KiboCUBE Academy

Lecture 08

Introduction to CubeSat Power Control System

Teikyo University

Department of Aerospace Engineering

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This lecture is NOT specifically about KiboCUBE and covers GENERAL engineering topics of space development and utilization for CubeSats.
The specific information and requirements for applying to KiboCUBE can be found at:
https://www.unoosa.org/oosa/en/ourwork/psa/hsti/kibocube.html

Lecturer Introduction

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(from Left) **UNIFORM-1, HODOYOSHI-3, HODOYOSHI-4**
Fight model picture before shipping, April 2014

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Position:

2010 - Ph.D. Degree in Kyushu University
2010 - Project Researcher, Kyushu University – QSAT-EOS Project
2011 - Project Researcher, Tokyo University – UNIFORM-1 & Hodoyoshi-3/4 Project, TRICOM Project
2017 - Project Lecturer, Tokyo University – AQT-D/RWASAT-1 Project, MicroDragon Project
2020 - Lecturer, Teikyo University – TeikyoSat-4 Project

Research Topics:
Micro/Nano/Pico-Satellite System Design and Electrical Components Design, Ground Station Development

Contents

1. Introduction

1.1. Introduction of EPS for Micro/Nano/Pico-satellite (CubeSat)

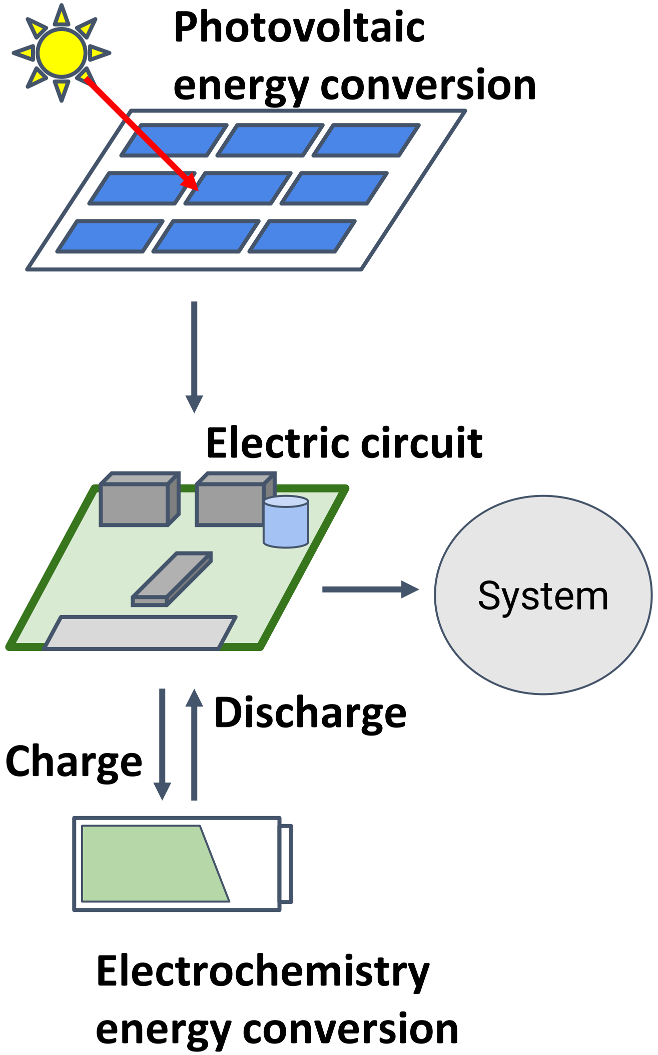
EPS (**Electrical Power Supply**) is the most important subsystem from the viewpoint of **energy handling**

Typically, the EPS Consists of
- ❑ Power **generation**
- ❑ Power **storage**
- ❑ Power **control** & **distribution**

Keywords;
- ❑ **Efficiency** (per unit mass or per unit area)
- ❑ **Robustness** (for mission success)
- ❑ **Redundancy** (for mission success)
- ❑ **Safety** (for Launcher requirements)

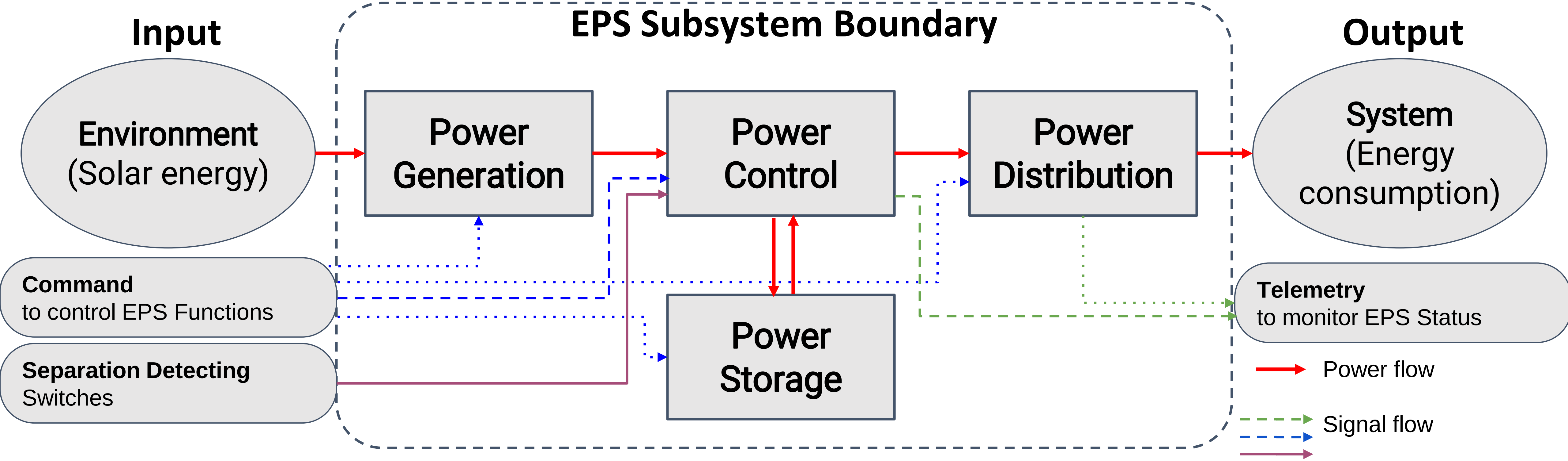
EPS

Electrical
Power
Supply
(Subsystem)



Architecture: the style and design of a building or buildings → the **style** and **design** of **a system**

- The number of components
- The kind of components
- The connections between components (voltage, current, signal, ground)



1.2. EPS Architecture Examples for Micro/Nano/Pico-satellite (CubeSat)

Typical EPS Architectures

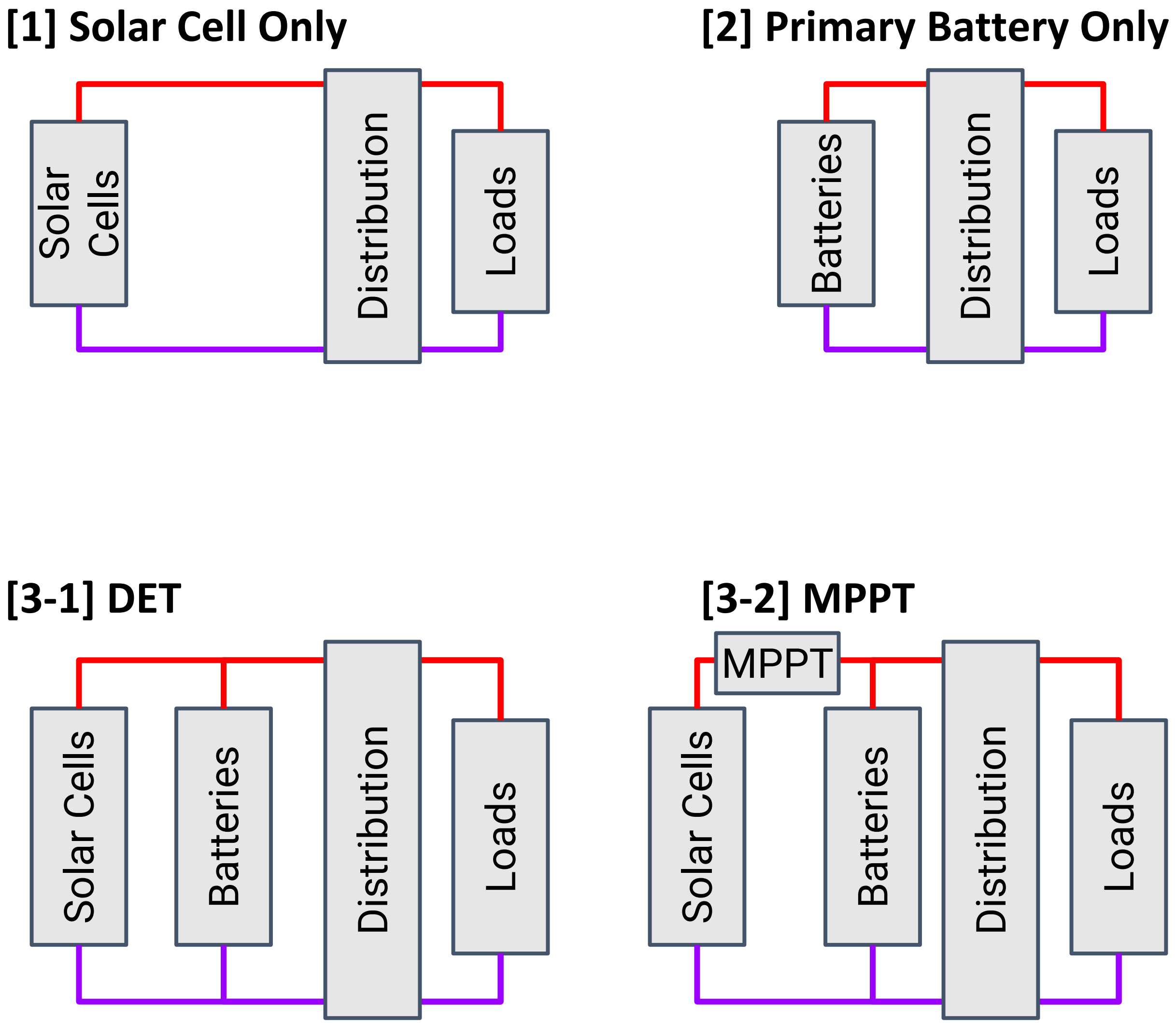
[1] Solar cell only: Rare case
(System is not able to work during an eclipse)

[2] Primary battery only: Rare case
(System is able to work up to the battery life)

[3] Solar cell + secondary battery: Major use
(for long-time operation)

