KiboCUBE Academy

Lecture 22

Propulsion Systems for Microsatellite

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Department of Aeronautics and Astronautics
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This lecture is NOT specifically about KiboCUBE and covers GENERAL engineering topics of space development and utilization for CubeSats.
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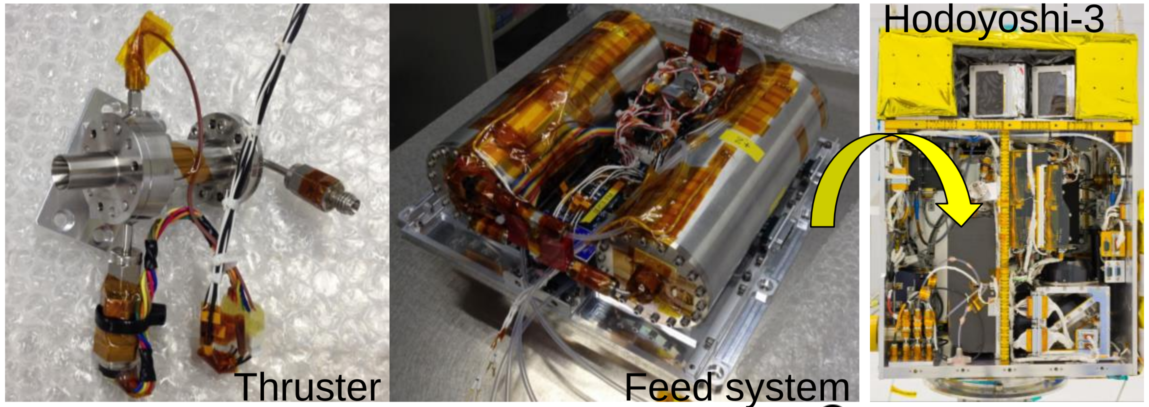
https://www.unoosa.org/oosa/en/ourwork/psa/hsti/kibocube.html

Lecturer Introduction



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SAHARA, Hironori, Ph.D.

Position:

1994	Graduated from Faculty of Engineering, Kyoto University
1996	Master’s degree in Engineering from Graduate School of Engineering, Kyoto University
1999	Ph. D from School of Engineering, University of Tokyo
2000 – 2003	Research Fellow, National Aerospace Laboratory of Japan (currently part of JAXA)
2004 – 2007	Research Associate in University of Tokyo
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Research Topics:

Development of innovative space systems as propulsion, system architecture, satellite structure, orbit cultivation, and their applications including artificial meteor.

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3. Chemical Propulsion
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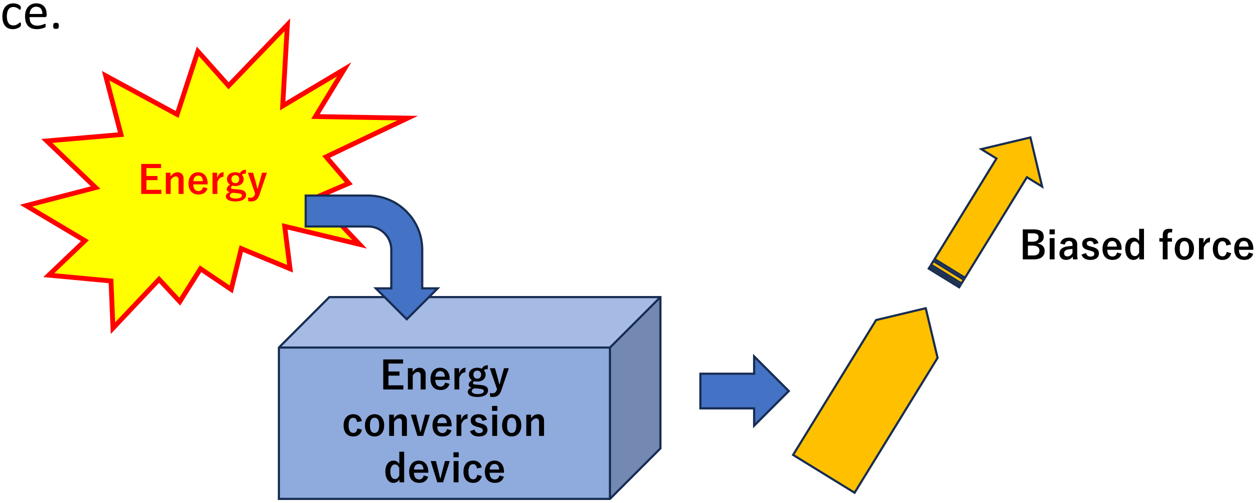
1. Fundamentals of Propulsion System

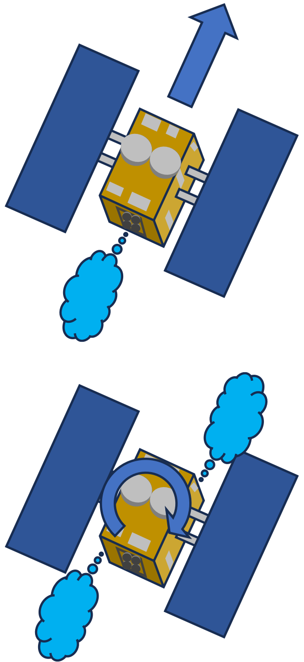
1.1 Classification of Propulsion

In a spacecraft,
A propulsion System is an energy conversion device that generates temporally and spatially biased kinetic energy from some energy source.



- If an external force is applied through the center of gravity of a spacecraft, a change in velocity occurs in that direction, causing the spacecraft to change its orbit.

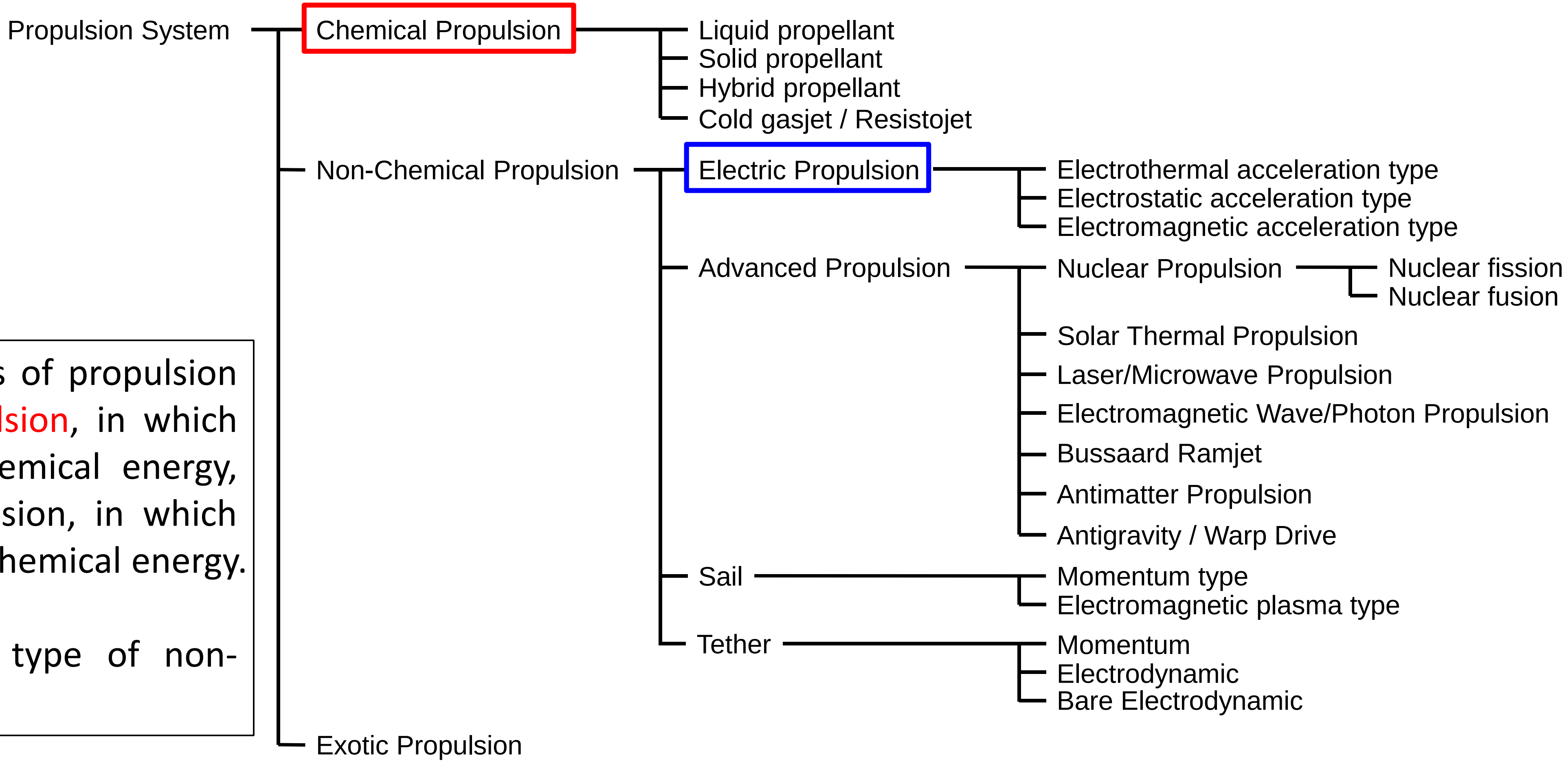
- An external force applied off the center of gravity of a spacecraft generates a torque, which is used for attitude control or unloading of reaction wheel.



1. Fundamentals of Propulsion System

1.1 Classification of Propulsion

Propulsion systems are classified according to what the energy source is and how the propellant is accelerated.



- Propulsion System
  - Chemical Propulsion
    - Liquid propellant
    - Solid propellant
    - Hybrid propellant
    - Cold gasjet / Resistojet
  - Non-Chemical Propulsion
    - Electric Propulsion
      - Electrothermal acceleration type
      - Electrostatic acceleration type
      - Electromagnetic acceleration type
    - Advanced Propulsion
      - Nuclear Propulsion
        - Nuclear fission
        - Nuclear fusion
      - Solar Thermal Propulsion
      - Laser/Microwave Propulsion
      - Electromagnetic Wave/Photon Propulsion
      - Bussaard Ramjet
      - Antimatter Propulsion
      - Antigravity / Warp Drive
    - Sail
      - Momentum type
      - Electromagnetic plasma type
    - Tether
      - Momentum
      - Electrodynamic
      - Bare Electrodynamic
  - Exotic Propulsion

- First, there are two types of propulsion systems: Chemical Propulsion, in which the energy source is chemical energy, and non-chemical propulsion, in which the energy source is not chemical energy.

- Electric Propulsion is a type of non-chemical propulsion.

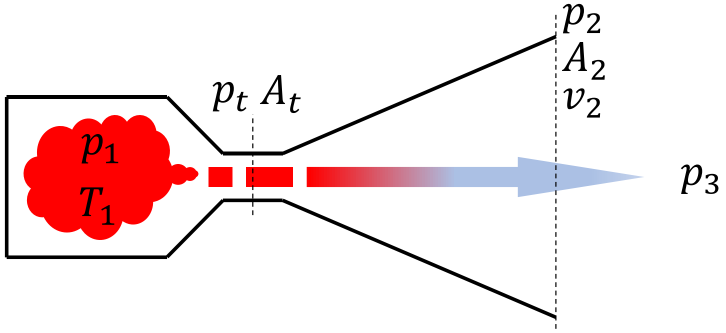
1. Fundamentals of Propulsion System

1.2 Need to Know about Propulsion Performance

- **Thrust**, F
  is the force exerted by a propulsion system. The larger the force, the greater the acceleration of spacecraft.

$$F = \boxed{\dot{m}v_2} + \boxed{(p_2 - p_3)A_2} = \dot{m}c = C_F A_t p_1 = \dot{m}c^* C_F = \dot{m}gI_{SP}$$

Momentum thrust   Pressure thrust



- **Specific Impulse**, I_{SP}
  is an indicator of the propellant consumption of a propulsion system, which indicates how many seconds the propellant can be injected for a given amount of propellant at a given thrust.

$$I_{SP} = \frac{F}{\dot{m}g}$$

Thrust and specific impulse tend to be opposites,
and thus, they can be compared to a sprinter with large thrust and a marathon runner with high specific impulse.

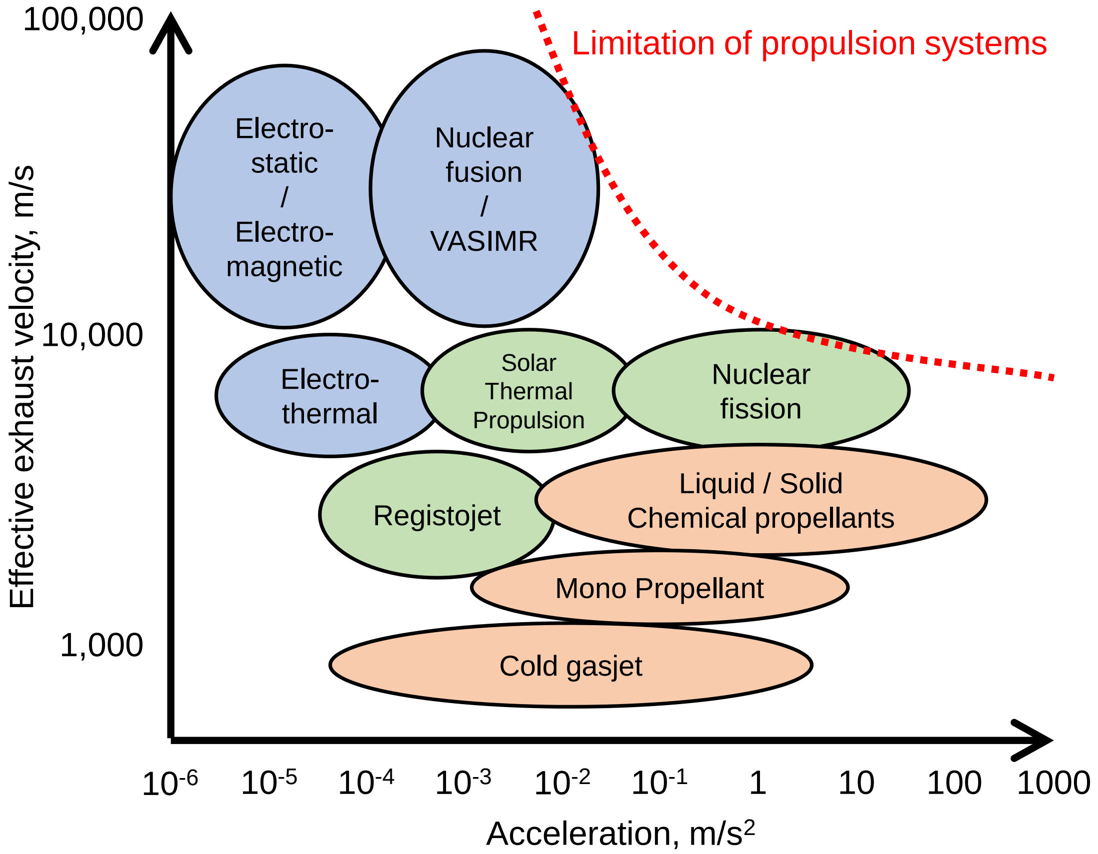
1. Fundamentals of Propulsion System

1.2 Need to Know about Propulsion Performance

Limitation of propulsion systems exist due to the relation between thrust and specific impulse:

- Chemical Propulsion has an upper limit to the chemical energy that the propellant possesses and can manifest.

- Theoretically, the more power is applied to Electric Propulsion, the better the performance. However, there is a practical upper limit to the amount of power that can be applied.



1. Fundamentals of Propulsion System

1.2 Need to Know about Propulsion Performance

- **Thrust density**
  is the thrust per unit area at the propellant exhaust surface, which affects the thruster dimensions.
- **Propellant mass flow rate**, $\dot{m}$
  is the mass flow rate of propellant consumed per unit time.
- **Effective exhaust velocity**, c
  is the exhaust velocity, which is the sum of momentum thrust and pressure thrust.

$$c = v_2 + \frac{(p_2 - p_3)A_2}{\dot{m}}$$

- **Characteristic exhaust velocity**, c^*
  is an indicator that allows evaluation of designs and propellants between different thrusters, and particularly in chemical propulsion, represents characteristics of the combustion chamber.

$$c^* = \frac{p_1 A_t}{\dot{m}} = \frac{g I_{SP}}{C_F} = \frac{c}{C_F}$$

1. Fundamentals of Propulsion System

1.2 Need to Know about Propulsion Performance

- **c^* efficiency**, η_{c^*}
  is the ratio of the characteristic exhaust velocity obtained from the measured combustion chamber pressure to the theoretical value. Because of the loss of thermal energy in the combustion chamber, values of 70-90% are taken.
- **Nozzle efficiency**, η_F
  is the ratio of the kinetic energy of the exhaust per unit mass to the theoretical value. It is about 90% depending on the effect of a boundary layer on the nozzle wall.
- **Nozzle correction factor**, λ
  If a nozzle is not the bell-shaped, the propellant diffuses at the nozzle exit.
  For a conical nozzle, when a half angle of the nozzle is α,
  $$\lambda = \frac{1}{2}(1 + \cos\alpha)$$
- **Thrust-to-weight ratio**
  is the amount of thrust that a propulsion system can exert per unit mass.

