The 7th Mission Idea Contest Lecture Series
For Deep Space Science and Exploration

Deep Space Exploration and Micropropulsion

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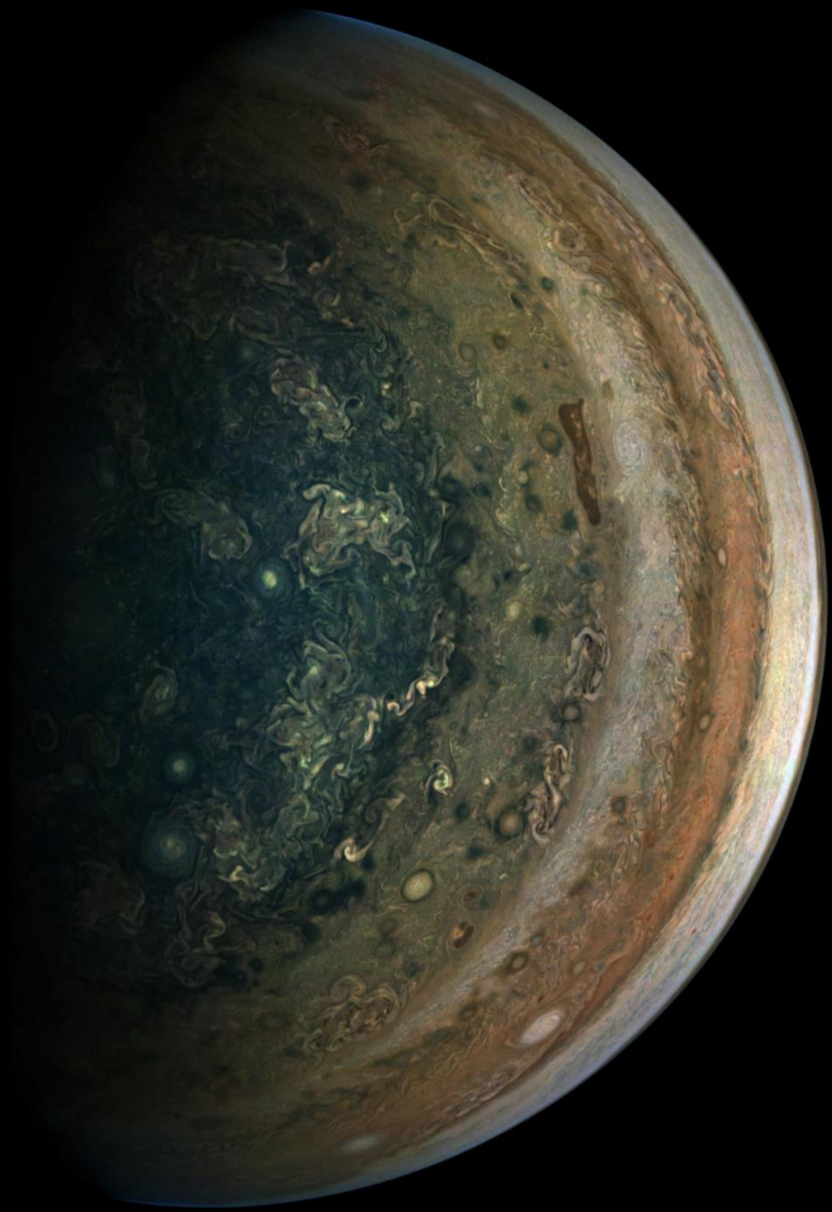