[3-1] DET(Direct Energy Transfer)
Direct solar cell connection

[3-2] MPPT (Max Peak Power Tracking) control



1.2. EPS Architecture Examples for Micro/Nano/Pico-satellite (CubeSat)

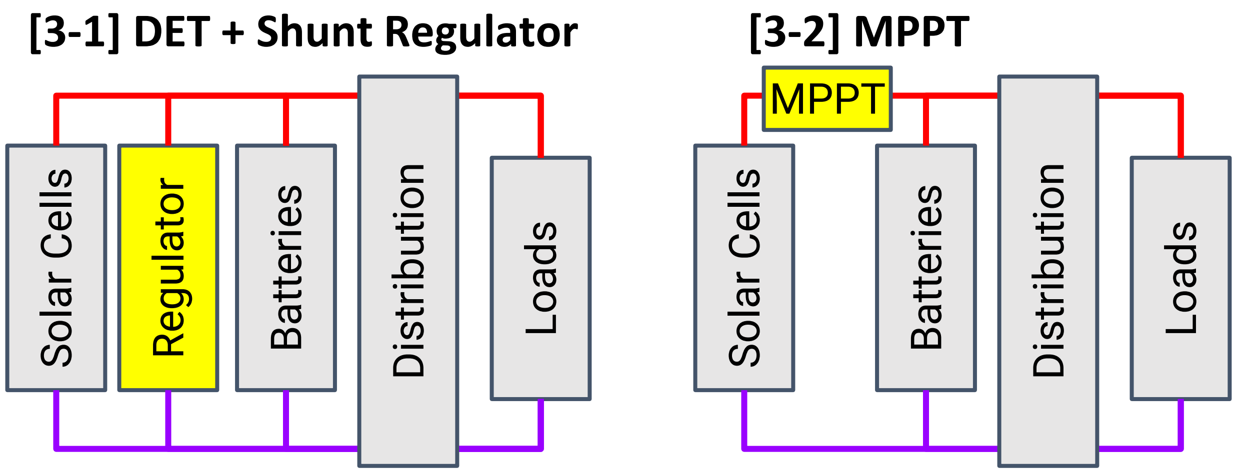
Comparison of DET vs MPTT

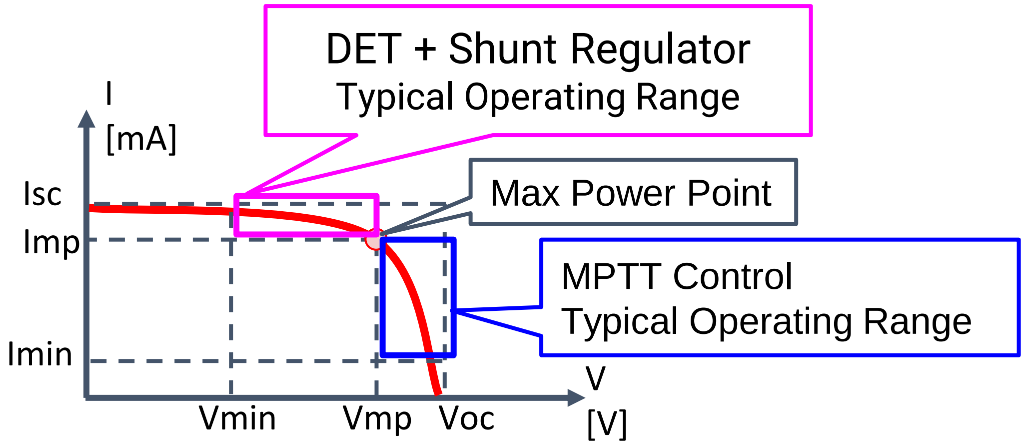
[3-1] DET(Direct Energy Transfer) + shunt regulator

- **Shunt regulator circuit** is connected between solar cells and batteries **in parallel** to control solar cell operating points
- Typical operating range: **near CC** (Constant Current) from Vmin to near Vmp

[3-2] MPPT (Max Peak Power Tracking) control

- **MPPT circuit** is connected between solar cells and batteries **in series** to control solar cell operating point
- Typical operating range: **near CV** (Constant Voltage) from Imin to near Imp





Solar Cell I-V Curve

Key Concepts for better EPS Design and Implementation

- **Efficiency** (per unit mass or per unit area)
  Solar cell: [W/m^2] → [%] (Solar energy conversion efficiency)
  Battery: [Wh/kg] (Capacity per unit mass)
  DC/DC converter: [%] (Energy transfer efficiency: output power / input power)

- **Robustness** (for mission success) Failure risk minimization

- **Redundancy** (for mission success) Fault tolerant, stand-by alternative functions, backup

- **Safety** (for launcher requirements) Never cause a catastrophic/critical hazard during launch

1.3. Key Concepts of EPS for Micro/Nano/Pico-satellite (CubeSat)

Primary Design Process for EPS

- ❑ **Step 1: Identify requirements**
  → Orbit type, mission life, payload definition, duty ratio of bus functions
- ❑ **Step 2: Select and size power source**
  → Power generation (solar cell)
- ❑ **Step 3: Select and size power storage**
  → Power storage (battery)
- ❑ **Step 4: Identify power control & distribution architecture**

Iteration is needed until all interface conditions and requirements are satisfied

Step	Information Required
1. Identify requirements	Top-level requirements, mission type and orbit (LEO or GEO) satellite configuration, mission life, payload definition
2. Select and size power source	Mission type, satellite configuration, average load for electrical power
3. Select and size energy storage	Mission orbital parameters, average and peak power load requirements
4. Identify EPS architecture	Power source selection, mission life, regulating for mission load thermal control requirement

1. Introduction

1.3. Key Concepts of EPS for Micro/Nano/Pico-satellite (CubeSat)

Consideration priority for a **reasonably reliable** EPS design and implementation

1. Keep a **simple** configuration and a **simple** operation plan (**single** task)
2. Select devices with **low power** consumption
   and that have been **demonstrated on-orbit as much as possible**
3. The CPU (or equivalent control unit / digital controller) of the EPS component
   should be able to **recover from hang-ups by a power-on reset**
   (especially, for tolerance against **TID/SEU/SEL**)
4. **Failure recovery** options and **redundant** configurations
5. Pursuit of **power conversion efficiency**
6. **Advanced** functions (Autonomous control, parallel tasks)

After upper level design and verification has been considered, move on to the next step

1. Introduction

1.3. Key Concepts of EPS for Micro/Nano/Pico-satellite (CubeSat)

Practical Know-How for Better Power Balance Design

- ❑ Relationship between **Power generation** and **satellite attitude mode (solar cell coverage ratio to sun)**
  - ❑ **Sun pointing**: Power generation is rich
  - ❑ **Earth pointing**: Depends on the angle b/t sunshine and solar cell panel
  - ❑ **Tumbling**: Smaller power generation

  Accuracy of power generation is dependent on the development level and maturity of the Attitude Control Subsystem

- ❑ Enough power modes (the combination of components being ON/OFF) should be defined

  The minimum power mode for survival independent on the satellite attitude

- ❑ Identify **constant power-ON** components and **ON/OFF controllable** components
  - ❑ Constant power-ON components: PCU, PDU, Sensors, MTQs, etc.
  - ❑ ON/OFF controllable components: Mission camera, mission data transmitter, etc.

    (operation plan example) Mission data downlink, 8 mins above Japan; image shooting 5 min×10 times

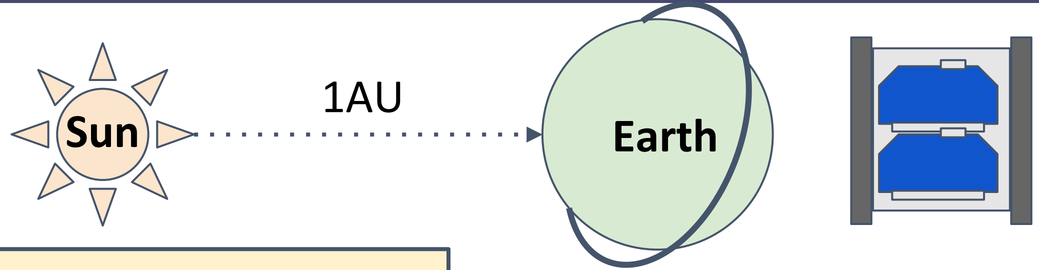
  Management of surplus or lack of power by controlling the operating time or duty ratio of the mission device, high-power transmitter, or actuators (MTQs or RWs)

2. Power Generation

2. Power Generation

2.1. Introduction of Solar Cell

- Power generation on CubeSats is realized by solar power architecture (solar cells / solar panels / solar arrays)
- Solar cell: a semiconductor device applying a photovoltaic effect (same structure as a diode)
- Solar power flux is **1367 [W/m²]** in orbit average at 1 AU (Astronomical Unit)
  - 100cm² (10cm x 10cm) → **~4.1 [W]** at solar cell **efficiency ~30% case**
  - Filling efficiency considering mechanical interface of a CubeSat frame is ~65-70% → **~ 2.6 [W] per 1 surface 1U CubeSat**
    (at nominal temperature condition: ~25 degC)



Solar power flux

1300 ~ 1400 [W/m²] @ 1AU

Average: **1367** [W/m²]

Summer: ~1300 [W/m²] (min.)

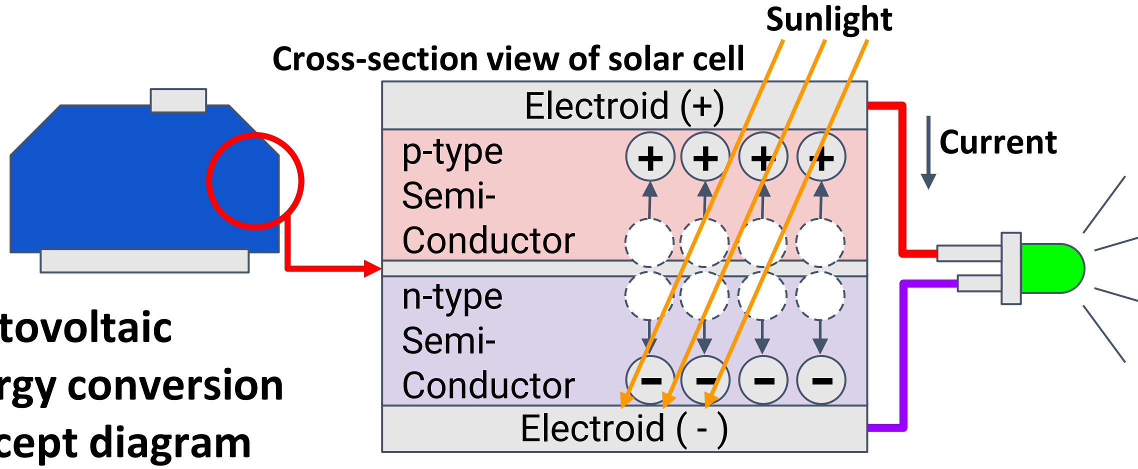
Winter: ~1400 [W/m²] (max.)