1. Fundamentals of Propulsion System

1.2 Need to Know about Propulsion Performance

- **Total impulse**
  is, as it is named, the total impulse, or the total momentum change exerted by a propulsion system in consuming all of propellant.
- **Impulse bit**, I_{bit}
  is an impulse obtained by the propulsion system in a given time of operation, and its minimum value (minimum impulse bit) is particularly important for sensitive trajectory change and attitude control.
- **Rise/Fall time**
  The rise time from an opening of the valve to a given thrust, and the fall time from an closing of the valve to the return of the thrust to zero affect responsiveness of the propulsion system and its effective impulse bit.
  When the rise and fall times are short, the propulsion system is also called a "sharp" propulsion system.
- **Throughput**
  is often expressed as the total propellant consumption that can sustain performance and is generally affected by catalyst degradation.
- **Continuous operation time**
  is a continuous injection time over which thruster performance is guaranteed and is greatly influenced by thermal constraints of the material and catalyst.

1. Fundamentals of Propulsion System

1.2 Need to Know about Propulsion Performance

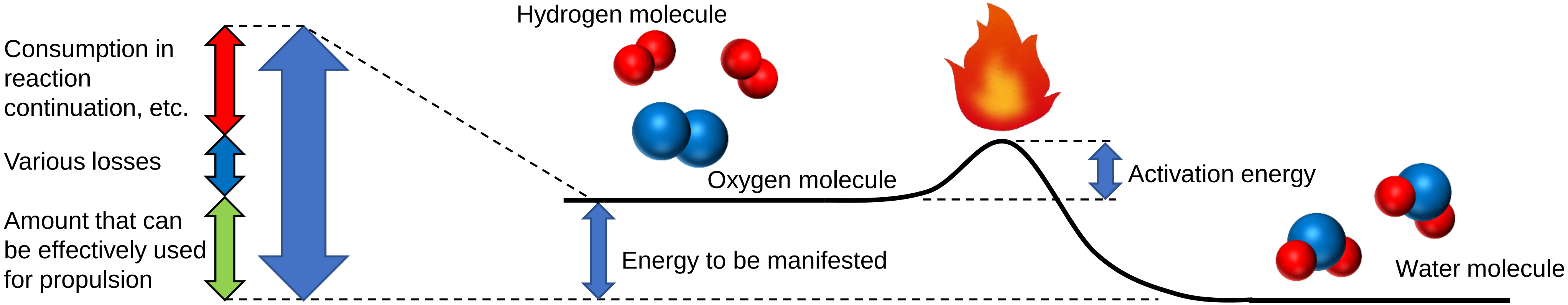
- **Thrust-to-power ratio**
  is the amount of thrust that a propulsion system can exert per unit of power and is especially important for electric propulsion.
- **Thrust efficiency**
  is the ratio of kinetic energy of propellant exhaust to power consumed by the propellant system, especially in electric propulsion.
- **Propellant utilization efficiency**
  is an indicator of how much propellant is available as ion beam, especially in electric propulsion, and is obtained as the actual extracted current relative to the extracted current obtained when all propellants are monovalent ions.
- **Ion production cost**
  is the value of ion beam current divided by power consumption.
- **Purviance**
  is particularly relevant to ion beam shape in ion thrusters and determines the characteristics of the ion beam current to be extracted.

The indicators listed in this page are exclusively referenced to electric propulsion and are rarely used in chemical propulsion.

1. Fundamentals of Propulsion System

1.3 Chemical Propulsion

- Chemical propulsion exploits the difference in chemical binding energy before and after a chemical reaction such as combustion or decomposition.



Chemical equation $H_2 + \frac{1}{2}O_2 \longrightarrow H_2O$

Thermochemical equation $H_2 + \frac{1}{2}O_2 = H_2O(L) + 286\text{kJ}$

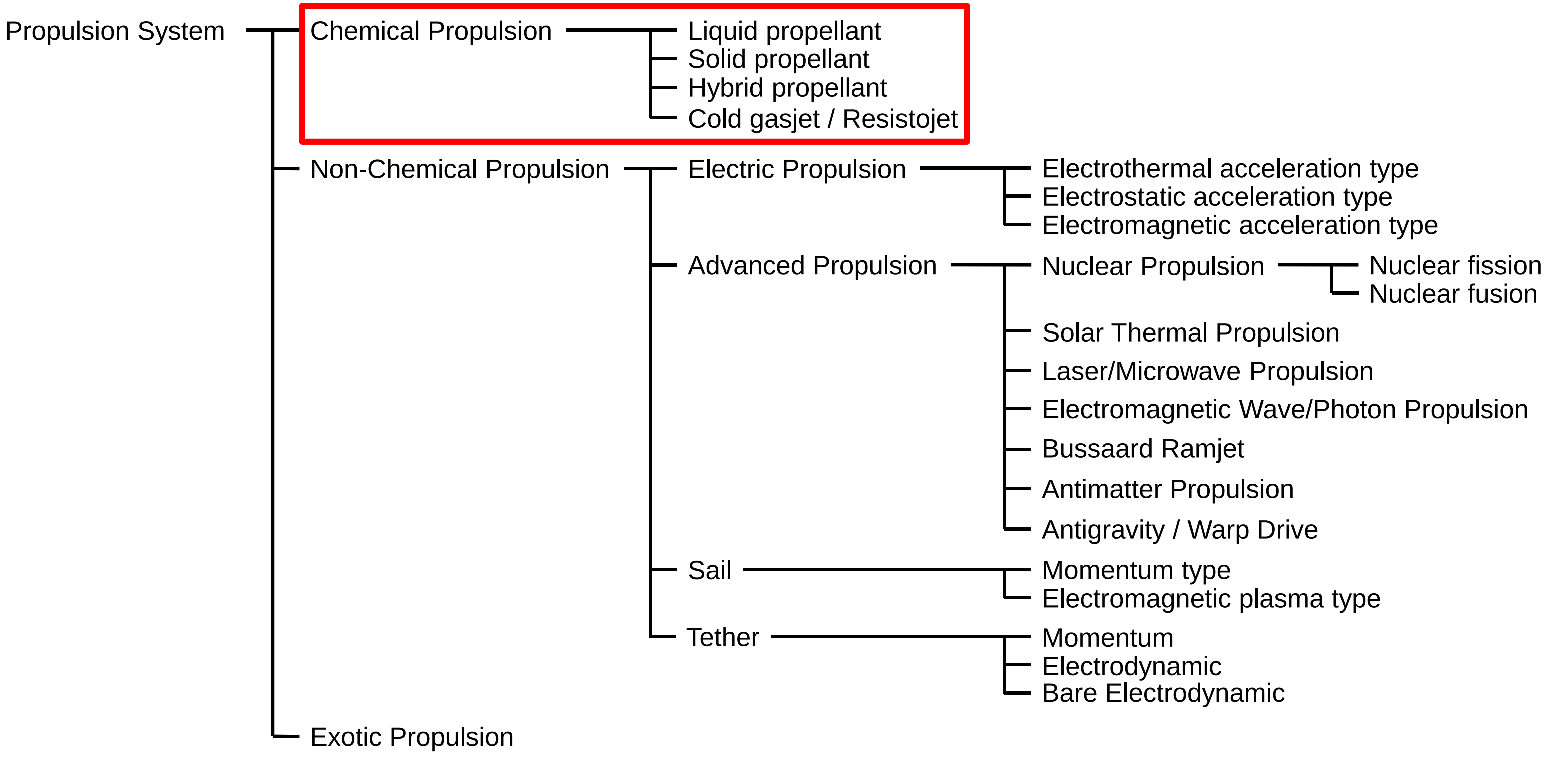
$H_2 + \frac{1}{2}O_2 = H_2O(G) + 242\text{kJ}$

- The rest of the energy manifested by the chemical reaction, excluding the portion used to continue the reaction or phase change and various losses, can be utilized by the propulsion system.

1. Fundamentals of Propulsion System

1.3 Chemical Propulsion

- In chemical propulsion, chemical energy is manifested by reacting one or several types of propellants.
- Classified as liquid-, solid-, or hybrid-propellant, depending on the phase state prior to chemical reaction.
- Depending on the number of propellants used, it is called mono-propellant type, bi-propellant type, and so on.
- Cold gas-jet, which does not involve chemical reactions, are also classified as chemical propulsion because they are based on physical and chemical properties such as temperature and pressure at the time of supply.
- Resistojet uses electrical energy to heat propellant with a heater, but only to change the physical properties of the propellant, so that is positioned as an enhanced version of cold gas-jet.

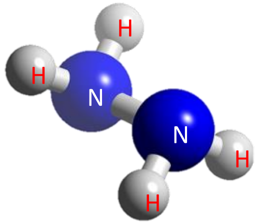


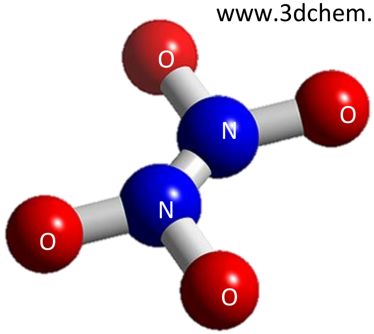
1. Fundamentals of Propulsion System

1.3 Chemical Propulsion

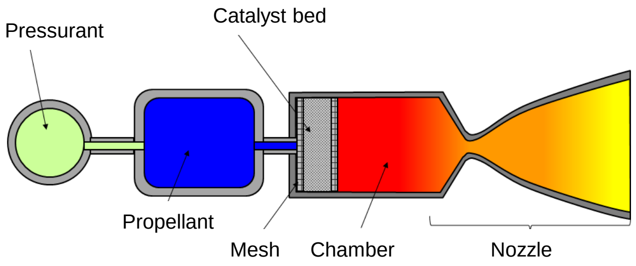
- **Mono-propellant**
  - Currently, hydrazine such as monomethylhydrazine are the mainstream.
  - Thrust can be set as desired, from 1 N to 4000 N, etc.
    Variable thrust by pulse actuation is also possible.
  - Simpler than bi-propellant type, but specific impulse is up to 200 to 250 sec.
  - Mainly used for Reaction Control System (RCS).
- **Bi-propellant**
  - Currently, the mainstream is to react fuel (hydrazine, monomethylhydrazine, asymmetric dimethylhydrazine, etc.) with an oxidizer (dinitrogen tetroxide, etc.)
    in a thrust chamber, where hypergolic propellant combinations are preferred.
  - Thrust is large.
  - Specific impulse is just over 300 sec.
  - It is mainly used to obtain a large velocity increment for orbit injection and orbit transfer.

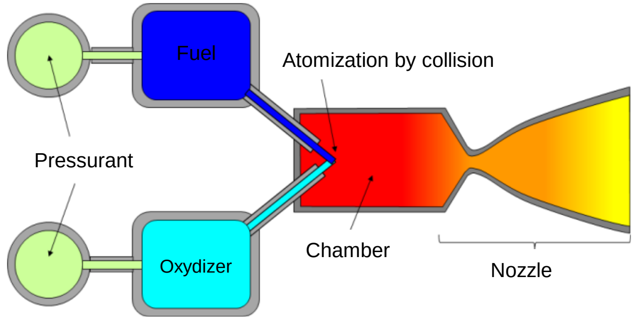
However, the toxicity of hydrazine-based propellants makes their use in microsatellites impractical, so that propulsion systems using low-toxicity propellants have therefore emerged as alternatives to hydrazine.





www.3dchem.com





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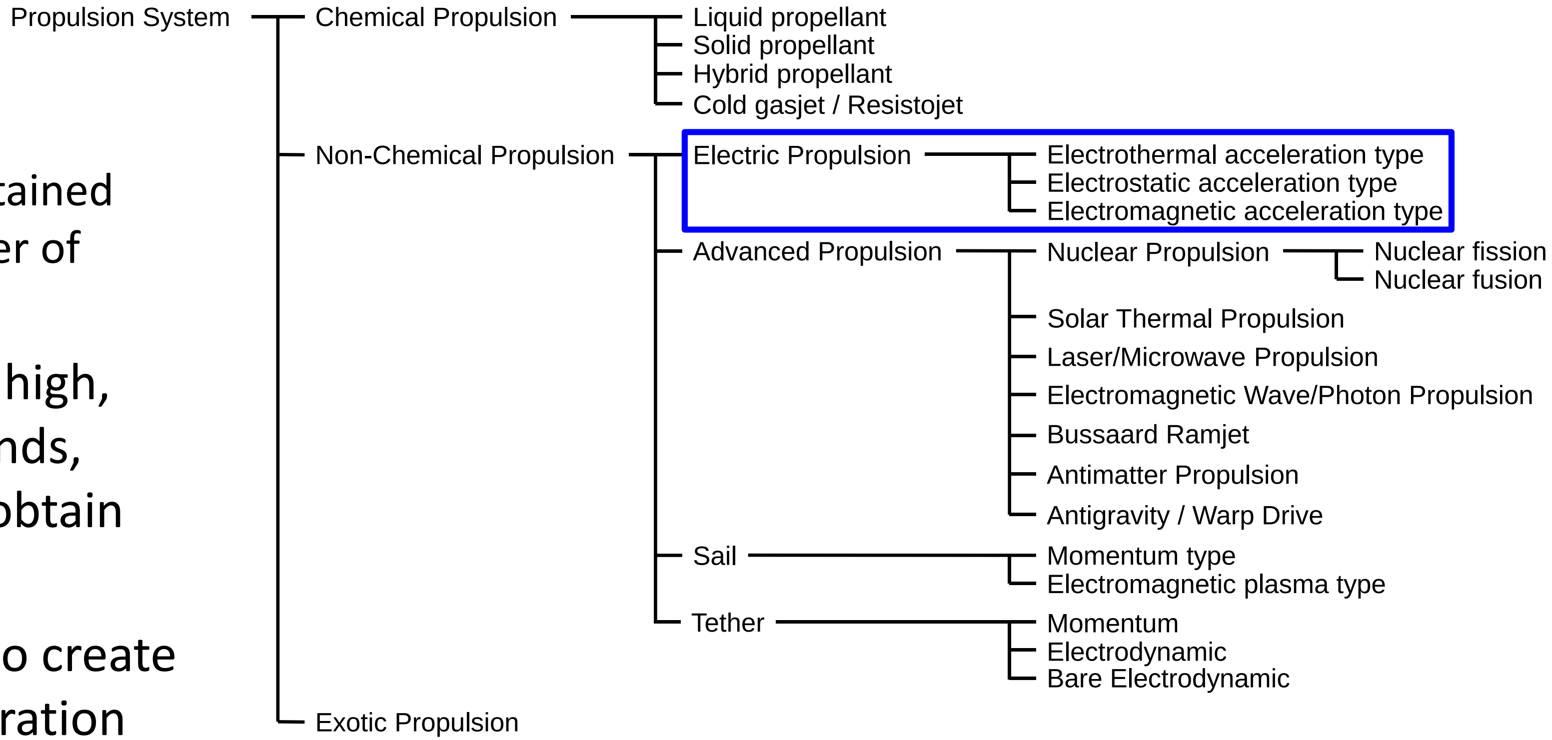
1. Fundamentals of Propulsion System

1.4 Electric Propulsion

- The energy source is external electrical energy.
  - If power is sufficient, the system will perform well.
  - In reality, however, electric power is not inexhaustible.
- As a practical consequence,
  - Limited to space use, no launch vehicle
  - Due to a limit to the energy that can be obtained by spacecraft, the thrust is only on the order of several mN.
- On the other hand, the specific impulse is high, ranging from hundreds to thousands seconds, so missions with long injection times can obtain large velocity increments.
- In most cases, electric propulsion is used to create a plasma state of propellant before acceleration and injection.



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    - Tether
      - Momentum
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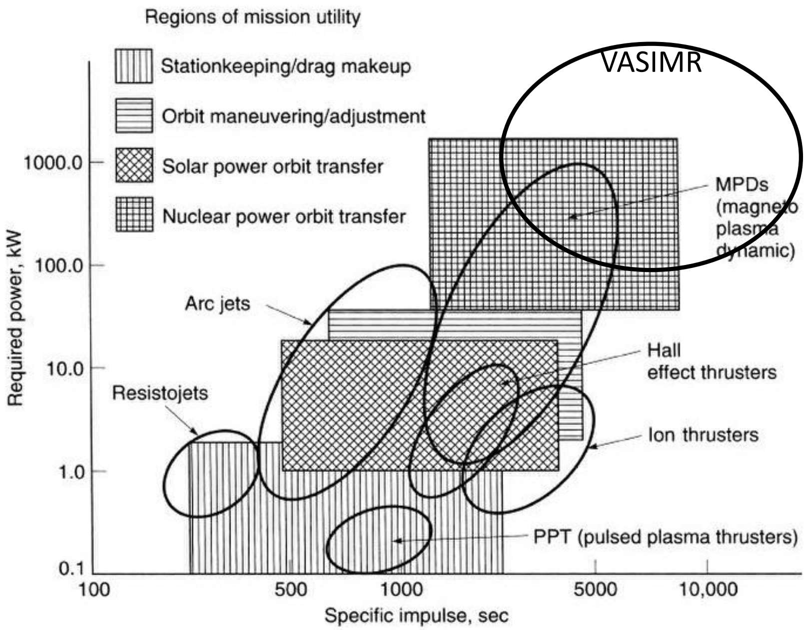
      - Bare Electrodynamic
  - Exotic Propulsion

1. Fundamentals of Propulsion System

1.4 Electric Propulsion

- The following are the major types of propulsion systems, depending on the method used to feed electrical energy into the propellant and ultimately convert it into kinetic energy:
  - Electrothermal acceleration type : DC arcjet
  - Electrostatic acceleration type : Ion engine, Hall thruster
  - Electromagnetic acceleration type : MPD arcjet, PPT
  - Integrated acceleration type : VASIMR

- There are various types of electric propulsion, each with different thrust density, specific impulse, and power consumption, so there is an optimal range of application depending on the mission.
  - Station keeping/drag makeup
    A certain amount of thrust is required, while the specific impulse is low.
  - Orbit maneuvering/adjustment
    Large velocity increment is required, so the specific impulse should be high.



