KiboCUBE Academy

Lecture 06 – Second Edition

CubeSat Design for Safety Requirements

Tohoku University

Department of Aerospace Engineering

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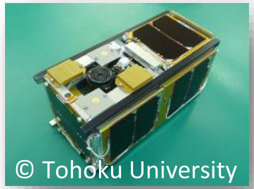
This lecture is NOT specifically about KiboCUBE and covers GENERAL engineering topics of space development and utilization for CubeSats.
The specific information and requirements for applying to KiboCUBE can be found at:
https://www.unoosa.org/oosa/en/ourwork/psa/hsti/kibocube.html

Lecturer Introduction



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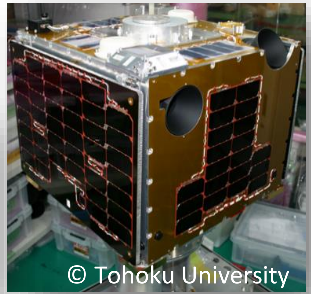

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Toshinori Kuwahara, Dr. –Ing.

Position:

2015 - Associate Professor, Department of Aerospace Engineering, Tohoku University
2017 - Technical Advisor, Nakashimada Engineering Works, Ltd.
2017 - Technical Advisor, ALE Co., Ltd.
2020 - Chairperson, University Space Engineering Consortium Japan (UNISEC)
2021 - Co-founder/CTO, ElevationSpace Inc.

Research Topics:
Space Development, Utilization, and Exploration by Small Spacecraft Technologies

Contents

1. CubeSat System Engineering Process

1. CubeSat System Engineering Process

1.1. System Engineering Process

CubeSat Mission Initiation

Output

Mission Analysis and Design — Mission Definition

Mission Definition Review (MDR)

System Analysis and Design — System Definition

System Definition Review (SDR)

Preliminary Design — Development of **Breadboard Model (BBM)**

Preliminary Design Review (PDR)

Detailed Design — Development and Verification of **Engineering Model (EM)**

Critical Design Review (CDR)

Satellite Manufacturing — Manufacturing and Testing of **Flight Model (FM)**

Qualification Review (QR)

Launch Readiness Review (LRR)

Launch and Operation!

Requirements

Definition

Verification

1.2. Mission Analysis and Design

Input: Mission Objectives

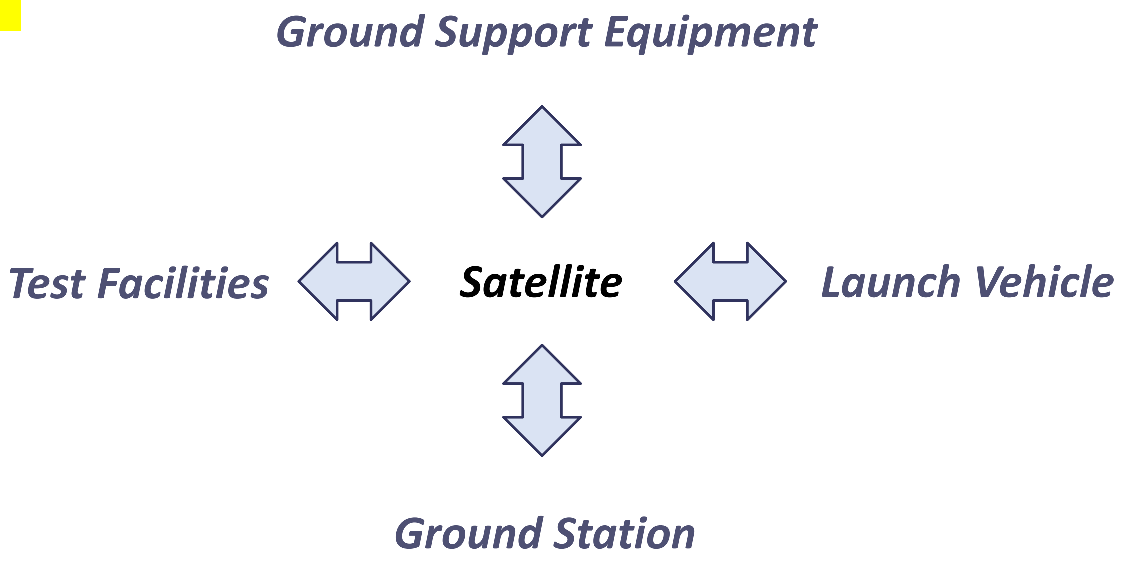
Output: Mission Requirements and Constraints

- Functional Requirements
- Operational Requirements
- Constraints

Safety Requirement!

Mission Constraints:

- Launch Opportunities
  (Mass properties, Size, Launch Environment, Orbit, etc.)
- Schedule
- Cost
- Human Resources
- Development Facilities
- Interfaces
- Regulations
- Space Environment



1.3. System Analysis and Design

Input: Mission Requirements

Output: System Definition

- Preliminary Mission Concept
- Satellite Orbit, Number of Satellites
- Payload Instruments
- Satellite Bus System
- Launch Vehicle Selection
- Operation Planning
- Ground Station
- Ground Support Equipment

Payload Instruments

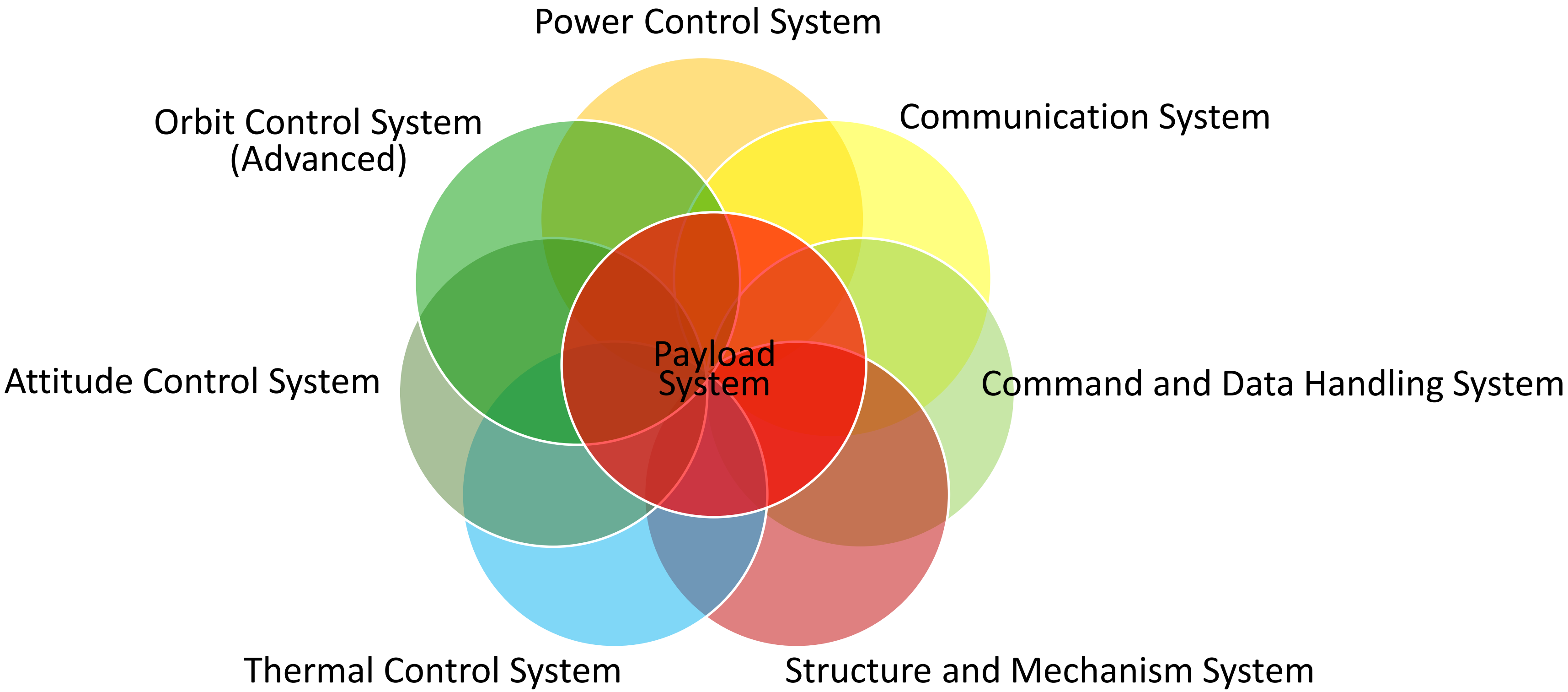
- Types of Instruments
  - Communication
  - Optical Observation
- Mass
- Size
- Power Consumption
- Voltage
- Telemetry Data
- Mission Data
- Command Data
- Thermal Control
- Pointing Accuracy
- Operational Constraints

Bus System

- Mass
- Size
- Power Consumption/Generation
- Attitude Control
- Telemetry Data
- Command Data
- Computational Capability
- Communication Capability
- Thermal Control Capability
- Orbit Control
- Propulsion
- Autonomy

1.4. Satellite Subsystems

A satellite system consists of several subsystems. Typical categorization is as follows:



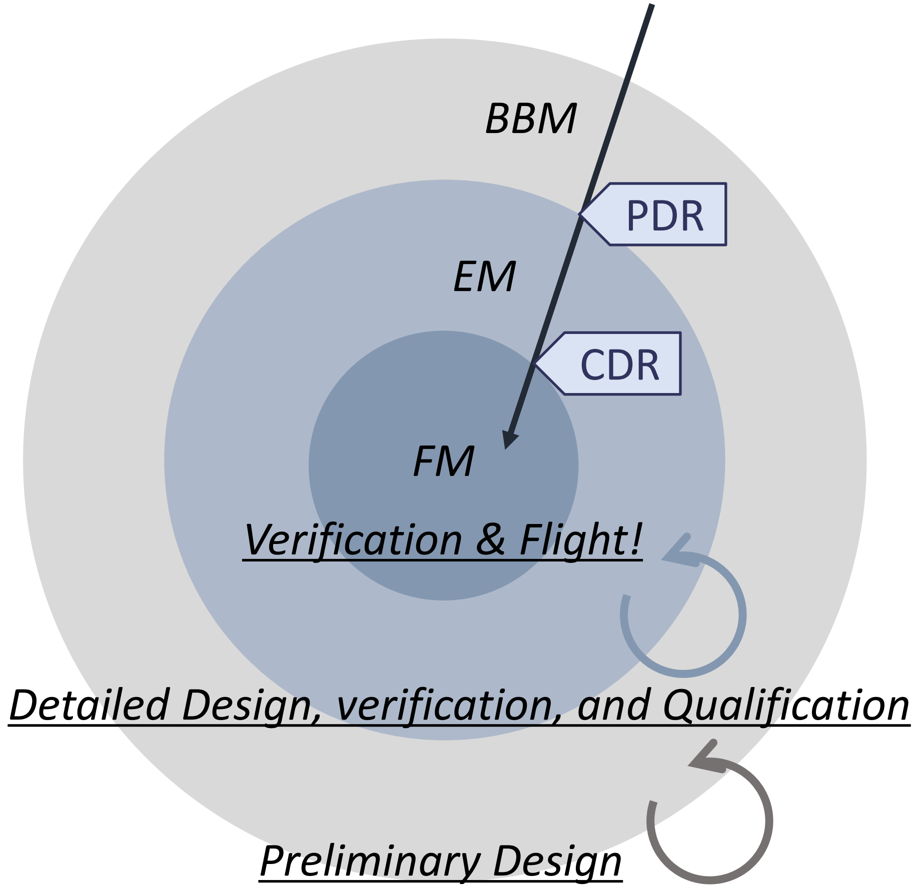
+ Harness System

1. CubeSat System Engineering Process

1.5. Satellite System Design and Verification

- Iterative design refinement and verification process
- Satellite system sizing and budget control through trade-offs
  - Mass Budget (Mass property)
  - Power Budget (Power consumption, generation, and storage)
  - Size Budget
  - Communication Budget
  - Data Storage Budget
  - Computational Budget
  - Operation Time Budget
  - Financial Budget
  - Schedule Budget

Satellite system design is an art!



1. CubeSat System Engineering Process

1.6. Small Satellite System Engineering Activities

<u>Space Education through Small Satellite Projects</u>

Project members and students experience:

- Mission Analysis
- System Design
- System Development
- Component Procurement
- Component Development
- System Integration
- On-board Software / Algorithm Development
- Ground Verification
- Ground Environmental Test
- Safety Design, Safety Review
- Satellite Delivery and Launch
- Ground Station Installation
- Satellite Operation, Instrument Calibration
- Satellite Data Analysis

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2. Safety and Mission Assurance Activities

2. Safety and Mission Assurance Activities

2.1. Introduction to Safety and Mission Assurance (S&MA)

Mission Assurance:

- Satellite projects shall conduct activities to maximize the probabilities of mission success, by mitigating any risks that threaten mission success, such as design failure, production failure, test and verification failures, etc.

Safety Assurance:

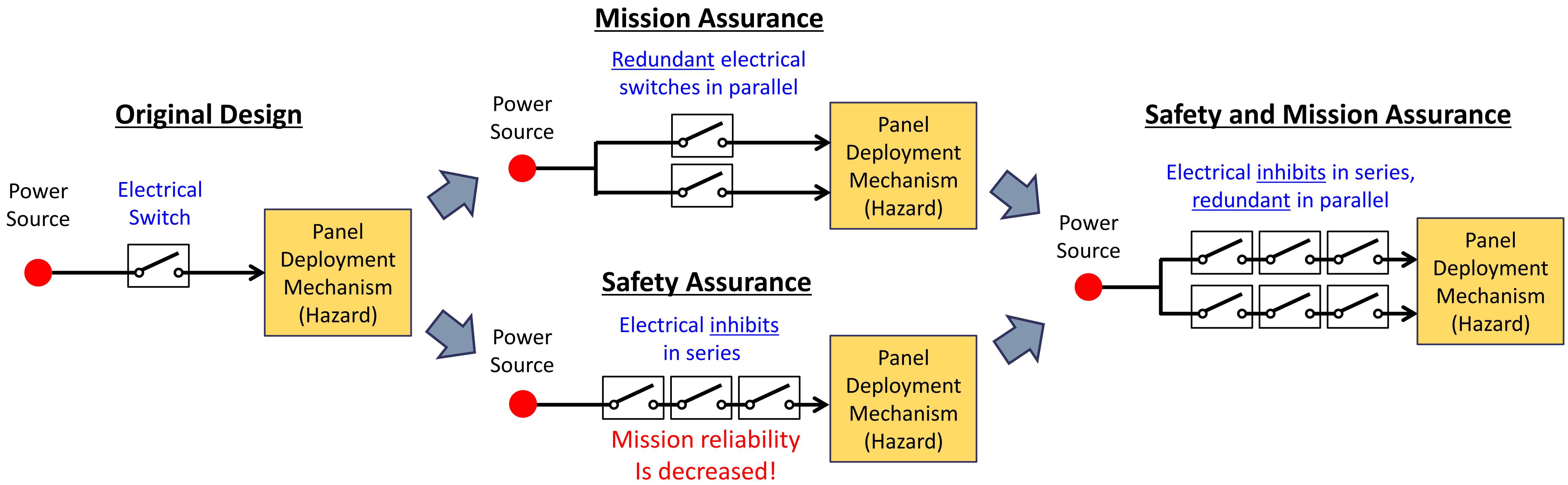
- Safety design requirements necessitate satellite systems to be equipped with multiple inhibits against the hazards for the safety of the surrounding environment of the satellite, which could result in excess restrictions of the satellite functionalities.

Safety and Mission Assurance:

- Satellite projects shall find the best balance between safety design and mission assurance within the limited resources of the satellite system, as well as the project.