Efficiency: ~30% case

~ 410 [W] @ 1m²

~ 4.1 [W] @100cm²

~ 41 [mW] @1cm²

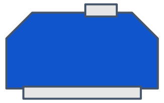


Photovoltaic energy conversion concept diagram

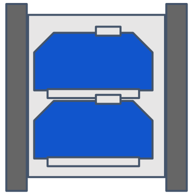
2.2. Major Characteristics of Solar Cell

Solar Cell Selection Checkpoints

- ❑ **Triple-Junction**(**TJ**) (or **Multi-Junction**) type solar cell is popular (high-efficiency)
- ❑ Solar cell hardware configuration
  CIC: Cover-glass Interconnected Cell
  is better from the viewpoint of easy assembly
- ❑ **Thickness of cover-glass** affects the lifetime against total dose on-orbit
- ❑ **Dimension** and **position of the electrodes** affects the solar panel design (cell layout)
- ❑ **Within 80 x 40 mm** size cell is popular
  → In the case of 1U CubeSat,
  2 solar cells are allocated on a surface
  option: **2 series ?** or **2 parallel ?**
  (depends on the power control circuit design)



Typical 1U CubeSat Surface



Typical Spec. of Solar cell	Typical Si-Cell	Typical TJ
Open Circuit Voltage [V]	0.6	2.7
Short Circuit Current [mA]	1150	410
Max. Power [W]	0.5	1.0
Max. Power Voltage [V]	0.5	2.5
Max. Power Current [mA]	1000	500
Efficiency	15 ~ 17 %	28 ~ 30%
Dimensions [mm]	60 x 40	80 x 40
Mass [g]	~~	~~

Solar Cell Panel Array Considerations
How many in series? : MPPT input voltage
How many in parallel? : Operational time & margin

2.3. Design and Testing of Solar Cell Panel

Solar Cell Properties Investigation

- ❑ Performance test: V_{OC}, I_{SC}, I_{mp}, V_{mp}, P_{mp}
  - ❑ Using solar simulated light: 100% on orbit (with isothermal stage to change the cell surface temperature)
  - ❑ Performance evaluation : I-V curve and P-V curve corresponding to datasheets
  - ❑ Nominal Pmp : **~1.25 [W]** @Vmp = 2.0 [V]
    Hot case: **~1.0 [W]** @Vmp = 2.5 [V]
    Cold case: **~1.5 [W]** @Vmp = 3.0 [V]

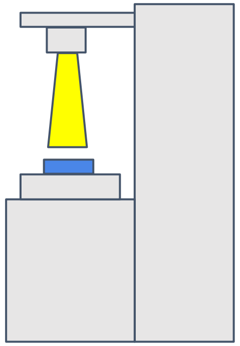
(Refer to the datasheet when this kind of performance test is not able to be performed by your own project)

[Important]

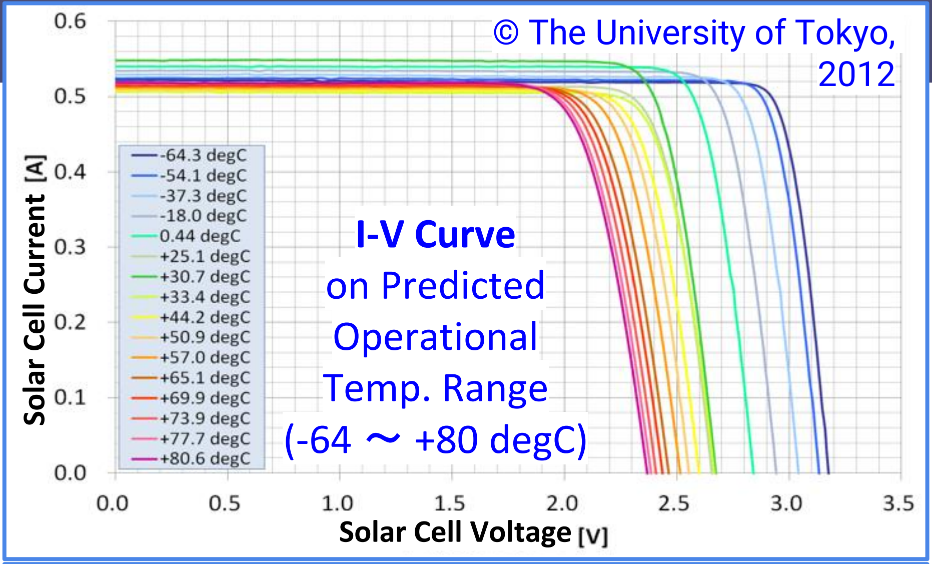
Identification of performance change on the operational temperature range

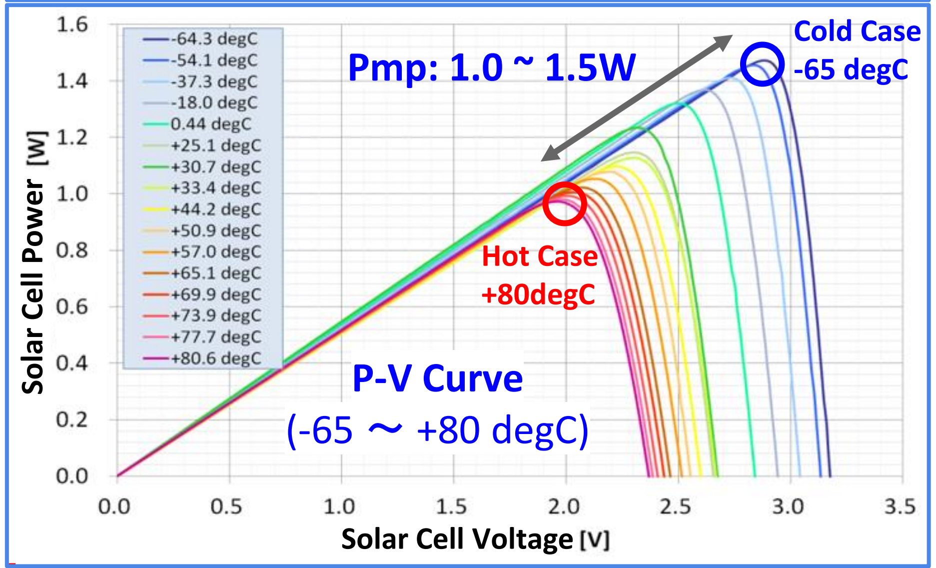
Test cell coupon

Triple-Junction (GaInP2/GaAs/Ge) CIC-type product efficiency: ~29%



Test facility conceptual image



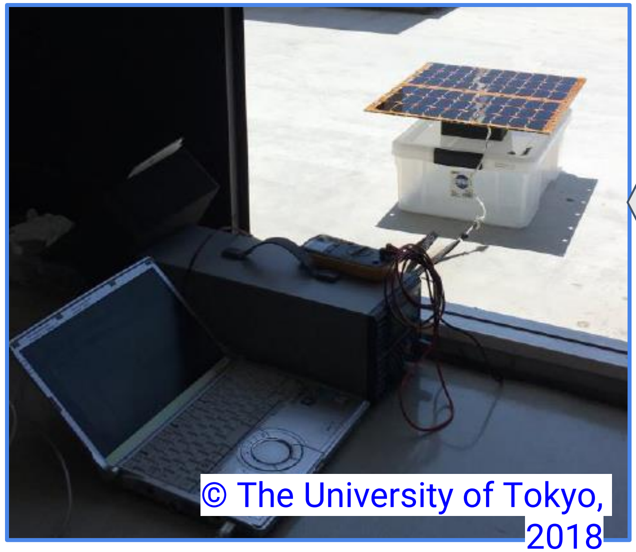


Data example based on a past MicroSat mission

2.3. Design and Testing of Solar Cell Panel

Solar Cell Panel Tests

- ❑ Functional tests to confirm workmanship
  - ❑ Under natural sunlight
  - ❑ Using solar simulated light
  - ❑ Using large testing facility
- ❑ Performance evaluation test: I-V curve
  - ❑ Under natural sunlight
  - ❑ Using large testing facility

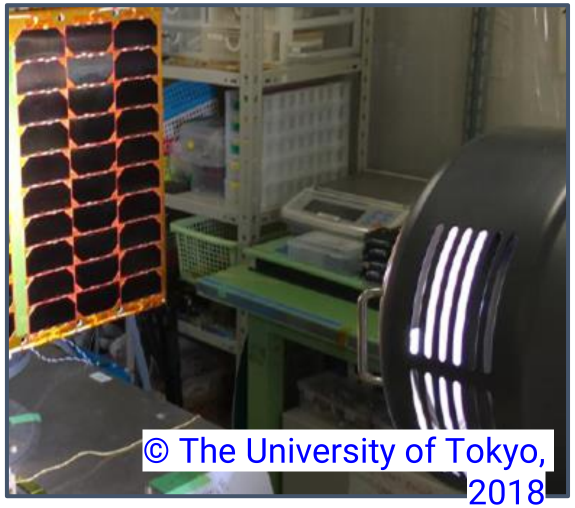


Outdoor
by using
natural sunlight

~ 65 - 70%
of 1 Solar on Orbit

Inside room
by using
small solar lamp

~ 10 -15%
of 1 solar on orbit

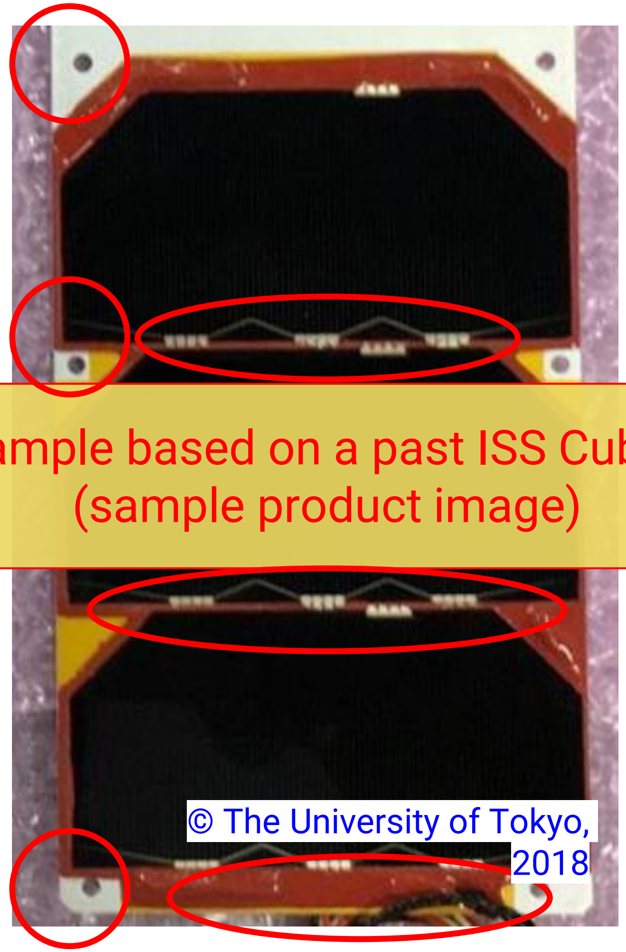


Experiment image example based on past MicroSat mission

2.4. Examples of Solar Cell Panel Products

Solar Cell Panel Design Example (for CubeSat)