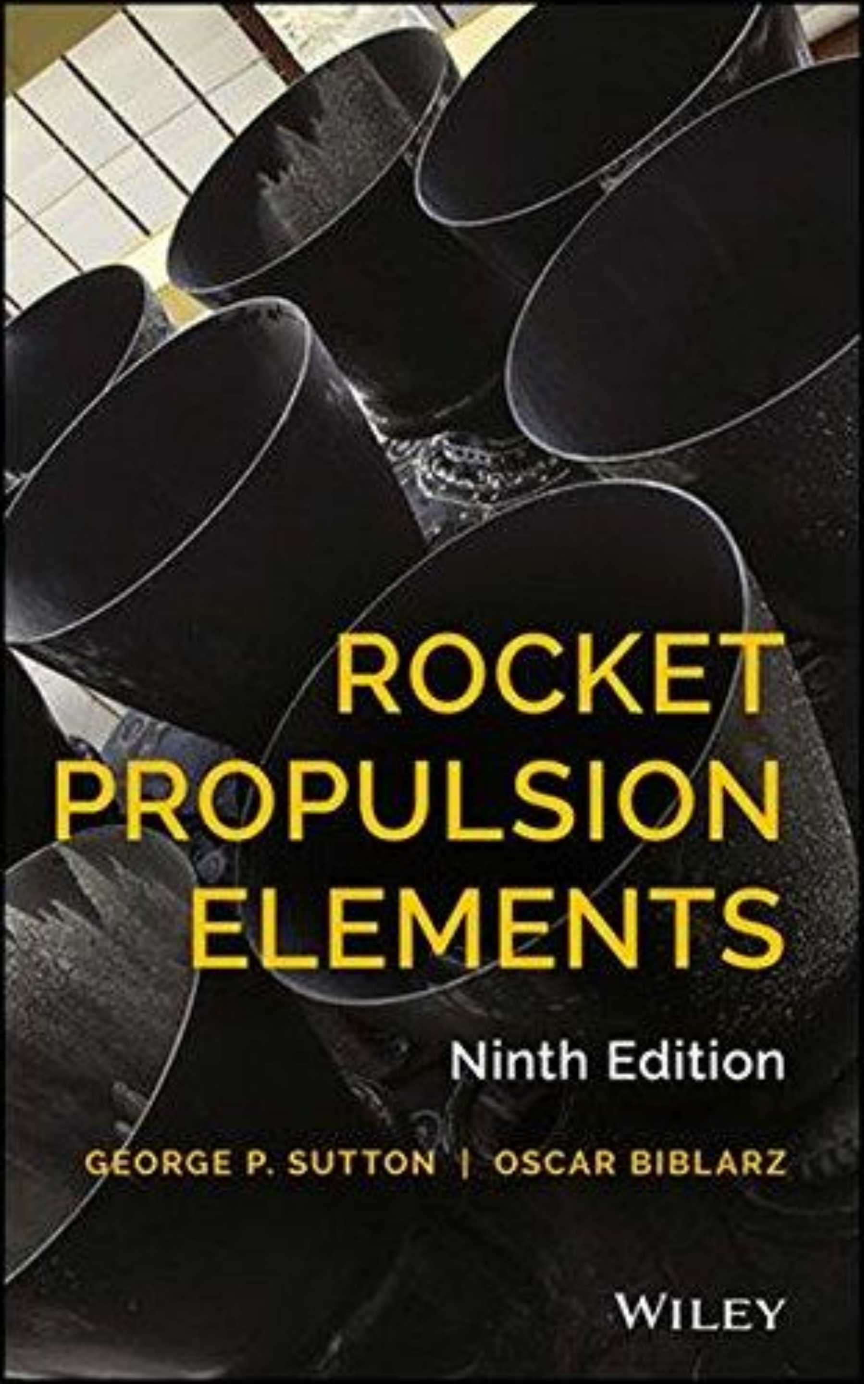
0: Preface

CommentScreen

Anonymous comment app.

Freely input your question, comments, & impressions.