2.2. Safety and Mission Assurance Activity

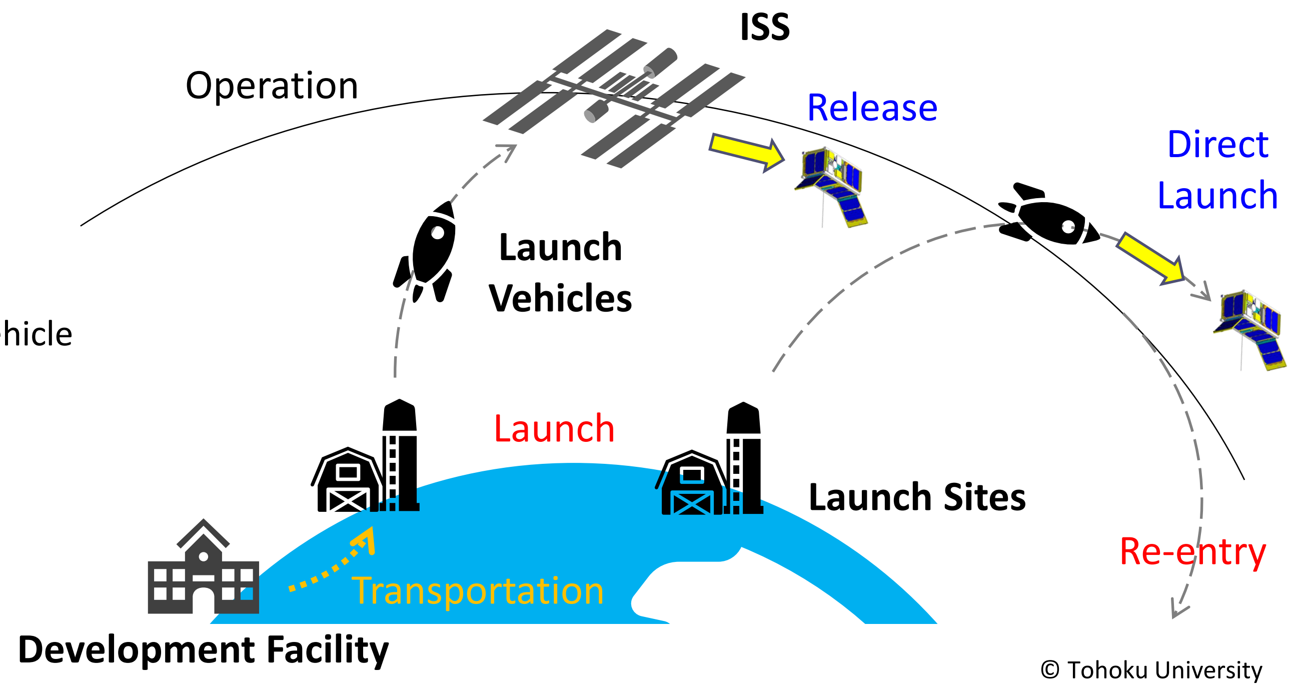
- Safety assurance and mission assurance are often design drivers in opposing directions.
- It is very challenging that both aspects are satisfied in the limited resources of a small satellite system, especially their small mass and envelope.
- Reducing the number of components, ensuring reliability of each component, and eliminating redundant design as much as possible is the key design approach.



2. Safety and Mission Assurance Activities

2.3. Safety Design of Satellite System

- Satellite development projects shall consider safety design aspects for the entire project life cycle.
  - Development and handling phase on ground
    - Ground facilities and equipment
    - Personnel
    - Transportation
  - Satellite launch phase
    - Launch site
    - Launch vehicle and other satellites being launched by the same vehicle
  - Satellite release phase (in case it is released from the ISS)
    - International Space Station
    - Astronauts
  - Operational phase
    - International Space Station and other spacecraft
    - Environment and humans on Earth



- Safety design requirements depend on launch vehicles and release systems.
- The safety design plan, implementation, and verification results shall be confirmed by safety reviews.
- Safety design requirements can greatly affect the system design of the satellite, and hence they shall be considered from the very beginning of the satellite project.

2. Safety and Mission Assurance Activities

2.4. CubeSat Standardization History

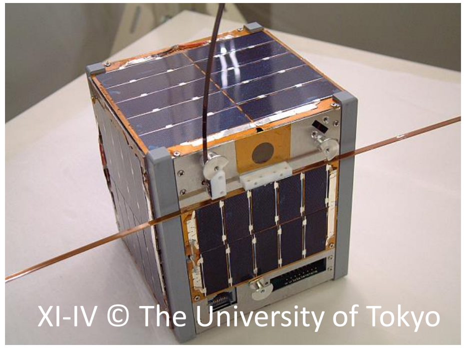
Some standards are available:

- CubeSat Design Specification rev.13 (2014/2/20)
  6U CubeSat Design Specification rev. 1.0 (2018/6/7)
  - California Polytechnic State University
  (https://www.cubesat.org/)

- CubeSat Subsystem Interface Definition version 1.0
  - UNISEC Europe (2017/8/24)
  (http://unisec-europe.eu/wordpress/wp-content/uploads/CubeSat-Subsystem-Interface-Standard-V2.0.pdf)

- ISO Space systems – Cube satellites (CubeSats)
  (https://www.iso.org/standard/60496.html)

- JEM* Payload Accommodation Handbook Vol.8 D
  - JAXA (* Japanese Experiment Module (JEM) = Kibo)
  (https://iss.jaxa.jp/kibouser/provide/j-ssod/#sw-library)
  English (2020/7/31)
  (https://humans-in-space.jaxa.jp/kibouser/library/item/jx-espc_8d-d1_en.pdf)
  Japanese (2020/5/25)
  (https://humans-in-space.jaxa.jp/kibouser/library/item/jx-espc_8d-d1.pdf)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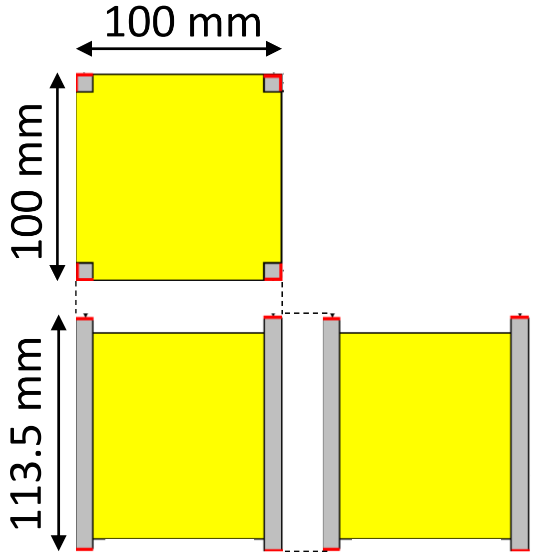


1 Unit: 10 cm cube, 1.33kg

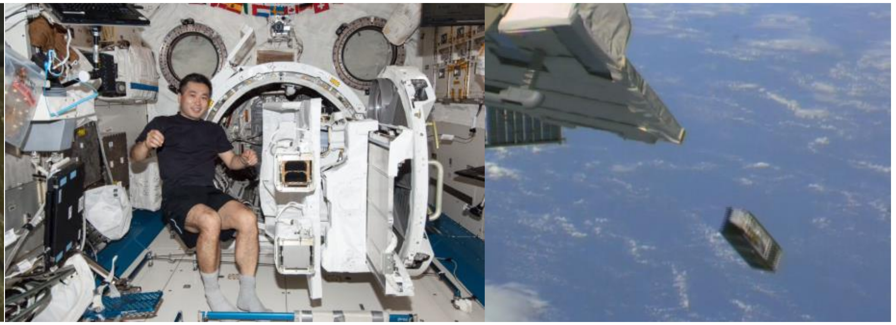
Refence Document: JAXA Common Technical Documentation (https://sma.jaxa.jp/en/TechDoc/index.html)

2. Safety and Mission Assurance Activities

2.5. KiboCUBE Launch Opportunity

- “KiboCUBE” provides deployment opportunities from the ISS Kibo module.
- The possible launch vehicle can be one of the transfer vehicles to the ISS:
  - HTV-X: JAXA H-II Transfer Vehicle
  - Dragon: SpaceX
  - Cygnus: Orbital Sciences Corporation
- The launch environment is different in each vehicle.
- CubeSats are installed in the satellite deployment POD (J-SSOD: Japanese Experiment Module (JEM) Small Satellite Orbital Deployer) and stowed inside the Cargo Transfer Bag (CTB) with soft packing material.
- Vibration conditions are very mild relative to those encountered during a direct launch.
- Frequent launch opportunities are provided, up to 4 times per year.
- Adopting an approximate orbital altitude of 400 km ensures the CubeSats re-enter the atmosphere after their mission lifetime without becoming space debris.

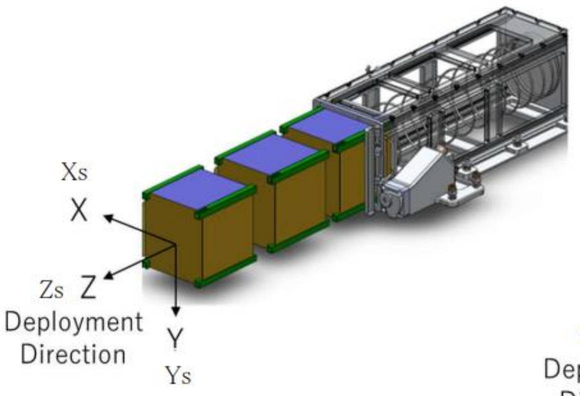
CubeSat Transfer to the ISS © JAXA

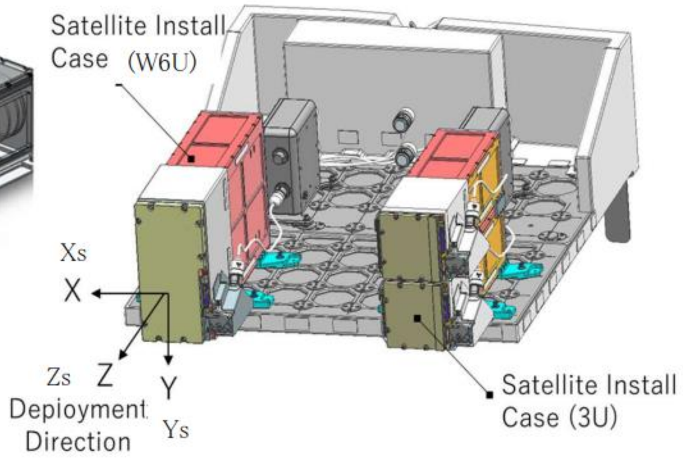


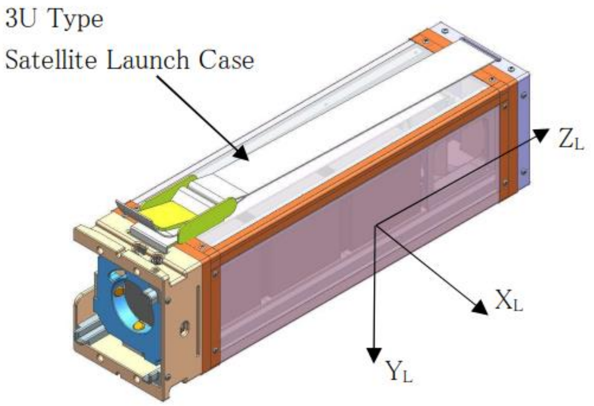
Deployment from the ISS © JAXA

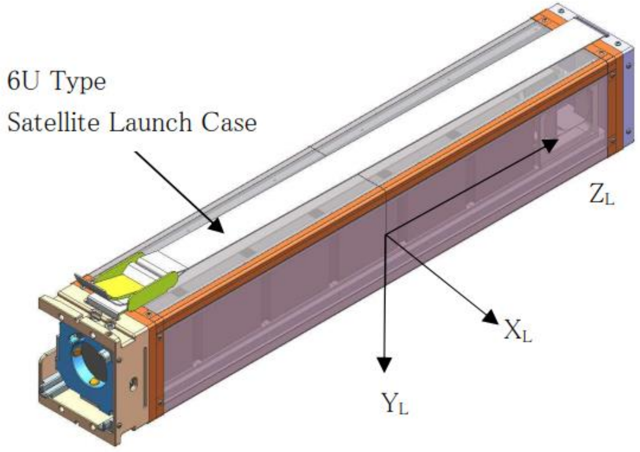
2. Safety and Mission Assurance Activities

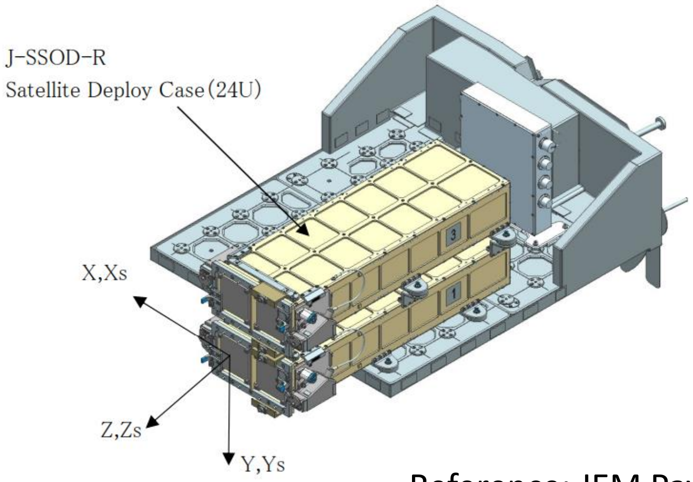
2.6. Kibo Release Opportunities











		Exterior Dimensions (*1)	Rail Dimension	CubeSat Installation
10cm Class satellite	1U	X:100×Y:100×Z:113.5mm	More than 8.5mm squares	Ground / ISS
	1.5U	X:100×Y:100×Z:170.2mm		ISS
	2U	X:100×Y:100×Z:227.0mm		Ground / ISS
	3U	X:100×Y:100×Z:340.5mm		Ground / ISS
	4U	X:100×Y:100×Z:454.0mm		ISS
	5U	X:100×Y:100×Z:567.5mm		ISS
	6U	X:100×Y:100×Z:681.0mm		ISS
	W6U	X:100×Y:226.3×Z:340.5 or 366.0mm		Ground

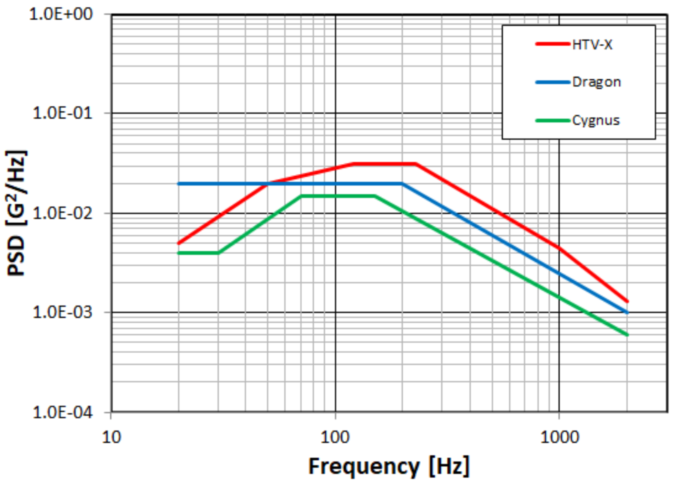
(*1) Nominal dimension including rails

Reference: JEM Payload Accommodation Handbook Vol. 8 D (English)
https://humans-in-space.jaxa.jp/kibouser/library/item/jx-espc_8d-d1_en.pdf

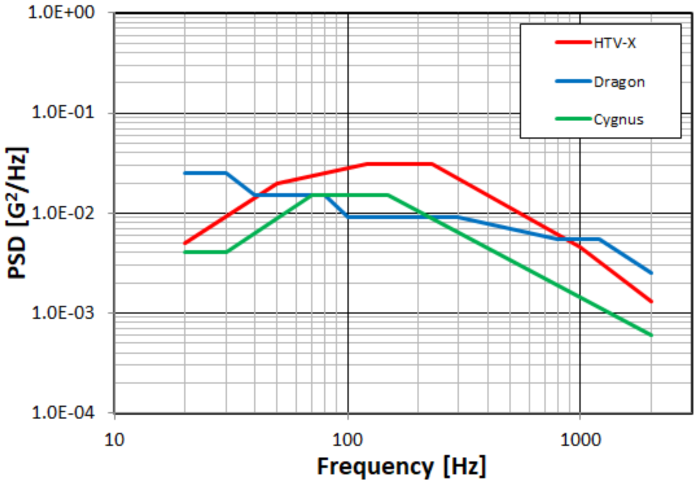
2.7. Launch Conditions of KiboCUBE's Launch Vehicles

- Random vibration condition

HTV-X		Dragon		Cygnus	
Freq. (Hz)	PSD (g²/Hz)	Freq. (Hz)	PSD (g²/Hz)	Freq. (Hz)	PSD (g²/Hz)
20	0.005	20	0.02	20	0.004
50	0.02	200	0.02	30	0.004
120	0.031	2000	0.001	70	0.015
230	0.031			150	0.015
1000	0.0045			2000	0.0006
2000	0.0013				
Overall (grms)	4.05	Overall (grms)	3.2	Overall (grms)	2.44
Duration (sec)	60	Duration (sec)	60	Duration (sec)	60



Dragon	
Freq. (Hz)	PSD (g^2/Hz)
20	0.0250
30	0.0250
40	0.0150
80	0.0150
100	0.0090
300	0.0090
800	0.0055
1200	0.0055
2000	0.0025
Overall (grms)	3.41
Duration (sec)	60



New Random Vibration Condition of SpaceX Dragon

- Quasi-static acceleration condition
  - HTV-X: 6.0 [g]
  - SpaceX Dragon: 9.0 [g]
  - Orbital Cygnus: 9.0 [g]

- Shock condition
  - N/A

Reference: JEM Payload Accommodation Handbook Vol. 8 D (English)
https://humans-in-space.jaxa.jp/kibouser/library/item/jx-espc_8d-d1_en.pdf