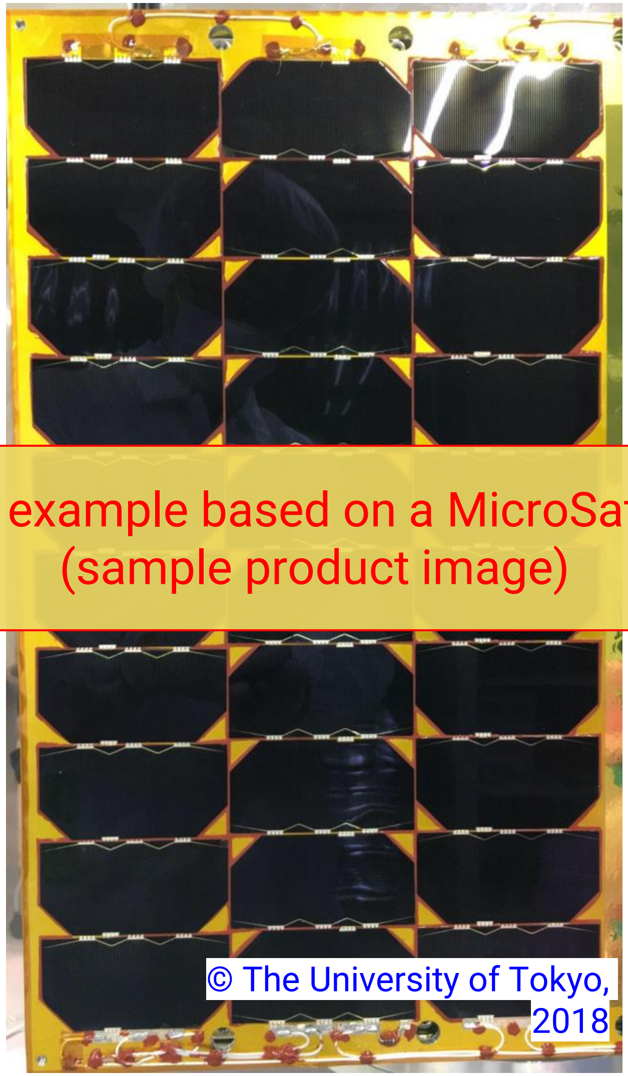
- Solar Cell: **3 series** x **1 parallel** configuration
- 1 String(series connection) : 1 same surface
  (Never connect on the other surface in series)
- Solar cell panel assembly checkpoints
  - Interconnectors (electrodes) attaching process (**soldering** or **spot welding**)
  - Gluing workmanship for cell attaching
    → **air bubbles remaining** must be avoided
  - **Clearance** b/t cells and bolt holes
  - **Electrical insulation**



2.4. Examples of Solar Cell Panel Products

Solar Cell Panel Design Example (for MicroSat)

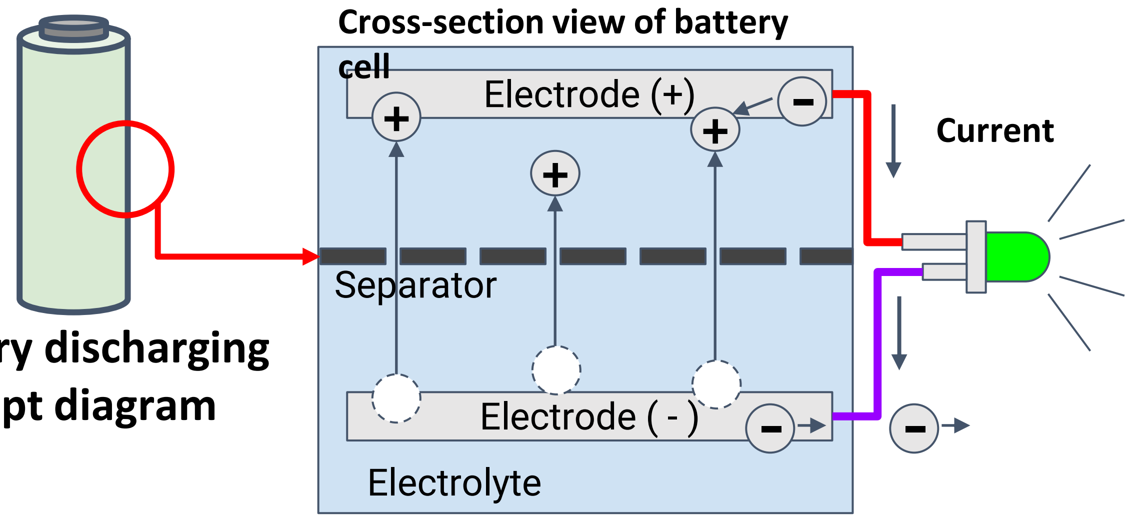
- 1 solar cell string = 10 or 20 series
- Same checkpoints as the CubeSat case are also important
- **Solar cell layout** & **clearance each cells**
  - As increasing of series number, difference of voltage b/t closest cells must be careful
    → To reduce the risk of discharging to cause dielectric breakdown of cells
    [Recommended min. clearance: **1mm**]
  - Current loop of each solar cell string
    → To reduce the effect of magnetic force generation by current loop
    (one of attitude anomaly causes)



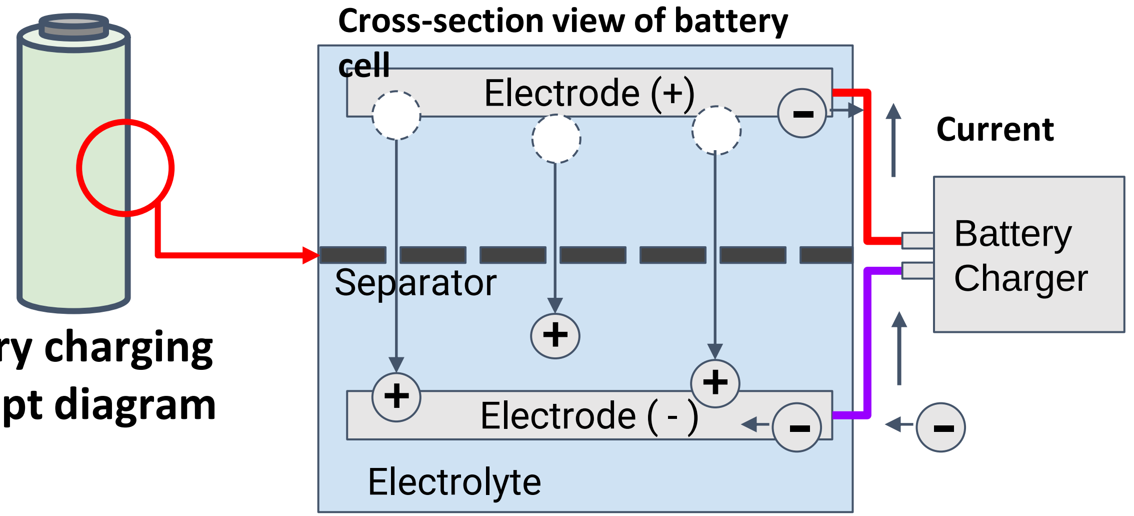
3. Power Storage

3.1. Introduction of Battery

- ❑ Solar energy is not always available during operations; the orbit condition (eclipse), or peak loads over the solar cell power generation
- ❑ Primary and secondary batteries are used for power storage
- ❑ Battery cell is an electrochemistry device applying oxidation-reduction reactions (ion generation)
- ❑ Batteries are classified according to their different electrochemistry.
- ❑ As primary-type batteries are not rechargeable, they are typically used for short mission durations



Battery discharging concept diagram



Battery charging concept diagram

3. Power Storage

3.2. Major Characteristics of Battery

Secondary Battery (Rechargeable) Options

- ❑ **Datasheets** must be checked before purchasing the battery cells
- ❑ Initial inspection and screening tests should be performed by the project to select better cells for the fight model
- ❑ **Ni-MH** type is **safer**, but mass efficiency is smaller than typical Li-Ion cell
- ❑ **Li-Ion** type is **more efficient**, but the hazard risk is relatively high

Project decision: Ni-MH or Li-Ion (depends on the maturity level of project members) especially for the case of Li-Ion, a well-educated person must handle the cell

Typical Spec. of Battery	Typical **Ni-MH**	Typical **Li-Ion**
Typical Voltage [V]	~1.2	~3.6
Voltage Range [V]	1.0 ~ 1.5	2.5 ~ 4.2
Capacity [Ah]	1.0 ~ 2.5	3.0 ~ 3.5
Max. Discharging Current [A]	~ 5.0	3.0 ~ 6.0
Temperature Range [degC]	-20 ~ +50	0 ~ +40
Dimensions [mm]	Φ15 x L50	Φ18 x L65
Mass [g]	30	50

Battery Module Assembly
How many in series? : Bus voltage
How many in parallel? : Operational time

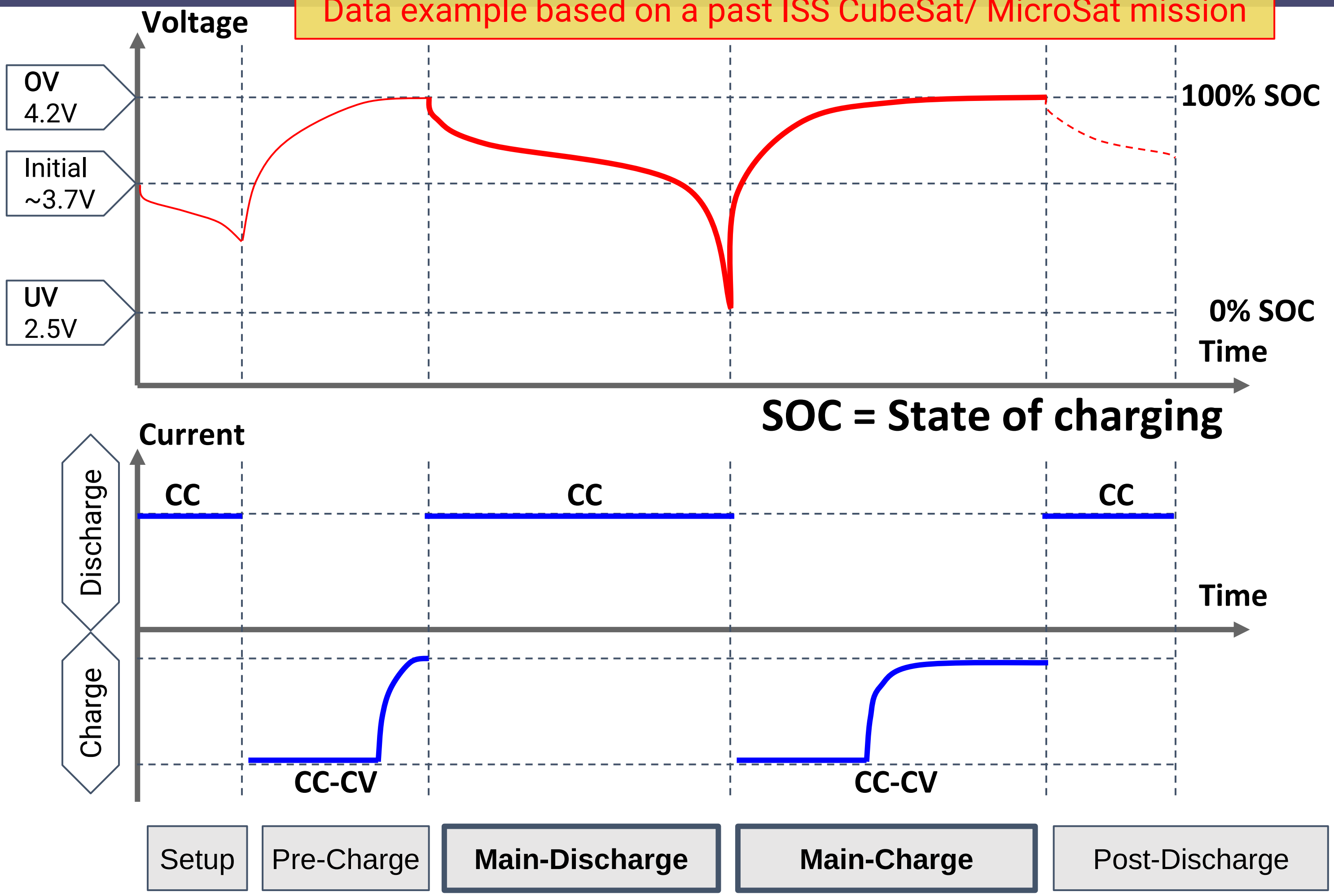
3.3. Design and Testing of Battery

Battery Cell Performance Verification

- ❑ Use common charging and discharging profiles for battery cell performance measurements
- ❑ Current condition, charging stop voltage (Over Voltage Condition), discharging stop voltage (Under Voltage Condition) depends on the individual battery cell-type (Check the battery cell datasheet)
- ❑ (Recommended option) Keep a constant temperature during measurement by using an isothermal chamber

[Important]
Temperature characteristics must be checked!