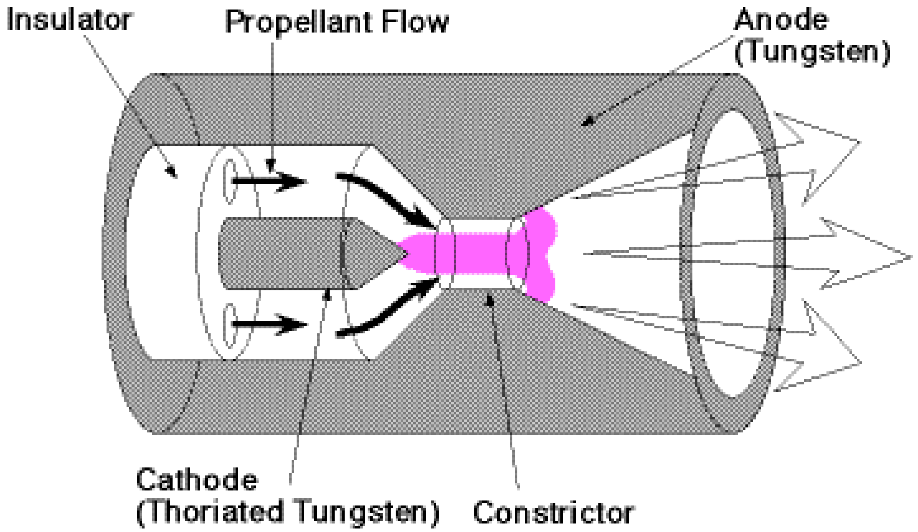
Some additions were made by Author to
G. P. Sutton, Oscar Biblarz: Rocket Propulsion Elements, 7th ed.

1. Fundamentals of Propulsion System

1.4 Electric Propulsion

- **DC arcjet**
  - Electric energy is supplied by Joule heating in arc discharging between a cathode and nozzle anode.
  - Acceleration of propellant is done at a nozzle as in chemical propulsion.
  - In practice, hydrazine and ammonia are used for storage convenience. Recently, eater is also being considered.
  - At low powers of a few 10 W or less, a glow discharge instead of an arc discharge tends to occur, resulting in insufficient heating and acceleration of the propellant.

- Because of its high thrust density, it could be used for large-scale orbit transportation.
- Stabilization of operation and protection of electrodes by flow path design are issues.



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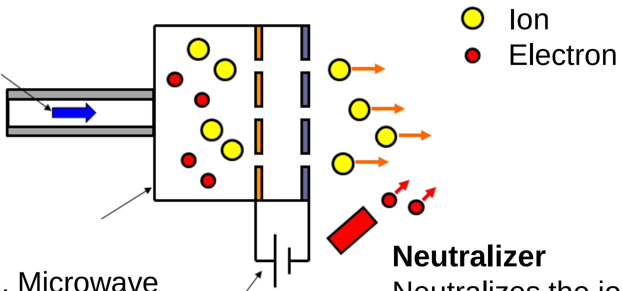
1. Fundamentals of Propulsion System

1.4 Electric Propulsion

- **Ion engine / Hall thruster**
  - Ions are accelerated and injected by the potential difference between electrodes or locally in space.
  - Used in combination with a neutralizer that emits electrons to maintain the electrical neutrality of the spacecraft.
  - Both have a very high specific impulse of more than 2,000 s.
  - The thrust density of the Hall thruster is 10 times higher than that of the ion engine, but both have small thrust. Hall thrusters require fewer power sources than ion engines.
- Leading candidates for all-electric satellites

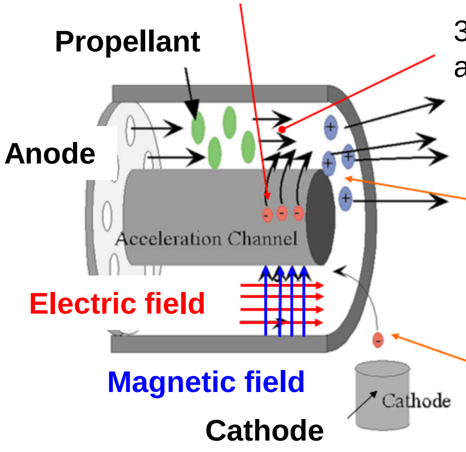


Propellant
Xenon is used because of its low discharge voltage and high molecular weight.

Plasma generator
propellant is ionized to be plasma. Microwave and direct current discharges are used.

Neutralizer
Neutralizes the ions by emitting the same amount of electrons as the injected ions.

Power supply for acceleration
Ions are accelerated and injected by a potential difference of several kV.



2. Electrons move circumferentially due to EXB drift in electric and magnetic fields.

3. Electrons collide with the propellant and ionize it.

4. The ions are accelerated by the electric field and are injected, resulting in thrust.

1. Electrons are emitted from the cathode and attracted to the anode.

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1. Fundamentals of Propulsion System

1.4 Electric Propulsion

- **MPD arcjet**
  - Propellant accelerated by electromagnetic force, $F = q\boldsymbol{v} \times \boldsymbol{B}$, due to current in plasma and self-induced magnetic field.
  - Generally, it is expected to be a next-generation electric propulsion machine because of its large thrust (N-class) and high specific impulse (up to 5,000 seconds).
  - However, it requires a large amount of power.

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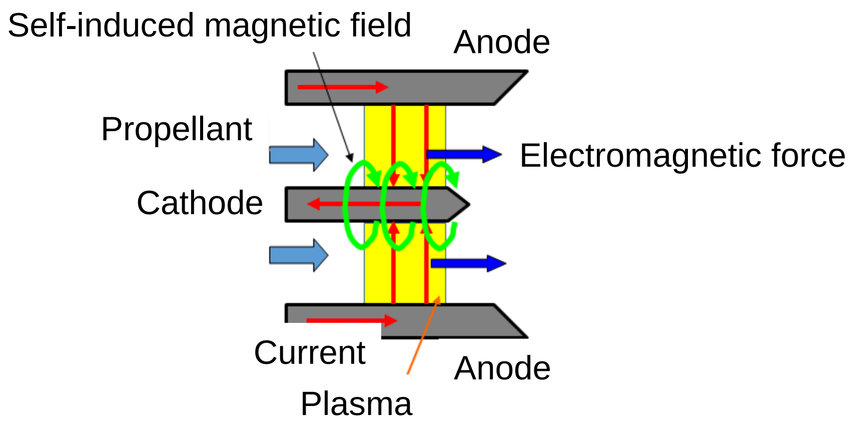
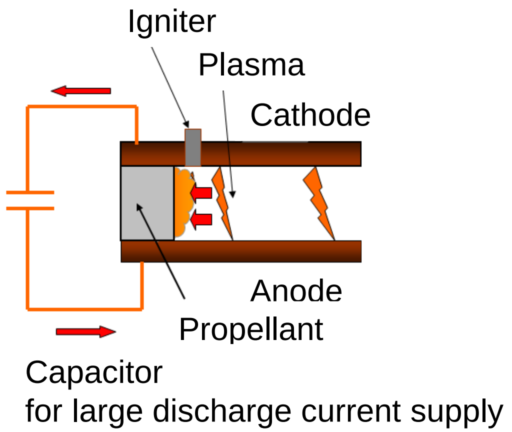


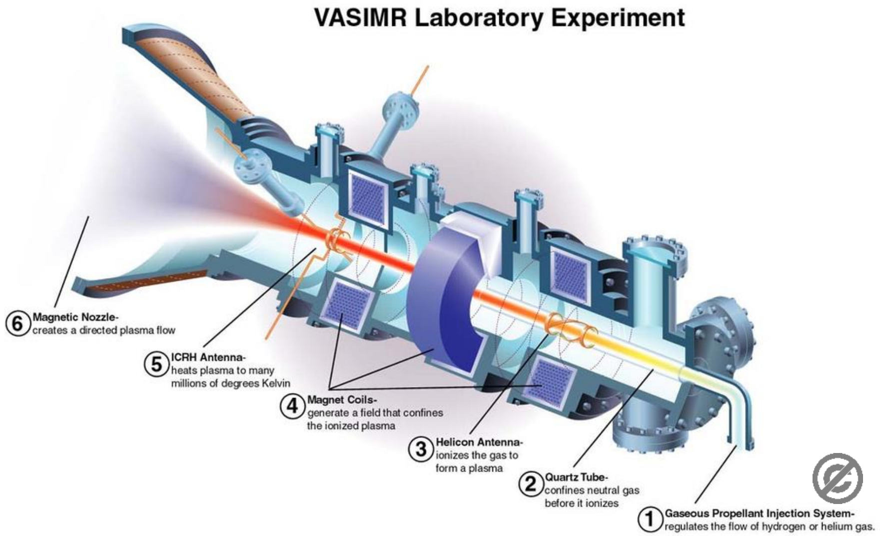
- **PPT (Pulsed Plasma Thruster)**
  - Can be called a kind of pulsed MPD.
  - Pulse discharge of 10kA, 10ms is made with operation frequency of several Hz.
  - A solid propellant such as Teflon is used.
  - Liquid propellants such as water are also being investigated.
  - PPT is suitable for microsatellites because it can be made very small and simple.

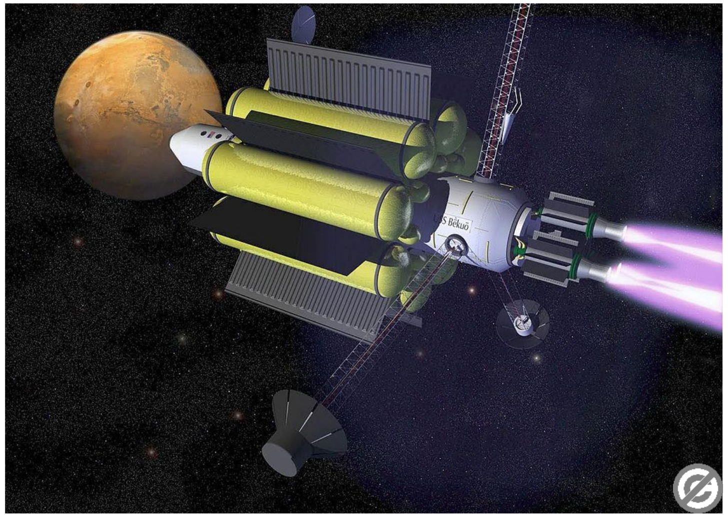


1. Fundamentals of Propulsion System

1.4 Electric Propulsion

- **VASIMR (Variable Specific Impulse Magnetoplasma Rocket)**
    - It consists of three sections, in which the plasma generator, heating section, and acceleration section are divided.
    - Therefore, it is an integrated acceleration type electric propulsion that combines electrothermal and electromagnetic acceleration.
    - Since the plasma generation and heating sections are separated, the balance between thrust and specific impulse can be freely controlled by adjusting the power input.
- It is considered to be an essential propellant for the spread of humankind in the solar system.
- However, it requires a large amount of power, so continued research and development is needed to make it a reality.





Wikipedia,
https://ja.wikipedia.org/wiki/%E6%AF%94%E6%8E%A8%E5%8A%9B%E5%8F%AF%E5%A4%89%E5%9E%8B%E3%83%97%E3%83%A9%E3%82%BA%E3%83%9E%E6%8E%A8%E9%80%B2%E6%A9%9F

1. Fundamentals of Propulsion System

1.5 Others

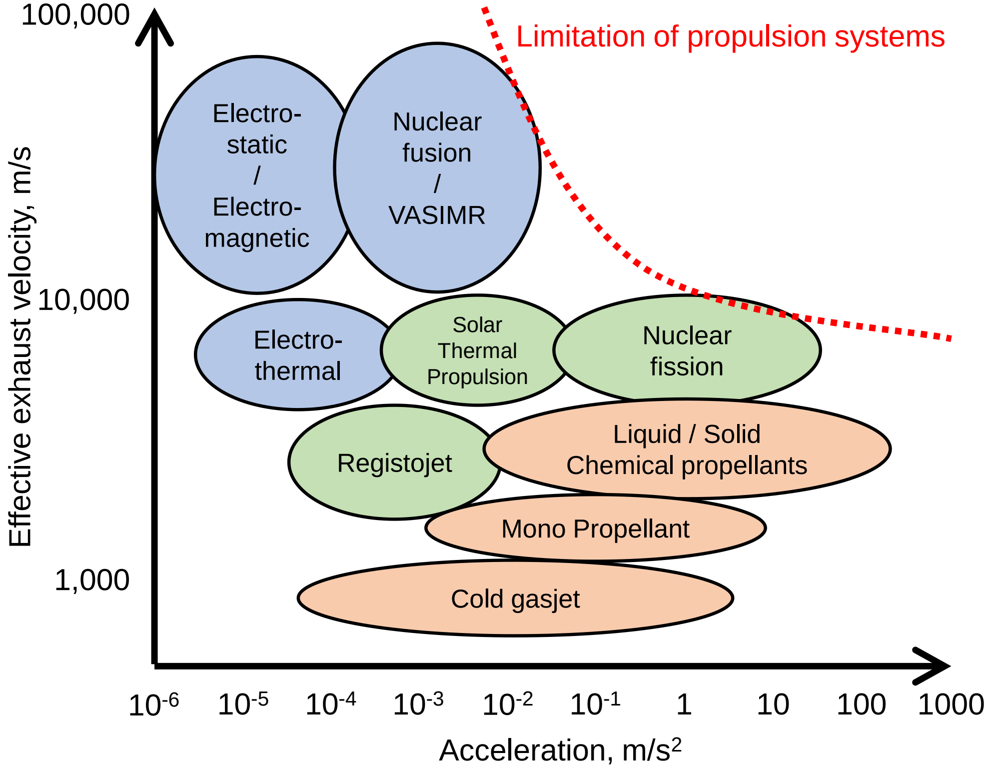
Which propulsion system should we choose?

First, let's decide whether to use chemical or electric propulsion:

- **Chemical Propulsion**
  - Has Larger thrust density, but lower specific impulse.
  - Does not require a large amount of power.

  Choose this if you want to complete the gain in velocity increment in a short period.
- **Electric Propulsion**
  - Has higher specific impulse, but smaller thrust.
  - Requires larger amount of power.

  Choose this if power is available and a longer period is acceptable to obtain the velocity increment.

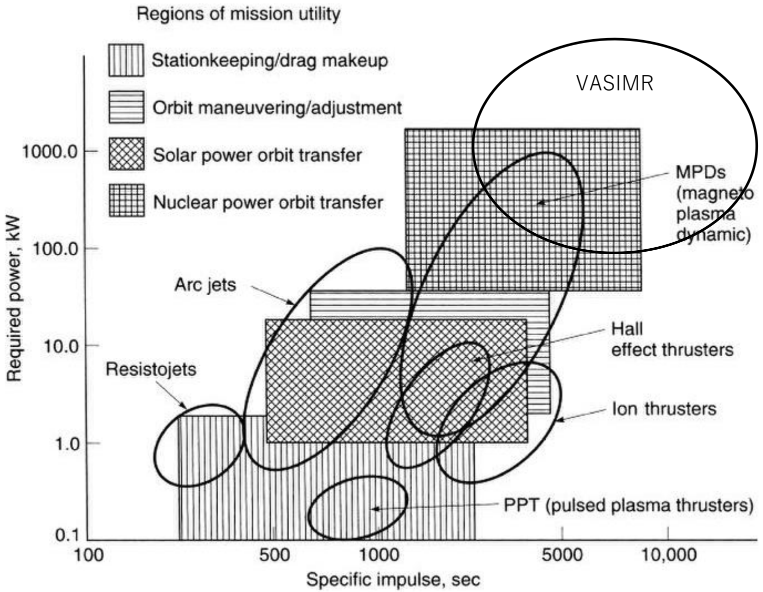


1. Fundamentals of Propulsion System

1.5 Others

High specific impulse of electric propulsion is attractive if you can provide enough power and operation time.

- In particular, PPTs are suitable for microsatellites because they do not require a heavy power supply for plasma generation, heating, and acceleration, and can be made into small modules, and can demonstrate a given impulse bit by pulsed operation.
- Whatever the choice, it should be made in light of system requirements, system constraints, thrust-to-power ratio, application range, and other factors.



Created with reference to G. P. Sutton, Oscar Biblarz: *Rocket Propulsion Elements*, 9th ed.

