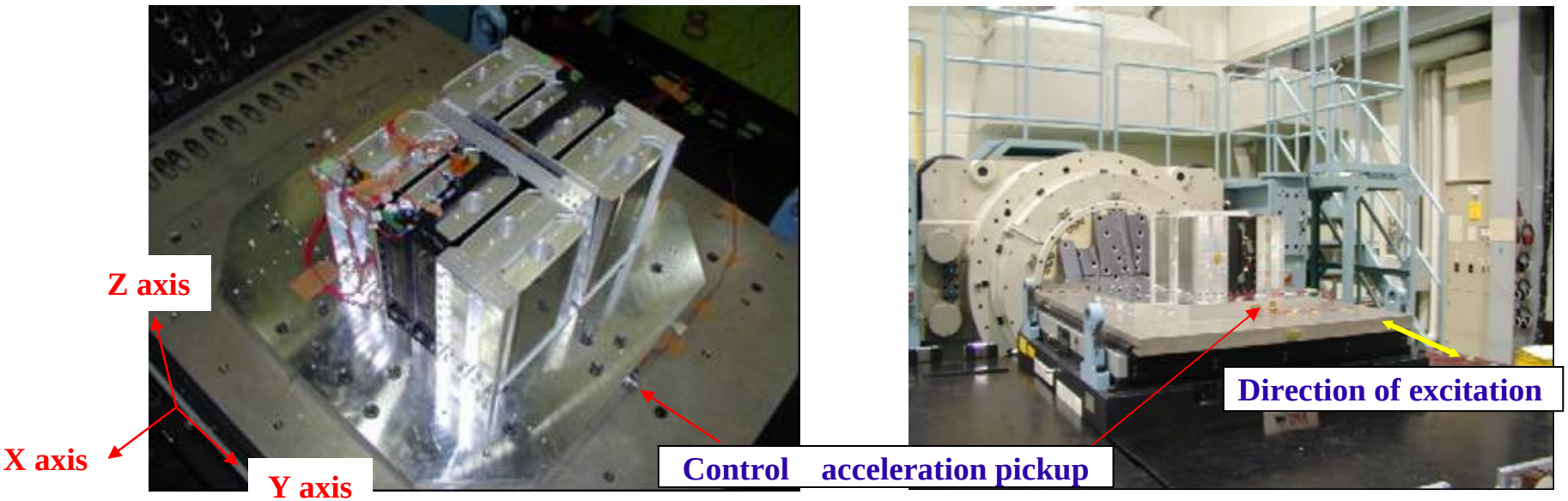
⇩

Improvement of CFRP chassis's flatness need for reducing contact thermal resistance between CFRP chassis and cell, between CFRP chassis and base-plate

Vibration test

The vibration test was executed by the configuration shown in the following. The test have executed by using 12 cells ASSY composed of the evaluation module with CFRP chassis and the module with aluminum chassis.

A modal survey, a random vibration, and the sine vibration was executed, and the evaluation of the 1st resonance frequency and strength have executed.



Configuration of Vibration test

Vibration test

[Modal survey (random modal)]
Axis:all axis
Frequency：20-2,000Hz
Level (PSD)：0.001×[9.8(m/s^2)]^2/Hz
Over all：1.41×[9.8(m/s^2)]

[Sine vibration level]

Axis	Frequency(Hz)	Single Amplitude
Y	5 – 21.2 21.2 - 100	6.3mm 196m/s^2 (20G)

[Random vibration level]

Axis Excitation time	Frequency (Hz)	Level
Y 180 s	20 - 50 50 - 1000 1000 - 2000	+6dB/oct 0.1g^2/Hz - 3dB/oct
	Overall	12.88Grms

Sweep rate : 2 oct/min

The vibration condition is shown. Modal survey executes with all axes, and confirms the resonance frequency. Sin vibration and Random vibration are impressed to only Y axis. The battery is a structure that the first mode appears to Y axis, and strength is confirmed by impression to Y axis with which the load is the severest.

Development of CFRP chassis

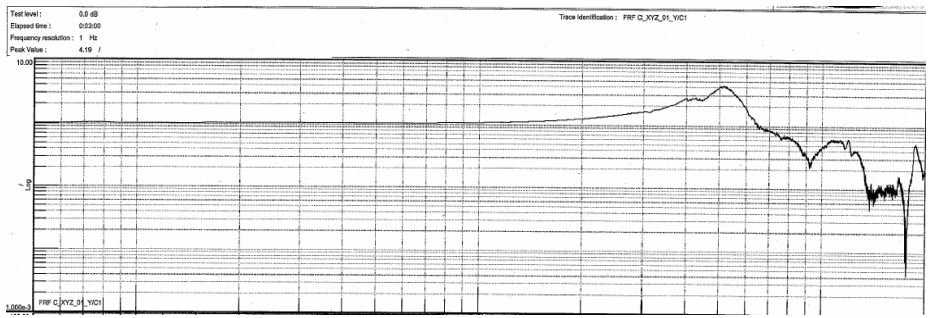
Vibration test

axis	1st resonance [Hz]
X	520
Y	215
Z	721

1st resonance (CFRP chassis)

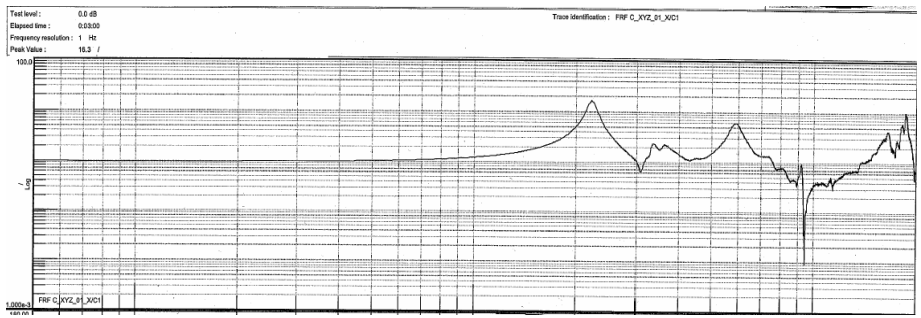
axis	1st resonance [Hz]
X	420
Y	186
Z	710

1st resonance (12cell ASSY model with aluminum chassis)



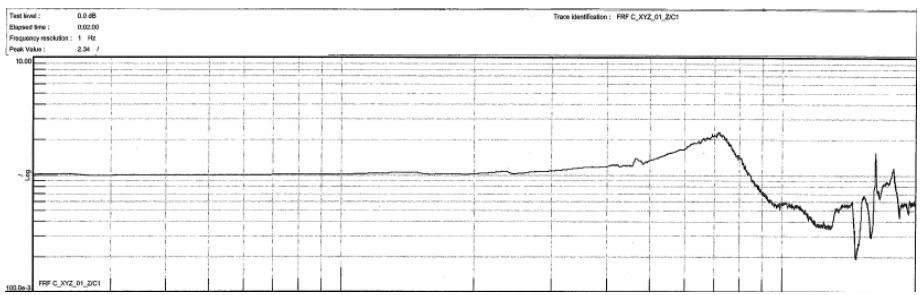
10Hz 100Hz 1000Hz

X axis Modal survey (520Hz)



10Hz 100Hz 1000Hz

Y axis Modal survey (215Hz)