Data example based on a past ISS CubeSat/ MicroSat mission



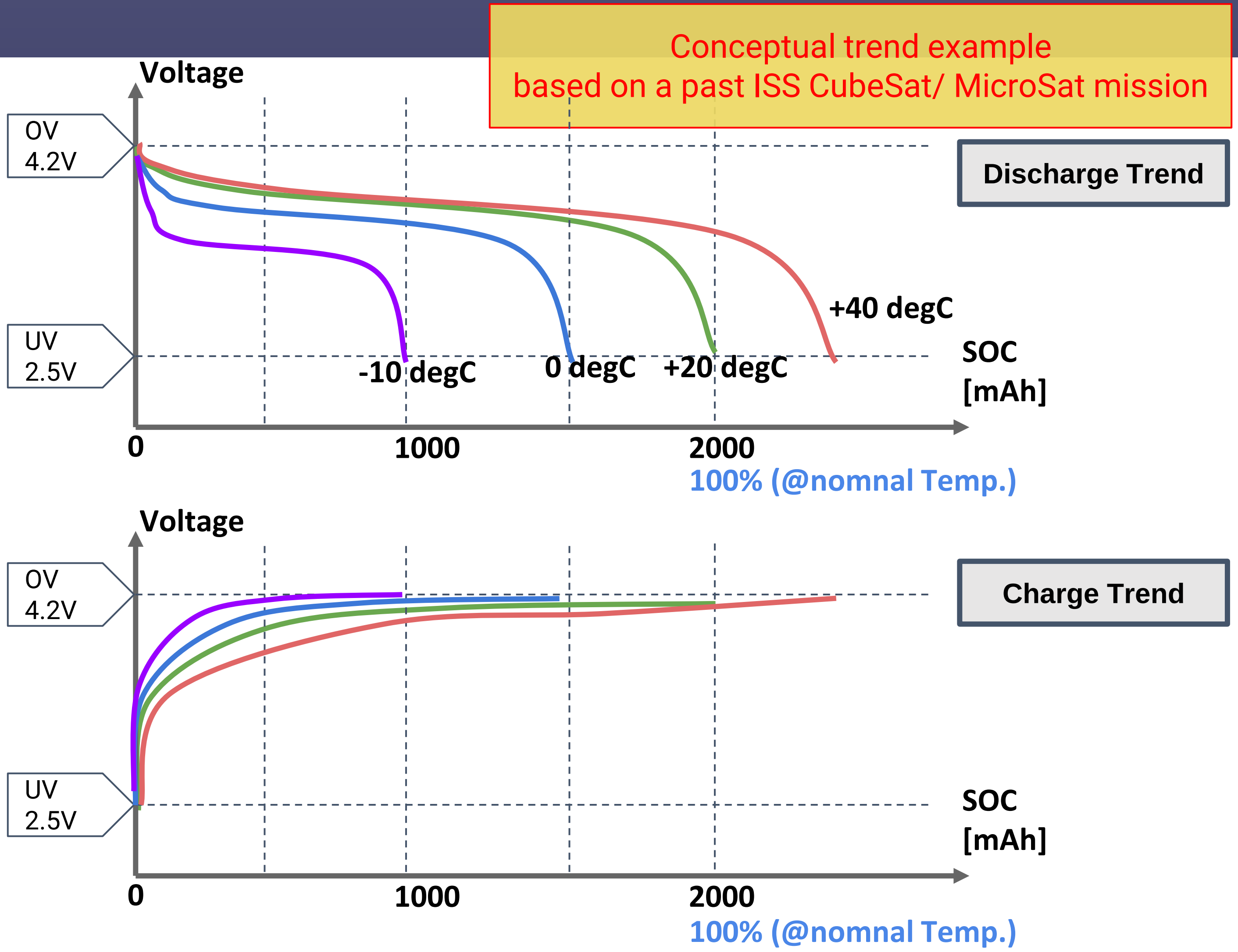
Charging and discharging measurement profile setting example

3.3. Design and Testing of Battery

Battery cell performance on the operational temperature range

- ❑ General properties of a battery cell against temperature changing
  - ❑ Hot condition is **better** [**+25 ~ +40 degC**] (enhance internal electrochemical reaction)
  - ❑ Cold condition is **bad** [**< 0 degC**] (become severe to perform charging/discharging by **internal resistance** increasing)

consider this point for power budget analysis

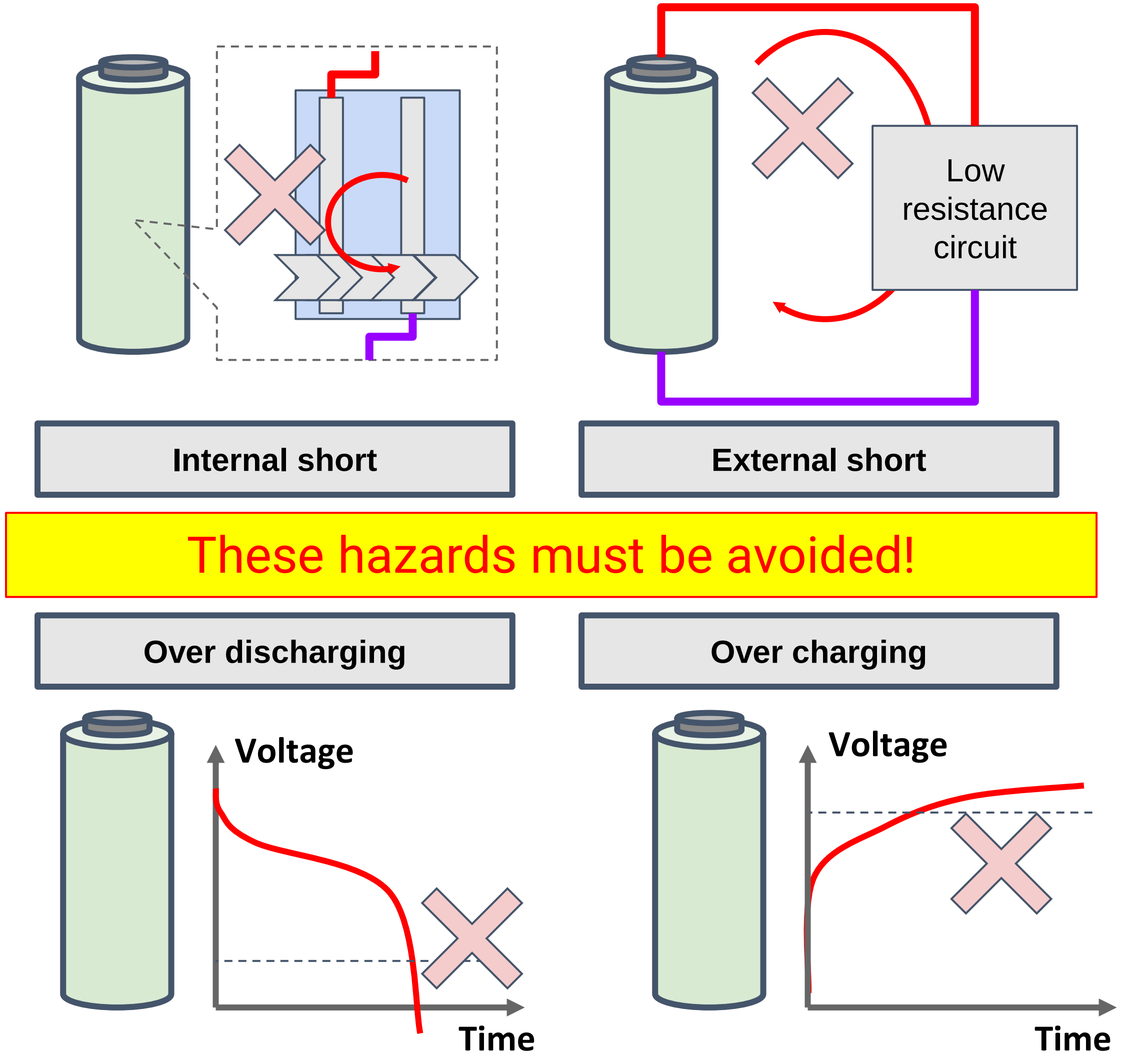


Charging and discharging measurement profile setting example

3.4. Safety Design and Testing of Battery

Typical Battery Cell Hazards

- **Internal short**: Initial failure, structural damage
  [Action] screening test (described on next page)
- **External short**: Circuit failure, workmanship error
  [Action] current shut-down function test of **fuse** device or **PTC** (**Positive Temperature Coefficient**) device
- **Over charging**: Circuit failure, workmanship error
  [Action] power control circuit function test or battery protection circuit function test
- **Over discharging:** Circuit failure, workmanship error
  [Action] power control circuit function test or battery protection circuit function test



3.4. Safety Design and Testing of Battery

Battery Cell Safety Properties Verification (to mitigate the risk of internal short)

- ❑ Standard check process including charging and discharging profile measurements
- ❑ 2-kinds of environmental tolerance tests
  - ❑ **Vacuum leak test**
    If there are any cells with a leakage problem, its mass could change significantly before and after the test
  - ❑ **Random vibration test**
    If there is a cell with a problem in its internal structure, there could be a large difference in charge/discharge characteristics before and after the test

Must refer to the latest test requirement documents from the launch opportunity

Example test & check flow (based on past CubeSat mission)

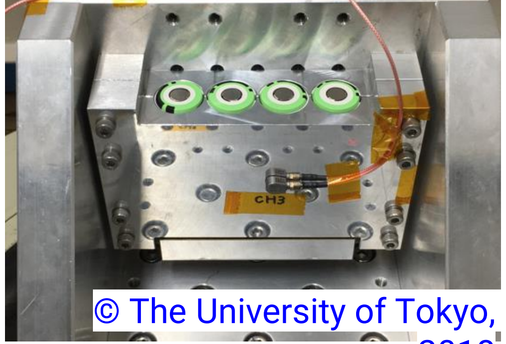
Check #1 → Vacuum leak test → Check #2 → Random vibration test → Check #3

Contents of Check (Common for #1, #2, #3)

- Visual inspection / Odor confirmation
- Mass measurement
- OCV (Open Circuit Voltage) measurement
- Charge and discharge characteristics
- Discharge temperature characteristics test
- Discharge capacity measurement