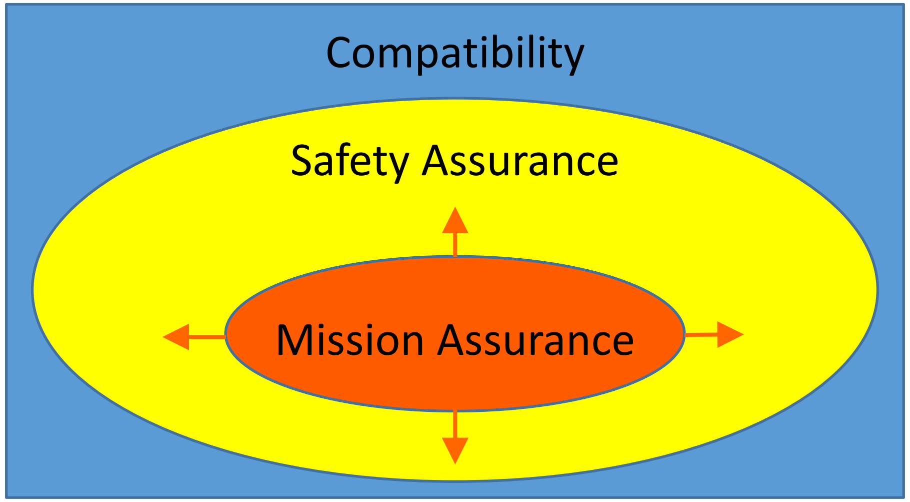
2.8. Environment Conditions: Launch and at the ISS

- Maximum Air pressures
  - HTV-X: 104.8 [kPa]
  - Dragon: 102.7 [kPa]
  - Cygnus: 104.8 [kPa]
  - Inside the ISS: 104.8 [kPa]
- Air pressure changing rates
  - HTV-X: 0.878 [kPa/sec]
  - Dragon: 0.891 [kPa/sec]
  - Cygnus: 0.891 [kPa/sec]
  - Inside the ISS: 0.878 [kPa/sec]
  - Inside the JEM Airlock: 1.0 [kPa/sec]
- Temperature conditions
  - HTV-X: +10 ~ +32 [deg C]
  - Dragon: +18.3 ~ +29.4 [deg C]
  - Cygnus: +10 ~ +46.1 [deg C]
  - Inside the ISS: +16.7 ~ +29.4 [deg C]
  - Outside the ISS: -15 ~ +60 [deg C]
- Humidity conditions
  (Dew Point, Relative Humidity)
  - HTV-X: -34 [deg C], N/A
  - Dragon: N/A, 25~75 [%]
  - Cygnus: +4.4 ~ +15.6 [deg C], 25~75 [%]
  - Inside the ISS:
    +4.4 ~ +15.6 [deg C], 25~75 [%]

Reference: JEM Payload Accommodation Handbook Vol. 8 D (English)
https://humans-in-space.jaxa.jp/kibouser/library/item/jx-espc_8d-d1_en.pdf

2.9. Relationship between Compatibility, Safety Assurance, and Mission Assurance

- Space systems including CubeSats are required to satisfy compatibility requirements of the corresponding launch vehicles such as mass, size, environmental conditions, etc.
- Safety Assurance activities are applicable within the scope of compatibility compliance which imposes further and more severe requirements to the space systems.
- Mission Assurance activities are applicable within the scope of safety assurance compliance which attempts to achieve a desired system reliability by managing resources of the space systems, retaining a portion as spare for introducing redundancies and/or even more design margins.



3. Safety Design Process

3. Safety Design Process

3.1. Safety and Design Reviews

Satellite projects experience several design reviews.

- JAXA/NASA Safety Reviews
  - Satellites to be launched by Japanese launch vehicles and/or to be released from the ISS through JAXA need to pass the JAXA's safety reviews (Phase 0/I/II/III).
  - A Safety Assessment Report (SAR) shall be submitted to JAXA for the reviews.
  - Satellites are required to fulfill safety design requirements described in JAXA's standard documents, such as:
    - JMR-001C: System Safety Standard (https://sma.jaxa.jp/en/TechDoc/Docs/E_JAXA-JMR-001C.pdf)
    - JMR-002D: Launch Vehicle Payload Safety Standard (https://sma.jaxa.jp/en/TechDoc/Docs/E_JAXA-JMR-002D.pdf)
    - JMR-003D: Space Debris Mitigation Standard (https://sma.jaxa.jp/en/TechDoc/Docs/E_JAXA-JMR-003D.pdf)
    - **JX-ESPC-101133-D: JEM Payload Accommodation Handbook Vol.8 D** (https://humans-in-space.jaxa.jp/kibouser/library/item/jx-espc_8d-d1_en.pdf)
    - JERG-1-007E: Safety Regulation for Launch Site Operation (https://sma.jaxa.jp/en/TechDoc/Docs/E_JAXA-JERG-1-007E.pdf)
    - JERG-2-025: Hazard Analysis Handbook for Small Satellites (Japanese) (https://sma.jaxa.jp/TechDoc/Docs/JAXA-JERG-2-025.pdf)
    - JERG-2-213A: Insulation (https://sma.jaxa.jp/en/TechDoc/Docs/E_JAXA-JERG-2-213A.pdf)
    - JAXA Common Technical Documentation: https://sma.jaxa.jp/en/TechDoc/index.html
- Japanese Cabinet Office Safety Review
  - Satellites with Japanese nationalities and or operated from Japan need to be safety reviewed by the Japanese Cabinet Office.
- JAXA Compatibility Verification Review
  - Confirmation of the compatibility of the satellite verification results with the requirements from JAXA before the delivery.

3. Safety Design Process

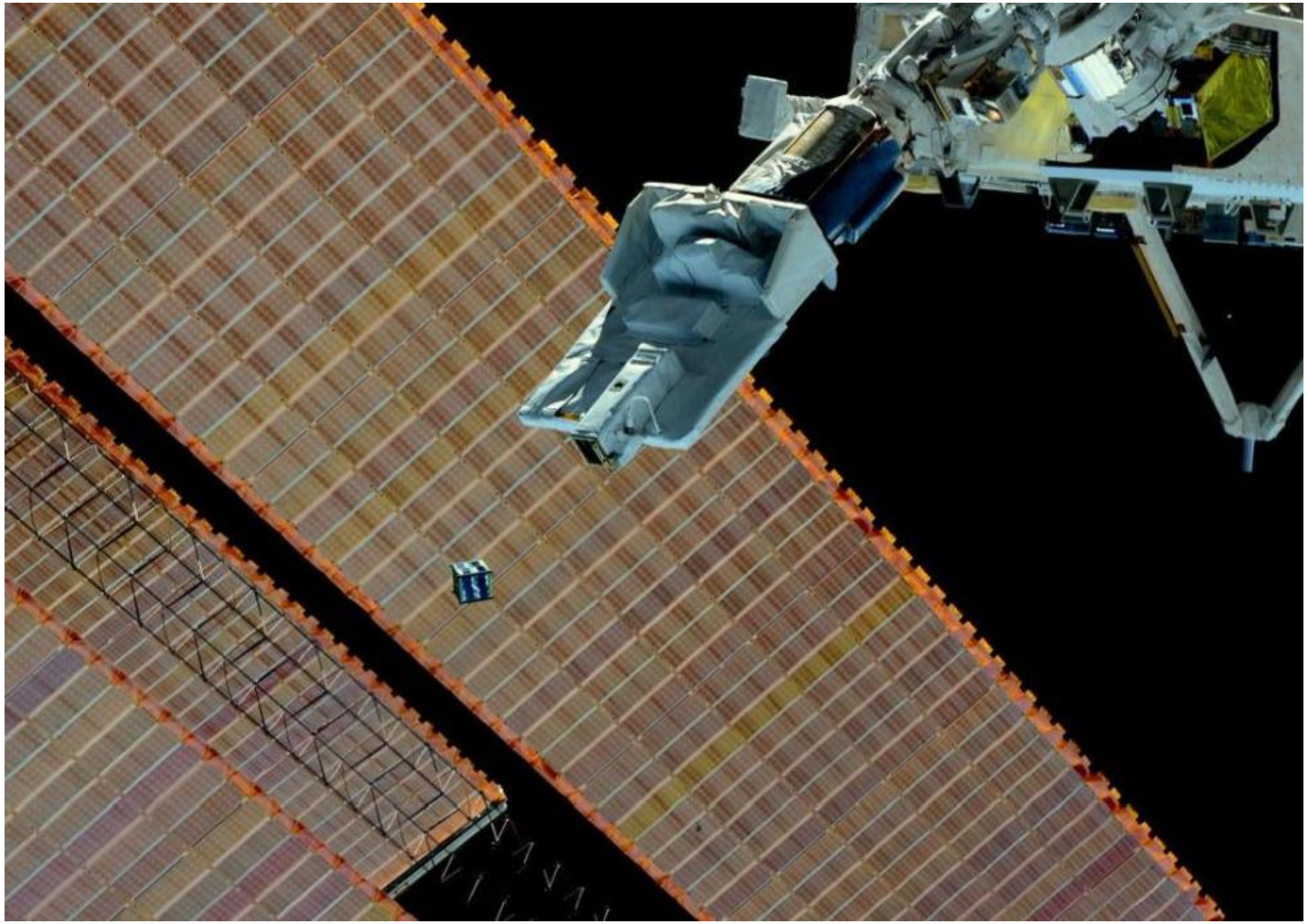
3.2. Safety Design Precedence

Safety design precedence described in the system safety standard of JAXA is as follows:

<u>Safety Design Precedence</u>

1. Design to eliminate hazards.
2. Design to minimize hazards.
3. Design to control hazards.
4. Use of safety devices.
5. Use of protective devices.
6. Use of warning devices.
7. Application of hazard control methods relying on special procedures and/or training.

Basically, CubeSats to be released from the ISS are required to apply the above mentioned (1) ~ (3) approaches for their safety designs.



JMR-001C(E) System Safety Standard, JAXA, 2018 (https://sma.jaxa.jp/en/TechDoc/Docs/E_JAXA-JMR-001C.pdf)

3.3. Safety Review Processes

Satellite projects are responsible to conduct system safety program activities throughout the life cycle to ensure safety related to the systems in order to minimize risks and keep them within an allowable level throughout the design, manufacture, test, and operation phases.

<u>Safety Review Processes:</u>

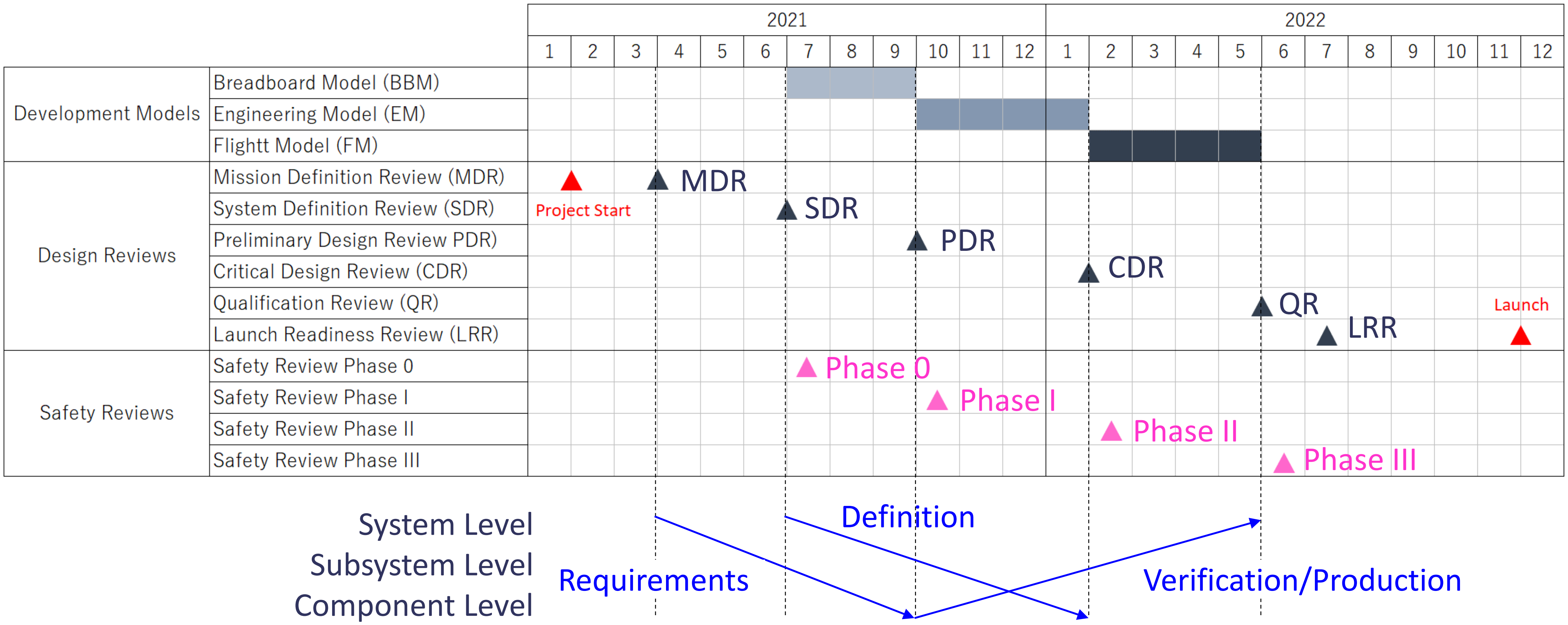
- Safety Review Phase 0
  - System safety program plan shall be established, and hazard analysis shall be started to identify hazards.
- Safety Review Phase I
  - Detailed safety requirements shall be established, influences and measures of system hazards shall be examined.
- Safety Review Phase II
  - Detailed safety assessment shall be conducted, and design compliance with the safety requirements shall be verified.
  - Safety-related verification tests shall be conducted and their results shall be reviewed.
- Safety Review Phase III
  - The results of verification of hazard controls shall be clarified, and it shall be confirmed that all safety verifications have been completed.
  - Operational procedures shall be prepared, including emergency measures, handling, storage, and transportation, etc.

JMR-001C(E) System Safety Standard, JAXA, 2018 (https://sma.jaxa.jp/en/TechDoc/Docs/E_JAXA-JMR-001C.pdf)

3. Safety Design Process

3.4. Satellite Development Schedule and Safety Reviews

Relationship between Satellite Development Schedule, Design Reviews, and Safety Reviews



3. Safety Design Process

3.5. Standard Hazards and Unique Hazards

- Safety design begins with identifying the possible sources of hazards. Hazards can be classified into "Standard Hazards," that are common for general satellite systems, and "Unique Hazards," that are unique for each satellite system.

Standard Hazards

1. Flammable Material
2. Material Off-gassing
3. Dust, Toxic or Biological Hazardous Materia
4. Sharp Particles
5. Exposure to mechanical hazards and translation path obstructions
6. Exposure to Touch Temperature Exceedances
7. Exposure to Light Amplification by Stimulated Emission of Radiation and/or Incoherent Electromagnetic Radiation Emissions.
8. Exposure to Noise Limit Exceedances
9. Injury/Damage as a Result of Improperly Bonded and Grounded Equipment
10. Injury/Damage as a Result of Improper Power Distribution Circuitry and Circuit Protection Devices
11. Mating and Demating of Energized Connector
12. Non-Ionizing Radiation Interference
13. Injury/Damage as a result of Rotating Equipment Failure
14. Injury/Damage as a result of Sealed Container Failure

Typical Unique Hazards

- Leakage of electrolyte or rupture of battery
- A collision of the deployed CubeSat with structure failure against the ISS structure.
- A collision of the deployed CubeSat with inadvertent deployable part against the ISS structure.
- Others…

3. Safety Design Process

3.6. Unique Hazards

- The satellite development team is responsible for the identification of the unique hazards which are specific to each satellite, as only the project team knows about the detailed design of the satellite.
- “Hazard identification” shall be performed throughout all phases. A hazard identification table shall be prepared at the beginning of the project phase and it shall be updated as the design matures.
- Engineers shall be honest in their safety design activities.

Possible Unique Hazards:

- Structure failure (JERG-2-320A (Japanese))
- Deployment mechanisms (JERG-2-330B)
- Shatterable materials (glasses, etc.)
- Handling of heavy items, specifically utilized for the satellite, such as the satellite itself, transport container, etc.
- Electrical short circuit of batteries.
- Propulsion systems
- Pressurized systems
- Unexpected radio frequency emission.

3.7. Hazard Level Classification

Hazard severity levels can be classified into the following four categories.

Hazard Severity Level Classification

Hazard Level	Term	Description
I	Catastrophic	Death or severe personal (ISS crew) damage Irreversible significant environmental impact Loss of, or severe damage to, public or third party property Loss of system (ISS, Launch Vehicles) or launch site facilities
II	Critical	Major personal damage Reversible significant environmental impact Major damage to public or third party property Severe damage to system or launch site facilities
III	Marginal	Minor personal damage Reversible moderate environmental impact Minor damage to public or third party property Major damage to systems
IV	Negligible	Any conditions that causes less significant damage than that posed by hazard levels I, II, and III.