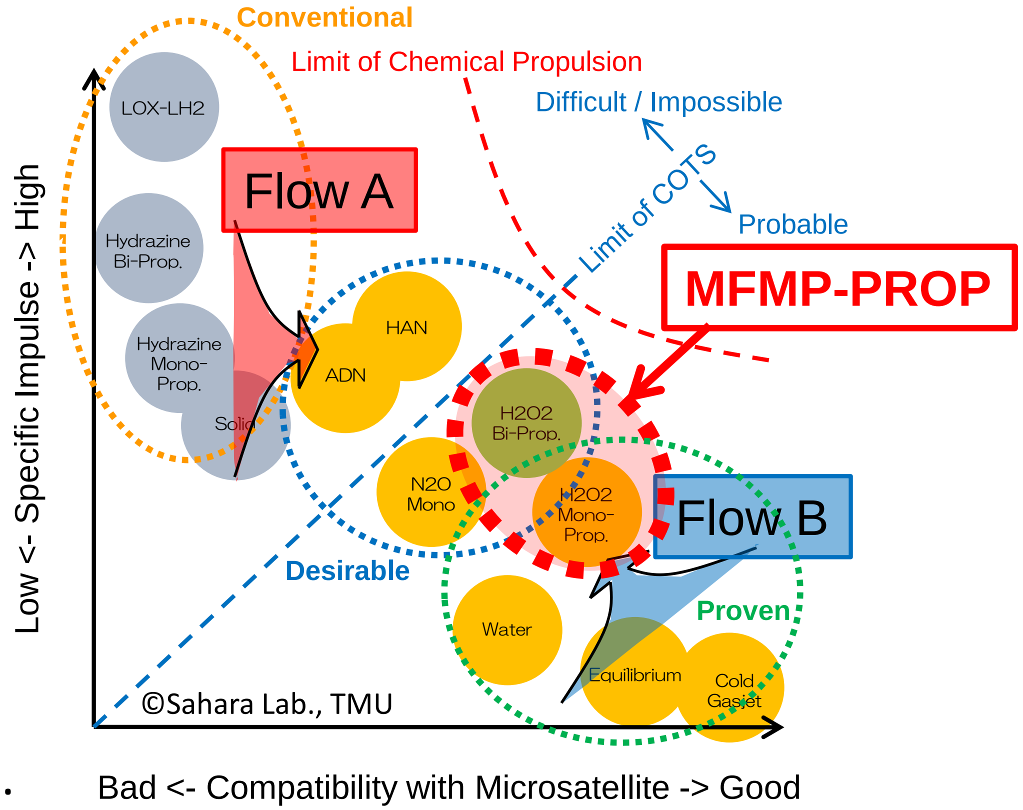
Type	Thrust, mN	Isp, s	Thrust-to-Power ratio N/kW or mN/W
DC arcjet	100 – 1,000	400 – 800	0.3 – 0.5
Ion engine	0.01 – 500	1,500 – 8,000	0.01 – 0.1
Hall thruster	0.01 – 2,000	1,500 – 2,000	0.01
MPD arcjet	0.001 – 2,000	2,000 – 5,000	0.01
PPT	0.05 – 10	600 – 2,000	0.02 – 0.1
cf.) Resistojet	Hundreds	200 – 350	0.1 – 2
cf.) Mono-propellant chemical propulsion	30 – 500,000	200 – 250	N/A

1. Fundamentals of Propulsion System

1.5 Others

If you have chosen chemical propulsion, now choose which propellant to use.

- Hydrazine should not be used for microsatellites due to various restrictions.
- Therefore, a chemical propulsion system using an alternative propellant is chosen, but unlike rockets, liquid oxygen-liquid hydrogen engines cannot be used.
- Currently, there are two mainstream of alternative propulsion systems:
  - Flow A to improve compatibility with microsatellites while maintaining performance equivalent to hydrazine propulsion systems, such as HAN or ADN-based propellant
  - Flow B to improve performance while prioritizing compatibility with nano-satellites from the beginning, such as Microsatellite-Friendly Multi-Purpose Propulsion (MFMP-PROP) developed by the author
- For example, Flow A is to supply F1 cars or luxury cars to users who want private cars, while Flow B is to supply mini cars.
- Note, however, that some Flow B vehicles are not cars but bicycles.



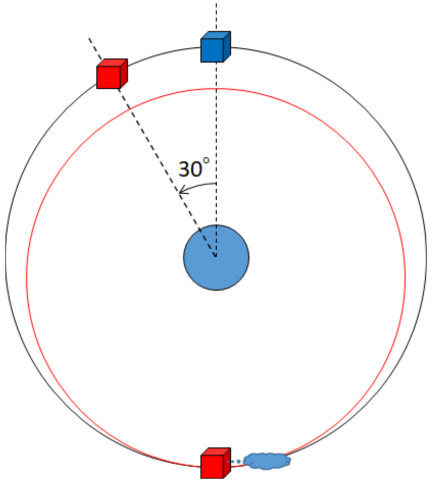
2. From Orbit Design to System Design

1. Velocity Increment
2. Tsiolkovsky Rocket Equation
3. System Requirement from Propulsion System

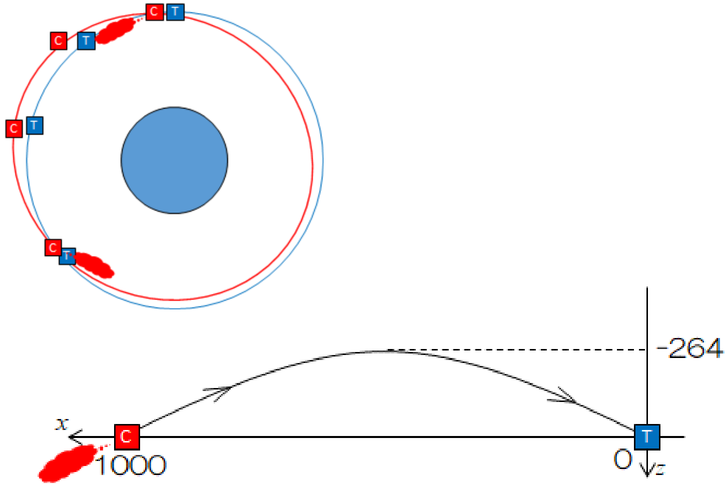
2. From Orbit Design to System Design

2.1 Velocity Increment

The first step in selection and design of a propulsion system is to determine the velocity increment, ΔV, required to accomplish the mission. So, let an orbit designer first do their best and present the ΔV.



Phase shift to construct a constellation with satellites



Rendezvous of a chaser toward a target

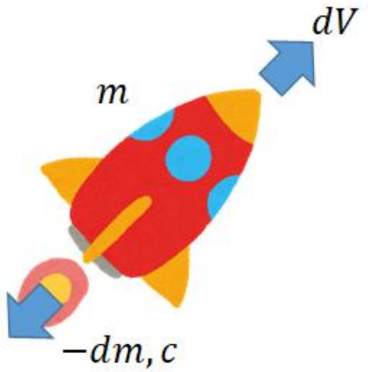
Then, the person in charge of the propulsion system devises a propulsion system to achieve the total velocity incremental ΔV presented by the orbit designer in light of the system requirements and system constraints.

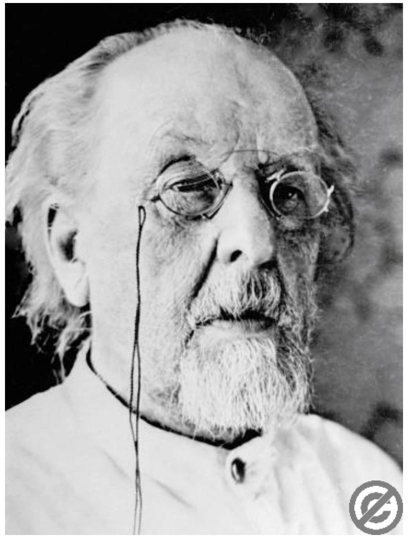
Once the ΔV is presented, it is carried over to system design by the following Tsiolkovsky Rocket Equation.

2. From Orbit Design to System Design

2.2 Tsiolkovsky Rocket Equation

Consider the situation where propellant with mass, $-dm$, and relative velocity, c, is injected from a rocket of mass, m, and the rocket shows a velocity change of dV.





Konstantin Eduardovich Tsiolkovsky is considered the father of spaceflight, said, "*The Earth is the cradle of the mind, but one cannot live in the cradle forever.*"

From the law of conservation of momentum,

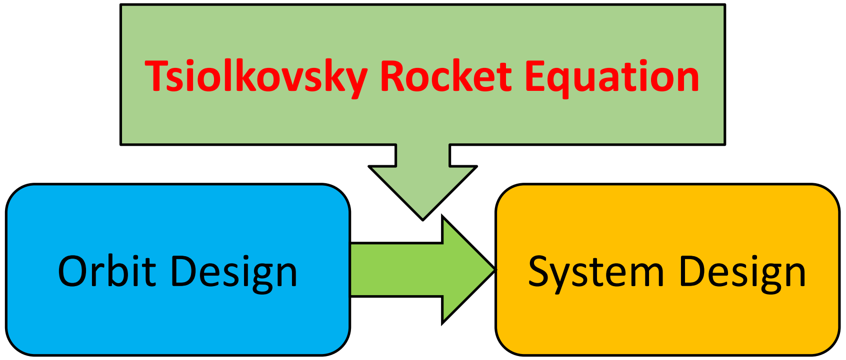
$$mv = [m - (-dm)](v + dv) + (v - c)(-dm)$$
$$\longrightarrow \quad mdV + cdm = 0$$

By transforming the equation, we obtain

$$dV = -c\frac{dm}{m}$$

When integrated, the result is

$$\boxed{\Delta V = gI_{sp} \ln\frac{m_i}{m_f}}$$



where the effective exhaust velocity $c = gI_{SP}$ from p.9, m_i and m_f are the initial and the final mass, respectively.

This is called Tsiolkovsky Rocket Equation, which serves as a bridge between orbit design and system design via ΔV!!!

2. From Orbit Design to System Design

2.2 Tsiolkovsky Rocket Equation

Ex.1) Find the velocity increment that can be obtained by a spacecraft with an initial mass of 50 kg, a propulsion system with specific impulse of 200 s, and a propellant mass of 10 kg.

Ans.1)

$$\Delta V = gI_{sp} \ln \frac{m_i}{m_f} = 9.8 \times 200 \times \ln \frac{50}{50 - 10} = 437 \text{ m/s}$$

Ex.2) If a satellite with an initial mass of 50 kg requires a velocity increment of 200 m/s for its mission, find how much propellant is needed, where let the specific impulse of the propulsion be 200 s.

Ans.2)

$$\Delta V = gI_{sp} \ln \frac{m_i}{m_f} \quad \longrightarrow \quad m_f = m_i \exp\left(-\frac{\Delta V}{gI_{sp}}\right) = 50 \times \exp\left(-\frac{200}{9.8 \times 200}\right) = 45.15 \quad \therefore m_p = m_i - m_f = 4.85 \text{ kg}$$

2. From Orbit Design to System Design

2.3 System Requirement from Propulsion System

However, it is necessary not only from the top-down perspective of the mission, system, and orbit, but also from the bottom-up perspective to the satellite side to present requirements and constraints based on the following knowledge that only a propulsion engineer can provide:

- Constraints on total injection time and single-shot injection time
- Variable thrust by flow control or PWM control
- Heat generation
- Power consumption

In some cases, this may lead to the denial of mission requirements or a fundamental revision of the mission, but it must be asserted unreservedly as a system factor.

e.g.)

"Go to Jupiter in 3 days.“
-> Orbit designer: "It is not physically possible.“

"The total speed increment requirement is 10,000 m/s, and electric propulsion is not possible due to the power situation."
-> Propulsion engineer: "It is not possible because 97% of the weight is propellant even with the best solution.“

Ideally, the project should have both an orbit designer and a propulsion engineer, or a very rare person who can do both orbit design and propulsion engineering. (Experience in system integration through satellite development or at least CanSat would be even better.)

2. From Orbit Design to System Design

2.3 System Requirement from Propulsion System

Let us consider the previous example.

If the density of propellant is 1 g /cc, the required tank volume is 10,000 cc.
If this is stored in two cylindrical tanks with a volume ratio of 80 %, the internal volume of one tank is 6,250 cc.

On the other hand, if the total length of the tank is limited to 40 cm by satellite restrictions, then the maximum length of the tank is limited to 30 cm or so. Thus, the inner diameter of the tank would be 16.3 cm.

If a thickness of the cylindrical part of the tank is 3.5 mm in consideration of pressure resistance, the external dimensions of the tank are 17 cm in diameter and 30 cm in length.

Considering the propulsion system's electronics, valves, piping, etc., the propulsion system requires the satellite to allocate a volume of 40 cm in width, 40 cm in length, and 20 cm in height as a bottom-up requirement, and the satellite needs to make a comprehensive decision on whether or not this is acceptable.

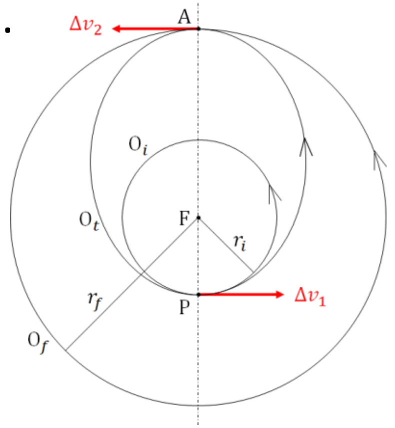
3. Examples of Design

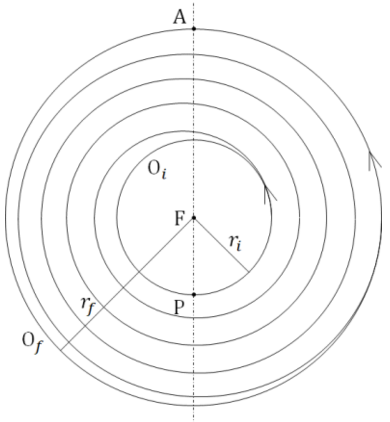
1. Orbit Transfer from LEO to GEO
2. Phase Adjustment
3. Rendezvous

3. Examples of Design

3.1 Orbit Transfer from LEO to GEO

- **Mission requirement**
  "Inject the satellite from LEO into GEO"
- **System constraint**
  - Due to launch vehicle availability, the satellite will depart from a circular orbit at an altitude of 200 km.
  - The maximum weight of the satellite is 100 kg in wet.
  - The weight distribution that a propulsion system can occupy is less than 50 kg, and the volume is 50cm x 50cm x H20cm, due to the convenience of the mission equipment and the bus.
  - The power that can be supplied at any time is 50 W.
- The following is the work of the propulsion engineer.
  - In the case of the Hohmann transfer, the required ΔV is 3,930 m/s, and if this is attempted with a low-toxic propulsion system with a specific impulse of 250 s,
    from $m_f = 100 \times \exp\left(-\frac{3930}{9.8 \times 250}\right) = 20.1 \quad \therefore m_p = m_i - m_f = 79.9$ kg, non-conforming.
  - For the spiral transfer, the required ΔV is 4,710 m/s, which, if obtained by a Hall thruster with a specific impulse of 2,000 s,
    from $m_f = 100 \times \exp\left(-\frac{4710}{9.8 \times 2000}\right) = 78.6 \quad \therefore m_p = m_i - m_f = 21.4$ kg, possibility of conformity.





3. Examples of Design

3.1 Orbit Transfer from LEO to GEO

- Now that we know that electric propulsion is likely to acquire the ΔV, we can make a simple resource estimate.
  - The propellant required to achieve the orbit transfer is 32 kg, assuming a margin of about 1.5 times.
  - Therefore, everything else in the propulsion system, i.e., tanks, valves, piping and other supply systems, electronic systems, filling and discharging interfaces, etc., must be made of $50-32=18$ kg or less. We assume that this is sufficiently feasible (although product selection and design development are actually difficult).
  - The propellant is krypton in consideration of performance, availability, and price. Since the density of liquefied krypton is 2.413 kg/L, its volume is 32÷2.413≒13.3L
  - For a single tank,
    - A spherical tank with $V=\frac{4}{3}\pi r^3 \quad \longrightarrow r=\sqrt[3]{\frac{3V}{4\pi}}=\sqrt[3]{\frac{3\times 13300}{4\pi}}\cong 14.7$ cm is required, which violates the height limitation.
    - A cylindrical tank, assuming an inner diameter of 15 cm, has $V=\pi r^2 L \quad \longrightarrow L=\frac{V}{\pi r^2}=\frac{13300}{\pi\times 7.5\times 7.5}\cong 75$ cm in length, which violates the height and width restrictions.
  - For two tanks,
    - One spherical tank with $r=\sqrt[3]{\frac{3V}{4\pi}}=\sqrt[3]{\frac{3\times 6650}{4\pi}}\cong 11.7$ cm is required, which violates the height limitation.
    - One cylindrical tank, assuming an inner diameter of 15 cm, has $L=\frac{V}{\pi r^2}=\frac{6650}{\pi\times 7.5\times 7.5}\cong 37.6$ cm in length, which is within the acceptable limits.

3. Examples of Design

3.1 Orbit Transfer from LEO to GEO

- For electric power,
  - Suppose it is found that out of the 50 W of power that can be supplied at any time, only 30 W can be used for thrusters.
  - From the thrust-to-power ratio of a Hall thruster of 0.01 mN/W, the thrust is 0.01mN/W x 30W = 0.3 mN.
- The satellite weight is reduced from 100 kg to 78.6 kg by constant injection.
  - For simplicity, the average weight is 89.3 kg.
  - From the equivalence of momentum and Impulse, $M\Delta V = F\Delta t$, the injection time should be

$$\Delta t = \frac{M\Delta V}{F} = \frac{89.3 \times 4710}{0.3 \times 0.001} = 1402010000\mathrm{sec} = 44\ \mathrm{yrs}$$

  Oh my gosh! How is it possible to take so long to make the orbit transfer?

Unfortunately, the estimations to this point have shown that the orbit transfer using low-toxic propulsion or electric propulsion is not feasible.

In such cases,
the propulsion engineer must assert themselves against the mission requirements or the system constraints.