Check points
Mass change
OCV change
Capacity change

Vibration test jig example

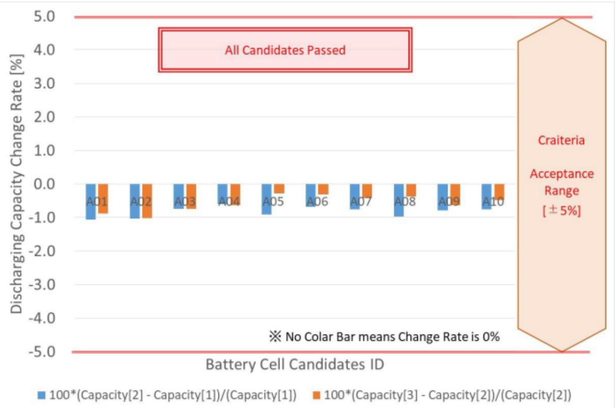


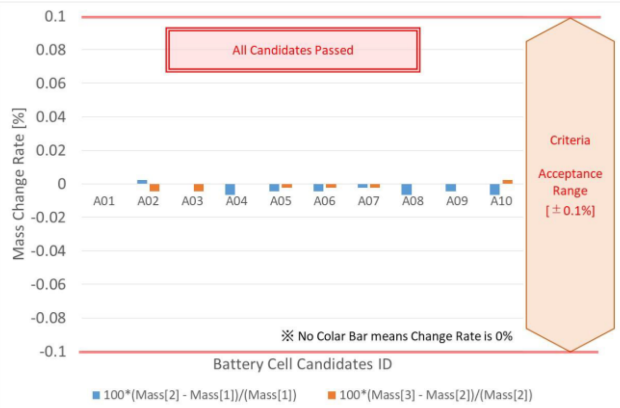
Battery Cell Safety Properties Verification
(to mitigate the risk of internal short)

- ❑ Differences of each check (**#1→#2**, **#2→#3**) should be summarized in a table
  (Example: Table as shown in the upper left)
- ❑ Check which of these differences meet the requirement or not
  (Example: Graphs as shown in the lower left)
- ❑ Select the passed cells and consider pairing of the same parallel combinations
  (similar profile cells must be paired)

Example of battery cell check result table & figures

ID	Visual Check	Odor Check	Mass [g]	OCV [V]	Internal Resistance [mΩ]	Discharge Capacity [mAh]	Discharge Temp. Increase [degC]	Charging Discharging Profile
A01	Fine	Fine	45.838	3.673	36.5	3160.91	+5.2	Fine
A02	Fine	Fine	45.902	3.674	37.4	3162.15	+4.8	Fine
A03	Fine	Fine	45.831	3.673	40.0	3149.74	+4.3	Fine
A04	Fine	Fine	45.663	3.674	39.6	3162.91	+4.2	Fine
A05	Fine	Fine	45.654	3.672	37.2	3149.92	+4.3	Fine

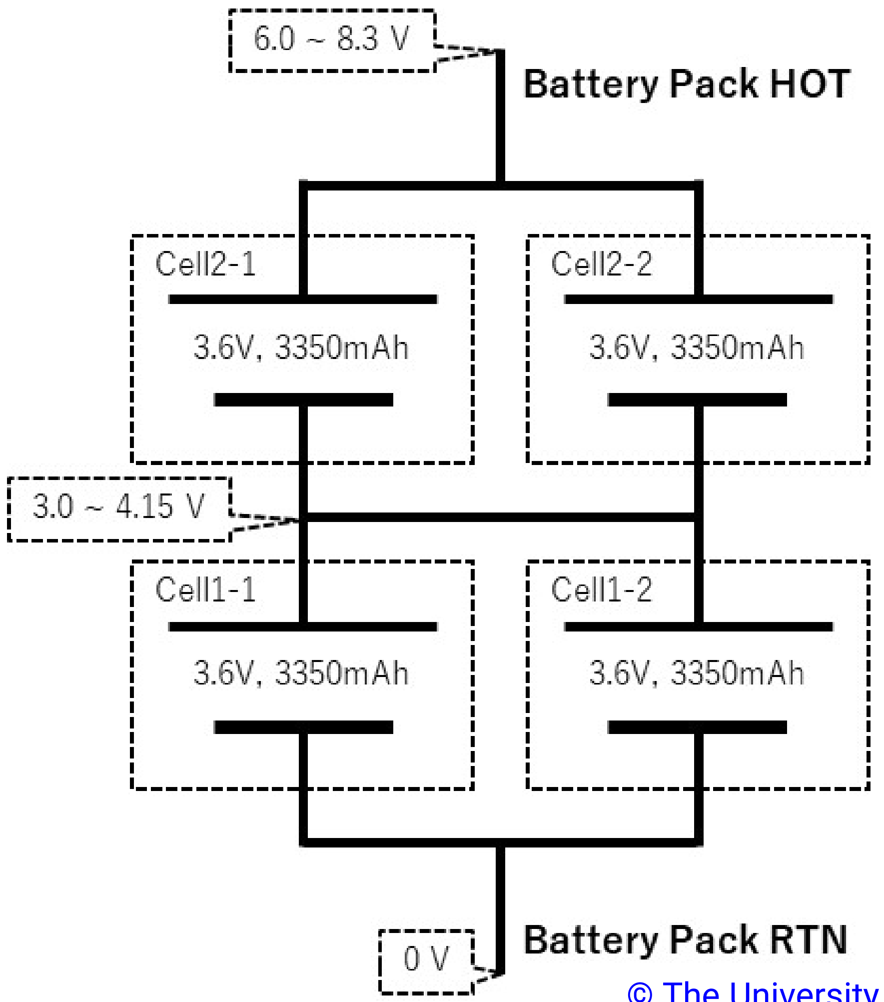




3.5. Examples of Battery Module Products

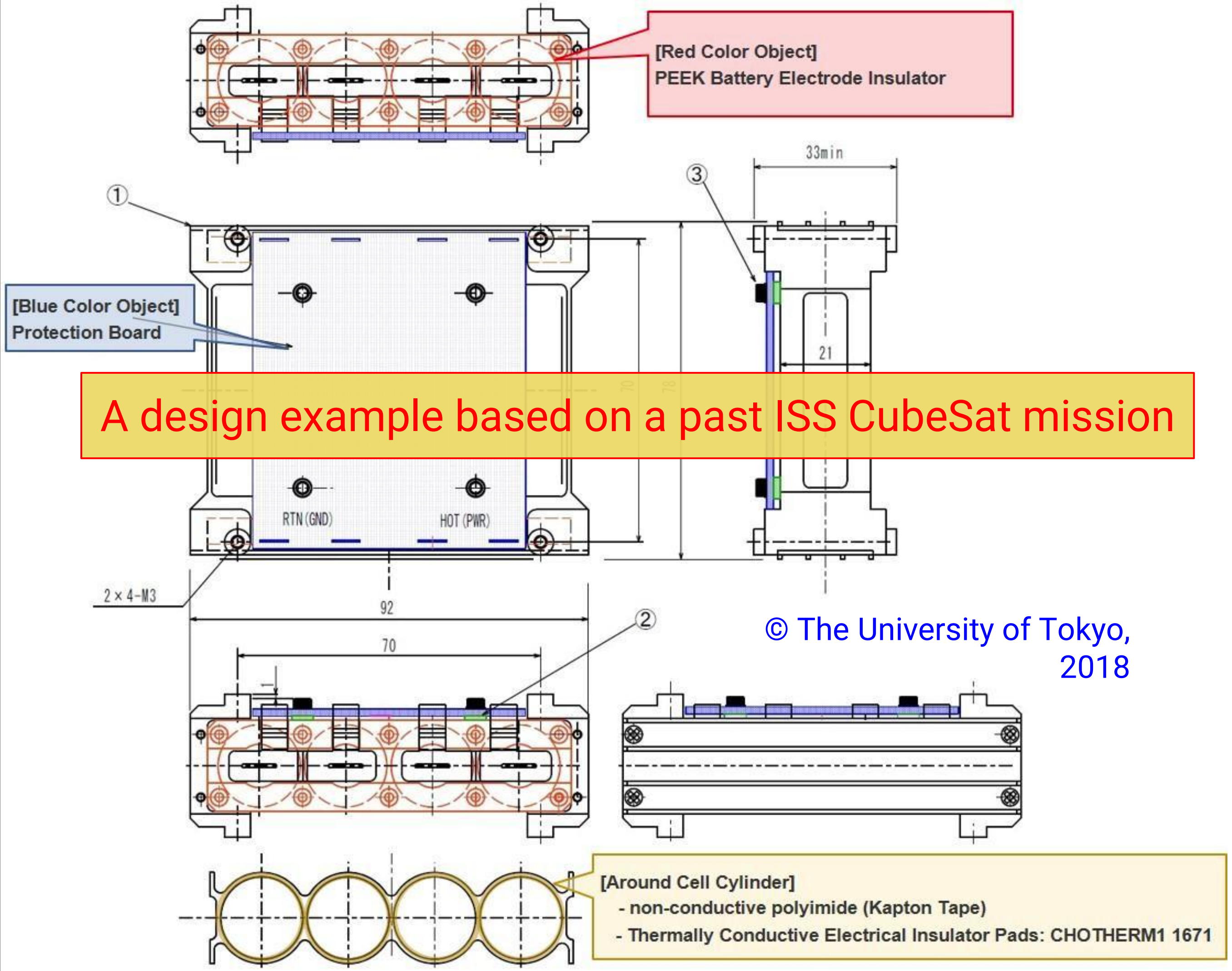
Battery Module Design Example

- ❑ Li-Ion battery: **2 series** x **2 parallel (2S2P)** configuration (Total : 4 cells)
- ❑ **Ladder-type connection**
  → Mid-point b/t 1st stage and 2nd stage is connected
  (depends on the cell characteristics)



Battery Module Design Example

- Li-Ion battery: 2 series x 2 parallel configuration (**4 cylindrical cells** case)
- Mechanical integration checkpoints
  - Fasten holdings around the cell to reduce the risk of displacement by vibration / shock conditions during launch
  - Thermal conductivity or thermal insulation conditions (depends on the thermal environment of the CubeSat)
  - Electrical insulation around electrodes (+ / -)



3.5. Examples of Battery Module Products

Battery Module Design Example

- ❑ Li-Ion battery: 2 series x 2 parallel configuration (**4 cylindrical cells** case)
- ❑ Mechanical spec. checkpoints
  - ❑ **Black color**
    thermal conductivity
    or thermal insulation condition
    (depends on thermal analysis of entire satellite)
  - ❑ **Electrical insulation**
    around electrode (+ / -)

A design example based on a past ISS CubeSat mission
(sample product image)