3.8. Risk Assessment

- Risk assessment criteria is based on the combination of “level of damage” and “the likelihood of occurrence.”
- Safety design shall be applied in order to control hazards and reduce the likelihood of their occurrence.
- Safety design approaches:
  1. Fault Tolerance Design
  2. Design for Minimum Risk
  3. (Probabilistic Risk Assessment)

Risk Criteria

		Likelihood of occurrence				
		A. frequently	B. occasionally	C. infrequently	D. only rarely	E. almost never
Level of damage	I. Catastrophic					
	II. Critical					
	III. Marginal					
	IV. Negligible					

Distinguished as unacceptable risk

Requiring an acceptable / unacceptable decision

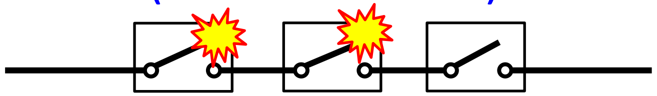
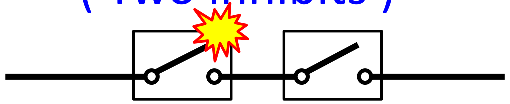
Acceptable risk

Reduce the likelihood of occurrence

3.9. Safety Design Method – Fault Tolerant Design

The following fault tolerance design requirements shall be satisfied to control hazards, and reduce the likelihood of their occurrence to an allowable level in accordance with the hazard level.

1. Double failures, a combination of one failure and one human error, as well as double human errors shall not cause a catastrophic failure.
2. One failure or one human error shall not cause a severe accident.

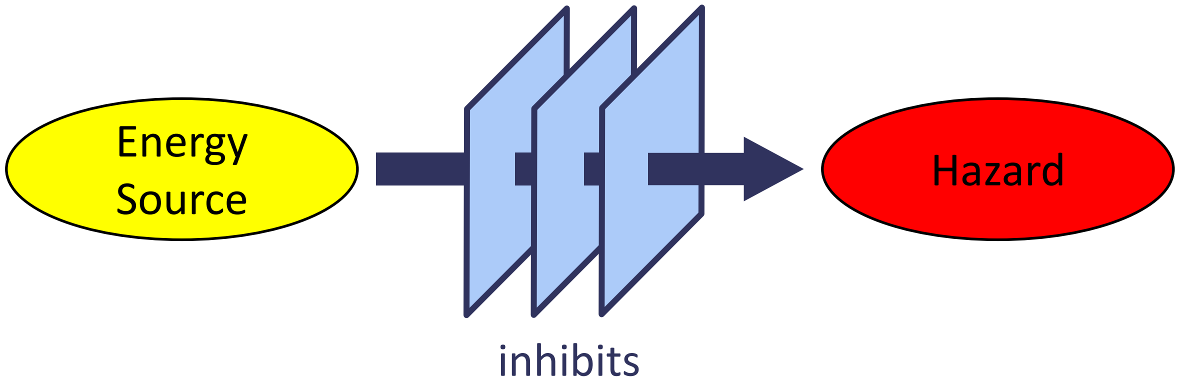
Hazard Level	Term	Description	Required Control
I	Catastrophic	Death or severe personal (ISS crew) damage Irreversible significant environmental impact Loss of or severe damage to public or third party property Loss of system (ISS, Launch Vehicles) or launch site facilities	Double Fault Tolerant Design (Three inhibits) 
II	Critical	Major personal damage Reversible significant environmental impact Major damage to public or third party property Severe damage to system or launch site facilities	Single Fault Tolerant Design (Two inhibits) 

3. Safety Design Process

3.10. Safety Design Method – Design for Minimum Risk

- For some design cases, fault tolerant design cannot be applied, such as structural design, or pressure vessels. In these cases, design shall be managed by considering sufficient design margins, safety factors, and appropriate selection of material and EEE parts.

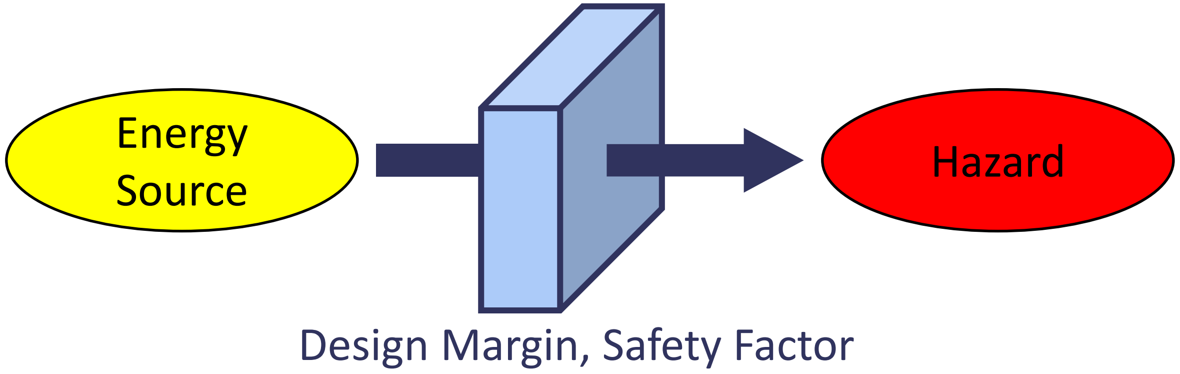
1. Fault Tolerant Design



Applicable design fields:

- Structures
- Pressure vessels
- Pressurized piping and joints
- Pyrotechnic devices
- Material flammability
- Safety-critical mechanisms (mechanisms)
- Material compatibility

2. Design for Minimum Risk



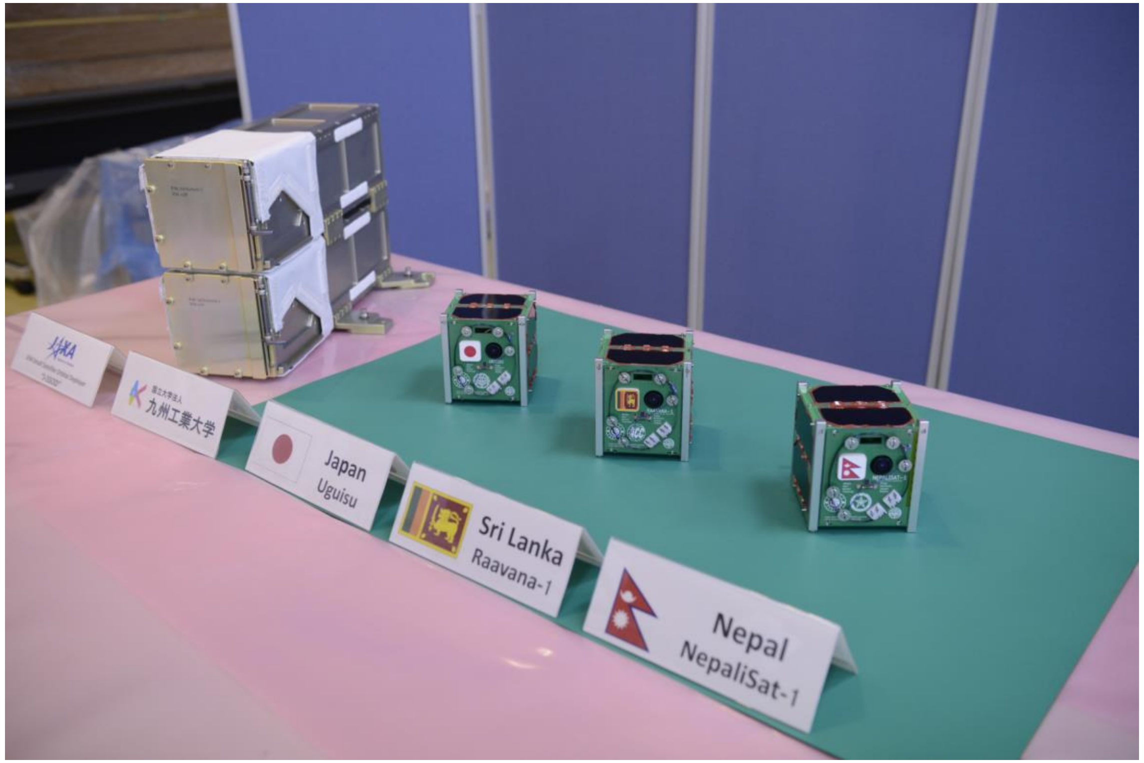
4. Safety Design of CubeSat

4.1. Safety Design Examples of CubeSats

This chapter provides some lessons learned from safety design examples of small satellites.

<u>Examples of CubeSat Safety Design:</u>

1. Separation Switches
2. Electrical Circuits
   - Double Insulation
   - Remove Before Flight Pins
   - Flight Connectors
3. Deployment Mechanisms
4. Wire Mechanisms for Deployment Structures



© JAXA

Safety design depends on each satellite!

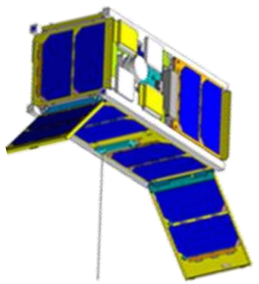
4. Safety Design of CubeSat

4.2. Separation Switches

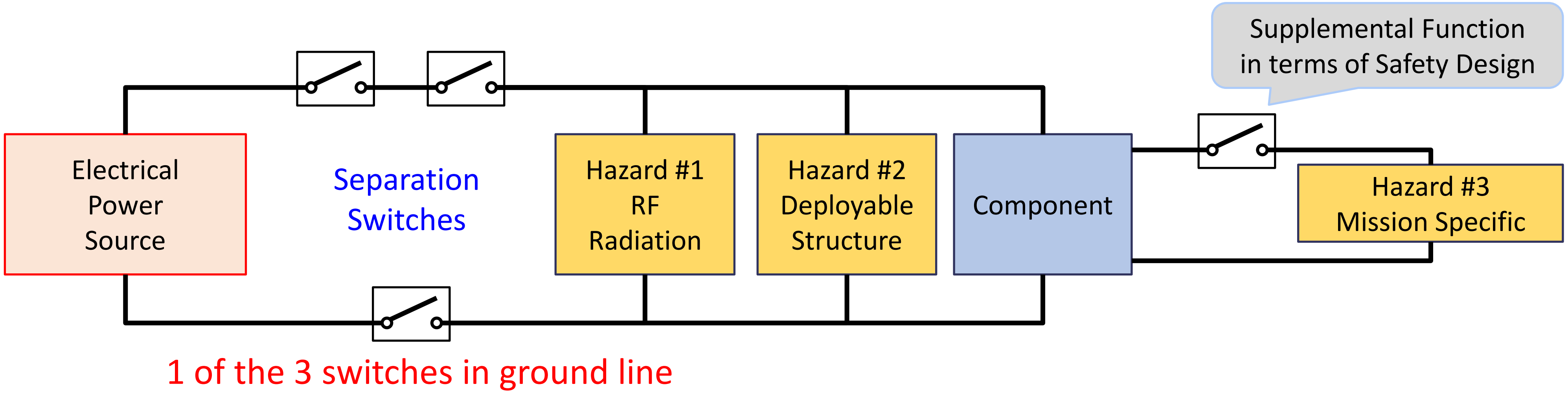
In general, a CubeSat has different kinds of common catastrophic hazards.

CubeSat Catastrophic Hazards:

1. Structural Failure ➡ KiboCUBE Academy Lecture #11, #12
2. Battery Failure ➡ KiboCUBE Academy Lecture #08
3. Radio Frequency (RF) radiation
4. Deployable structures (antenna, solar panels, etc.)
5. Other mission specific failures



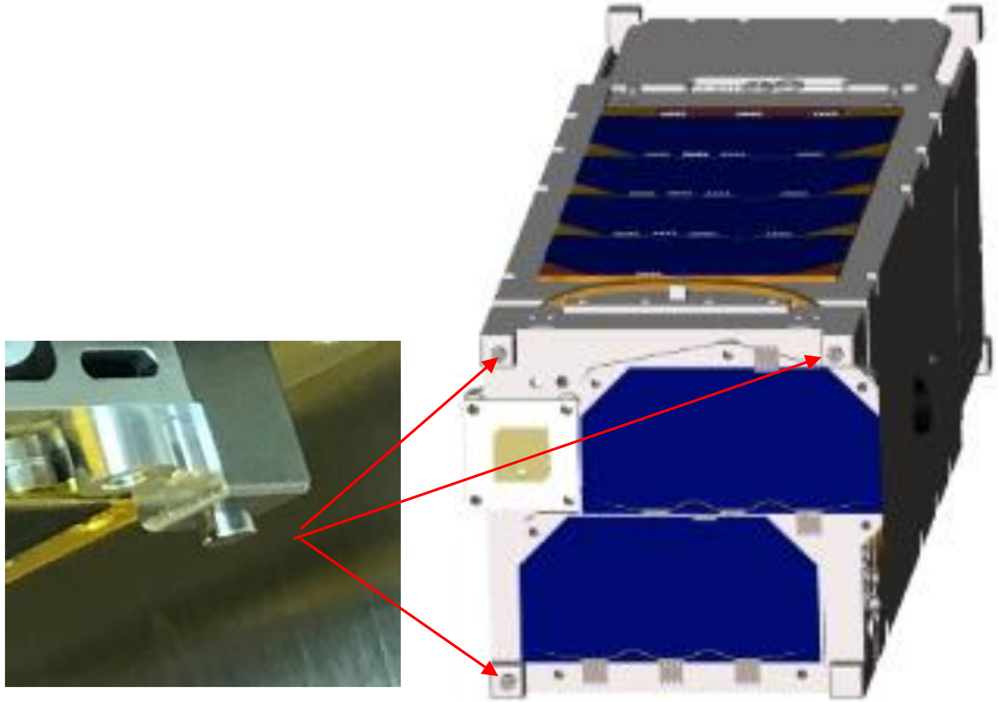
The strategic electrical safety design is to use separation switches to control as many hazards as possible, which are related to the electrical power supply

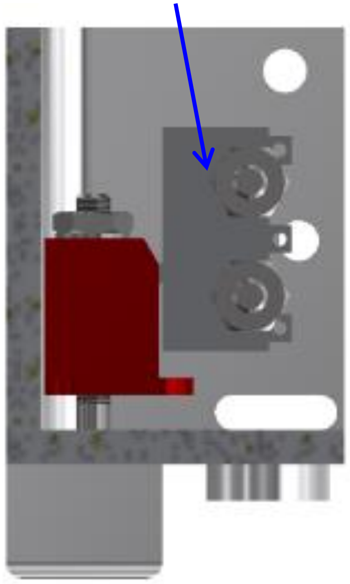


4.3. Separation Switches

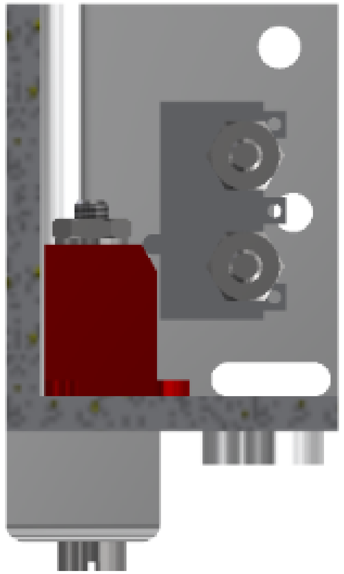
- A CubeSat (Small Satellite) is equipped with several (typically three) mechanical separation switches so that it can be securely powered-off while it is stored in the release pod.
- Mechanical switches can be directly inserted in the main current stream, or can drive other electrical switches, such as FET switches. In the former case, relatively large current flows, and in the latter case, little current flows.