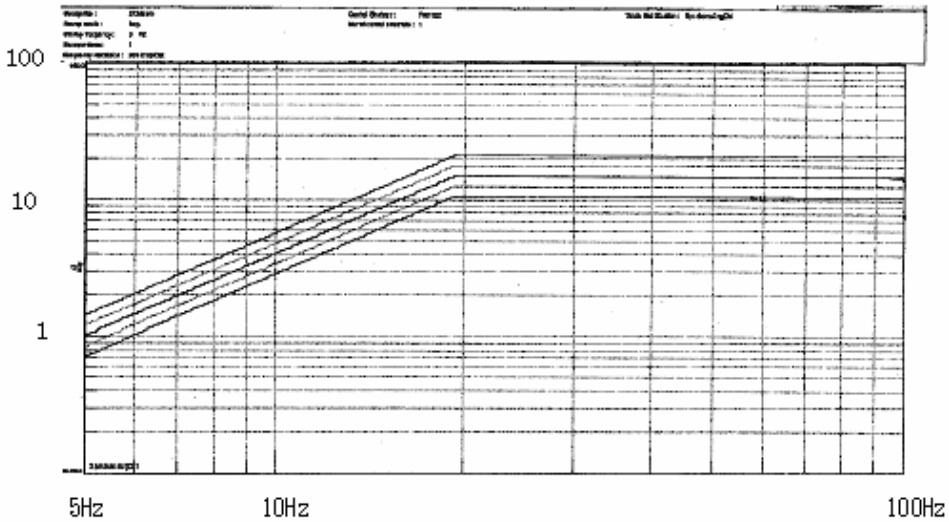
10Hz 100Hz 1000Hz

Z axis Modal survey (721Hz)

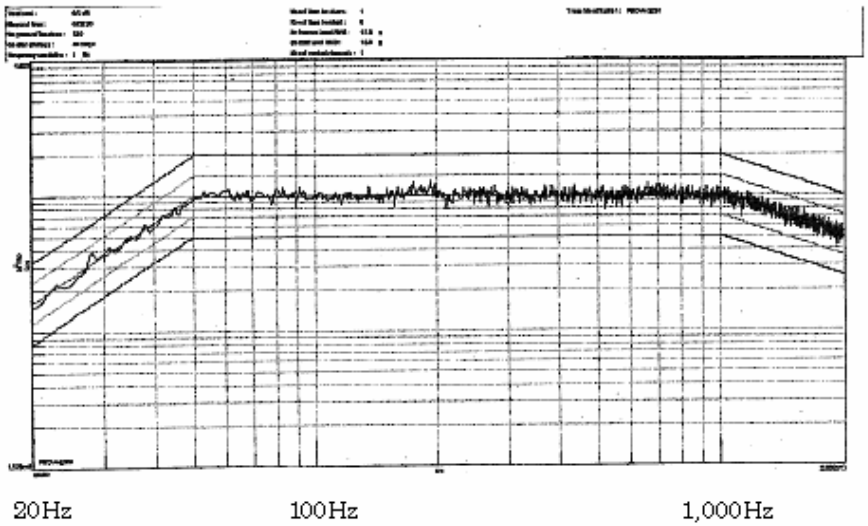
According to the design, the first mode of vibration appeared to Y axis , and The resonance frequency confirmed that there were 120Hz or more, and an enough rigidity was possessed.

Development of CFRP chassis

Vibration test



sine vibration (QT)



Random vibration (QT)

A sine vibration and a random vibration were impressed, the change of the resonance frequency before and after the vibration was not seen. From this result , it confirmed that enough strength was possessed.

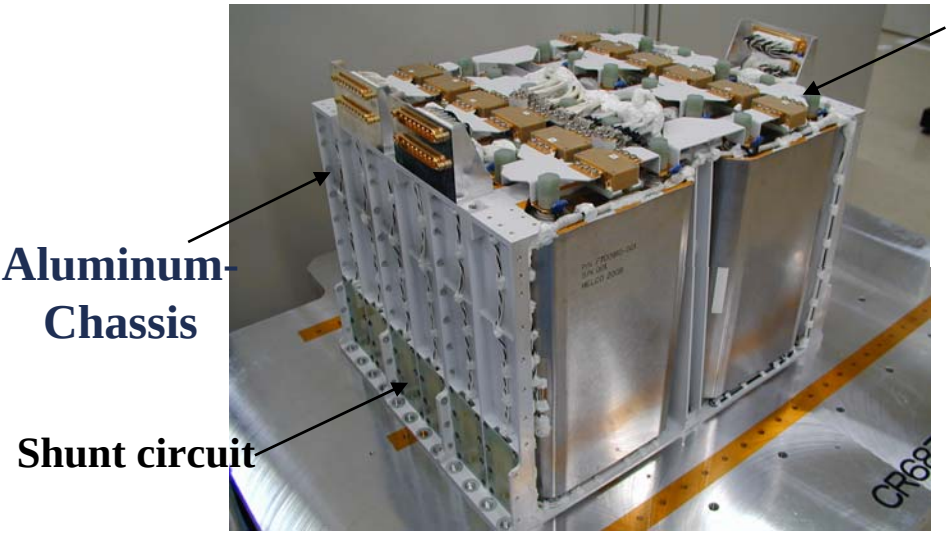
3 Qualification test (QT) Lightweight Li-ion battery with CFRP chassis.

CFRPバッテリ

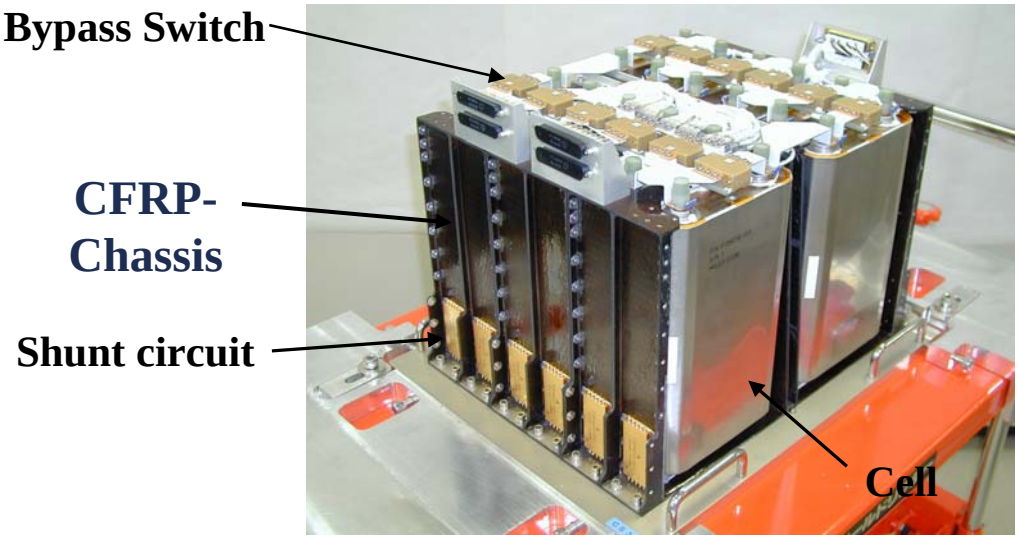
By using developed CFRP chassis in section 2, 12 cell ASSY module (evaluation model) was manufactured and the qualification test was executed. Both aluminum battery and CFRP battery were compared, and the verification was executed.