Dimensions: 92 x 78 x 34 mm
Mass: 330 g

4. Power Control and Distribution

4.1. Introduction of EPS Circuit Design

Simplified EPS Diagram

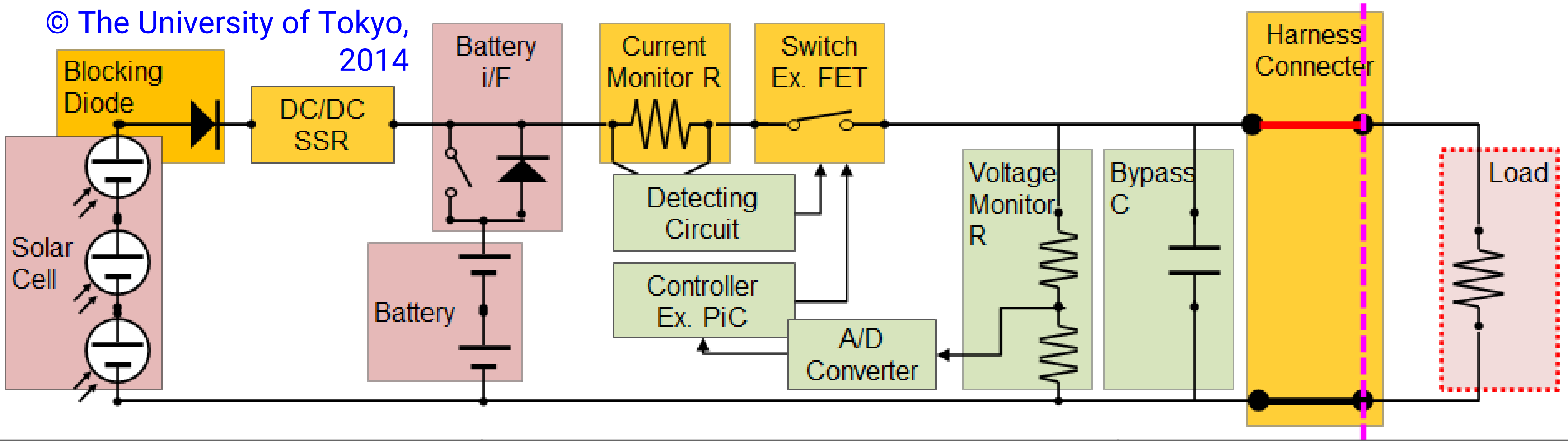
Responsibilities of EPS and interface Point
From Energy Source To Power Output Connecter End

Each
Compo.

Consideration points

How the item is connected between energy source (solar cell or battery) and load?

Series or Parallel

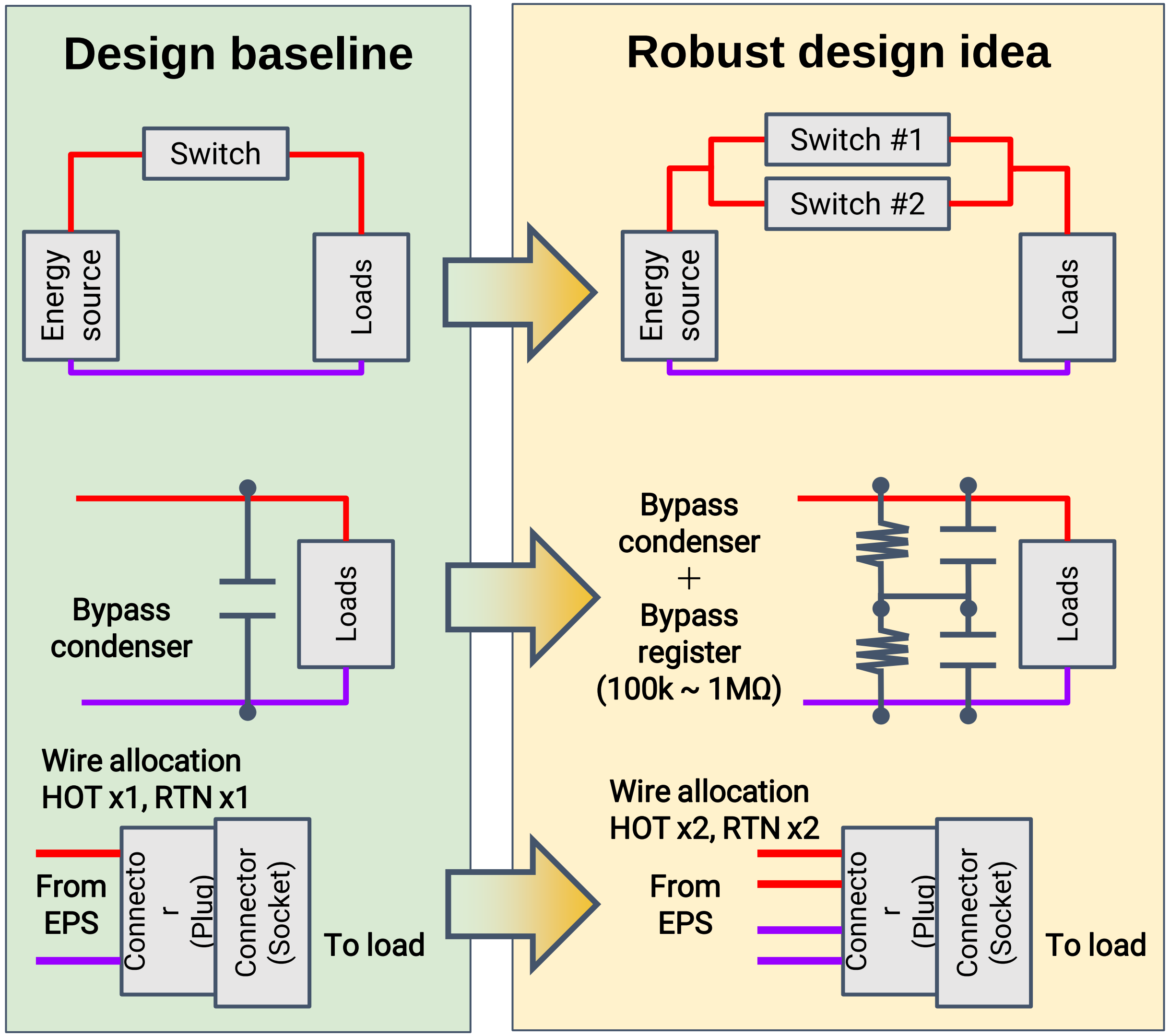


	Items (typical electrical parts)	**Open mode failure**	**Short mode failure**
Series connection	Blocking diode, DC/DC converter, switch(FET) current monitor, harness, connecter, etc.	Current path is cut off → **Critical !! Must be avoided**	Current is provided but, switch is not able to be turned off
Parallel connection	Over current detecting circuit, voltage monitor, bypass c, etc.	Power line is kept fine but, the function might be lost	Waste of large amount of current → **Critical !! Must be avoided**

4.2. EPS Circuit Design Examples

Design Trade-off: Element Redundancy vs System Resource (Mass or Volume or Area)

- ❑ High-priority loads (ex. main telecommunication, OBC, attitude control, fundamental bus-function) → as shown in robust design idea, **dual** or **triple allocation** of the circuit elements or parts is most useful approach
- ❑ **Current limit resistance** insertion is also an effective approach to protect against unexpected energy loss
- ❑ However, the area of PCB (Print Circuit Board) might be limited to mount all required circuits
  - ❑ [Action 1] **High density layout** of the circuit by using smaller package
  - ❑ [Action 2] Accept single points for **low priority loads** (mission camera, temperature sensor)



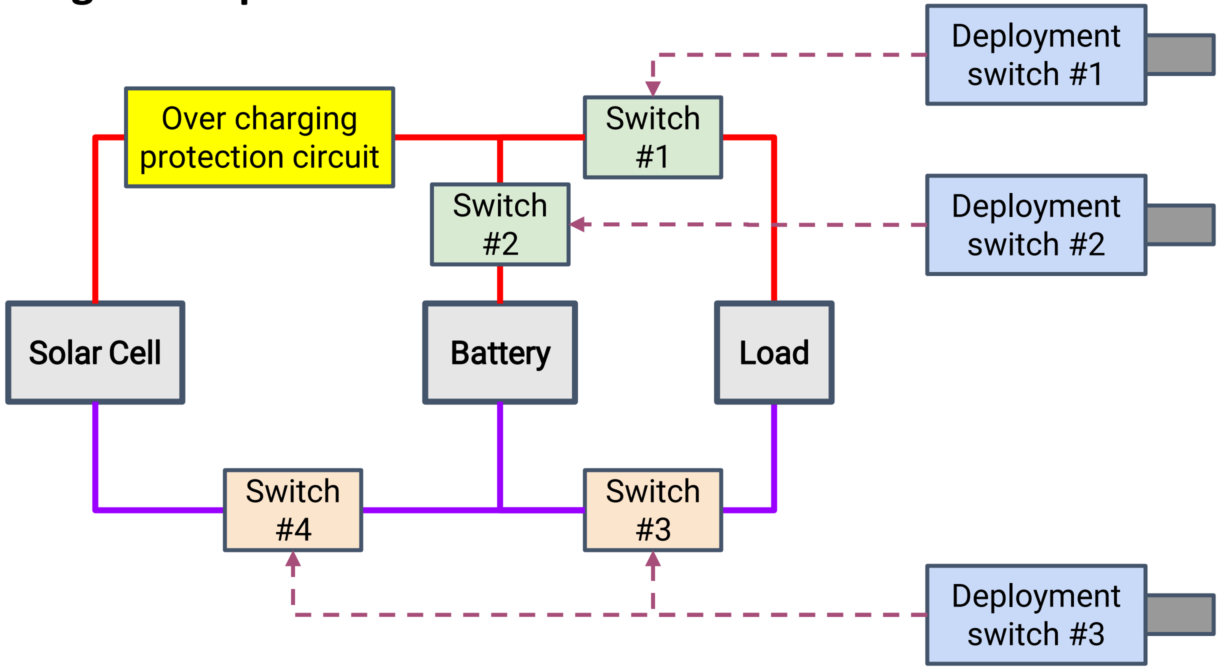
4.3. Safety Design and Testing of EPS Circuit (Inhibit Concepts)

Inhibit Requirement and Design Approach

- ❑ Typical ISS condition: 3-inhibit between energy source (solar cell or battery) and load
- ❑ 3-inhibit = 3 switches or fuses to **cut off energy transfer**
- ❑ “3” means “**2 fail-safe**”: the possibility of all 3 switches breaking at the same time is very small for a random failure
- ❑ The risk of design-induced failure of inhibit circuit must be mitigated by performing enough functional tests on the ground
- ❑ To avoid unexpected trouble after launch, **heterogeneous combination** is also useful

  ex) Switch #1 & #2 = Product-A,
  Switch #3 & #4 = Product-B,

Design Example of EPS Inhibit Architecture



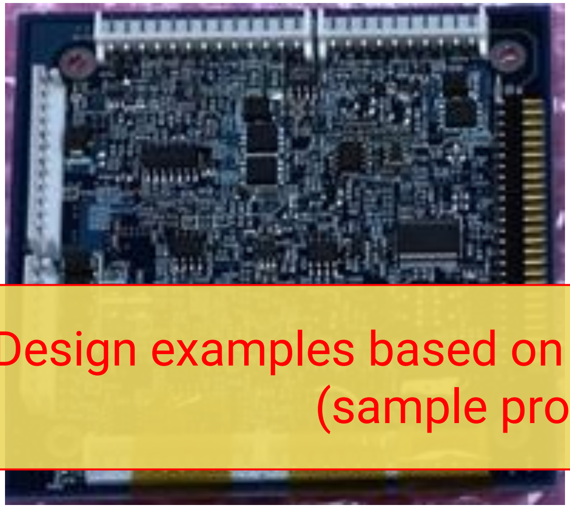
All Combinations are protected by 3-inhibit