<u>Design Example of Separation Switches</u>

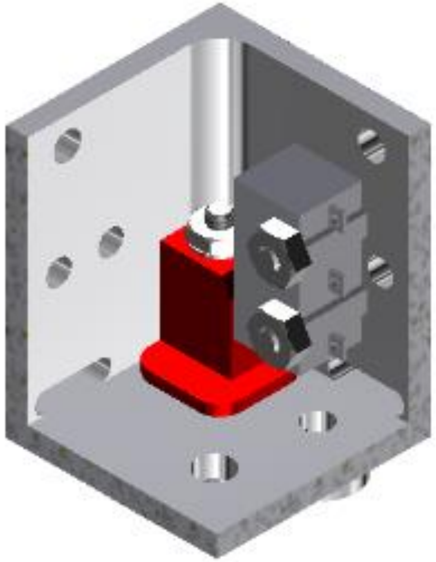




Before release



After release



4. Safety Design of CubeSat

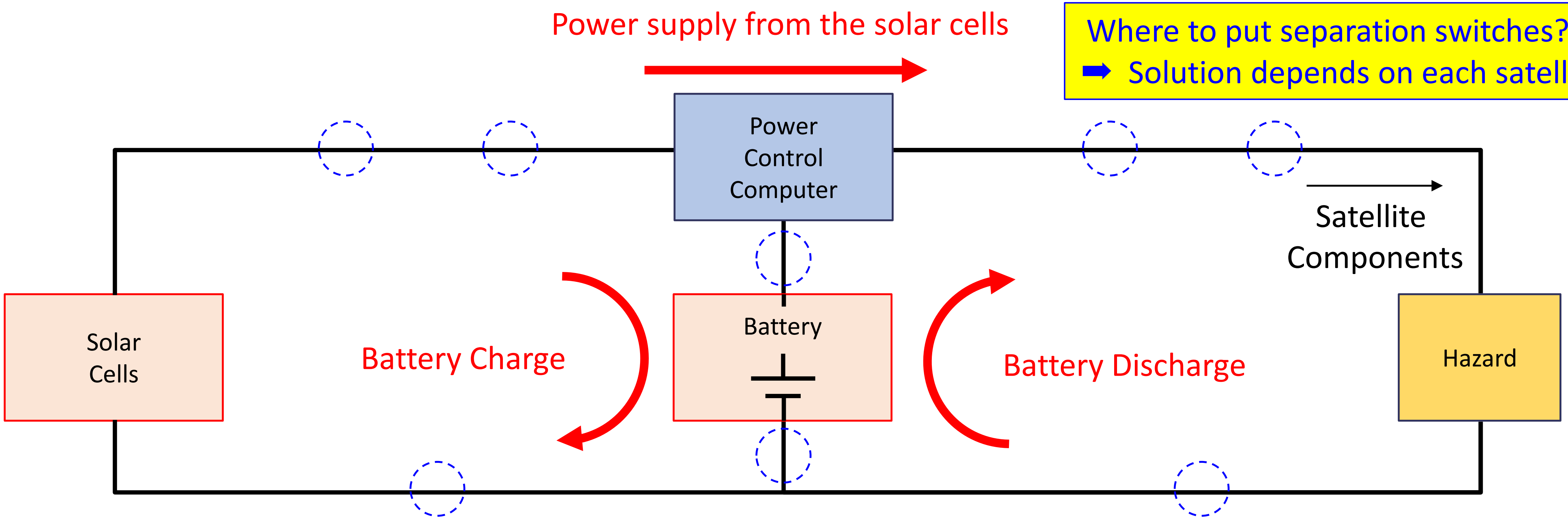
4.4. Electrical Circuit – Battery and Solar Panels

Electrical power sources of CubeSats:

- Solar Cells – Generate large volumes of power in space, but still generate small amounts in ground facilities. Disabled during launch.
- Battery – Subject to safety control even during a (cold) launch. Over charge and over discharge are also regarded as hazards as the battery could become too hot, and/or explode.

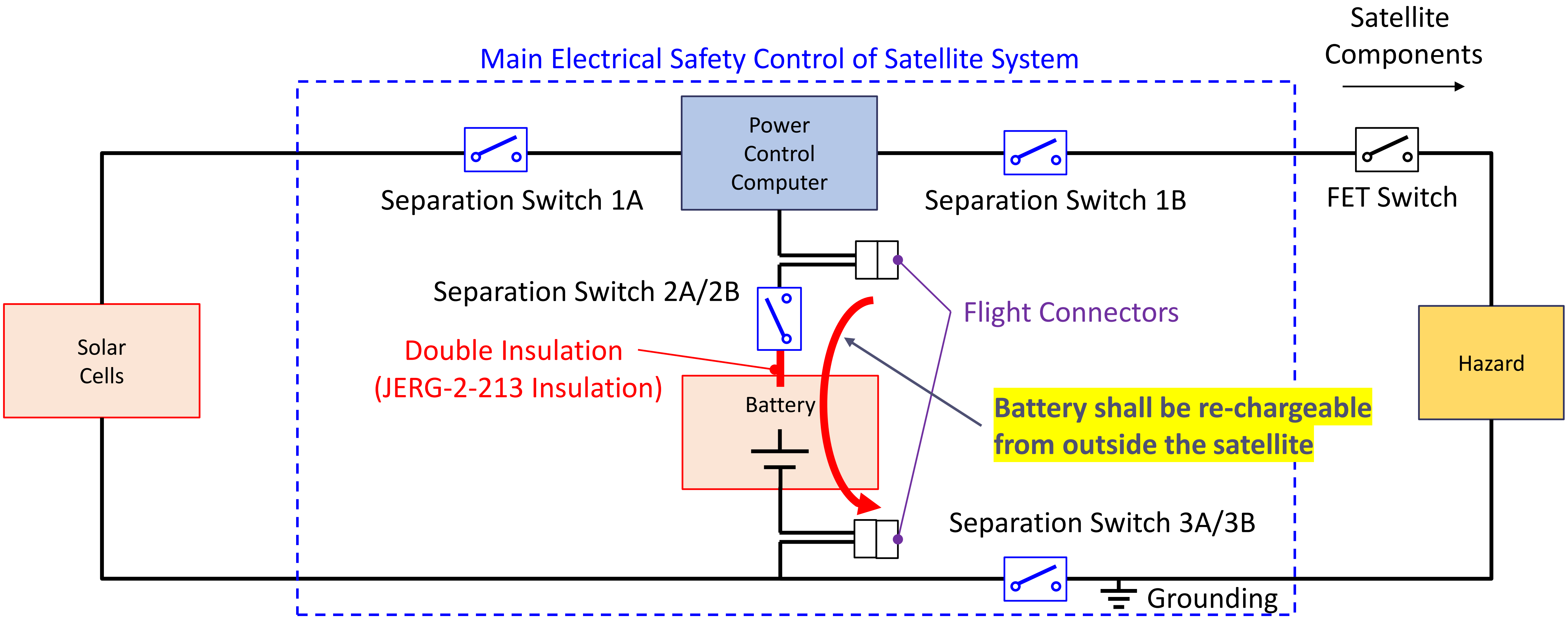
Hazard control can be electrical switches, protection ICs, double insulation, RBF (Remove Before Flight) pins, flight connectors, controlling computer, etc.

Where to put separation switches?
➡ Solution depends on each satellite.



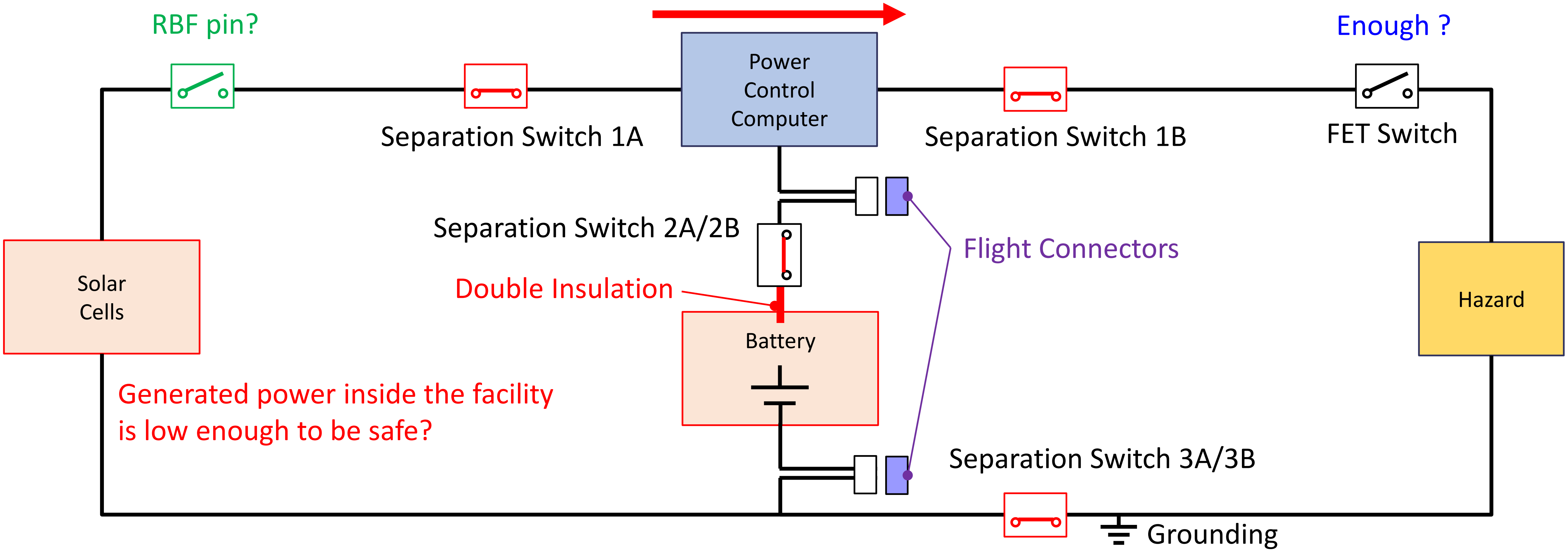
4.5. Example of Electrical Circuit Design of Power Supply System

Example of Electrical Circuit for Safety Design



4.6. Safety during Satellite Handover at Ground Facility

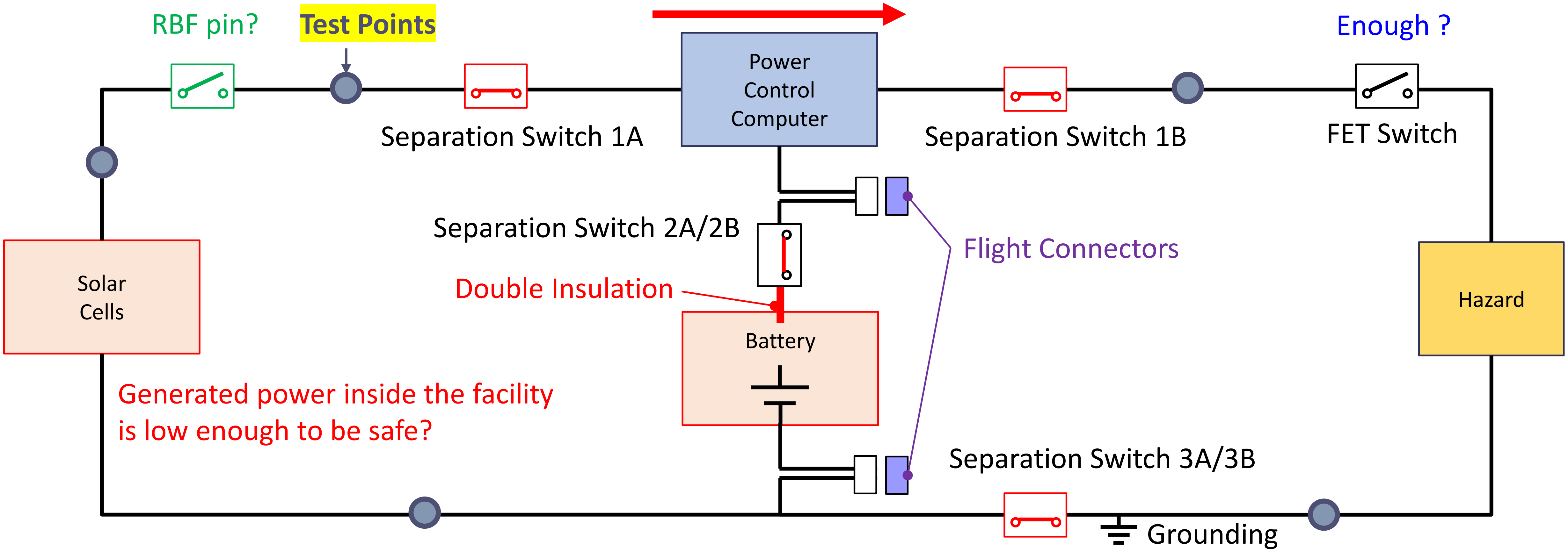
When handing over the satellite, separation switches are enabled before the insertion to the pod. It is necessary that safety is also assured in this configuration as well by means of flight connectors, RBF pins, additional switches, etc.



4.7. Test Port

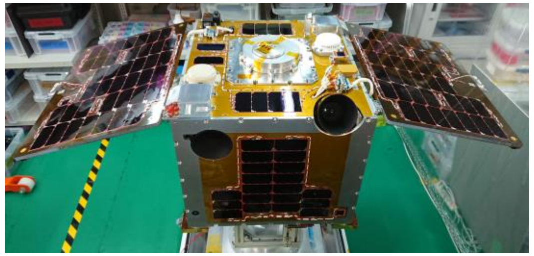
For health verification status of each inhibit for safety, test ports shall be accessible from the outside of the satellite in order to confirm the inhibits are intact through electrical measurements, such as resistances and/or voltages.

Battery shall be re-chargeable from outside the satellite through connectors.



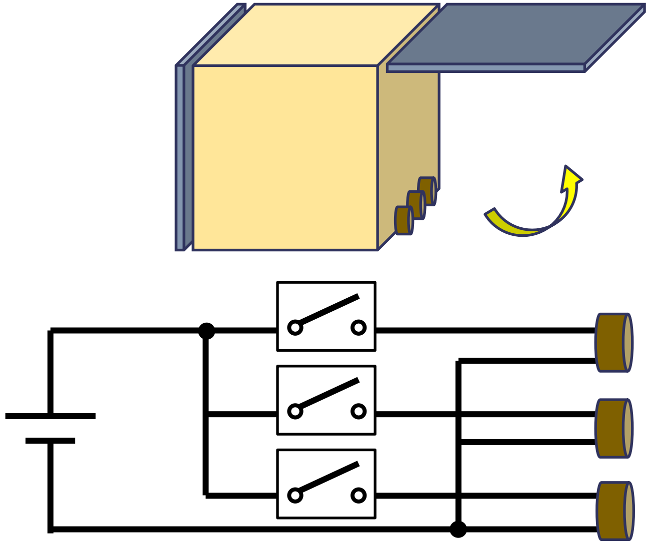
4.8. Deployment Mechanism

- All deployable mechanisms shall be designed to fulfill two-fault tolerant safety design criteria, as they are classified to be catastrophic hazards.
- Safety design approaches depend on the mechanism used, hardware resources of the satellite, and required reliability, etc.



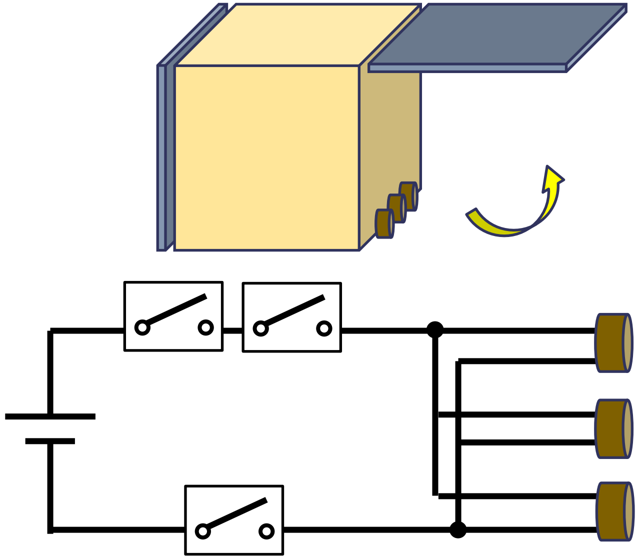
RISESAT © Tohoku University

A. Fault Tolerant Design 1



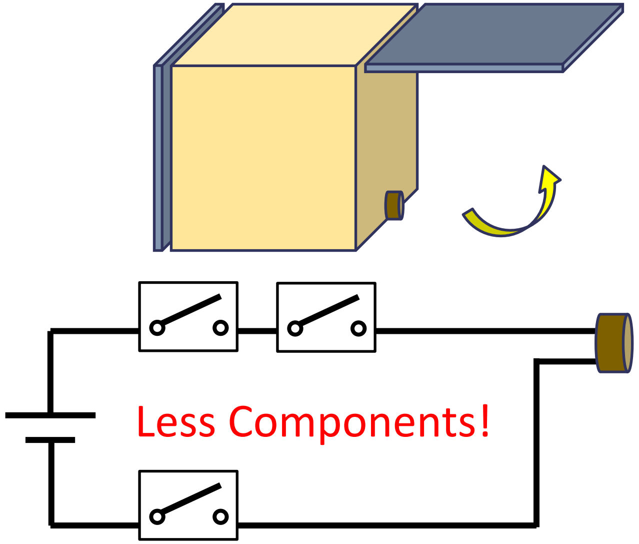
1 Electrical Switches + 1 Mechanical Switches
(Fault Tolerant Design)
x 3

B. Fault Tolerant Design 2



3 Electrical Switches (Fault Tolerant Design)
X
3 Mechanical Switches (Fault Tolerant Design)

C. Design for Minimum Risk + Fault Tolerant Design

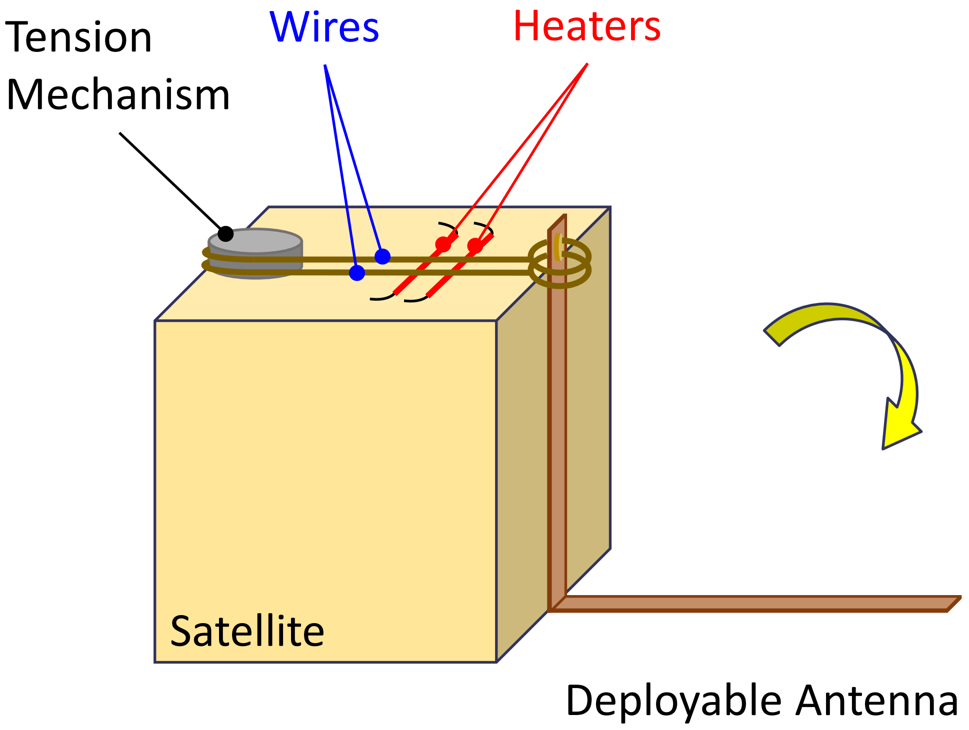


1 Mechanical Switch (Design for Minimum Risk)
X
3 Electrical Switches (Fault Tolerant Design)

4. Safety Design of CubeSat

4.9. Wire Mechanism of Deployment Structure

- Wire mechanisms can be used for the hold and release mechanism of deployable structures for CubeSats.
- Wire mechanism safety design shall fulfill the requirements specified as bellow.