3. Examples of Design

3.1 Orbit Transfer from LEO to GEO

- Based on the above considerations, the mission requirements cannot be met with the current system constraints.
  So, when recommending a review of system constraints, what degree of relaxation is sufficient?
  - It is understood that power and dimensional mitigation is difficult, which means that the adoption of electric propulsion is unrealistic in view of the thrust-to-power ratio.
- Therefore, we propose to employ conventional chemical propulsion, which is not low toxicity, to deal with the problem by relaxing the constraints and improving the performance.
  - If a bi-propellant propulsion of MMH/NTO with a specific impulse of 330 s is employed,

$$m_f = 100 \times \exp\left(-\frac{3930}{9.8 \times 330}\right) = 29.7 \quad \therefore m_p = m_i - m_f = 70.3\text{kg}$$

  - Assuming that everything related to the propulsion system is manufactured with a weight of approximately 10 kg, the wet weight of the propulsion system is 80 kg, which cannot be reduced any further.
- Or,
  - if the launcher can be re-selected and fed into the GTO, only a perigee ascending maneuver is required, so the need is only 1,477 m/s. For the use of the bi-propellant propulsion,

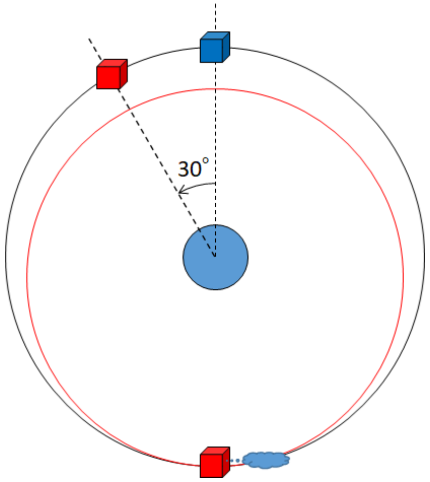
$$m_f = 100 \times \exp\left(-\frac{1477}{9.8 \times 330}\right) = 63.3 \quad \therefore m_p = m_i - m_f = 36.7\text{kg}$$

    If everything related to the propulsion system can be manufactured with a weight of approximately 10 kg, the wet weight of the propulsion system will be less than 50 kg.
    the tank dimensions are also considered, both the MMH and NTO tanks are approximately 10 cm in diameter x 20 to 30 cm in length, which is well within the allowable range (O/F = 1.6).

I did it! Found a solution that works! But will the satellite system have the courage to accept it?

3. Examples of Design

3.2 Phase Adjustment



- **Problem**
  - Two microsatellites weighing 100 kg were injected into a circular orbit at an altitude of 800 km by the rideshare.
  - However, for communication bandwidth reasons, it is necessary to maintain a 30° phase difference between the two satellites in orbit.

- **Solution**

  One satellite performs a phase adjustment of 30° in orbit.
  - As a phase control method, as shown in the figure on the right, the satellite makes a deceleration at a point in the original orbit (black), and waits for a while in the standby orbit (red) with the less semi-major axis. When the phase difference between the two increases with each revolution due to the difference in orbital period, the satellite makes an acceleration at the same injection point when the phase difference reaches a predetermined level, and returns to the original orbit.
  - The time required for this phase adjustment is 7 days without margin.

3. Examples of Design

3.2 Phase Adjustment

- **The orbit designer does their best.**
  - The orbital period of a circular orbit at an altitude of 800 km is $T = 2\pi\sqrt{\frac{a^3}{\mu}} = 2\pi\sqrt{\frac{(800+6378)^3}{398600}} = 6052$ sec.
    Since it is sufficient to shift 30 deg in 7 days, the phase difference per second is $30^\circ/(86400 \times 7) = 4.96 \times 10^{-5}$ deg/sec. In other words, only $4.96 \times 10^{-5} \times 6052 = 0.3^\circ$ of deviation per period of the original orbit is required.
    That is, $360^\circ \times \Delta t/6052 = 0.3$ deg, which means that an orbit with a period difference of $\Delta t = 5$ sec is a standby orbit.
  - Since the period of the standby orbit should be $T = 2\pi\sqrt{\frac{a^3}{\mu}} = 6052 - 5 = 6047$ sec,
    the semi-major axis of the standby orbit is calculated as $a = \sqrt[3]{\frac{\mu T^2}{(2\pi)^2}} = \sqrt[3]{\frac{398600 \times 6047^2}{(2\pi)^2}} = 7174$ km,
    and the apogee of the standby orbit is at the distance of $800 + 6378 = 7178$ km from center of the earth, so the perigee is at 7170 km.
  - The orbital velocity of the original orbit is $v = \sqrt{\frac{\mu}{a}} = \sqrt{\frac{398600}{800+6378}} = 7.452$ km/s,
    and velocity at the apogee of the standby orbit is $v = \sqrt{\mu\left(\frac{2}{r} - \frac{1}{a}\right)} = \sqrt{398600 \times \left(\frac{2}{800+6378} - \frac{1}{7174}\right)} = 7.450$ km/s,
    then, the ΔV required for the transition from the original orbit to the standby orbit is $7452 - 7450 = 2$ m/s.
- **A total ΔV of 4 m/s is required for the round trip!**

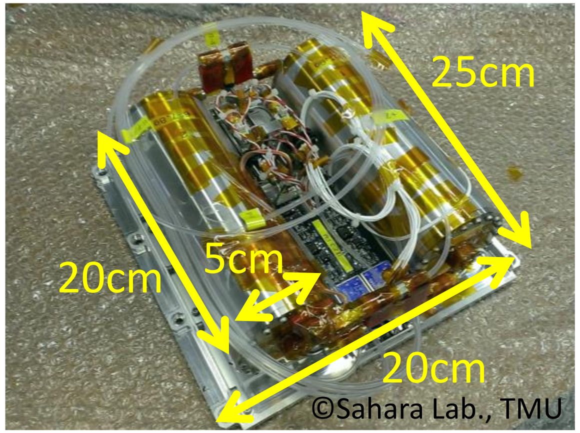
3. Examples of Design

3.2 Phase Adjustment

- **This ΔV is then handed on to the propulsion engineer for system study.**
  - The ΔV required for a round trip is 4 m/s, which is very small, and a specific impulse of about 80 seconds was judged to be sufficient, and the required propellant mass is

$$m_f = 100 \times \exp\left(-\frac{4}{9.8 \times 80}\right) = 99.5\text{kg} \quad \therefore m_p = m_i - m_f = 0.5\text{kg} = 500\text{g}$$

  - **In the case of a N2 cold gas-jet,**
    - Since the molecular weight of N2 is 28, 17.9 mol is required, which corresponds to 400,000 Ncc, where 10 atm filling requires a tank volume of 40,000 cc.
    - For example, a cylindrical tank with a diameter of 20 cm has a total length of 127 cm. If the tank is divided into two or four, the length of one tank is 64 cm or 32 cm, respectively.
    - **Therefore, it can be kept in a volume of about 50cm x 50cm x H30cm.**
  - **Using the mono-propellant propulsion of our MFMP-PROP,**
    - Since the specific gravity of 60 wt% hydrogen peroxide water is 1.24, the required tank capacity is 403 cc.
    - If the propellant is filled to 5/8 of the tank capacity, a tank volume of 645 cc is required. If this is divided into two tanks, the volume is 323 cc/tank.
    - For example, if this is a cylindrical tank and flanges and fittings are taken into account, its dimensions would be ϕ5cm x L20cm.
    - **The entire propulsion system is about 20 cm x 25 cm x 7 cm, which is feasible.**



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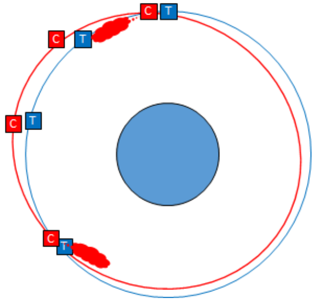
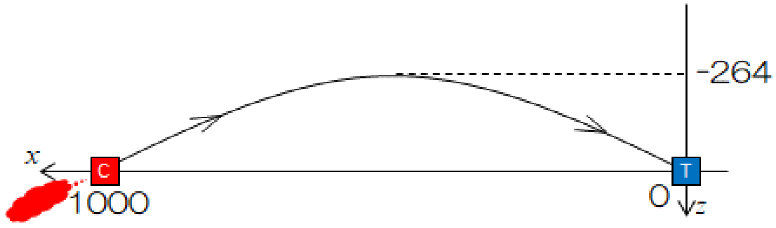
3. Examples of Design

3.3 Rendezvous

- **Problem**
  - The chaser is staying in a circular orbit at an altitude of 400 km with a relative velocity of zero at a distance of 1 km from the space station in the forward direction on the same orbit.
  - Then, the chaser is to reach zero distance and zero velocity to the space station in 1/3 of the orbital period of the space station.

- **Solution**
  Cue the orbit designer!
  - Use the C-W solution in the rendezvous problem.
  - Initial condition: $\delta\mathbf{r}_0 = \begin{bmatrix} 1000 \\ 0 \\ 0 \end{bmatrix}, \quad \delta\mathbf{v}_0 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$, and the time limit: $nT = \frac{2\pi}{3}$
  - From





$$\Phi_{11}(T) = \begin{bmatrix} 1 & 0 & -3\sqrt{3}+4\pi \\ 0 & -\frac{1}{2} & 0 \\ 0 & 0 & \frac{11}{2} \end{bmatrix}, \quad \Phi_{12}(T) = \begin{bmatrix} 2\sqrt{3}-2\pi & 0 & 3 \\ 0 & \frac{\sqrt{3}}{2} & 0 \\ -3 & 0 & \frac{\sqrt{3}}{2} \end{bmatrix}, \quad \Phi_{21}(T) = \begin{bmatrix} 0 & 0 & 9 \\ 0 & -\frac{\sqrt{3}}{2} & 0 \\ 0 & 0 & \frac{3\sqrt{3}}{2} \end{bmatrix}, \quad \Phi_{12}(T) = \begin{bmatrix} -5 & 0 & \sqrt{3} \\ 0 & -\frac{1}{2} & 0 \\ -\sqrt{3} & 0 & -\frac{1}{2} \end{bmatrix},$$

we obtain $\Delta\mathbf{V}_1 = \begin{bmatrix} -0.149 \\ 0 \\ -0.517 \end{bmatrix}, \quad \Delta\mathbf{V}_2 = \begin{bmatrix} 0.149 \\ 0 \\ -0.517 \end{bmatrix}$, and $\Delta\mathbf{V}_{total} = |\Delta\mathbf{V}_1| + |\Delta\mathbf{V}_2| = 1.08\ \mathrm{m/s}$.

Since the required DV is so small, even a simple propulsion system such as a cold gas jet is feasible, although it depends greatly on the mass of the chaser.

It would be a good exercise to consider this on your own.

4. Considerations

1. Laws & Regulations
2. Guidelines
3. Example of Solution

4. Considerations

4.1 Laws & Regulations

Since propulsion systems handle chemicals including toxic substances, high-pressure gases, and pressure vessels, they must be developed and operated in accordance with various laws and regulations.

It should be emphasized that each country has its own laws and regulations, and satellite developers, including propulsion engineers, need to thoroughly examine and understand them.

Note that the following is based on Japanese laws and regulations,
and that that the English names of laws and regulations may not be defined.

- **High Pressure Gas Safety Act**
  includes propellant storage and consumption, manufacturing, filling, etc.
- **General High Pressure Gas Safety Regulations**
  is a rule that should be observed even if the matter does not fall under the High Pressure Gas Safety Act.
- **Poisonous and Deleterious Substances Control Act**
  is applicable when the propellant is classified as toxic and deleterious.

4. Considerations

4.1 Laws & Regulations

- **Fire Service Act**
  applies when the propellant is a hazardous material as defined by the Law.
- **Industrial Safety and Health Act**
  It is necessary to ensure the safety and health of those who handle chemical propellants.
- **Laws and Regulations on transportation**
  Laws and regulations concerning underwater tunnels, aircraft and ships, e.g. Ship Safety Law, Civil Aeronautics Law, etc.
- **Environmental Laws and Regulations**
  Some chemicals may cause environmental destruction and abnormal increase or decrease of microorganisms.

When launching from an overseas launch site, you must comply with the laws and regulations of the country concerned as well as your own national laws, international laws, and international standards.

In order to find out what laws and regulations regulate the chemical substances you are about to handle, be sure to read the Material Safety Data Sheet (MSDS) carefully in advance.

MSDS contains important information such as the physical and chemical properties of substances, measures to be taken in case of exposure, disposal methods, related laws and regulations, and originally what is hazardous, and so on.

In most cases, you can easily find the MSDS you are looking for by searching for "substance name MSDS" on Google.

So be sure to read the MSDS!

4. Considerations

4.1 Laws & Regulations

In addition to the laws and regulations, there are other guidelines and systems that must be followed, all of which must be reviewed and understood.

- **CE Mark** 
  Is a mark of conformity that is attached to products that meet the standards of all EU (European Union) member countries.
- **ATEX Directive** (ATEX: Atmospheres Explosibles / Potentially Explosive Atmospheres) 
  - Covers electrical and electronic equipment intended for use in potentially explosive atmospheres, as well as pneumatic actuators (cylinders) that are subject to friction, impact, and wear.
  - The product nameplate and self-declaration will bear the ATEX mark and the explosion protection symbol along with the CE mark. In compliance with the European ATEX directive, explosion-proof equipment that fits the hazardous zone may be used only within Europe.
- **CE Marking**
  - This means that the product must be certified as conforming to the relevant EU Directive and marked with the CE Mark.
  - Products with CE marking can be freely distributed in EU member countries + EFTA member countries.

Ex.) To clarify manufacturer responsibility for pumps, power supplies and transformers used to fill the propulsion system at the launch site, the launch organization may require ATEX directives or CE marking.

4. Considerations

4.1 Laws & Regulations

In the case of Japan,
the Ministry of Economy, Trade and Industry (METI) provides for Security Export Control.

- **List Control**
  - According to the Cabinet Order established under the Foreign Exchange and Foreign Trade Control Law, items that fall under the list of items subject to trade restrictions may not be exported without permission from the Minister of Economy, Trade and Industry.
  - Items stipulated by the Export Trade Control Order and the Foreign Exchange Order, as well as items that do not fall under the above but are stipulated by the Customs Act, may be subject to catch-all restrictions.
- **Catch-All Control**
  - Even if a product is not subject to the list regulation, permission from the METI may be required.
  - There are two types of Catch-Alls, “Weapon of Mass Destruction Catch-All” and “Conventional Weapon Catch-All.”
  - Regulated by “The ‘Know’ Condition” (confirmed by the exporter) and “The ‘Informed’ Condition” (notified by METI), an application for a permit is required if either requirement is met.

4. Considerations

4.1 Laws & Regulations

Under U.S. and international laws,

- **Export Administration Regulations (EAR)**
  - This applies when exporting "Dual-Use" items (goods (general purpose), software, technology) from the U.S. to foreign countries.
  - It also applies to re-exports from countries other than the U.S. to third countries.
    - If you are re-exporting to parties on the most recent list of persons and companies denied by the U.S. Department of Commerce Bureau of Industry and Security (BIS), you must obtain a re-export license from the BIS.
    - Some products are subject to U.S. export regulations but do not require a U.S. export license, and if an Export Control Classification Number (ECCN) is required, the product can be exported under EAR99 (off-list ready-made product).
- **International Traffic in Arms Regulations (ITAR)**
  - Regulates the export, re-export, and re-transfer of products, technologies, etc. listed on the U.S. Military Item List (USML).
  - If a certain component is imported from the U.S., it may be applicable in the following situations:
    1. The component is loaded onto a satellite and launched from another launch site country.
    2. Transfer of control of the satellite to a third country.
    3. Providing technical materials.

4. Considerations

4.1 Laws & Regulations

- If there are any relevant elements or components to be considered for security trade control, the relevant decision must be documented.
- Catch-all regulations must be checked even if they do not apply to the list regulations.
  If the information requirement is applicable, an export license application is required regardless of the flow chart.
  In other cases, decisions are made according to the flow chart shown by the relevant ministry.
- **Especially in the case of rocket-related and space-related research, amateur judgment is dangerous, and it is necessary to seek the judgment of an appropriate person.**
- **A fictitious example**
  - Suppose that a certain U.S.-made part can be purchased from a U.S. manufacturer through a Japanese sole agent, can be re-exported under EAR99, is not subject to listing restrictions, and does not require a separate application for catch-all restrictions.
  - However, it was found that some specifications of the part needed to be changed in order to put it on the satellite, and the manufacturer responded that they could accommodate this.
  - **In this case, it may not be possible to re-export the product under EAR99 because it is a modified product that differs from the certified form. In such a case, it is necessary to start with the prescribed procedures or the certification of the product with the changed specifications.**
  - **In any case, shallow judgments by amateurs are very dangerous. First and foremost, consult with the appropriate people!**

4. Considerations

4.2 Guidelines

Space agencies specify their own design standards and guidelines.
Some of these are publicly available, so they should be carefully referred to and reflected in the design.

For example, in the case of JAXA, there is the JAXA Management Requirement (JMR) and the JAXA Engineering Requirement (JERG).

* Note that the document names below are the authors' own English translations.

- **Propulsion and pressure systems**
  - JERG-4-011 Publicly Offered Small Satellite/H-IIA User's Manual
  - JERG-0-001 Technical Standard for High Pressure Gas Equipment for Space Use
    - Relaxation of the technical standards stipulated by the High Pressure Gas Safety Act, which is a special exception for high-pressure gas equipment installed on unmanned rockets and payloads.
    - The safety factor of the pressure vessel shall be 1.5 or more for yield stress and 2.0 or more for tensile strength.
  - JERG-1-007 Launch and Flight Operation Safety Technical Standards (Safety Requirements Compliance Matrix)
    - Propellant work (Section 4.3), Pressure systems (Section 4.4)
  - JERG-2-001 Safety Design Handbook for Small Satellites
    - Structure/Mechanism (Section 5.2), Propulsion system and propellant (Section 5.3), Pressure system (Section 5.4)

4. Considerations

4.2 Guidelines

- JMR-002 Rocket Payload Safety Standard (Safety Requirements Conformance Matrix)
  - Item number corresponding to JERG-2-001B
  - Liquid propulsion systems (Section 5.3.1), Pressure systems (Section 5.4), GSE (propulsion system equipment) (Section 5.10.6)
- JMR-003 Space debris generation prevention standard (debris control requirement conformance matrix)
  - Treatment of residual liquid propellants and high-pressure fluids
  - If discharge treatment is not possible, provide sufficient safety or a pressure boost limiting mechanism.
  - The discharge system is not prevented from discharging by freezing.