3.1 configuration of Li-ion battery

Li-ion battery



Battery of aluminum chassis



Battery of CFRP chassis

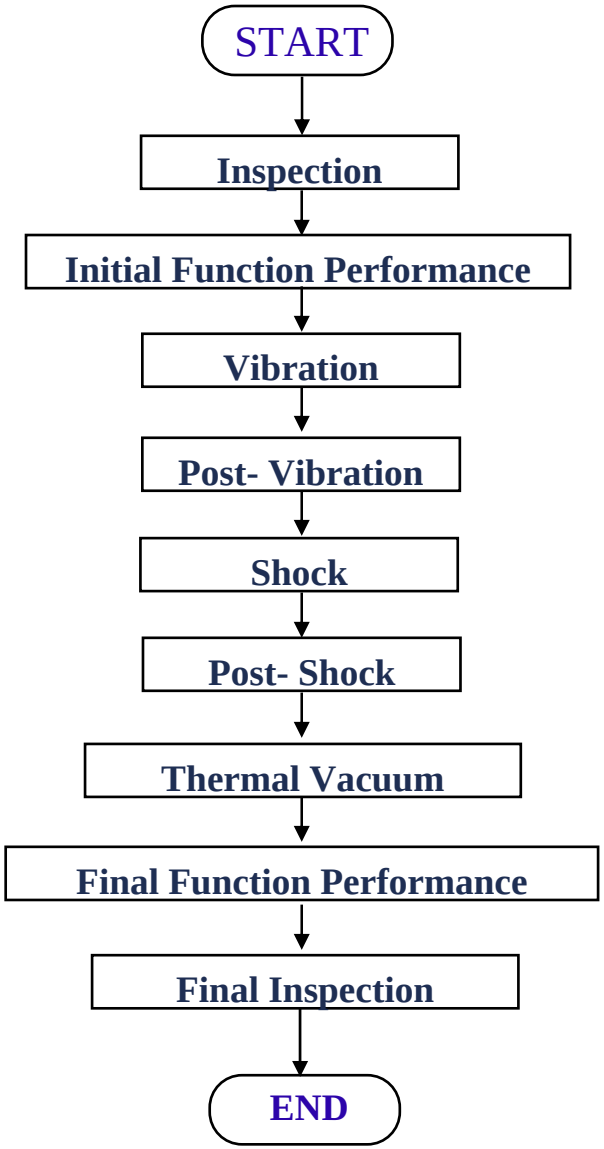
Voltage	: 39.6-49.2(V)
Cell Capacity	: 175(Ah)
Quantity of Cells	: 12 cells in series
Width	: 449 mm
Length	: 510
Height	: 344 MAX
Mass	: 74.7 kg

Voltage	: 39.6-49.2(V)
Cell Capacity	: 175(Ah)
Quantity of Cells	: 12 cells in series
Width	: 449 mm
Length	: 510
Height	: 344 MAX
Mass	: 72.8 kg

Detail of structure had been *presented in 2005* NASA battery workshop

3.2 Result of Qualification test (QT)

3.2 Qualification test (QT)



TEST CONTENTS \ QUALIFICATION TEST	Inspection	Initial Function Performance	Vibration	Post-Vibration	Shock	Post- Shock	Thermal Vacuum	Final Function Performance	Final Inspection
inspection	x			x		x			x
Dimensions/Mass/Gravity Center	x								x
Bonding inspection	x								x
Insulating inspection	x			x		x			x
Cells/Battery voltage monitor		x		x		x		x	
Cell potential monitor		x		x		x		x	
AC impedance		x		x		x		x	
Capacity		x						x	
Benchmark test		x					x	x	
Pulse characteristics		x						x	
DC resistance		X						x	
Thermistor characteristic		x						X	
Charge retention		x							
Sine vibration			x						
Random vibration			x						
Shock					x				
Leak test							x		
Thermal vacuum							x		

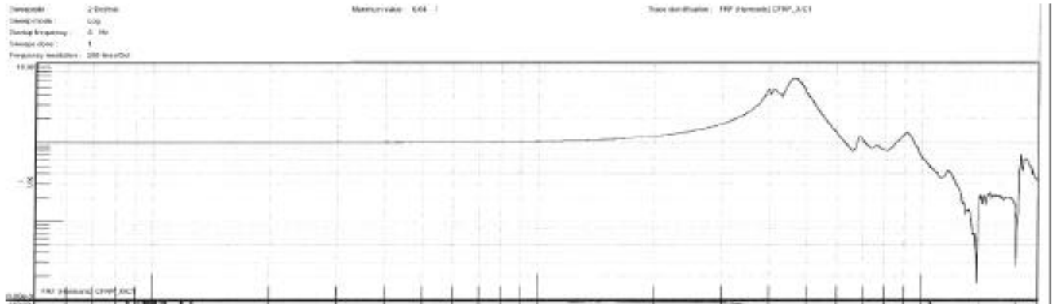
The performance evaluation of the entire battery was executed by aluminum chassis battery previously developed. Battery of CFRP chassis executes the evaluation giving priority to the mechanical performance.

3.2 Qualification test (QT)

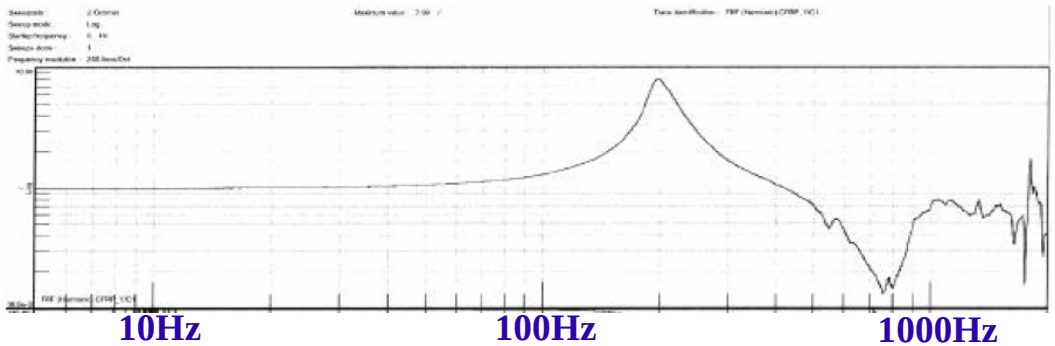
Vibration test (modal survey)

Modal survey is performed by following condition.

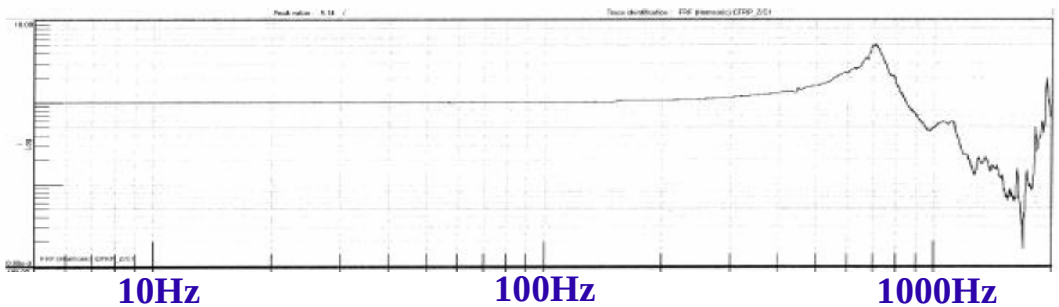
- Axis : X,Y,Z
- Frequency : 20-2kHz
- acceleration : 4.9m/s^2 (0.5G)
- Sweep Rate : 2oct/min (one side sweep)



X axis Modal survey (390Hz)



Y axis Modal survey (190Hz)



Z axis Modal survey (710Hz)

Comparison of 1st resonant

	1st resonant (Hz)	
	alminium chassis	CFRP chassis
X axis	420	400
Y axis	186	190
Z axis	710	710

By result of 1st resonant , rigidity is same between CFRP chassis and aluminum chassis.