Control for Wire Mechanism of Deployment Structure

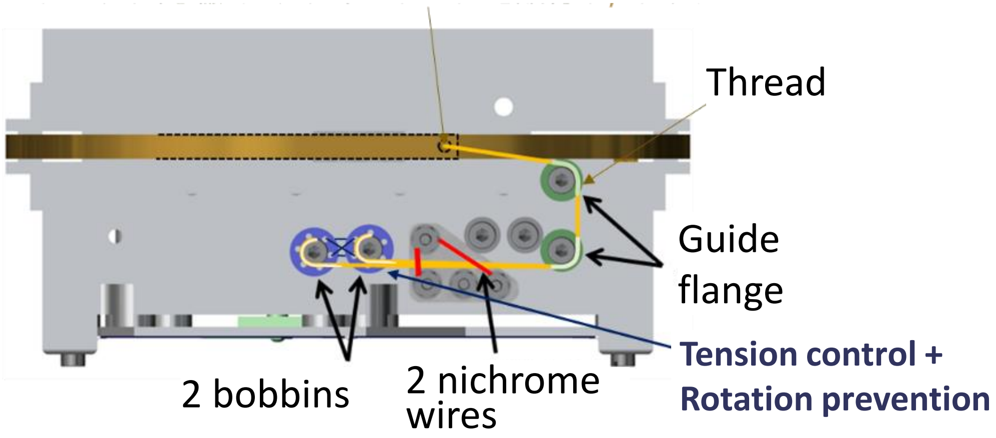
No.	Requirement
1	More than two wires are required for one constraining object
2	Test to withstand the expected maximum load by only one wire as a proof test.
3	Inspect not to exist appearance abnormality after the proof test.
4	Add cautions when using in the assembly procedure.
5	If contact between a wire and the other structure is inevitable, the contact surface of the structure shall be rounded adequately.
6	If a wire mechanism has a knot, loosening shall be prevented by adequate method.

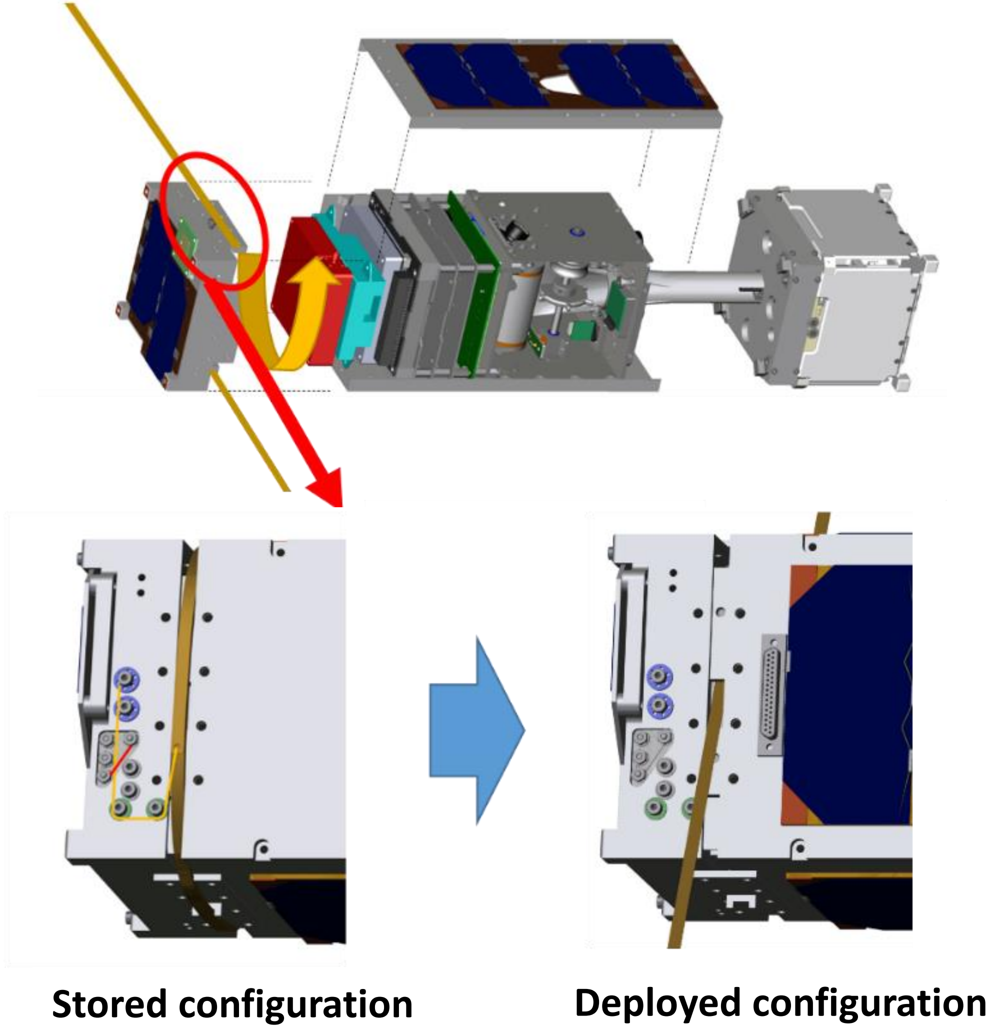
Reference: J-SSOD・Wire Strength Test Report
(https://humans-in-space.jaxa.jp/kibouser/library/item/j-ssod/25_%5BSat%20Name%5D-WTR-01_Wire_Strength_Test_Report_v2020-01.docx)

4.10. Example of Wire Mechanism of Deployment Structure – OrigamiSat-1

Example: Convex deployment antenna of OrigamiSat-1

- ✓ Wrap the two phosphor bronze convex-tape antennas around the satellite structure.
- ✓ Shorter antenna (430 MHz) is wrapped first, followed by the longer antenna (145 MHz) wrapped on top of it.
- ✓ Restrain the tip of the 145MHz antenna with Vectran® threads, fixed to the satellite body.
- ✓ Burn threads with nichrome wires.

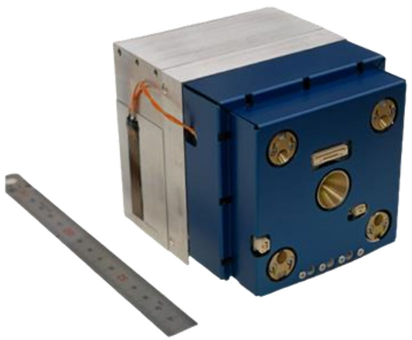
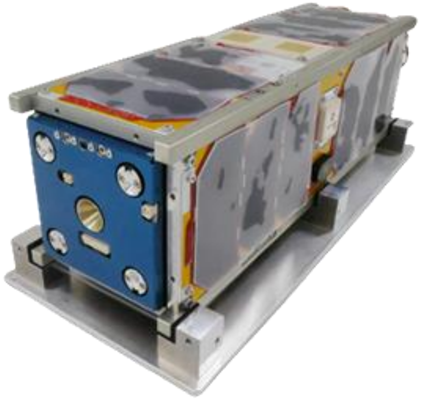




4. Safety Design of CubeSat

4.11. Thruster System

- Some of the recent advanced CubeSats are equipped with thruster systems.
  - Thruster systems are utilized to change and maintain orbits, as well as de-orbit spacecraft.
  - Technology demonstration missions are conducted to improve the performance of thruster systems for CubeSats.
- 3U CubeSat AQT-D (Pale Blue Inc.)
  - Technology demonstration of water resistojet thruster system
  - Released from the ISS on November 20, 2019. (Follow up mission on ARTEMIS I)
- Thruster systems need to fulfil safety requirements, which includes various engineering aspects, such as pressure tank, fuel materials, orbital maneuver (crash against the ISS), etc.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4. Safety Design of CubeSat

4.12. Thruster System - Hazard Identification

- Thruster systems can be hazardous against the launch vehicle, ISS, and astronauts, when an unintentional leak/explosion/misfire of propellant happens.
- Hazards shall be identified in all related mission phases, such as Launch & Release phase, astronaut operation phase, and orbital operation phase.
- Satellites released from the ISS require a safety assessment even during the orbital operation phase.
  - CubeSats shall have a lower ballistic coefficient than the ISS to ensure their lower orbital altitude than the ISS.
  - Keep-Out-Zone (KOZ) from the ISS, ±2km in the altitude direction and ±25km in the along-track and cross-track directions, shall not be penetrated by the use of thruster systems to avoid collision with the ISS.
- Identified hazards shall be controlled by applying countermeasures such as:
  - Limit the continuous injection time to suppress the maximum ΔV by implementing three independent timers.
  - Wait until the satellite altitude becomes low enough before starting the use of thrusters, so that the satellite will not enter to the KOZ even if the maximum ΔV is output.
- Reference Document: "SSP 51721 Baseline ISS Safety Requirements Document"

4.12. Thruster System - Hazard Identification

- Hazards shall be identified, and their criticality shall be analyzed in all related mission phases, such as Launch & Release phase, astronaut operation phase, and orbital operation phase.

Hazard Identification and Hazard Level Classification

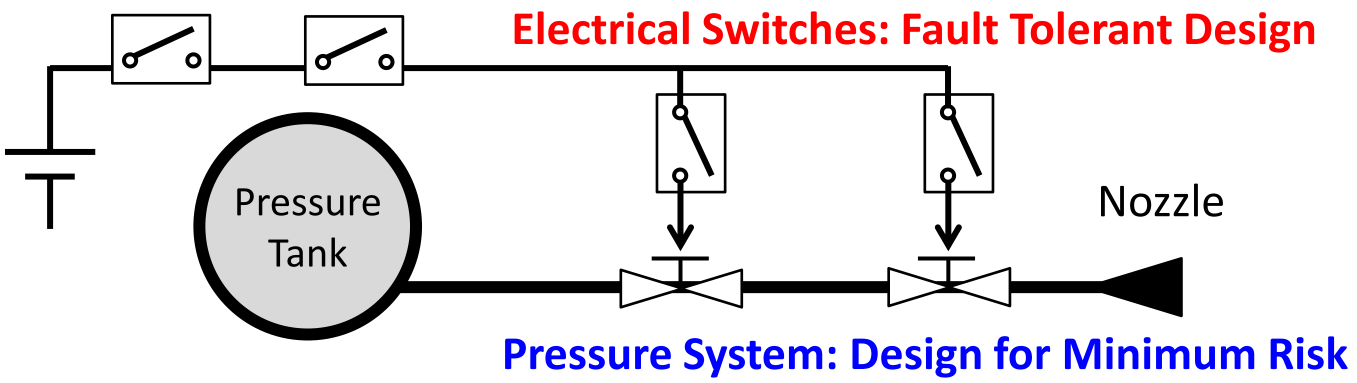
Phase	#	Hazard	Hazard Level
1). Launch & Release	1) -1	Debris from bursts of propulsion systems (propellant tanks, valves, etc.) can damage other satellites.	Catastrophic
2). ISS/IVA Clue	2) -1	Toxic propellant leakage from the propulsion system (propellant tanks, valves, etc.) can damage ISS/IVA crews.	Catastrophic
	2) -2	Debris from bursts of propulsion systems (propellant tanks, valves, etc.) can damage ISS/IVA crews.	Catastrophic
3). After Release	3) -1	Improper ejection of the propulsion system (propellant tanks, valves, etc.) can alter trajectory and collide with ISS structures and visiting vehicles.	Catastrophic
	3) -2	Debris from bursts of propulsion systems (propellant tanks, valves, etc.) may collide with ISS and visiting vehicles.	Catastrophic
	3) -3	Due to deformation of the propellant tank, it may interfere with the rails inside the CubeSat deployment mechanism (J-SSOD-R), preventing the satellite from being released at the specified speed and causing a collision with the ISS structures and visiting vehicles.	Catastrophic
	3) -4	Possibility of collision with ISS or visiting vehicles due to inappropriate operational planning.	Catastrophic

4. Safety Design of CubeSat

4.12. Thruster System - Hazard Causes Analysis

- It is necessary to identify the root causes of the hazards and clarify causal relationships with the hazards as illustrated in the below table.

Thruster System Block Diagram



Hazard Causes Identification

#	Hazard Causes	Hazard
a)	Physical failure of propellant tanks and surrounding components.	1)-1, 2)-2, 3)-1, 3)-2
b)	Selection of propellants unsuitable for handling onboard the ISS.	2)-1
c)	Erroneous application of power to the mechanism due to an electrical failure.	3)-1
d)	Contamination inside the valve due to improper dust control.	3)-1
e)	Undesired thrust generation due to inappropriate design and manufacturing.	3)-1
f)	Deformation exceeding the allowable range due to the launch and on-orbit environment.	3)-3
g)	Inadequate operational planning.	3)-4

4. Safety Design of CubeSat

4.12. Thruster System - Hazard Control Design

- After identifying the hazard causes, it is necessary to examine each control method.
- A single cause may require multiple controls, which requires a very careful engineering analysis.

Relationships between Hazard Causes and Hazard Controls

#	Hazard Causes	#	Hazard Controls
a)	Physical failure of propellant tanks and surrounding components.	i)	Structural analysis or environmental tests (acceleration, vibration, pressure, temperature, etc.).
b)	Selection of propellants unsuitable for handling onboard the ISS.	ii)	Use of non-toxic, non-flammable and inert liquid fuels.
c)	Erroneous application of power to the mechanism due to an electrical failure.	iii)	3 inhibits by 3 separation switches during the launch and before release.
		iv)	3 inhibits by 3 FET switches after release.
d)	Contamination inside the valve due to improper dust control.	v)	Dust protection measures for the valve openings.
e)	Undesigned thrust generation due to inappropriate design and manufacturing.	vi)	Confirmation of propulsion force through testing.
f)	Deformation exceeding the allowable range due to the launch and on-orbit environment.	i)	Structural analysis or environmental tests (acceleration, vibration, pressure, temperature, etc.).
g)	Inadequate operational planning.	vii)	Formulation of operation implementation plan.

4.12. Thruster System Safety Design and Management

- As the results of safety design activities, relationships of hazards, hazard causes, and hazard controls shall be summarized so that the progress of safety design and verification can be traceable.
- The identification and verification status of the hazard controls are confirmed by safety reviews.

Relationships between Hazards, Hazard Causes, and Hazard Controls

# Hazards	# Hazard Causes	# Hazard Controls
1)-1	a)	i)
2)-1	b)	ii)
2)-2	a)	i)
3)-1	a) c) d) e)	i) iii), iv) v) vi)
3)-2	a)	i)
3)-3	f)	i)
3)-4	g)	vii)

4. Safety Design of CubeSat

4.12. Thruster System – Safety Design Aspects

- NASA's TOPO (Trajectory Operations and Planning Officer) team will participate in orbital operation safety assessment.
- In case the CubeSat is equipped with thruster systems, it is necessary to pay attention to the fact that there are more review processes than satellites without thruster systems, and hence it takes longer to complete the entire review process.
- The use of software to control hazards requires a CBCS (Computer Based Control System) review. Strict design reviews will be carried out from the following aspects:
  - Whether the hazard control is canceled even if the memory contents are changed due to SEU, etc.
  - Whether abnormal commands can be detected and rejected.
  - Whether appropriate exception handling being performed.
- When performing hazard control after release, it is easy to use microcomputers or logic devices, but in that case, it is necessary to demonstrate that "no matter how much they malfunction, hazard control will not be disabled."
- CBCS can be applied not only to thruster systems but also to other hazard control. Conversely, if you have a high-performance computer that supports CBCS screening, the number of hardware hazard controls can be reduced.