Other Matters

- **Stress corrosion cracking**
  - CSA-112023 Guideline for Dealing with Stress Corrosion Cracking in Publicly-Offered Piggy-back Satellites
  - MSFC-STD-3029 Guidelines for the Selection of Metallic Materials for Stress Corrosion Cracking Resistance in Sodium Chloride Environments
  - NASA-STD-6016 Standard Material and Processes Requirements for Spacecraft
  - JERG-0-025 Selection criteria for mechanical parts and structural materials for rockets and satellites

4. Considerations

4.2 Guidelines

- **Cumulative fatigue**

JERG-2-320	Structural Design Standard
JERG-2-130-HB002	Acoustic Testing Handbook (especially Appendix D/E)

- **Others**

DOT/FAA/AR-MMPDS-01	Metallic Materials Properties Development and Standardization (MMPDS)
ATEX Directive	Equipment and protective systems intended for use in potentially explosive atmospheres

4. Considerations

4.3 Example of Solution

- **Premise**
  - Read the MSDS carefully.
  - Read carefully the text of relevant laws and regulations, international standards, etc.
  - Read carefully the rocket user's manual, launch site manual, etc.
- **In selecting a product,**
  - Selection will be made from non-ITAR applicable products.
  - Selection will be made from products and forms that can be re-exported under EAR99.
  - Try to find a manufacturer or distributor that is accustomed to making such decisions.
- **Regarding re-export,**
  - Inquire with the manufacturer or distributor whether the product is regulated or not.
    If it is possible to determine whether the product is regulated or not, be sure to obtain a Classification Sheet.
  - Consult with relevant ministries and agencies.
  - Ensure that the type, quantity, and weight of items brought into and taken out of the launch country are controlled.
    Particular attention should be paid to items to be consumed locally.
    In the case of weight control, differences in values between outbound and inbound may cause problems.

4. Considerations

4.3 Example of Solution

Example, tanks

- JERG-0-001 describes in detail the design, manufacturing and certification of high pressure gas appliances.
- No problem when purchasing an approved tank, but care must be taken when designing and fabricating your own tank.

By the way, there are also exemptions such as

- In section 2.2, containing the exemption provisions,
  In any of the following cases, a part of this technical standard shall be exempted from application at the time of conformity assessment with this technical standard for design and manufacturing.
- In section 2.2.1, in the case of safety factor of 4 or more,
  - At the time of conformity assessment for design,
    The following items required in Section 3 "Design" may be waived by submitting the results of thickness calculations for body plates, mirror plates, and piping: 3.5.1 Stress Analysis, 3.5.2 Determination of LBB (analysis and testing), 3.5.3 Fatigue Damage Analysis and Testing, and 3.5.4 Crack Growth Analysis and Testing
  - At the time of conformity assessment for manufacturing,
    The following documents may be submitted to waive the other examination items required in Section 4 "Manufacturing":
    a) Mill sheet of metal materials used, inspection report of composite/non-metal materials, etc.
    b) Results of pressure resistance test at 1.5 times or more than the maximum expected working pressure
    c) Results of airtightness test at 1.5 times or more than the maximum expected working pressure
    d) Results of non-destructive inspection of welds
    e) Thickness measurement results (when minimum thickness cannot be confirmed on a mill sheet)

In view of the cost of development and testing, there is no reason not to apply such exemptions.

4. Considerations

4.3 Example of Solution

Define MEOP

- In a pressure system, the MEOP (Maximum Expected Operating Pressure) is a first set.
  - When the expected maximum temperature in the satellite is 40 + margin 15 = 55 degC., if the gas pressure or vapor pressure of the liquefied gas is 1 MPa, set the MEOP to 1 MPa.
  - If the tank pressure is theoretically and experimentally predicted to be 3 MPa after 5 years of satellite operation due to natural decomposition of propellant, then set the MEOP to 3 MPa.

Provide evidence of validity.

- Proofs are given using tables of properties and physical laws.
- A table showing that the observed pressure increase due to spontaneous decomposition over a long period of time under conditions judged to be reasonable are given as the proof.

Establish a verification method.

- The pressure or vapor pressure can be estimated from the ambient temperature, so the ambient temperature is measured.
- There should be no difference between the measured and expected values at the launch site.
  - For measurement, a mechanical pressure gauge is used because the satellite is turned off before launch in principle, or permission is obtained to energize the satellite locally, etc.
  - In orbit, acquired by pressure sensor and confirmed by telemetry

4. Considerations

4.3 Example of Solution

Design on the assumption that the exemption provisions are applied.

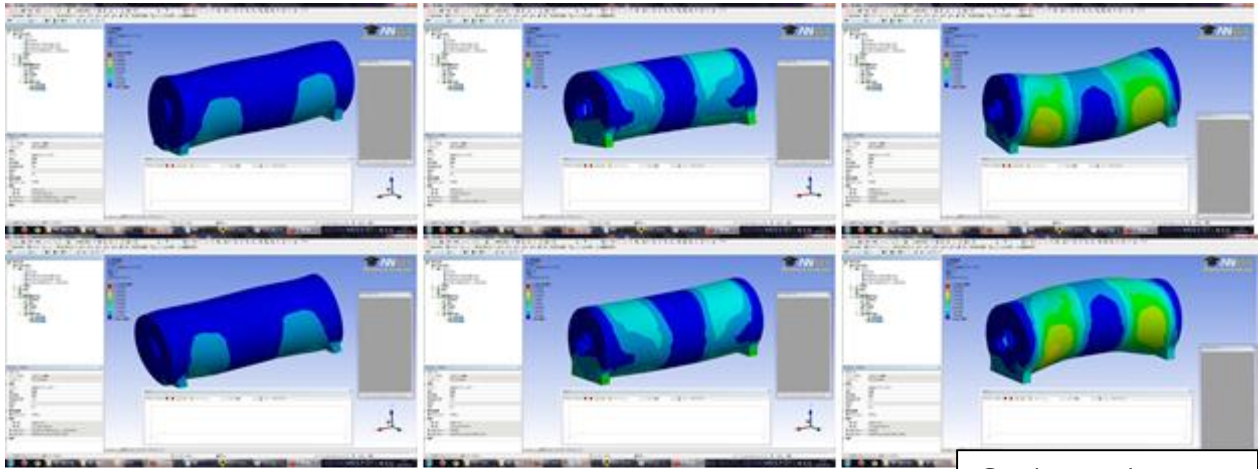
- All parts, fasteners, and other parts subjected to internal pressure should have a safety factor of 4.
  - For bolts, the tightening torque is specified based on a reasonable torque coefficient.
    Normally the standard tightening torque is sufficient, but an explanation that the standard tightening torque is reasonable is necessary.
  - In the case of a flange with an O-ring, the compression of the O-ring must also be taken into account when specifying the flange.
  - The female thread strength should be appropriate for the material. In the case of helical inserts, the recognition is rubbed together.
  - How to express composite stress? If Mises stress is adopted, it is necessary to explain the rationale.
  - Not only axial and shear forces, but also bending moments must be considered.
- Obtain a mill sheet (material certification), conduct a pressure resistance test at MEOP x 1.5, an airtightness test at MEOP, and a nondestructive inspection of welds.
- It should be designed as a worst-case scenario.
- If more than one case is possible, all should be considered.
  - If there is a case where the maximum expected internal pressure at launch is 1 MPa + maximum acceleration of 40 G at the worst axis due to the mechanical environment and a case where the maximum expected internal pressure on orbit is 3 MPa, the worst case is adopted if one can encompass the other.
  - However, if it cannot be comprehensive (e.g., different axial directions), the worst case is adopted for each item (e.g., MEOP is set to 1 MPa on the ground and 3 MPa in orbit).

4. Considerations

4.3 Example of Solution

Strength Calculation

- Use reliable methods and tools. However, all items must be accounted for.



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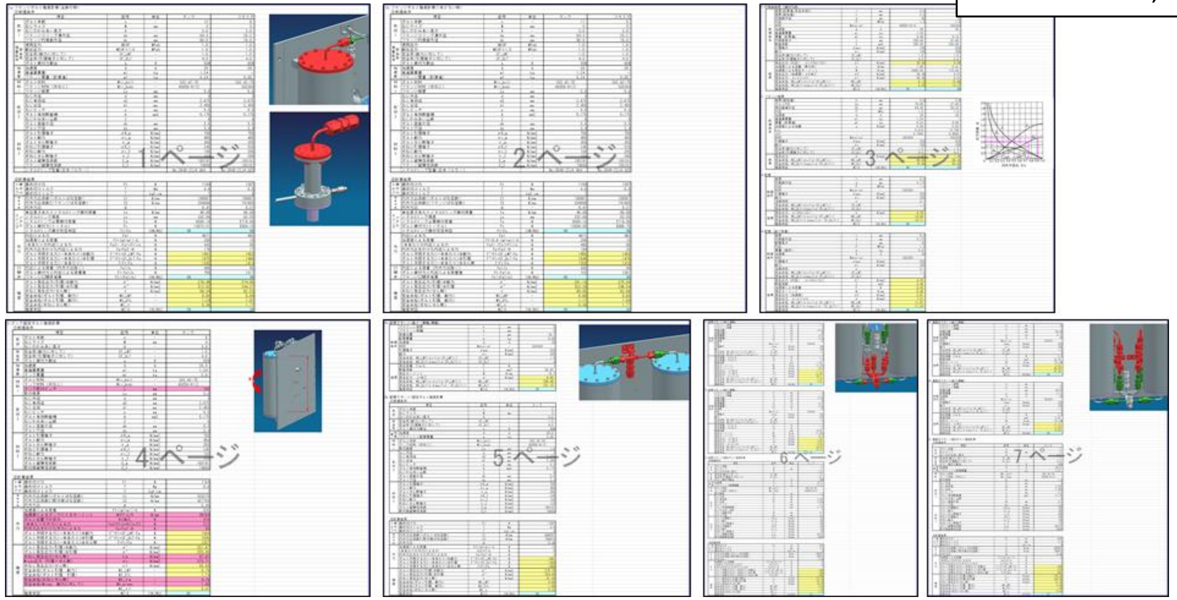
- Verify the results by hand (calculator, Excel, etc.), as high-end simulations may not reveal the principles and fundamentals of the system.



4. Considerations

4.3 Example of Solution

Stress corrosion cracking

- Applying "authoritative documents" to countermeasures can lead to cost reductions.
  An authoritative document is one that is based on a great deal of experience and has been applied in a great number of cases.
- If the tank material is A5056 because of its workability and availability, the following was found to be appropriate based on MSFC-STD-3029 Rev. A.
  - Since the Mg content is equal to or greater than that of the example material, (3) in the table on the right applies, and therefore A5056-H112 is used.
  - Since it contains more than 3% Mg, (4) in the table on the right applies, and the maximum working temperature should be 66 degC. or lower.

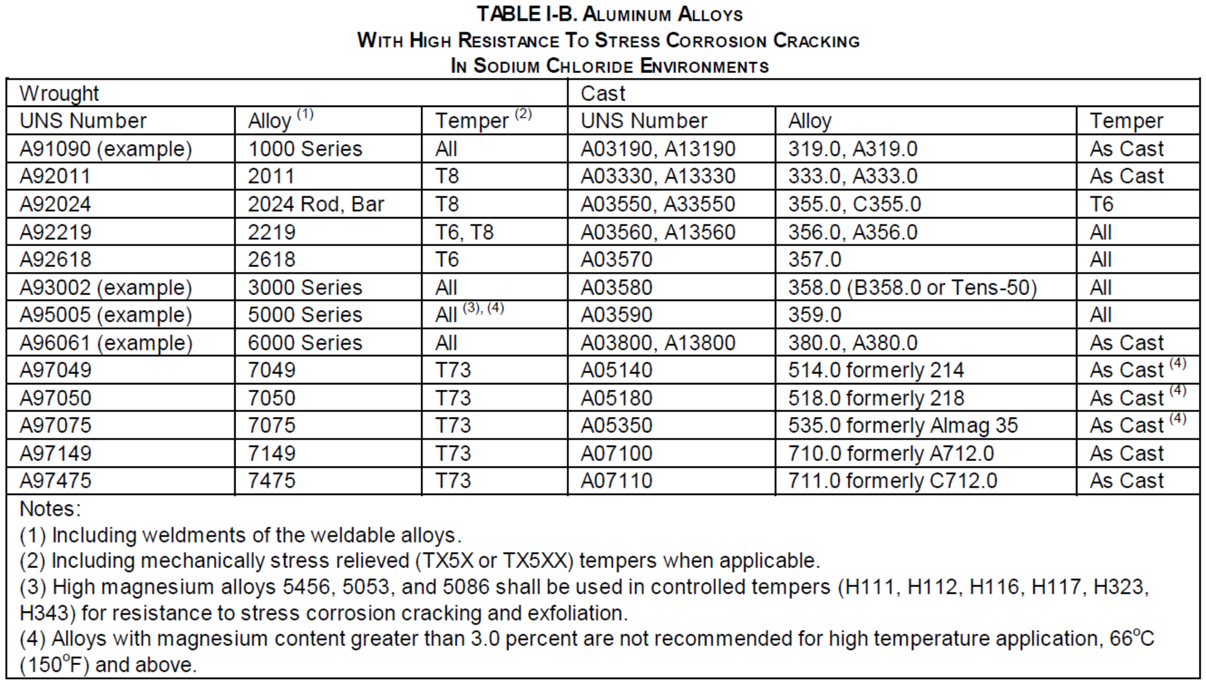


TABLE I-B. Aluminum Alloys
With High Resistance To Stress Corrosion Cracking
In Sodium Chloride Environments

Wrought			Cast		
UNS Number	Alloy (1)	Temper (2)	UNS Number	Alloy	Temper
A91090 (example)	1000 Series	All	A03190, A13190	319.0, A319.0	As Cast
A92011	2011	T8	A03330, A13330	333.0, A333.0	As Cast
A92024	2024 Rod, Bar	T8	A03550, A33550	355.0, C355.0	T6
A92219	2219	T6, T8	A03560, A13560	356.0, A356.0	All
A92618	2618	T6	A03570	357.0	All
A93002 (example)	3000 Series	All	A03580	358.0 (B358.0 or Tens-50)	All
A95005 (example)	5000 Series	All (3), (4)	A03590	359.0	All
A96061 (example)	6000 Series	All	A03800, A13800	380.0, A380.0	As Cast
A97049	7049	T73	A05140	514.0 formerly 214	As Cast (4)
A97050	7050	T73	A05180	518.0 formerly 218	As Cast (4)
A97075	7075	T73	A05350	535.0 formerly Almag 35	As Cast (4)
A97149	7149	T73	A07100	710.0 formerly A712.0	As Cast
A97475	7475	T73	A07110	711.0 formerly C712.0	As Cast

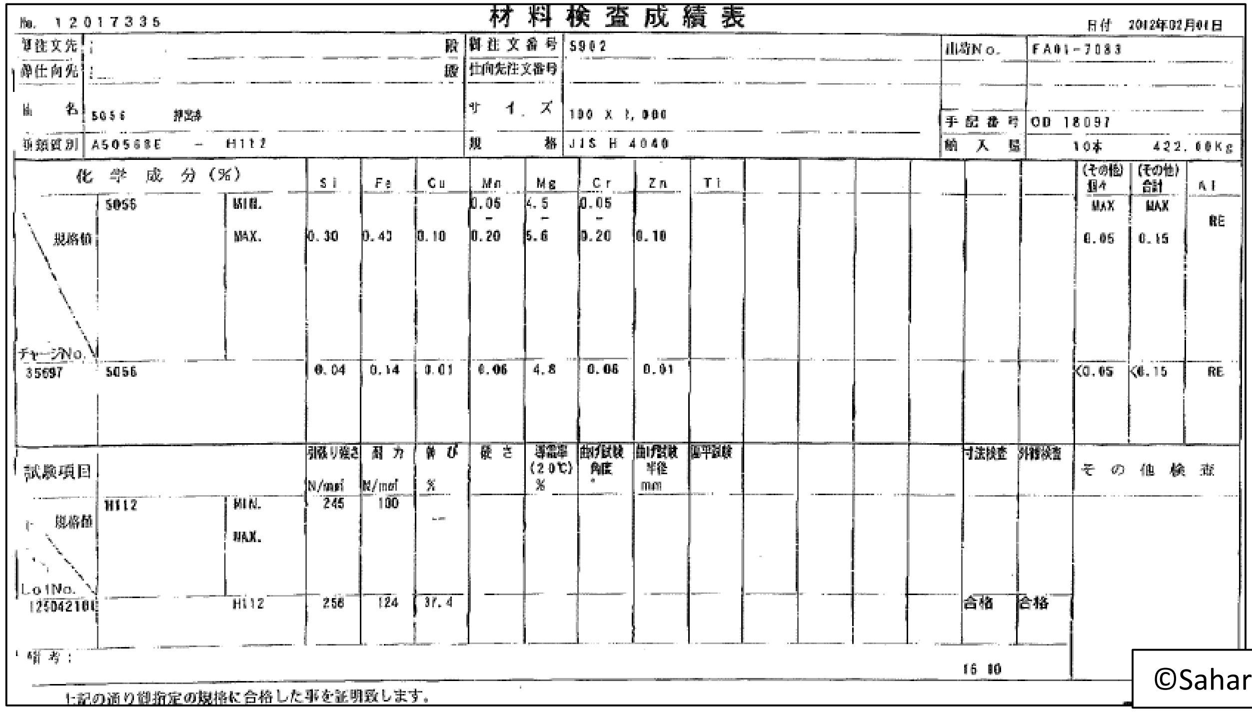
Notes:
(1) Including weldments of the weldable alloys.
(2) Including mechanically stress relieved (TX5X or TX5XX) tempers when applicable.
(3) High magnesium alloys 5456, 5053, and 5086 shall be used in controlled tempers (H111, H112, H116, H117, H323, H343) for resistance to stress corrosion cracking and exfoliation.
(4) Alloys with magnesium content greater than 3.0 percent are not recommended for high temperature application, 66°C (150°F) and above.