3.2 Qualification test (QT)

Vibration test

[Sine vibration level]

Axis	Frequency(Hz)	Single Amplitude
Z	5 – 22.3 22.3 - 100	10mm 196m/s^2 (20G)
X , Y	5 – 21.2 21.2 - 100	6.3mm 196m/s^2 (20G)

Sweep rate : 2 oct/min

[Random vibration level]

Axis Excitation time	Frequency (Hz)	Level
Z 180 s	20 - 80 80 - 600 600 - 2000	+6dB/oct 0.2 g^2/Hz - 3dB/oct
	Overall	15.94Grms
X, Y 180 s	20 - 50 50 - 1000 1000 - 2000	+6dB/oct 0.1g^2/Hz - 3dB/oct
	Overall	12.88Grms

【Battery Voltage】

Before and after vibration：47.8±0.6V

Chaging voltage all vibration：±0.12V and less than

A sine vibration and a random vibration were impressed, the change of the resonance frequency before and after the vibration was not seen. And the voltage change all vibration was ±0.12V and less than. From this result, it confirmed that enough strength was possessed.

3.2 Qualification test (QT)

Shock test

【Shock test level】

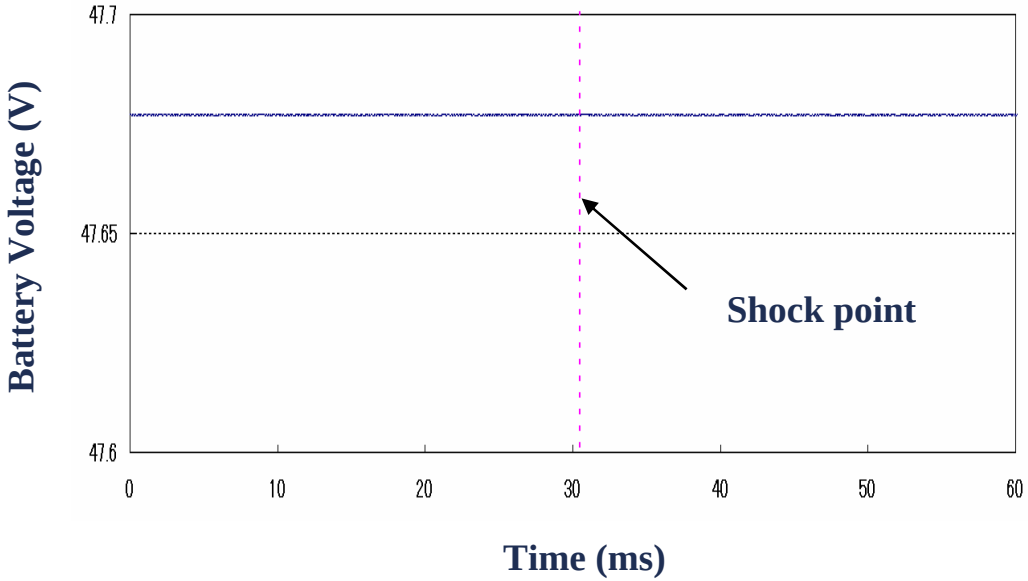
Frequency (Hz)	Shock spectrum (Q=10)
100 - 1000	+6dB
1000 - 4000	13720m/s^2 (1400G)

【Battery Voltage】

Before and after shock：47.8±0.6V

Changing voltage all shock：±0.12V and less than

【Voltage monitor when impress shock】



Changing Voltage before and after shock was not seen by the impact impression

3.2 Qualification test (QT)

Comparison of performance between aluminum battery and CFRP battery

	12cell ASSY (aluminum chassis)	12cell ASSY (CFRP chassis)	comment
Visual	○	◎	aluminum;74.7 kg CFRP;72.8 kg
Insulating inspection	○	○	
AC impedance	○	○	
Charge and discharge characteristics	○	○	
rigidity (resonant)	○	○	CFRP is designed as the rigidity becomes equal to aluminum.
Sin vibration	○	○	
Random vibration	○	○	
Shock	○	○	
Thermal vacuum	○	○	CFRP is designed as the thermal conductivity becomes equal to aluminum.

The battery of CFRP chassis was produced, and the qualification test was executed. As a result, the spec of electrical characteristic and the mechanical characteristic required the satellite was able to be cleared, and to verify the validity of an electric design and the mechanical design. In the viewpoint of light mass, 1.9Kg of Light mass was able to be achieved by changing aluminum to CFRP in 12 cell ASSY battery.

4 Conclusion

- The thermal conductivity in the direction of the heat pass improved by 19%

  compared with the aluminum chassis , and was 214W/m·K.
- As a result of the development of the CFRP chassis, 20% of light mass was able to be achieved from the aluminum chassis.
- It was confirmed to have an enough rigidity and strength as a result of the vibration test.
- As a result of the qualification test of 12cell ASSY composed of CFRP chassis, 1.9Kg of Light mass was able to be achieved by changing aluminum to CFRP in 12 cell ASSY battery.

Development of the Lightweight Li-ion battery with CFRP chassis.

Thank You

Cell characteristics

Specifications of 175Ah Lithium-Ion cell for satellite

P/N: LMG175AR*

Shape: Elliptic cylindrical

Dimensions (mm): H263, W165, T50

(Include terminal: H:269)

Mass: *4.6kg*

Rated capacity: 175Ah (*184Ah nominal*)

Minimum discharge voltage: 2.75V

Nominal discharge voltage: 3.6V

Specific energy :*144Wh/kg* @ nominal capacity

Case material: *Aluminum alloy*

Positive material: Lithium *cobalt* dioxide ($LiCoO_2$)

Negative material: Carbon materials

Separator: Micro porous plastic film

Electrolyte: Li salt dissolved in mixture of alkyl carbonate solvents

This cell had been *qualified in 2004* for Quasi-zenith satellite.

Cell over charge protection

Shunt circuit

The shunt circuit is not only to protect the over charge but also
-to equalize the each cell voltage when the each cell voltage may be drifted by leak current
-to be charging the connected battery cell to bypass the charge current if open failure on cell occurs.

- Dimensions (Case Size) : 75×40×6.5mm
- Foot Print : 30cm^2
- Mass : 40g

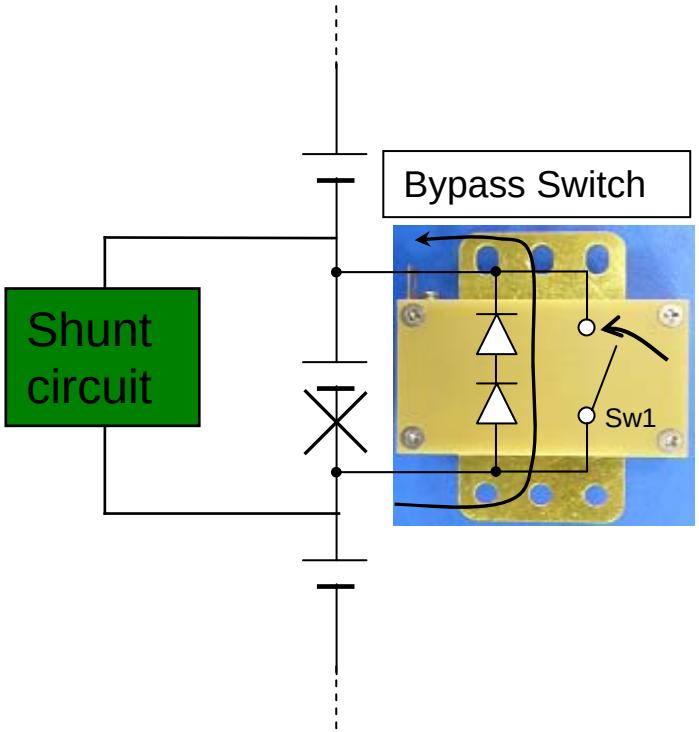
Detail had been *presented in 2004 , 2006* NASA battery workshop

One Cell Fail operation

Cell Bypass Switch

When one battery cell is failed as open mode, the Bypass Switch will activate to bypass the charge/discharge current out of cell in failure.