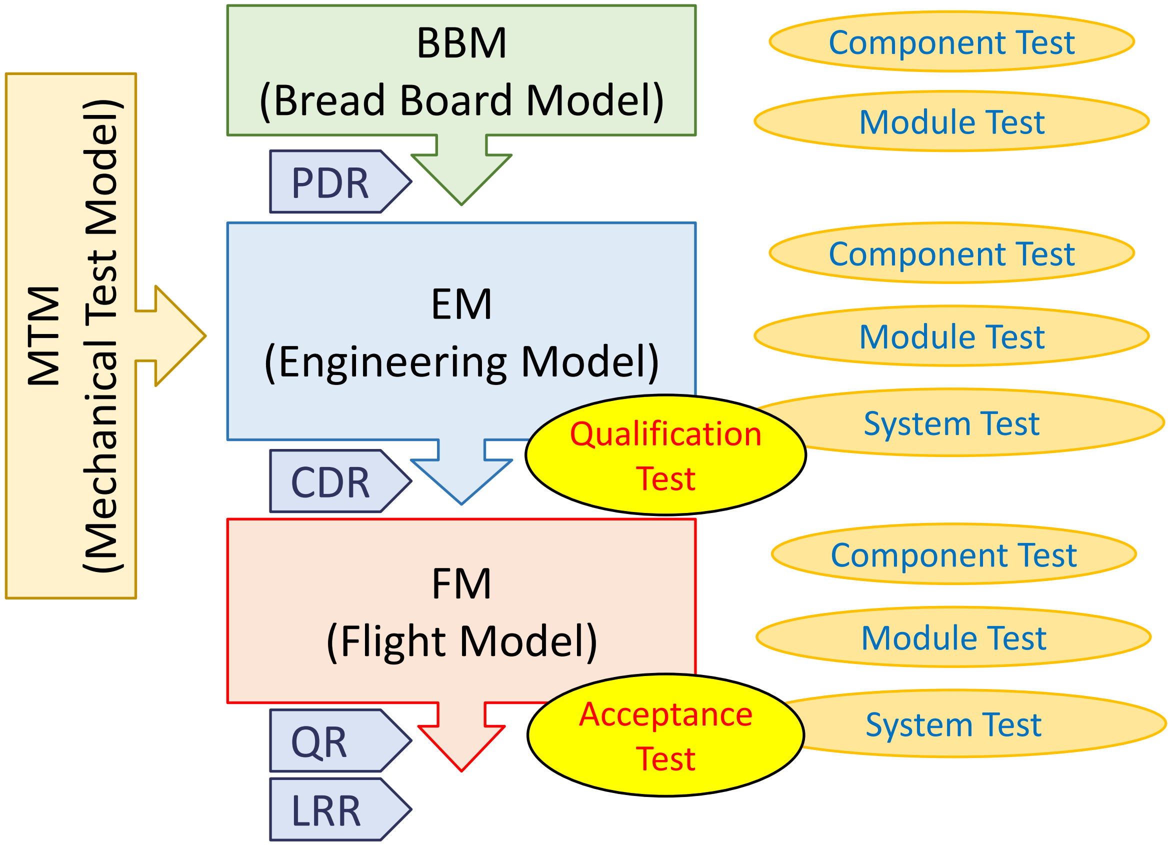
5. Documentation and Ground Testing

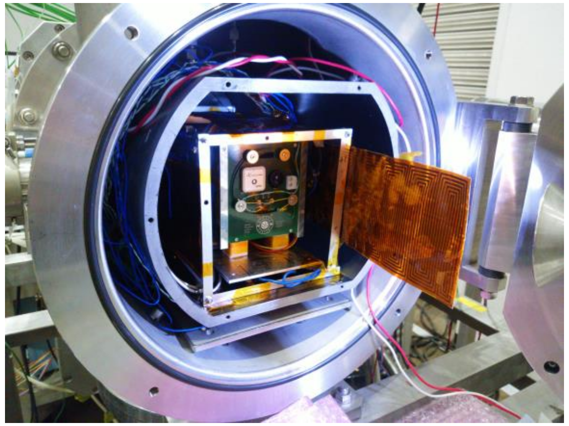
5. Documentation and Ground Testing

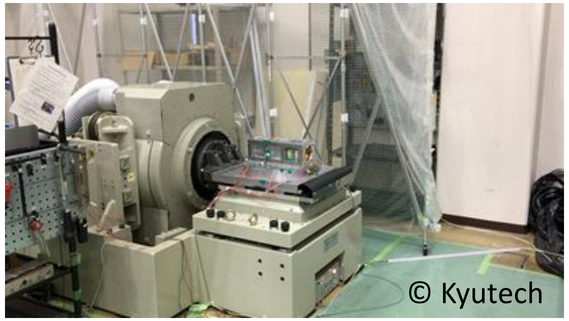
5.1. Verification Process

- Verification processes of a satellite can start from the Breadboard Model (BBM) concept verification.
- Detailed design solution of the satellite is verified using Engineering Model (EM).
- Flight Model (FM) is manufactured based on the verified design through EM, and minimum required tests are applied to obtain qualification for the launch.
- Sometimes a mechanical test model is utilized before manufacturing of the structure of the EM.

Satellite Verification Process

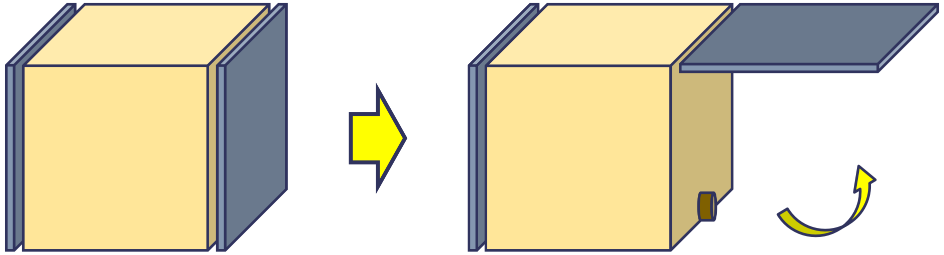






5.2. Traceability of Safety Requirements, Controls, and Verification Results

- The relationship between the safety requirements of the hazard, their controls, and verification results shall be traceable for the evaluation of the safety design.



Panel Deployment Mechanism

Hazard

Unexpected panel deployment is classified as catastrophic hazard
Unique Hazard #UH1

Causes

Electrical Failure
UH1-Cause1

Mechanical Failure
UH1-Cause2

⋮

Controls

3 electrical inhibits
UH1-Cause1-Control1

Redundant Wires
UH1-Cause2-Control1

No Sharp Edges
UH1-Cause2-Control2

Design Margin and Safety Factor
UH1-Cause2-Control3

⋮

Verification Methods

Verify electric circuit drawing.
UH1-Cause1-Control1-Verification1

Mechanical verification by vibration tests.
UH1-Cause1-Control1-Verification2

Verify mechanical drawing.
UH1-Cause2-Control1-Verification1

Visual inspection of FM.
UH1-Cause2-Control1-Verification2

⋮

Verification Results

Electrical Circuit Drawings

EM Vibration Test Plan

EM Vibration Test Results

FM Vibration Test Plan

FM Vibration Test Results

Mechanical Drawings

Visual Inspection Report

⋮

Documentation

5. Documentation and Ground Testing

5.3. Required Documents for CubeSats deployed from ISS

Required documents to be prepared and submitted to JAXA for the deployment from the ISS is listed below.

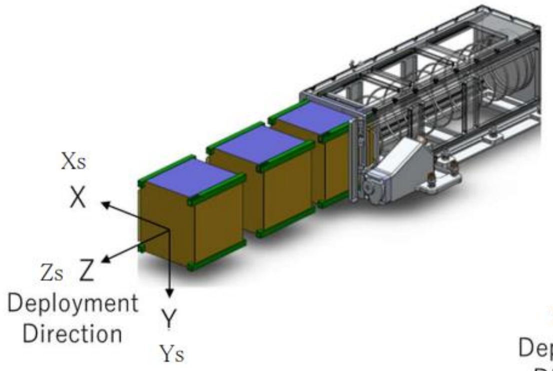
Required Documents for ISS CubeSats

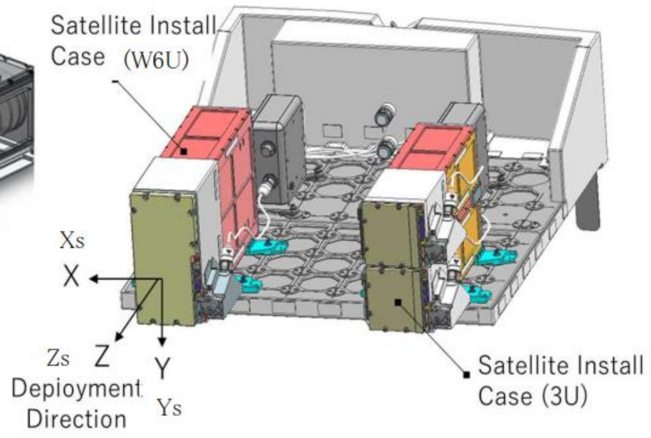
1. J-SSOD・Document List
2. J-SSOD・Satellite Information
3. J-SSOD・Structural Analysis Report
4. J-SSOD・Assembly Drawing
5. J-SSOD・Structure Fracture Control Evaluation Form
6. J-SSOD・Assembly Procedure
7. J-SSOD・Interface Verification Record
8. J-SSOD・Fit Check Test Report
9. J-SSOD・Inhibit Function Test Report
10. J-SSOD・Antenna Deployment and RF transmission Test Report
11. J-SSOD・Sharp Edge Inspection Report
12. J-SSOD・Battery Verification Test Report
13. J-SSOD・Vibration Test Report
14. J-SSOD・Wire Strength Test Report

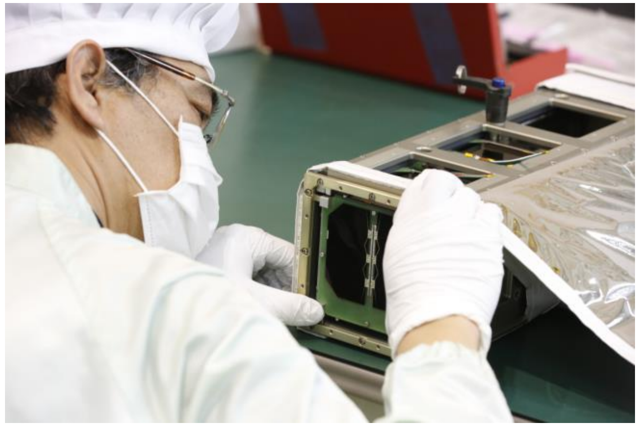
JAXA Document Templates for J-SSOD (https://humans-in-space.jaxa.jp/kibouser/provide/j-ssod/)

5.4. Fit Check

- “Fit check” is one of the most important tests of a CubeSat. A CubeSat’s mechanical and electrical compatibilities are tested using a mechanical Fit Check model of the CubeSat deployment pod.
- The manufacturing and integration of the mechanical system shall fulfill the mechanical requirements posed on CubeSats, such as dimension tolerance, surface accuracy, contact of mechanical switches, etc.
- Not only the structural design, but also the satellite integration process, shall be planned in the way that the satellite assembly and integration process is reproducible.
- It is very important that the assembly, integration and test results are carefully recorded in documents.





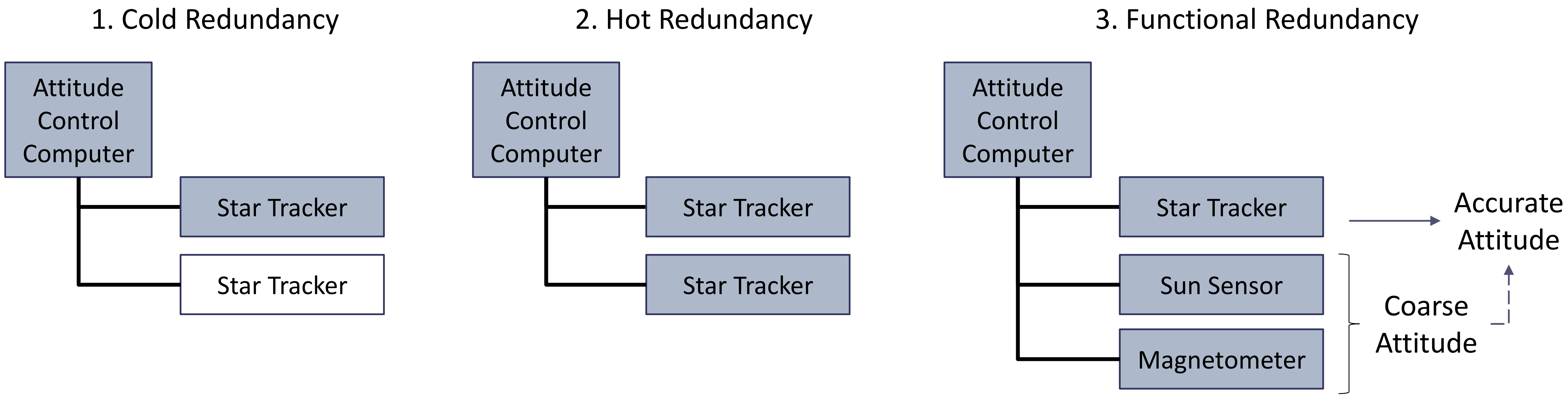


6. CubeSat Mission Assurance

6.1. Redundant Design for Mission Assurance

- Applying redundant design is one way to improve the system reliability. There are several types of redundant design approaches, such as cold redundancy, hot redundancy, and functional redundancy.
- Due to the limited resources of CubeSats, implementing functional redundancy as much as possible is the effective manner to achieve a higher improving system reliability. Some of these functional redundancy design can be implemented even just by improving on-board software.

Example of Redundant Design Application for CubeSats

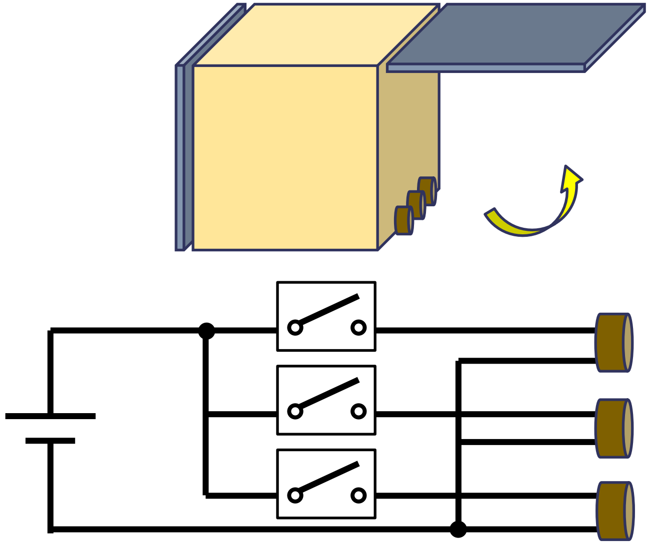


6. CubeSat Mission Assurance

6.2. Reduction of Inhibit Components for Mission Assurance

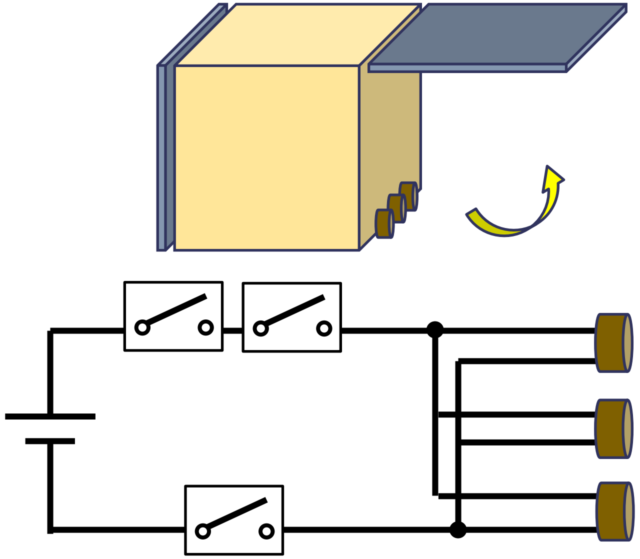
- The number of components to be implemented as the inhibits for hazard control shall be kept to as few as possible, in order to increase mission assurance.