4. Considerations

4.3 Example of Solution

For the application of exemption provisions,

a) Mill sheet of metal materials used, inspection report of composite/non-metal materials, etc.
b) Results of pressure resistance test at 1.5 times or more than the maximum expected working pressure
c) Results of airtightness test at 1.5 times or more than the maximum expected working pressure
d) Results of non-destructive inspection of welds
e) Thickness measurement results (when minimum thickness cannot be confirmed on a mill sheet)



No. 12017335

材 料 検 査 成 績 表

日付 2012年02月01日

御注文先	殿	御注文番号	5902	出荷No.	FA01-7083
御仕向先	殿	仕向先注文番号			
品名	5056 押出棒	サイズ	100 X 2,000	手配番号	OD 18097
種類質別	A5056BE - H112	規格	JIS H 4040	納入量	10本 422.00Kg

化学成分（%）			Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	(その他)個々	(その他)合計	Al
規格値	5056	MIN.				0.05	4.5	0.05			MAX	MAX	RE
		MAX.	0.30	0.40	0.10	0.20	5.6	0.20	0.10		0.05	0.15	
チャージNo. 35697	5056		0.04	0.14	0.01	0.06	4.8	0.06	0.01		<0.05	<0.15	RE

試験項目			引張り強さ N/mm²	耐力 N/mm²	伸び %	硬さ	導電率（20℃） %	曲げ試験 角度 °	曲げ試験 半径 mm	偏平試験	寸法検査	外観検査	その他検査
規格値	H112	MIN.	245	100	—								
		MAX.											
LotNo. 12504210		H112	256	124	37.4						合格	合格	

備考：

16 10

上記の通り御指定の規格に合格した事を証明致します。

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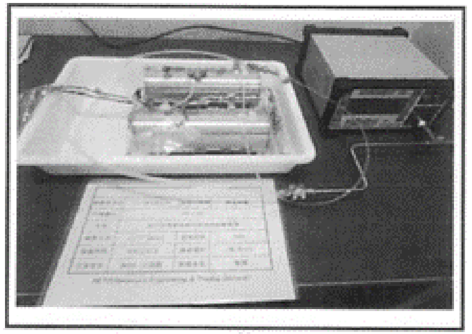
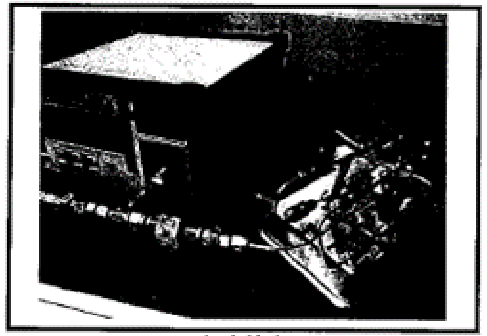


耐圧検査



気密検査

浸透探傷検査(浸透)

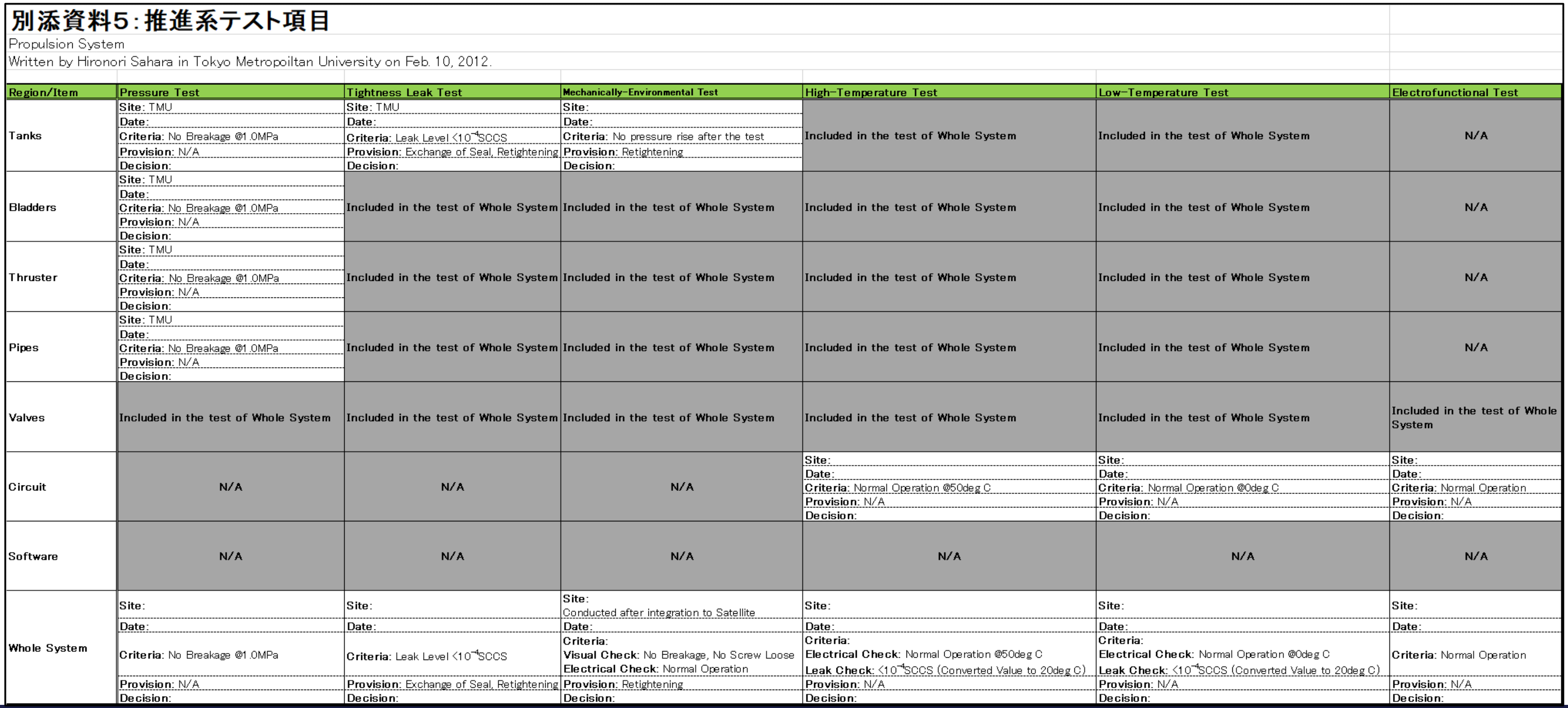
浸透探傷検査(現像)

4. Considerations

4.3 Example of Solution

Perform stand-alone testing.

- Apply QT levels for mechanical and thermal environments at each satellite's onboard location
- It is useful to have a table summarizing the subjects, test items, responsible persons and places for implementation, etc., and the corresponding test procedures.

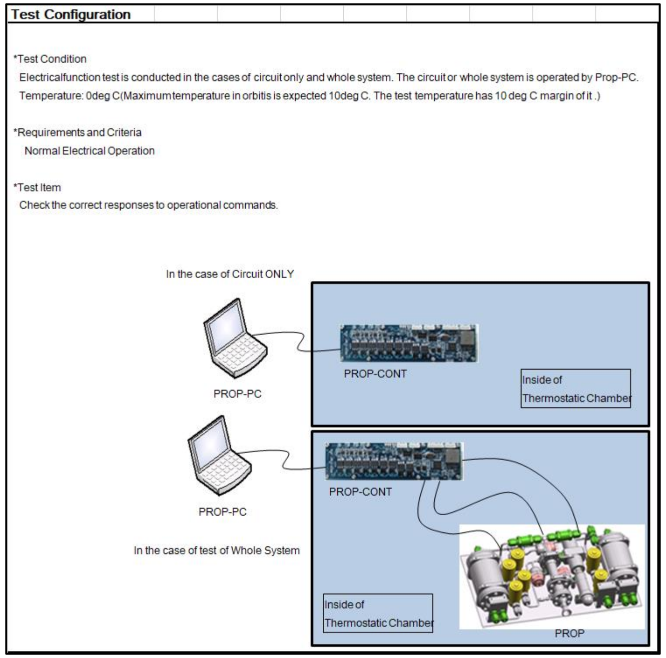


別添資料5：推進系テスト項目

Propulsion System

Written by Hironori Sahara in Tokyo Metropoiltan University on Feb. 10, 2012.

Region/Item	Pressure Test	Tightness Leak Test	Mechanically-Environmental Test	High-Temperature Test	Low-Temperature Test	Electrofunctional Test
Tanks	**Site**: TMU **Date**: **Criteria**: No Breakage @1.0MPa **Provision**: N/A **Decision**:	**Site**: TMU **Date**: **Criteria**: Leak Level $<10^{-4}$SCCS **Provision**: Exchange of Seal, Retightening **Decision**:	**Site**: **Date**: **Criteria**: No pressure rise after the test **Provision**: Retightening **Decision**:	Included in the test of Whole System	Included in the test of Whole System	N/A
Bladders	**Site**: TMU **Date**: **Criteria**: No Breakage @1.0MPa **Provision**: N/A **Decision**:	Included in the test of Whole System	Included in the test of Whole System	Included in the test of Whole System	Included in the test of Whole System	N/A
Thruster	**Site**: TMU **Date**: **Criteria**: No Breakage @1.0MPa **Provision**: N/A **Decision**:	Included in the test of Whole System	Included in the test of Whole System	Included in the test of Whole System	Included in the test of Whole System	N/A
Pipes	**Site**: TMU **Date**: **Criteria**: No Breakage @1.0MPa **Provision**: N/A **Decision**:	Included in the test of Whole System	Included in the test of Whole System	Included in the test of Whole System	Included in the test of Whole System	N/A
Valves	Included in the test of Whole System	Included in the test of Whole System	Included in the test of Whole System	Included in the test of Whole System	Included in the test of Whole System	Included in the test of Whole System
Circuit	N/A	N/A	N/A	**Site**: **Date**: **Criteria**: Normal Operation @50deg C **Provision**: N/A **Decision**:	**Site**: **Date**: **Criteria**: Normal Operation @0deg C **Provision**: N/A **Decision**:	**Site**: **Date**: **Criteria**: Normal Operation **Provision**: N/A **Decision**:
Software	N/A	N/A	N/A	N/A	N/A	N/A
Whole System	**Site**: **Date**: **Criteria**: No Breakage @1.0MPa **Provision**: N/A **Decision**:	**Site**: **Date**: **Criteria**: Leak Level $<10^{-4}$SCCS **Provision**: Exchange of Seal, Retightening **Decision**:	**Site**: Conducted after integration to Satellite **Date**: **Criteria**: **Visual Check**: No Breakage, No Screw Loose **Electrical Check**: Normal Operation **Provision**: Retightening **Decision**:	**Site**: **Date**: **Criteria**: **Electrical Check**: Normal Operation @50deg C **Leak Check**: $<10^{-4}$SCCS (Converted Value to 20deg C) **Provision**: N/A **Decision**:	**Site**: **Date**: **Criteria**: **Electrical Check**: Normal Operation @0deg C **Leak Check**: $<10^{-4}$SCCS (Converted Value to 20deg C) **Provision**: N/A **Decision**:	**Site**: **Date**: **Criteria**: Normal Operation **Provision**: N/A **Decision**:



Test Configuration

*Test Condition

Electricalfunction test is conducted in the cases of circuit only and whole system. The circuit or whole system is operated by Prop-PC.

Temperature: 0deg C(Maximum temperature in orbitis is expected 10deg C. The test temperature has 10 deg C margin of it .)

*Requirements and Criteria

Normal Electrical Operation

*Test Item

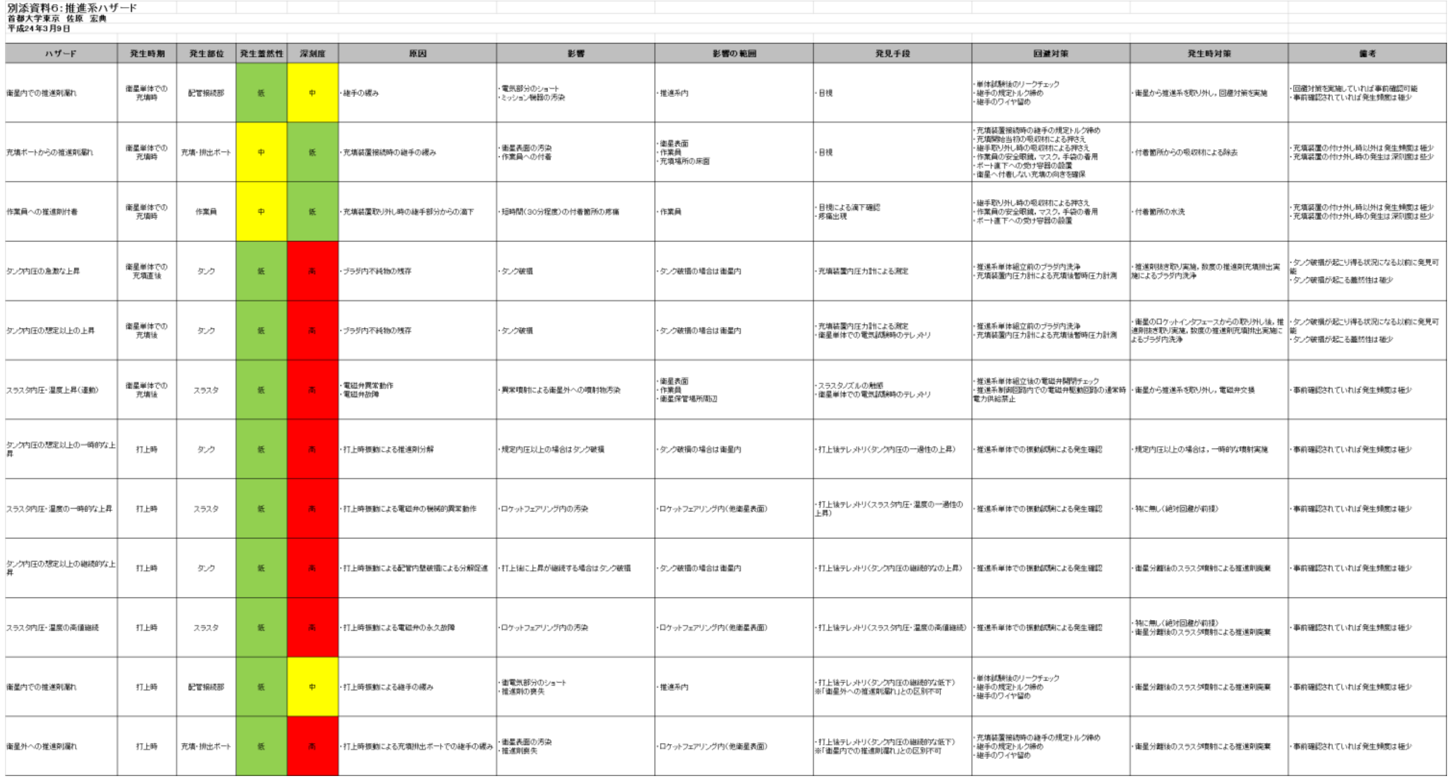
Check the correct responses to operational commands.

4. Considerations

4.3 Example of Solution

Hazard Analysis

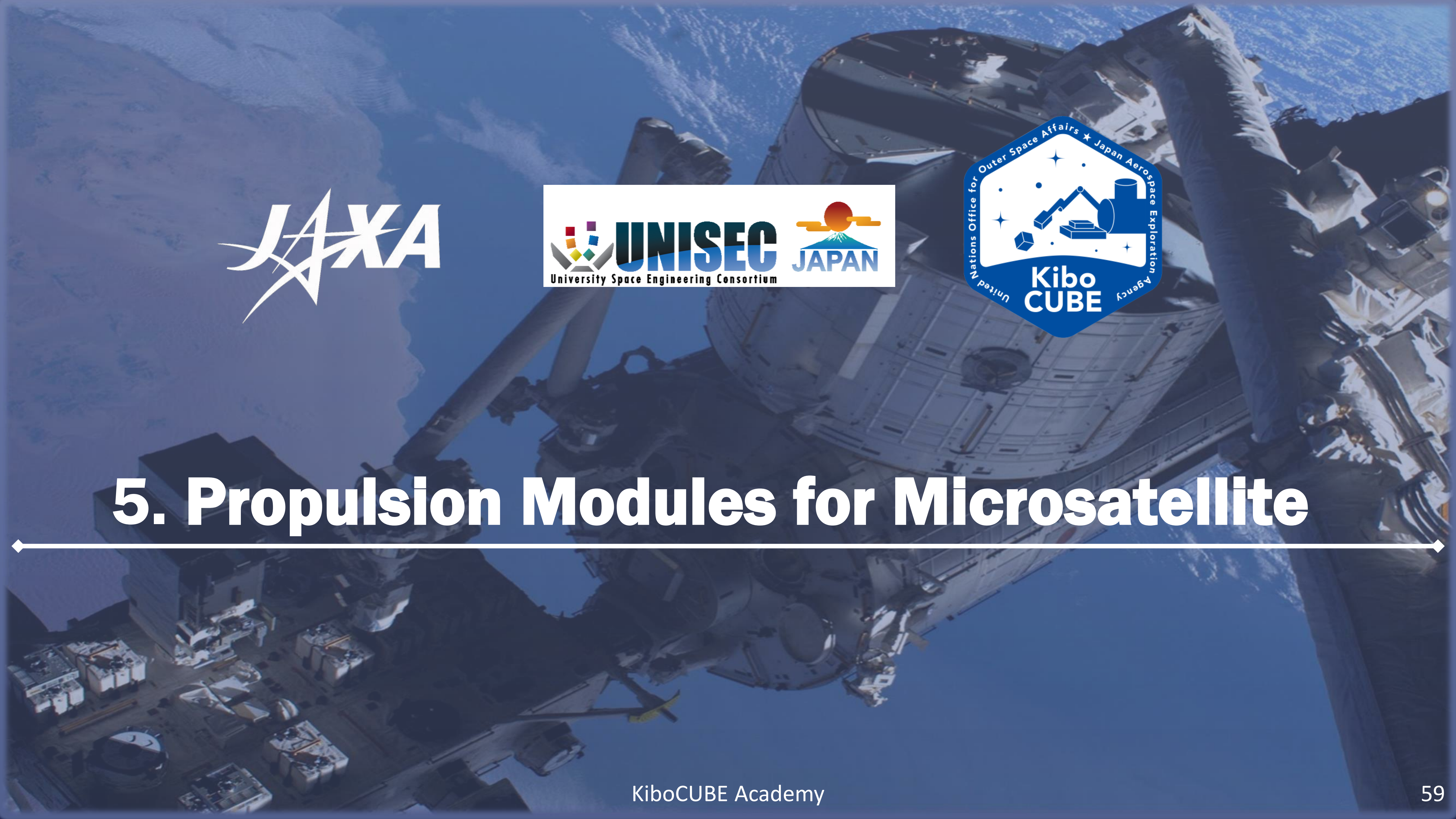
- Graded by two items: frequency of occurrence and severity
- If a satellite or its onboard subsystem is considered to have a unique hazard, a Unique Hazard Report (UHR) is set.
- The UHR identifies the causes of the hazard and summarizes control methods to avoid it, and methods to verify that it is achieved and safe.