When the Bypass Switch detects cell failure, Sw1 is closed detecting discharge current of the parallel diode.
As cell in failure is shorted by the switch, the battery keep alive.



Connection of Bypass switch

Details are *presented in 2005* NASA battery workshop

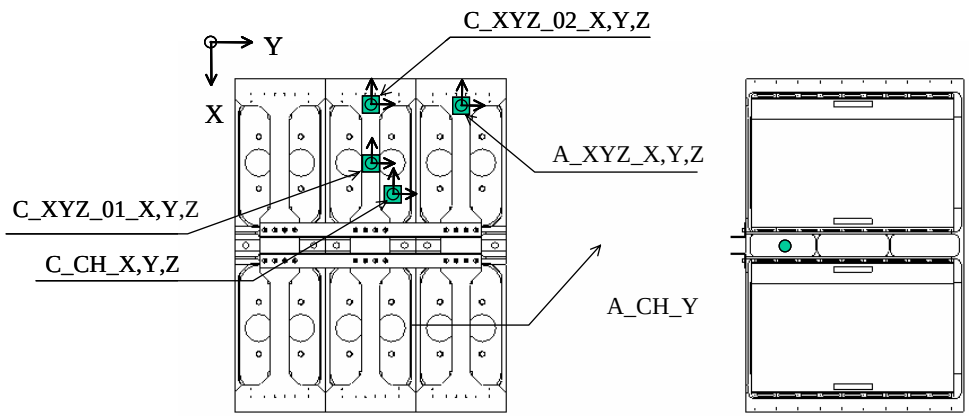
Requirement for the Quasi-zenith satellite battery

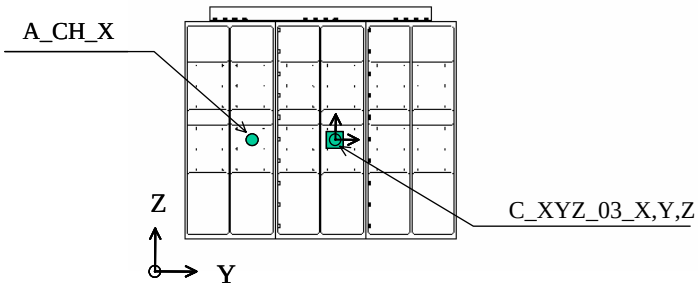
Item	Performance
Li-ion cell	175Ah(Nominal capacity) 16cells in series
Provide capacity	more than 20kWhr(BOL)
	more than 16kWhr(EOL)
Design life	over 15 years
Bus voltage	97 - 103V (Regulated)
Max DOD (Battery)	60%
Battery protection	Cell shunt circuit for overcharge protection
	Cell bypass switch for cell open failure
	Over temperature protection
	UVC protection for over discharge
Charge control	Constant Current:C/20 nominal
	Constant Voltage:C/100 nominal
	constant voltage is variable in orbit
Discharge control	Regulated by Battery Discharge Regulator

Development is executed with both aluminum chassis and CFRP chassis battery,
In consideration of results, The qualifying test have completed.
It is a schedule of installing in Quasi-zenith satellite as for the aluminum battery.

Development of CFRP chassis

振動試験





ピックアップ貼付位置：7箇所17Ch

Heat dissipation (P_{bat}) of battery

$$P_{bat}(w) = I^2 \cdot (\sum Rcell + \sum Rw) + I \cdot N \cdot Ke$$

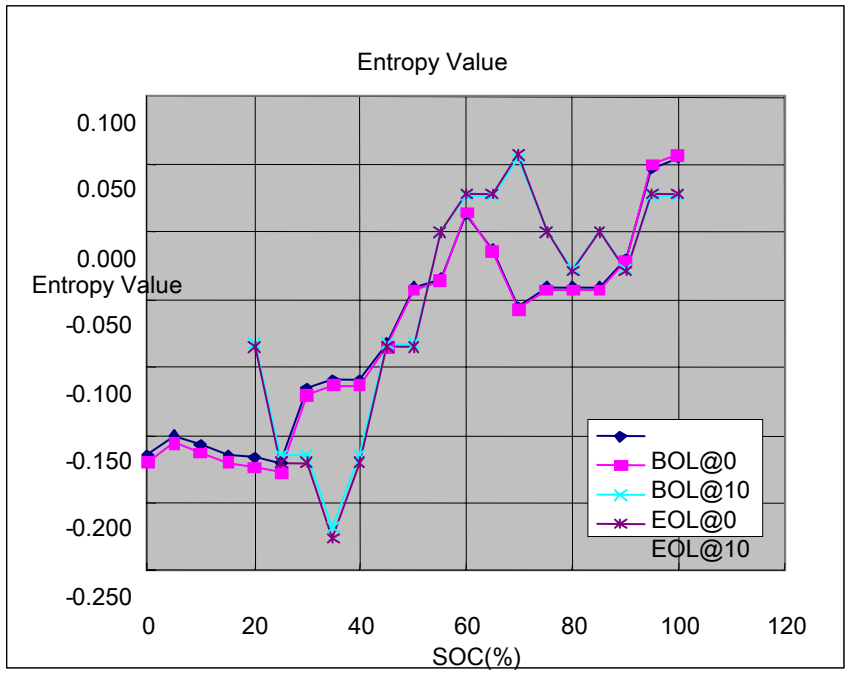
Rcell(Ω): Inherent Resistance of Cell

Rw (Ω) :Resistance of wire between Cells (include lead wire)

Ke (W/I) :Entropy values

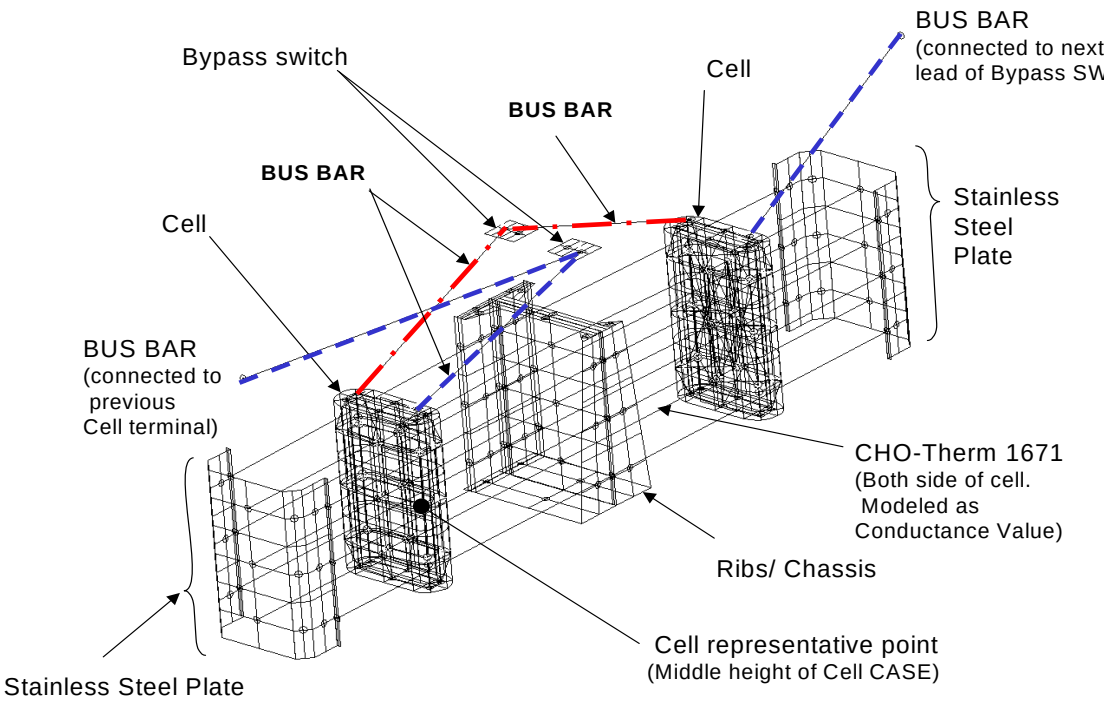
I (A) :Battery currentnt, (+:Discharge, -:Charge current)