A. Fault Tolerant Design 1



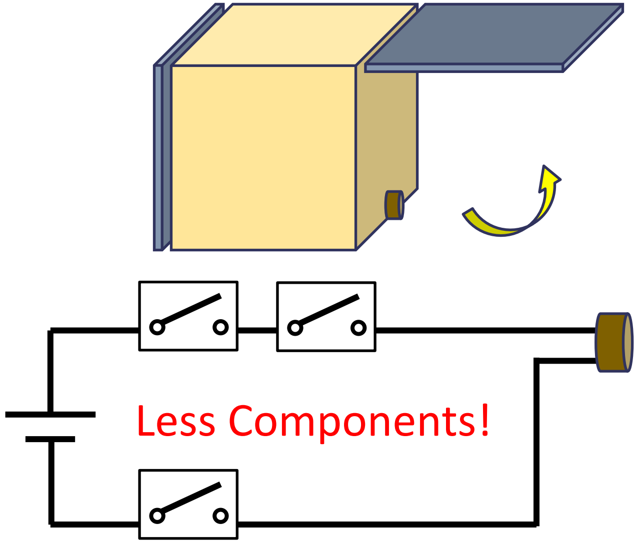
1 Electrical Switches + 1 Mechanical Switches
(Fault Tolerant Design)
x 3

B. Fault Tolerant Design 2



3 Electrical Switches (Fault Tolerant Design)
X
3 Mechanical Switches (Fault Tolerant Design)

C. Design for Minimum Risk + Fault Tolerant Design



1 Mechanical Switch (Design for Minimum Risk)
X
3 Electrical Switches (Fault Tolerant Design)

Less Reliable ⟷ **More Reliable**

6.3. Functional Evaluation for Mission Assurance

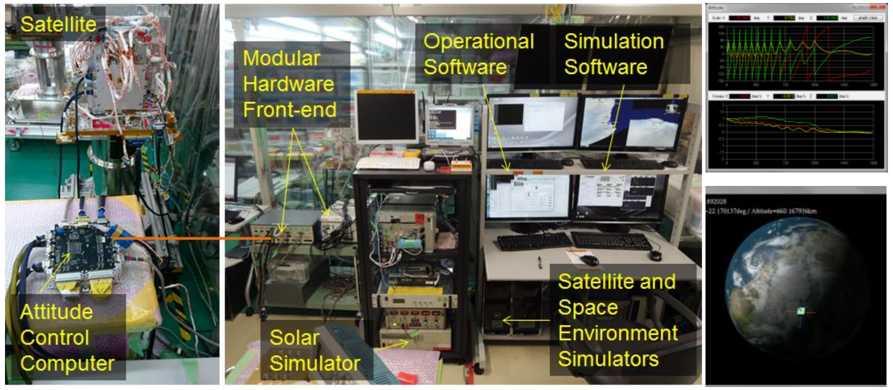
For mission assurance, planning and conducting thorough functional tests is the key to ensuring mission success in addition to the tests required for safety assurance.

Types of Tests related with Functional Evaluation:

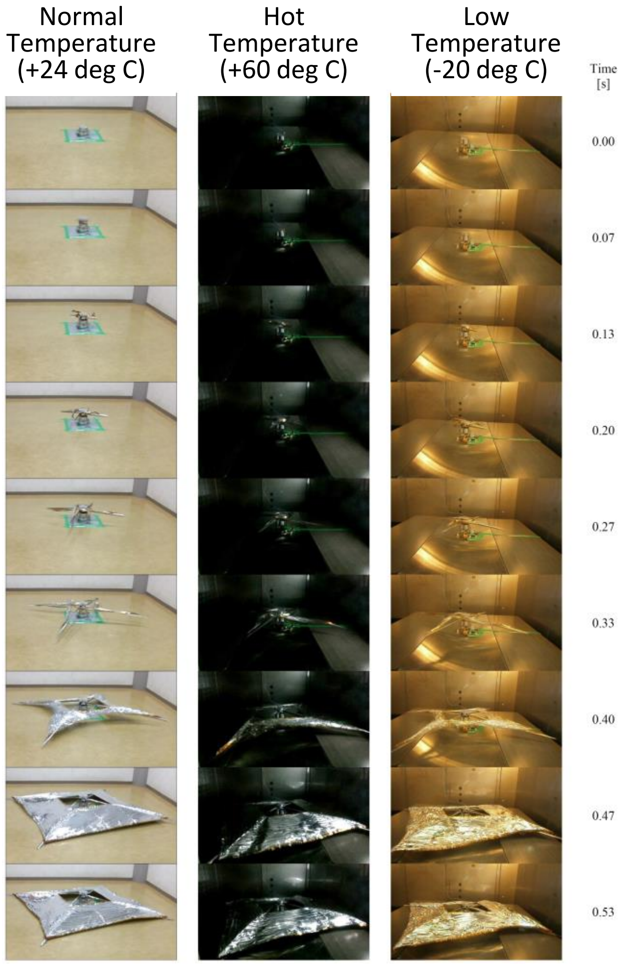
- Electrical test
- Deployment test
- Environmental test
  - Vibration test
  - Shock test
  - Thermal vacuum test
  - Radiation test
- End-to-end test
- Hardware-in-the-loop test
- Measurements
  - Antenna pattern measurement
  - Magnetic moment measurement
- Electromagnetic compatibility test
- Launcher interface test
- etc.

Electrical End-to-end Test

Ground Simulation Environment



Deployment Test of Drag-Sail



6.4. Technology Readiness Level of CubeSat Technologies

- For the effective mission assurance activities of CubeSats, it is important to evaluate and track satellite components' technology readiness levels. Components with high RTL will contribute to mission assurance.
- Strategic step-by-step in-orbit technology demonstrations through CubeSat projects for future missions is important.
- It is desired that technological heritage is shared with the community to accelerate technology development.

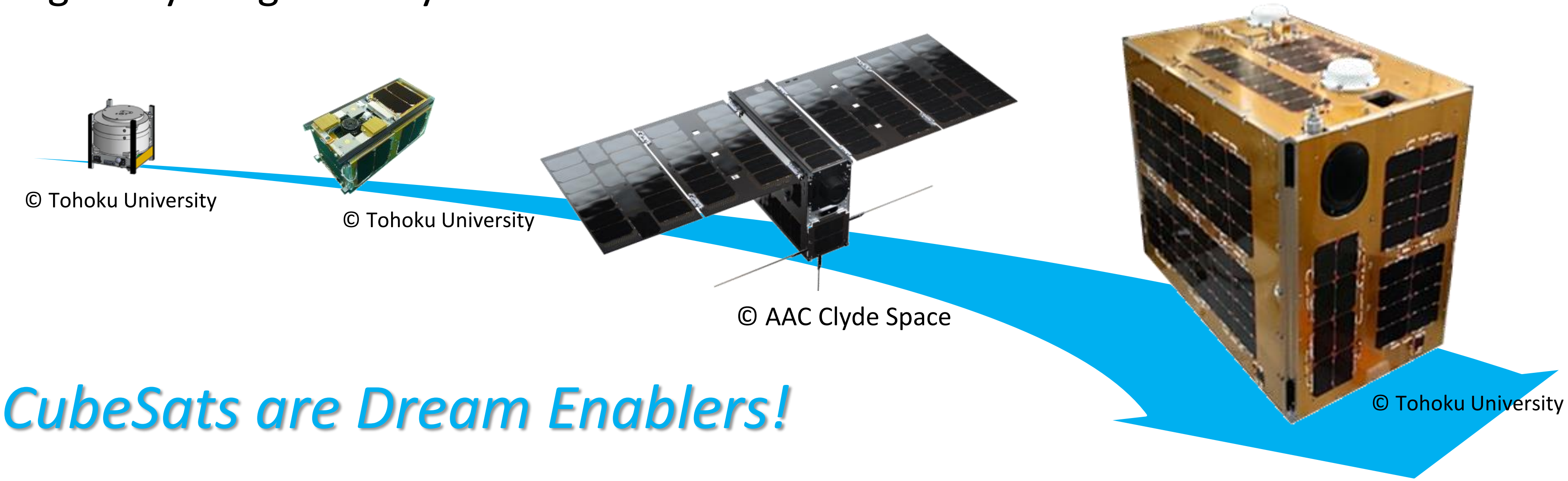
Technology Readiness Level

TRL 9	Actual model "flight proven" through in-orbit operations until the expected end of life in the actual operational environment.
TRL 8	Actual model demonstration "flight qualified" through system PFT or AT in an operational environment on the ground.
TRL 7	Qualification Model demonstration through system QT in an operational environment with adequate margins on the ground.
TRL 6	Qualification Model validation through component QT or PFT in relevant environment on the ground.
TRL 5	Engineering Model validation in relevant environment.
TRL 4	Breadboard Model validation in laboratory environment.
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept.
TRL 2	Technology concept and/or application formulated.
TRL 1	Basic principles observed and reported.

6.5. Stepwise Development of CubeSats and Beyond

"Start small, go big!"

- Recently, CubeSats have become a major game-changer in the world.
- Thanks to the technological advancement of small satellites, CubeSats are no longer for education only, but for actual space development and utilization.
- Achievements obtained from smaller CubeSats can be directly applied to larger satellites for even more advanced missions.
- 1U CubeSats bring everything within your reach!



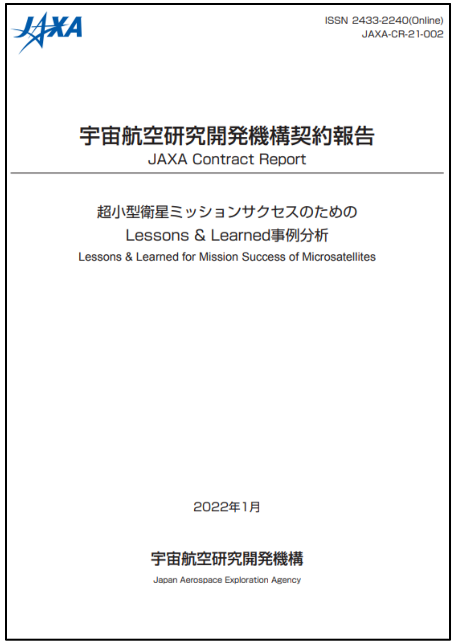
CubeSats are Dream Enablers!

6.6. UNISEC Space Engineering Education Activities

University Space Engineering Consortium

6.7. Mission Assurance Activities

- JAXA and UNISEC are now working closely together on the mission assurance activities for small space systems.
- Lessons Learned for Mission Success of Microsatellites (Japanese):
  (JAXA Contract Report AA2130015000; doi/10.20637/00048260)
- Mission Assurance Handbook for the University-built Lean Satellite:
  (http://unisec.jp/ma_files/mission_assurance_handbook_en.pdf)



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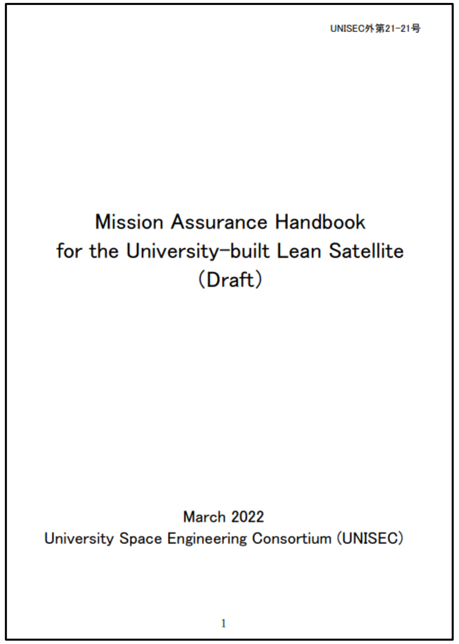
宇宙航空研究開発機構契約報告
JAXA Contract Report

超小型衛星ミッションサクセスのための
Lessons & Learned事例分析
Lessons & Learned for Mission Success of Microsatellites

2022年1月

宇宙航空研究開発機構
Japan Aerospace Exploration Agency



UNISEC外第21-21号

Mission Assurance Handbook
for the University-built Lean Satellite
(Draft)

March 2022
University Space Engineering Consortium (UNISEC)

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6.8. UNISEC-Global – Worldwide Space Engineering Community

- Non-Governmental Organization consisting of University Consortiums around the world.
- Established in 2013.
- Permanent observer status of UNCOPUOS (The United Nations committee on the Peaceful Uses of Outer Space) since 2017
- Aim to create a world where space science and technology is used by individuals and institutions in every country and offers opportunities across the whole structure of society for peaceful purposes and for the benefit of humankind.

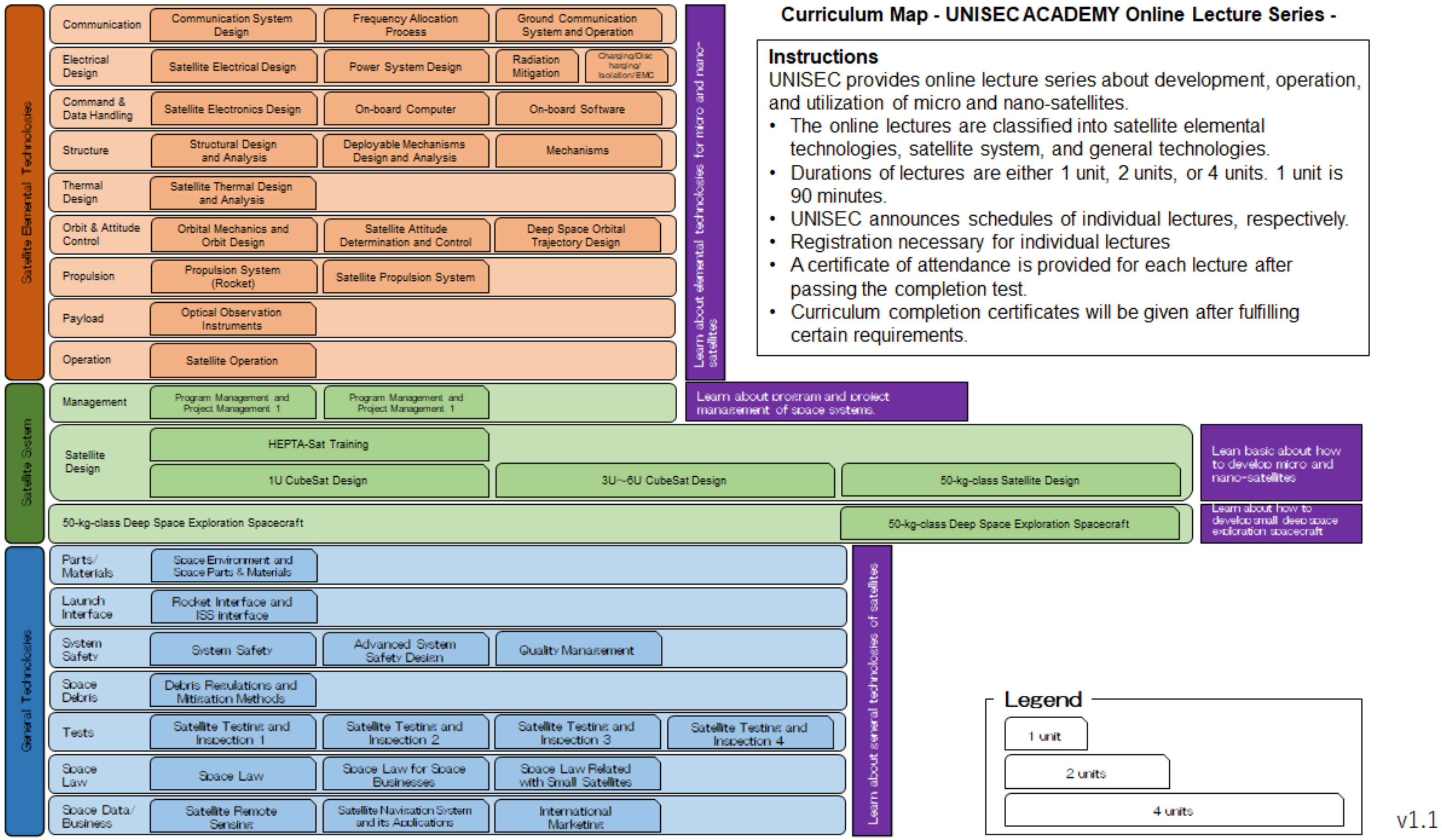
21 Local Chapters with 55 POC.

Vision 2030-All

"By the end of 2030, let's create a world where university students can participate in practical space projects in all countries."

6.9. UNISEC Academy – Curriculum for Space Development/Utilization

- UNISEC is offering a series of lectures for space development and utilization in Japanese. English curriculum is coming soon.



7. Conclusion

7. Conclusion

- System engineering processes of CubeSats were introduced and an overview of their design and review processes are explained. Satellite subsystems classification, satellite development models, such as BBM, EM, and FM, and related system engineering activities are described.
- Relationship of the safety and mission assurance (S&MA) activities, together with launch vehicle compatibility, were explained and safety design requirements, as well as the launch and release environment from the ISS was introduced.
- Detail of the safety design process was elaborated and CubeSat safety and design reviews, precedence in safety design approaches, relationship between satellite development models and their design/safety reviews are explained. Types (standard and unique) and severity level classification of hazards were introduced. Two major safety design methods were introduced, such as fault tolerant design and design for minimum risk.
- Examples of actual safety designs of CubeSats were introduced in terms of separation switches, electrical circuits, deployment mechanisms, wire mechanisms for deployment structures, and thruster systems.
- Verification and documentation activities related with satellite S&MA activities were explained.
- Related topics with CubeSat mission assurance were introduced, including redundant design methods, technology readiness level, strategic in-orbit demonstration approach, and space engineering education activities of UNISEC.

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.