- ❑ Solar cell to load: for unexpected load activation
- ❑ Battery to load: for unexpected load activation or battery external short or battery over discharging
- ❑ Solar cell to load: for battery over charging

4.4. Examples of EPS Circuit Boards Products

Checkpoints of EPS Circuit Board Design

- ❑ **Parts layout** : Clearance between mechanical interface (bolt holes) and closest parts
- ❑ **Large-current paths** should be made larger (**> 1 mm width** for copper pattern at **1A current**)
- ❑ Ground plane layout and consideration of categorization of GND to reduce unexpected noise transfer between analog and digital
- ❑ **Maintainability**: During replacing the discreet parts (like **R** or **C** or **L**) to change the circuit's constant or properties (like over current detecting constant, under voltage detecting constant, battery charging CC/CV setting, timer waiting setting, IC's mode setting), suitable layout or package size should be considered (like easy to perform soldering)



Design examples based on past ISS CubeSat missions
(sample product image)

Power Control Board

Dimensions: 90 x 90 x 8 mm
Mass: 45 g
Functions

- ➢ 3 Inhibit Circuit
- ➢ MPPT Circuit
- ➢ Battery charging Circuit
- ➢ 2 Output port (Unregulated bus) [1 for Power Distribution Board]

Power Distribution Board

Dimensions: 90 x 90 x 8 mm
Mass: 42 g
Functions

- ➢ 8 Output ports (+3.3V or +5V Regulated) [selectable by changing discreet parts]
- ➢ Current and Voltage monitoring A/D Conversion circuit

5. EPS Subsystem Integration

5. EPS Subsystem Integration

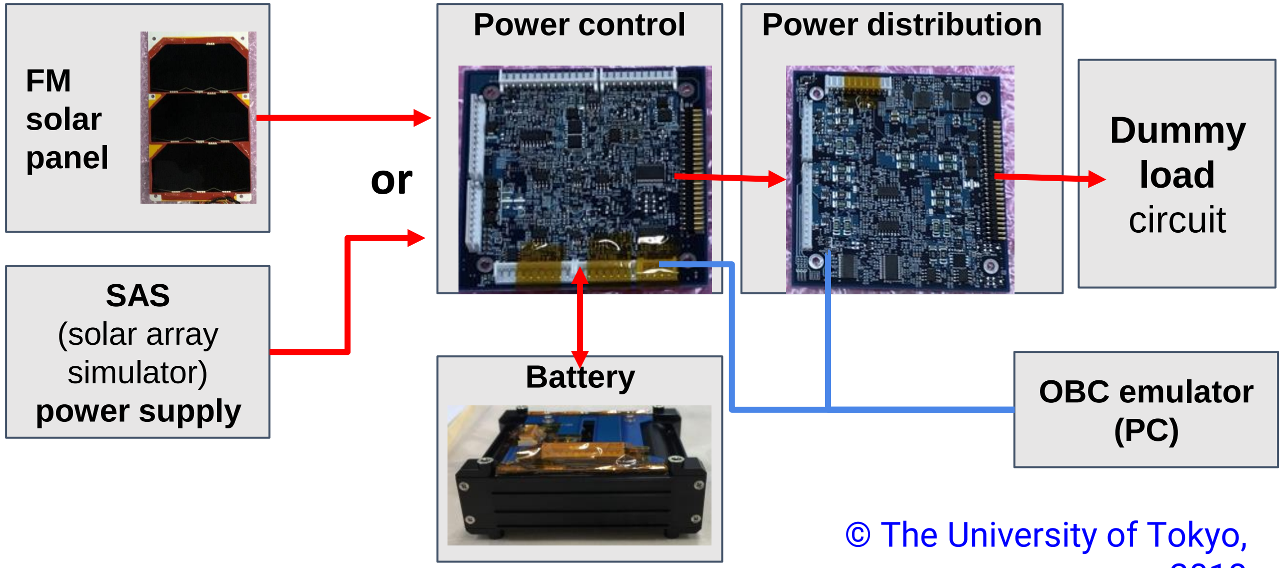
5.1. End-to-End Test of EPS

End-to-End Test

- ❑ To verify the **EPS integrated functionality** after individual design and production of EPS components (solar cell panel, battery, power control/distribution)
- ❑ Use a **test harness** or **actual FM harness** or **motherboard** to connect all EPS components (depends on purpose of test)
- ❑ **SAS (Solar Array Simulator) power supply** tends to be used on the table test in the case of focusing on the circuit boards and battery validation
- ❑ In the case of focusing on the actual FM solar panel performance or interface check, FM solar panels are attached to the power control boards

Suitable test configurations must be considered

An example of EPS subsystem end-to-end test configuration



Additional test devices

- ❑ **FM deployment switches**: for interface check
- ❑ **Multi-meter (current / voltage)**: to verify the monitoring functions of A/D conversion
- ❑ **Oscilloscope**: for checking the noise condition of power output or signal interface

5. EPS Subsystem Integration

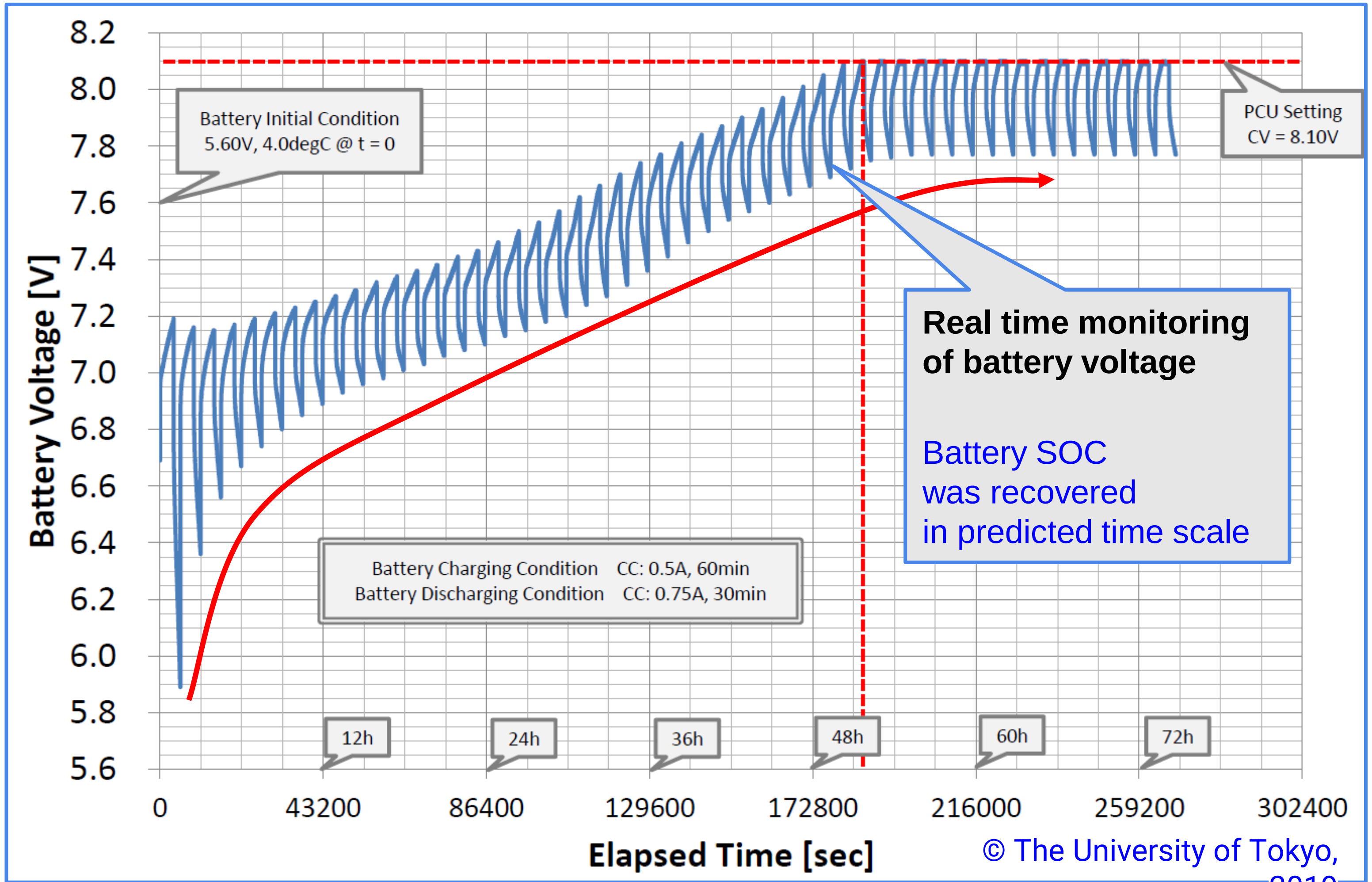
5.1. End-to-End Test of EPS

Example of EPS End-to-End Test
Battery Charging Test from 0% SOC
(Recovery from a dead battery state)
[Off-nominal case test]

Configuration: **EPS subsystem level**

Environment: **+4.0 degC constant**
(by isothermal chamber, based on the predicted temperature on-orbit)

Test condition: 60min charging, 30 min discharging (emulated orbit condition) constant current



Example test data based on a past ISS CubeSat mission

5.2. Key Concepts and Checkpoints of EPS Integration for Mission Success

Table. Checkpoints of EPS design and implementation summary

#	Category	Topic	
EPS-01	**Solar cell**	□ Temperature trends of I-V Curve / P-V Curve performance □ Series / parallel architecture design □ Panel hardware design	
EPS-02	**Battery**	□ Temperature trends of charging / discharging performance □ Screening test of the FM battery cells (for initial performance check) □ Screening test of the FM battery cells (for initial safety condition check) □ Series / parallel architecture design □ Module hardware design	
EPS-03	**Power control**	□ Power control method □ Selection of parts or modules or products □ Bus voltage □ The number of output ports □ Redundancy design	
EPS-04	**Power distribution**	□ The number of output ports □ Selection of parts or modules or products □ Properties of each output port (voltage, current limit) □ Redundancy design	
EPS-05	**Inhibit**	□ Corresponding to the safety requirements □ Connection to each deployment switch	
EPS-06	**End-to-end**	□ Test configurations □ Nominal case tests □ Off-nominal case tests	

6. Conclusion

6. Conclusion

- EPS is the most important subsystem from the viewpoint of energy handling
- Power Generation: State-of-the-art trend → Multi-Junction Solar Cell: **~30 % efficiency**
  I-V curve profile corresponding to the operational temperature range should be confirmed at the single cell level
- Power storage: State-of-the-art trend → Li-Ion battery is popular: **3.0 ~ 3.5 Ah capacity**
  charging/discharging profile corresponding to operational temperature range should be confirmed at the single cell level
- Li-Ion secondary battery is a very **hazardous** item
  → Learn how to handle the cell well before starting the actual product design
- Power control and distribution: **effective redundancy design** or **robust ideas** must be considered within system resources (like area or volume or mass)
- EPS subsystem end-to-end test: Not only **nominal case**, but also **off-nominal case**

Thank you very much.

[Disclaimer]
The views and opinions expressed in this presentation are those of the authors and do not necessarily reflect those of the United Nations.