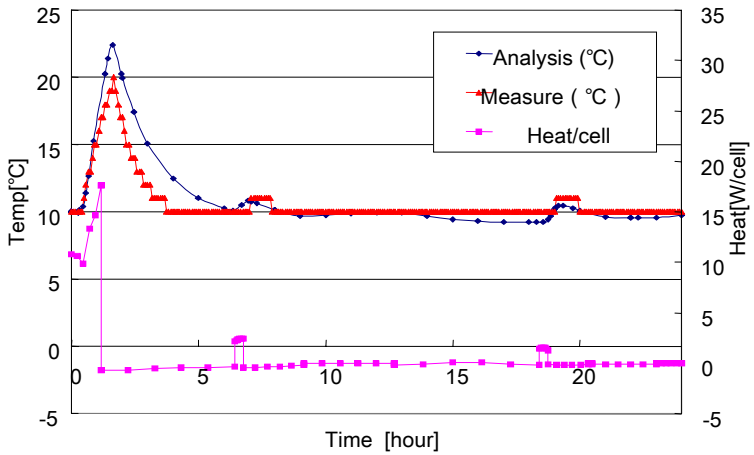
N :Quantity of cells

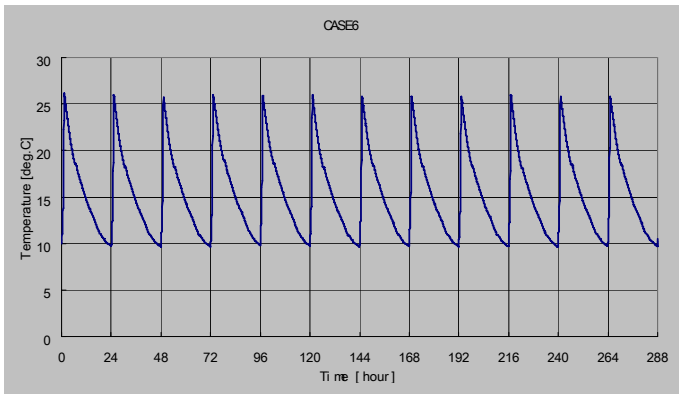


3 Engineering test results by 4-cells module

以上を元に、実運用もしくはワーストケースでの熱解析を実施し、試験にて熱設計の妥当性を検証する。下記に設計検証結果の例を示す。解析と実測結果が良く一致している。



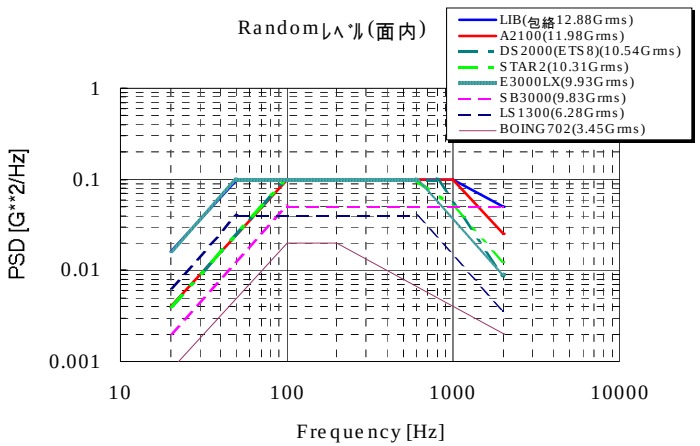


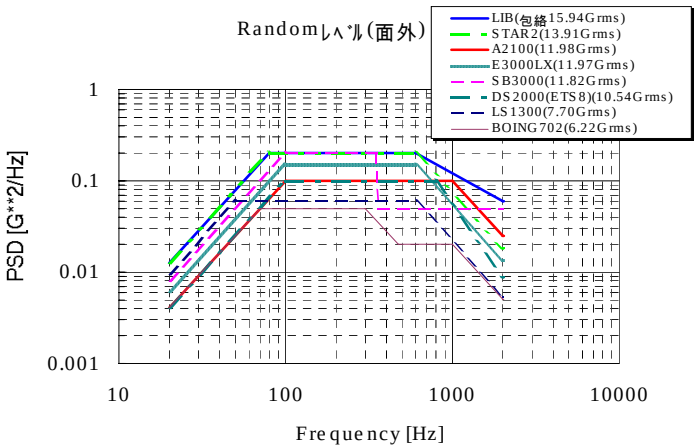


3.2 Test of Qualification

Vibration test (Random vibration)

	ﾗﾝﾀﾞﾑ振動条件 QT			
	Frequency [Hz] from	to [Hz]	SLOPE [dB/Oct]	PSD [G²/Hz]
LIB(包絡12.88Grms) 180秒 面内	20	50	6	
	50	1000		0.1
	1000	2000	-3	
	Overall level		12.88 [Grms]	
LIB(包絡15.94Grms) 180秒 面外	20	80	6	
	80	600		0.2
	600	2000	-3	
	Overall level		15.94 [Grms]	





Engineering model cleared QT level which cover the levels of major 7 satellite bus

4 Conclusion

The Figure-1 is the trade off study result on the mass for 15-year mission GEO satellite (100V bus).

Battery mass was calculated in the satellite power range between 10 kW to 20 kW. From the result, 175Ah Li-Ion battery can save the mass as 10 to 20% than smaller cell capacity Li-Ion battery in parallel.