別添資料6：推進系ハザード
首都大学東京　佐原　宏典
平成24年3月9日

ハザード	発生時期	発生部位	発生蓋然性	深刻度	原因	影響	影響の範囲	発見手段	回避対策	発生時対策	備考
衛星内での推進剤漏れ	衛星単体での充填時	配管接続部	低	中	・継手の緩み	・電気部分のショート ・ミッション機器の汚染	・推進系内	・目視	・単体試験後のリークチェック ・継手の規定トルク締め ・継手のワイヤ留め	・衛星から推進系を取り外し，回避対策を実施	・回避対策を実施していれば事前確認可能 ・事前確認されていれば発生頻度は極少
充填ポートからの推進剤漏れ	衛星単体での充填時	充填・排出ポート	中	低	・充填装置接続時の継手の緩み	・衛星表面の汚染 ・作業員への付着	・衛星表面 ・作業員 ・充填場所の床面	・目視	・充填装置接続時の継手の規定トルク締め ・充填開始当初の吸収材による押さえ ・継手取り外し時の吸収材による押さえ ・作業員の安全眼鏡，マスク，手袋の着用 ・ポート直下への受け容器の設置 ・衛星へ付着しない充填の向きを確保	・付着箇所からの吸収材による除去	・充填装置の付け外し時以外は発生頻度は極少 ・充填装置の付け外し時の発生は深刻度は些少
作業員への推進剤付着	衛星単体での充填時	作業員	中	低	・充填装置取り外し時の継手部分からの滴下	・短時間（30分程度）の付着箇所の疼痛	・作業員	・目視による滴下確認 ・疼痛出現	・継手取り外し時の吸収材による押さえ ・作業員の安全眼鏡，マスク，手袋の着用 ・ポート直下への受け容器の設置	・付着箇所の水洗	・充填装置の付け外し時以外は発生頻度は極少 ・充填装置の付け外し時の発生は深刻度は些少
タンク内圧の急激な上昇	衛星単体での充填直後	タンク	低	高	・ブラダ内不純物の残存	・タンク破損	・タンク破損の場合は衛星内	・充填装置内圧力計による測定	・推進系単体組立前のブラダ内洗浄 ・充填装置内圧力計による充填後暫時圧力計測	・推進剤抜き取り実施，数度の推進剤充填排出実施によるブラダ内洗浄	・タンク破損が起こり得る状況になる以前に発見可能 ・タンク破損が起こる蓋然性は極少
タンク内圧の想定以上の上昇	衛星単体での充填後	タンク	低	高	・ブラダ内不純物の残存	・タンク破損	・タンク破損の場合は衛星内	・充填装置内圧力計による測定 ・衛星単体での電気試験時のテレメトリ	・推進系単体組立前のブラダ内洗浄 ・充填装置内圧力計による充填後暫時圧力計測	・衛星のロケットインタフェースからの取り外し後，推進剤抜き取り実施，数度の推進剤充填排出実施によるブラダ内洗浄	・タンク破損が起こり得る状況になる以前に発見可能 ・タンク破損が起こる蓋然性は極少
スラスタ内圧・温度上昇（連動）	衛星単体での充填後	スラスタ	低	高	・電磁弁異常動作 ・電磁弁故障	・異常噴射による衛星外への噴射物汚染	・衛星表面 ・作業員 ・衛星保管場所周辺	・スラスタノズルの触感 ・衛星単体での電気試験時のテレメトリ	・推進系単体組立後の電磁弁開閉チェック ・推進系制御回路内での電磁弁駆動回路の通常時電力供給禁止	・衛星から推進系を取り外し，電磁弁交換	・事前確認されていれば発生頻度は極少
タンク内圧の想定以上の一時的な上昇	打上時	タンク	低	高	・打上時振動による推進剤分解	・規定内圧以上の場合はタンク破損	・タンク破損の場合は衛星内	・打上後テレメトリ（タンク内圧の一過性の上昇）	・推進系単体での振動試験による発生確認	・規定内圧以上の場合は，一時的な噴射実施	・事前確認されていれば発生頻度は極少
スラスタ内圧・温度の一時的な上昇	打上時	スラスタ	低	高	・打上時振動による電磁弁の機械的異常動作	・ロケットフェアリング内の汚染	・ロケットフェアリング内（他衛星表面）	・打上後テレメトリ（スラスタ内圧・温度の一過性の上昇）	・推進系単体での振動試験による発生確認	・特に無し（絶対回避が前提）	・事前確認されていれば発生頻度は極少
タンク内圧の想定以上の継続的な上昇	打上時	タンク	低	高	・打上時振動による配管内壁破損による分解促進	・打上後に上昇が継続する場合はタンク破損	・タンク破損の場合は衛星内	・打上後テレメトリ（タンク内圧の継続的なの上昇）	・推進系単体での振動試験による発生確認	・衛星分離後のスラスタ噴射による推進剤廃棄	・事前確認されていれば発生頻度は極少
スラスタ内圧・温度の高値継続	打上時	スラスタ	低	高	・打上時振動による電磁弁の永久故障	・ロケットフェアリング内の汚染	・ロケットフェアリング内（他衛星表面）	・打上後テレメトリ（スラスタ内圧・温度の高値継続）	・推進系単体での振動試験による発生確認	・特に無し（絶対回避が前提） ・衛星分離後のスラスタ噴射による推進剤廃棄	・事前確認されていれば発生頻度は極少
衛星内での推進剤漏れ	打上時	配管接続部	低	中	・打上時振動による継手の緩み	・衛電気部分のショート ・推進剤の喪失	・推進系内	・打上後テレメトリ（タンク内圧の継続的な低下） ※「衛星外への推進剤漏れ」との区別不可	・単体試験後のリークチェック ・継手の規定トルク締め ・継手のワイヤ留め	・衛星分離後のスラスタ噴射による推進剤廃棄	・事前確認されていれば発生頻度は極少
衛星外への推進剤漏れ	打上時	充填・排出ポート	低	高	・打上時振動による充填排出ポートでの継手の緩み	・衛星表面の汚染 ・推進剤喪失	・ロケットフェアリング内（他衛星表面）	・打上後テレメトリ（タンク内圧の継続的な低下） ※「衛星内での推進剤漏れ」との区別不可	・充填装置接続時の継手の規定トルク締め ・継手の規定トルク締め ・継手のワイヤ留め	・衛星分離後のスラスタ噴射による推進剤廃棄	・事前確認されていれば発生頻度は極少

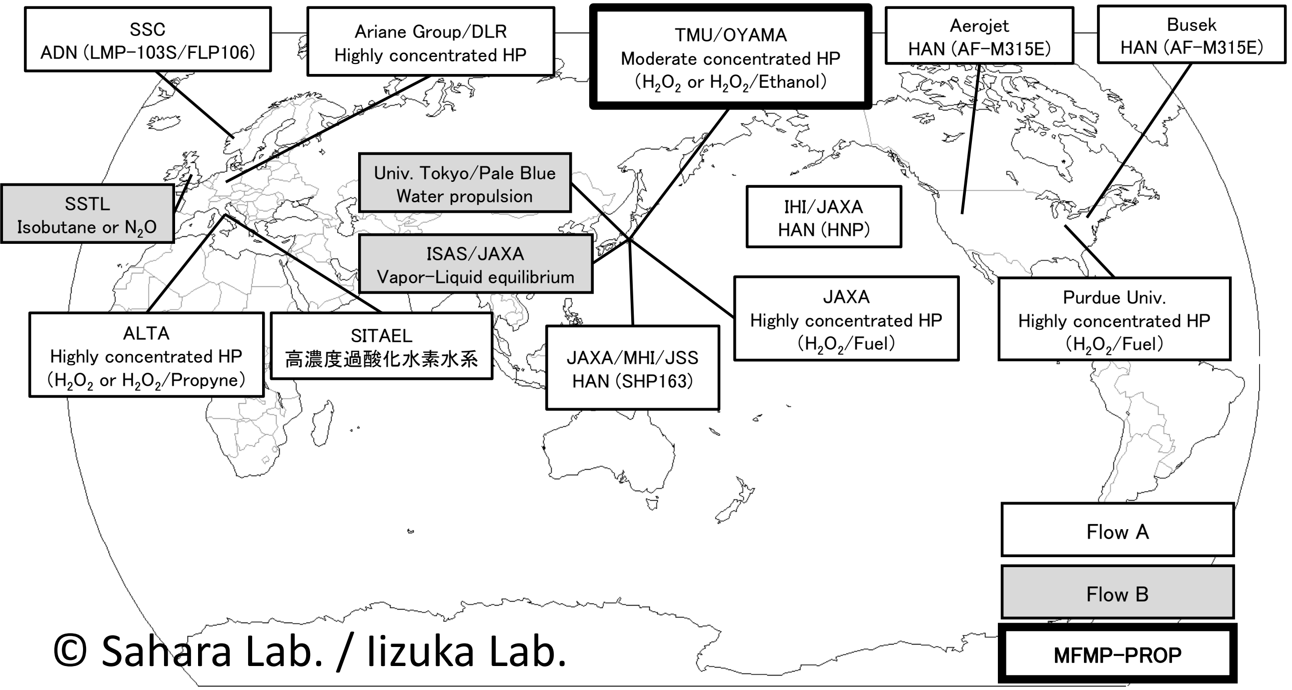
With the above documents and test results in hand, you are now ready for the safety review!



5. Propulsion Modules for Microsatellite

5. Propulsion Modules for Microsatellite

- Low-toxicity propulsion systems for microsatellites have already been supplied for both chemical and electric propulsion.
- The propellants are broadly classified into ADN-based, HAN-based, and highly-concentrated hydrogen peroxide-based propellants. You can find a variety of models by searching for the model number on the Internet.
- The authors have developed Microsatellite-Friendly Multi-Purpose Propulsion (MFMP-PROP) using moderate-concentrated hydrogen peroxide water.



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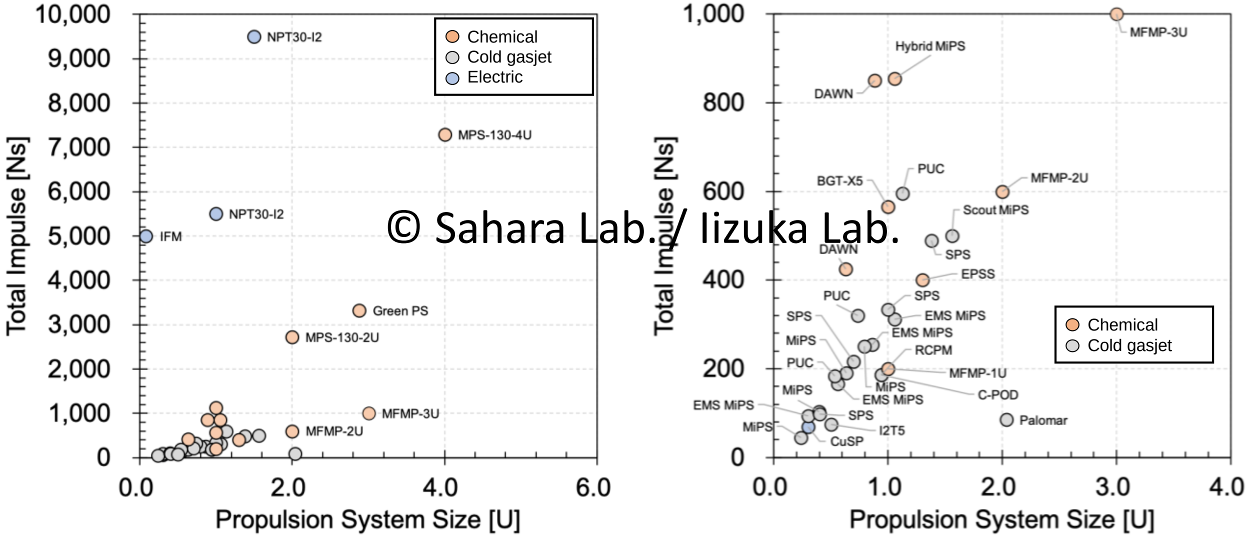

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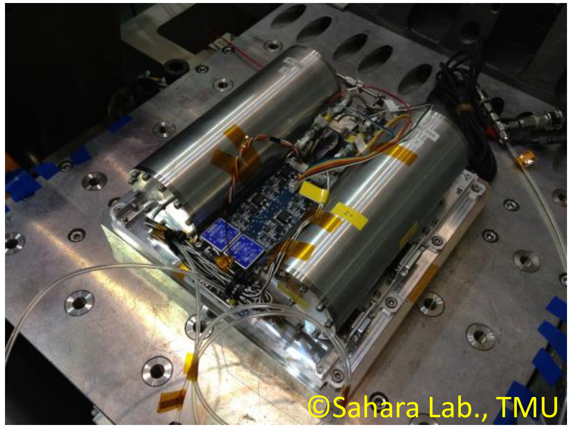
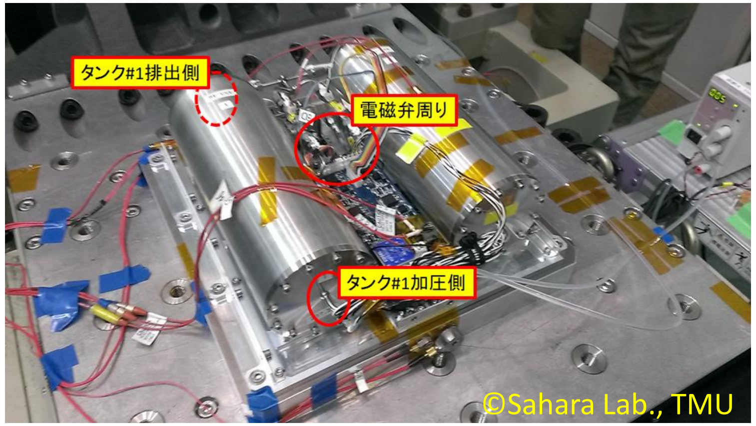
5. Propulsion Modules for Microsatellite

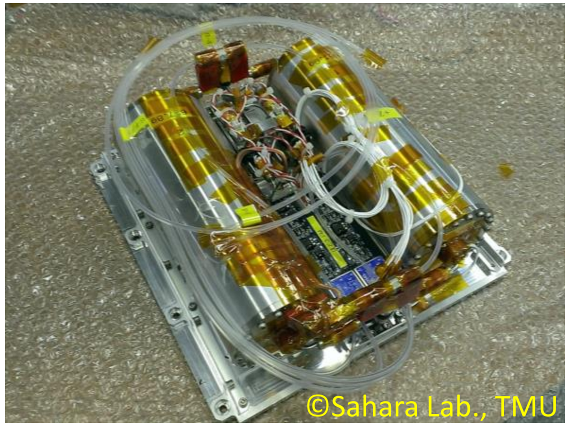
- Because of copyright issues, our MFMP-PROP is shown here.
- We have developed it for three satellites so far, and two of them have been launched with MFMP-PROP on board.



UNIFORM-1



Hodoyoshi-1



Hodoyoshi-3

- The difficulties in installing a propulsion system on a satellite are
  - securing an occupied volume that is said to be "too big" even though it only complies with mission requirements,
  - and ensuring that the tanks and piping are resistant to the mechanical environment.
- To solve such problems, we are currently developing MFMP-PROP, which can be easily installed on a satellite and satisfy mission requirements through a simple combination.

6. Conclusion

6. Conclusion

In this lecture, we discussed the following:

1. The basics of propulsion systems and parameters to be considered were explained.
   The choice of the propulsion system must be determined between various requirements and constraints.
2. The system design is based on velocity increment to realize the mission.
   Tsiolkovsky's rocket equation is the link between the two.
3. Several simple examples were given as examples of how to go from orbit calculation to system design.
4. When designing, developing, and installing a propulsion system on a satellite, various laws, regulations, and guidelines must be observed.
   Please note that difficult legal decisions may be necessary and should always be discussed with the appropriate person.
5. Modularized propulsion systems were introduced.
   In particular, the author's MFMP-PROP is now under development to support your mission.

In the future, many missions that require propulsion systems are expected to appear, even for microsatellites.

At that time, we hope that propulsion engineers, orbit designers, and system designers will cooperate well with each other so that appropriate designs can be made and the mission can be carried out without fail.

Thank you very much.