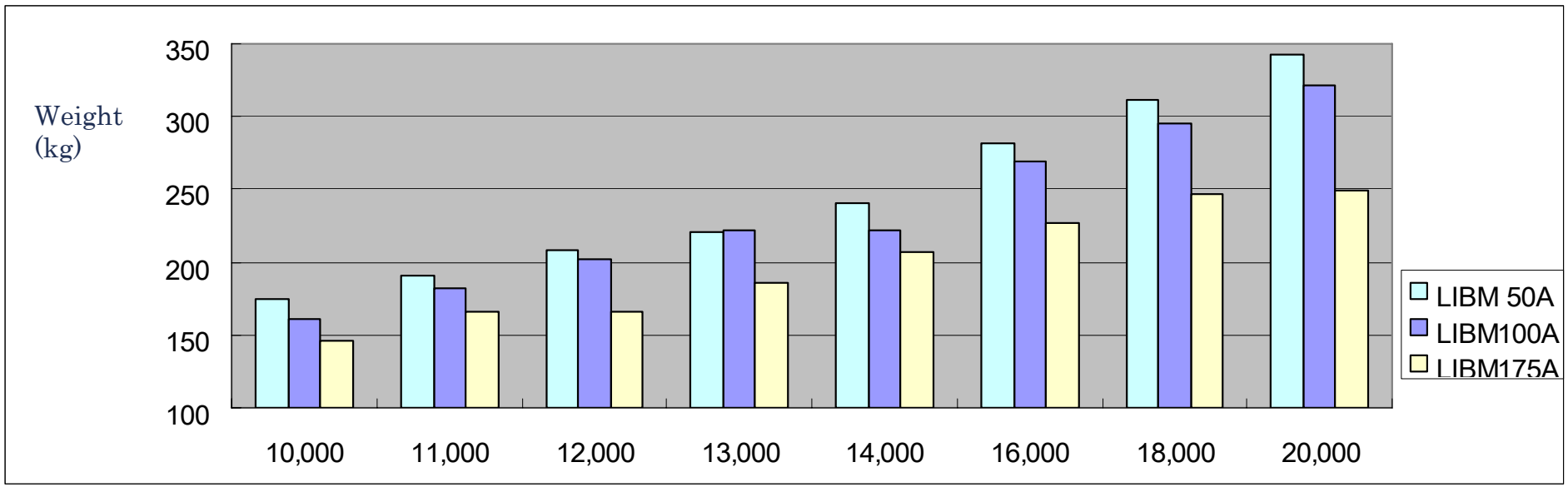


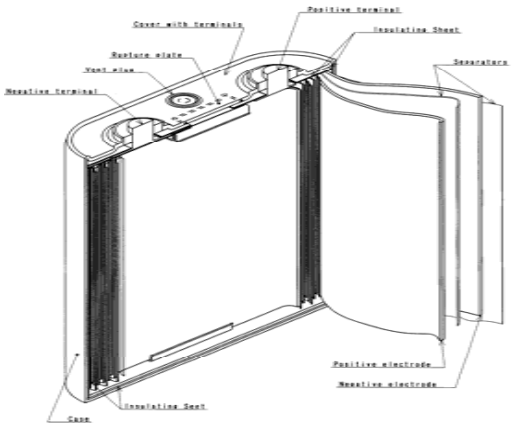
Figure-1

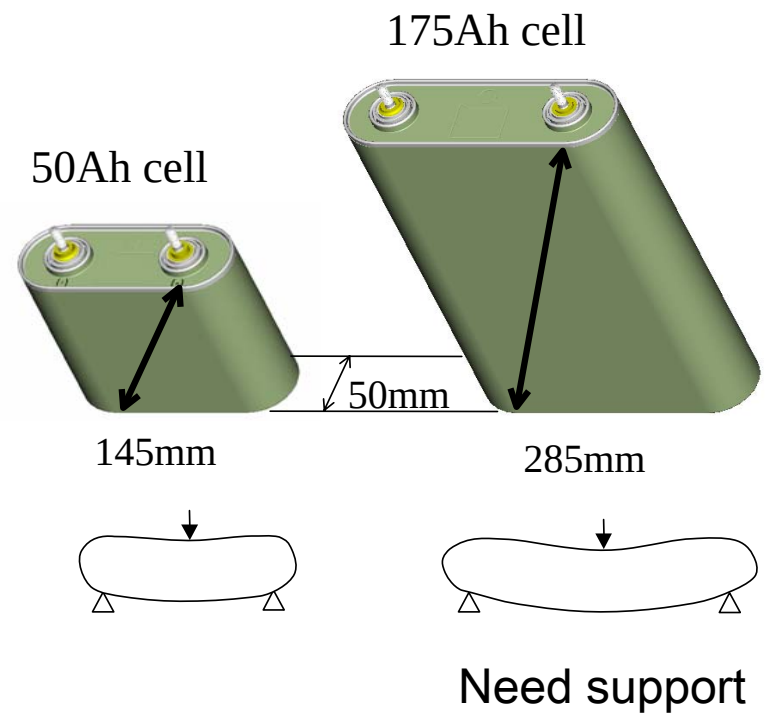
Acknowledgement

This development was governed by
-Ministry of Economy, Trade and Industry (METI),
-New Energy and Industrial Technology Development Organization (NEDO)
-Institute for Unmanned Space Experiment Free Flyer (USEF)
We would like to thank for many helpful guidance and advice in development.

2 Design concept of "Wall frame structure"

In large size battery design, how easy to handle with the battery at SYSTEM level becomes very important. Because in general, large battery has huge mass, low stiffness, temperature deviation.





And more..

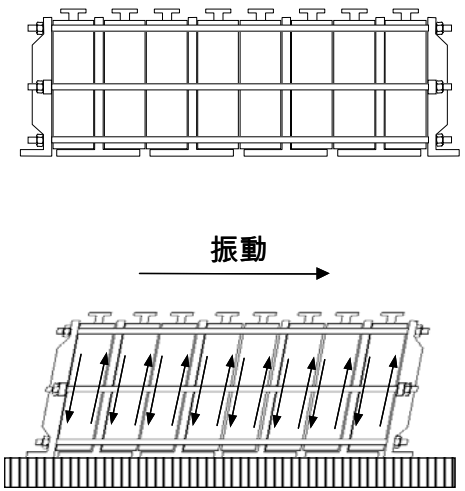
- Jerry-rolled Electrodes shows non-liniar spring coefficient in mechanically
- And it vary according to the SOC, capacity degradation (cyclic, calender)

→Very complex to establish the structural mathematical model

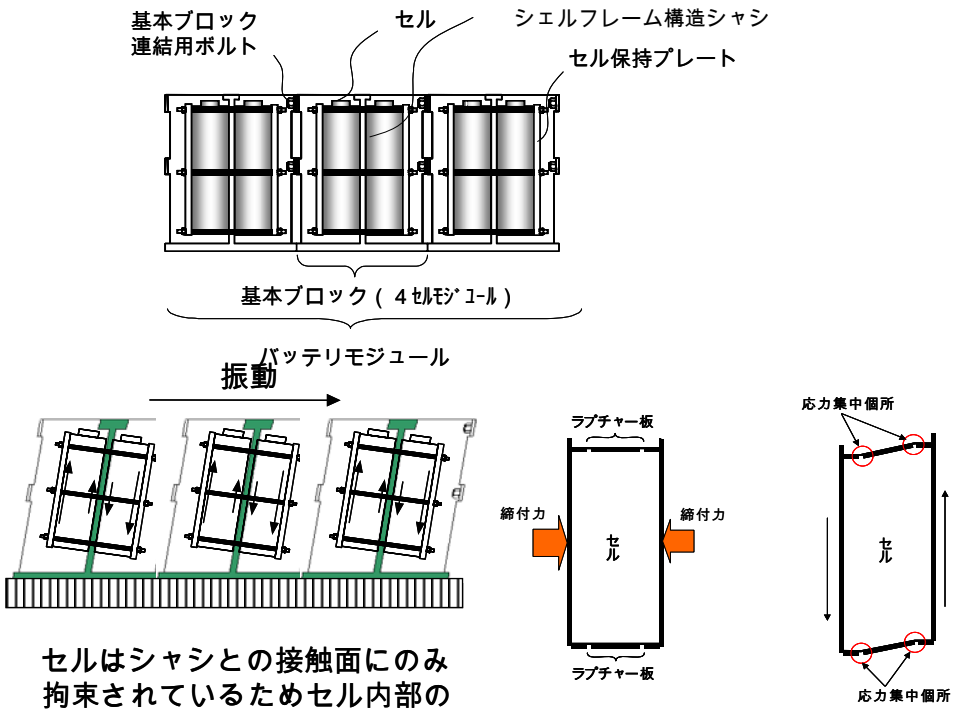
2 Design concept of “Wall frame structure”

individual mounting system of the cell using wall frame chassis

The cells are installed with each cell holding plate to chassis, which has “T”, shaped cross section. The “T” shape chassis gives higher stiffness and good heat transformation, and low temperature gradient across the contact surface to battery panel. Each chassis is designed to mount 4 cells and be connected neighboring chassis with ribs.
The battery itself can be fixed on battery panel with various fasteners. 本構造の特徴は、バッテリの主構造とセルを保持する構造とを切り分けた点にあり、ためセルにかかる外力はバッテリを構成するセル数によらない。その結果、大型バッテリを構成する場合にシャシの軽量化がはかれ、スタック構造と比べてバッテリ全体を軽量化することができる。



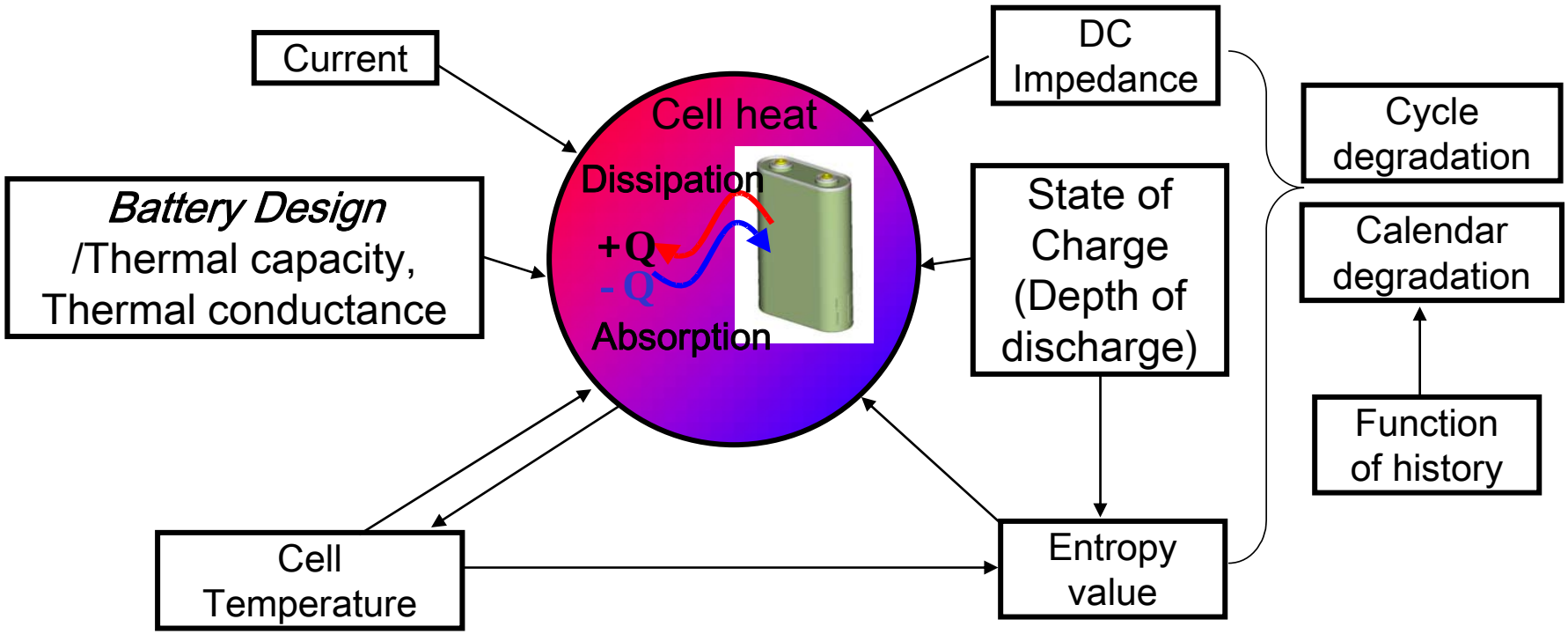
セルの両側面がstressに対して固定されている為にセル内部のせん断力が高い



セルはシャシとの接触面にのみ拘束されているためセル内部のせん断力は低い

2 Design concept of "Wall frame structure"

Functional parameters of heat dissipation



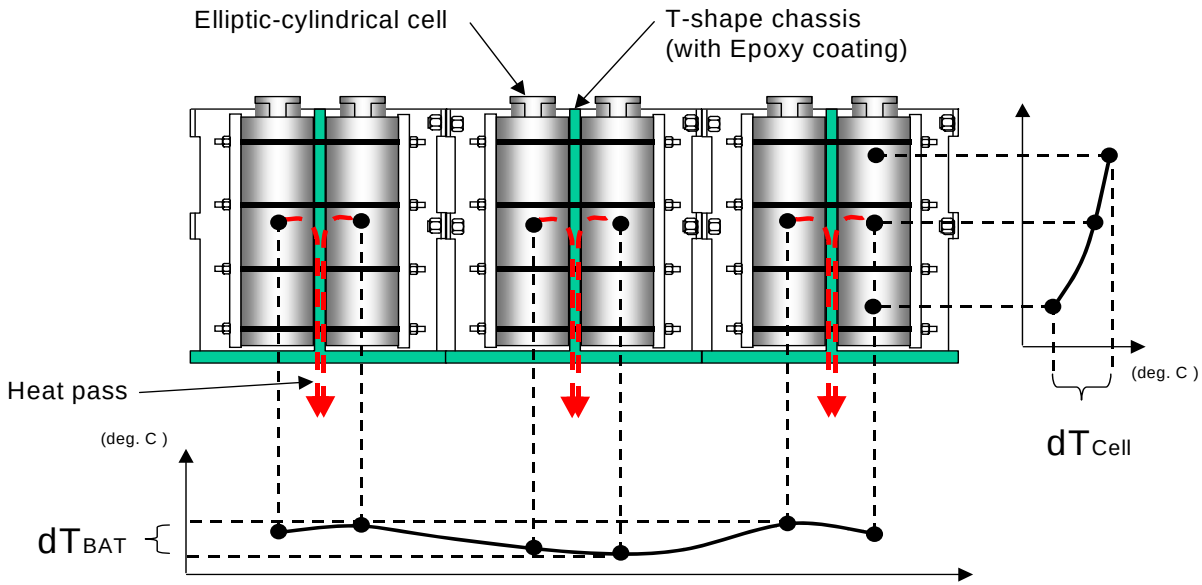
Heat dissipation depends on operation mode and history

It is preferable to optimize the heat design according to specific program and the usage (Life, Orbit, Mission, etc..).

Heat dissipation

The temperature balancing between the cells within the battery is very important for the lifetime. To achieve optimal heat dissipation path, the battery combines a T-shape chassis with elliptic-cylindrical cells. This technology produces very good results in preventing the overall temperature rising of the cells as well as for the temperature deviation between the cells.

-Low thermal resistance due to large contact area
-Low thermal gradient (dT_{BAT}) across the cells due to separating heat pass by Wall frame structure.



この構「上の均一性はバッテリ内部の温度均一性を実現するだけでなく、システム検討用熱モデルが簡略化しやすい