URL :
(check a chat)
https://commentscreen.com/comments?&id=IcjvccNIaUTKK9q6NqZh



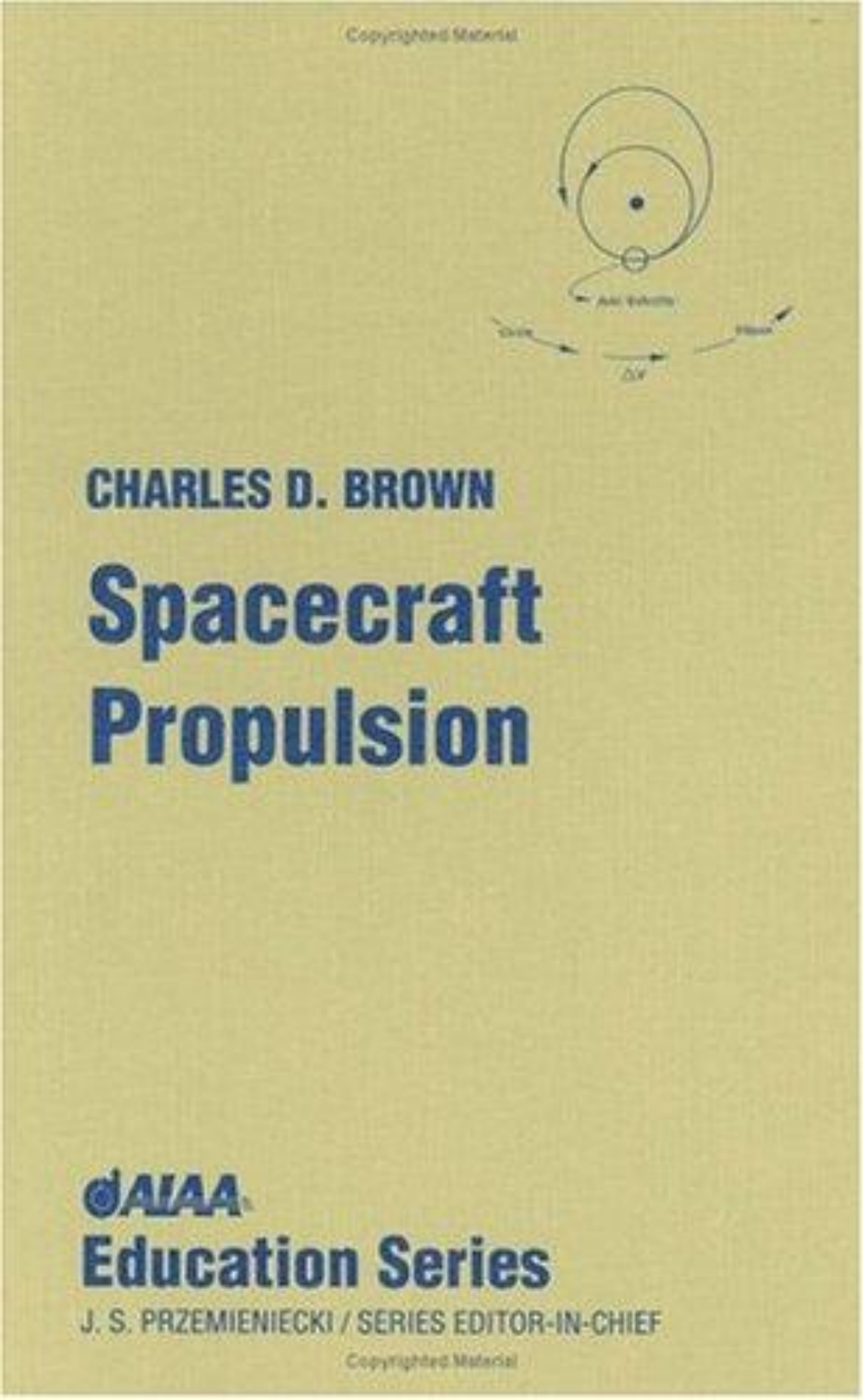
by G.P. Sutton & O. Biblarz

Classical & popular

Old but new (9th Edition)

Not recommend Jpn ver.
(old and expensive)

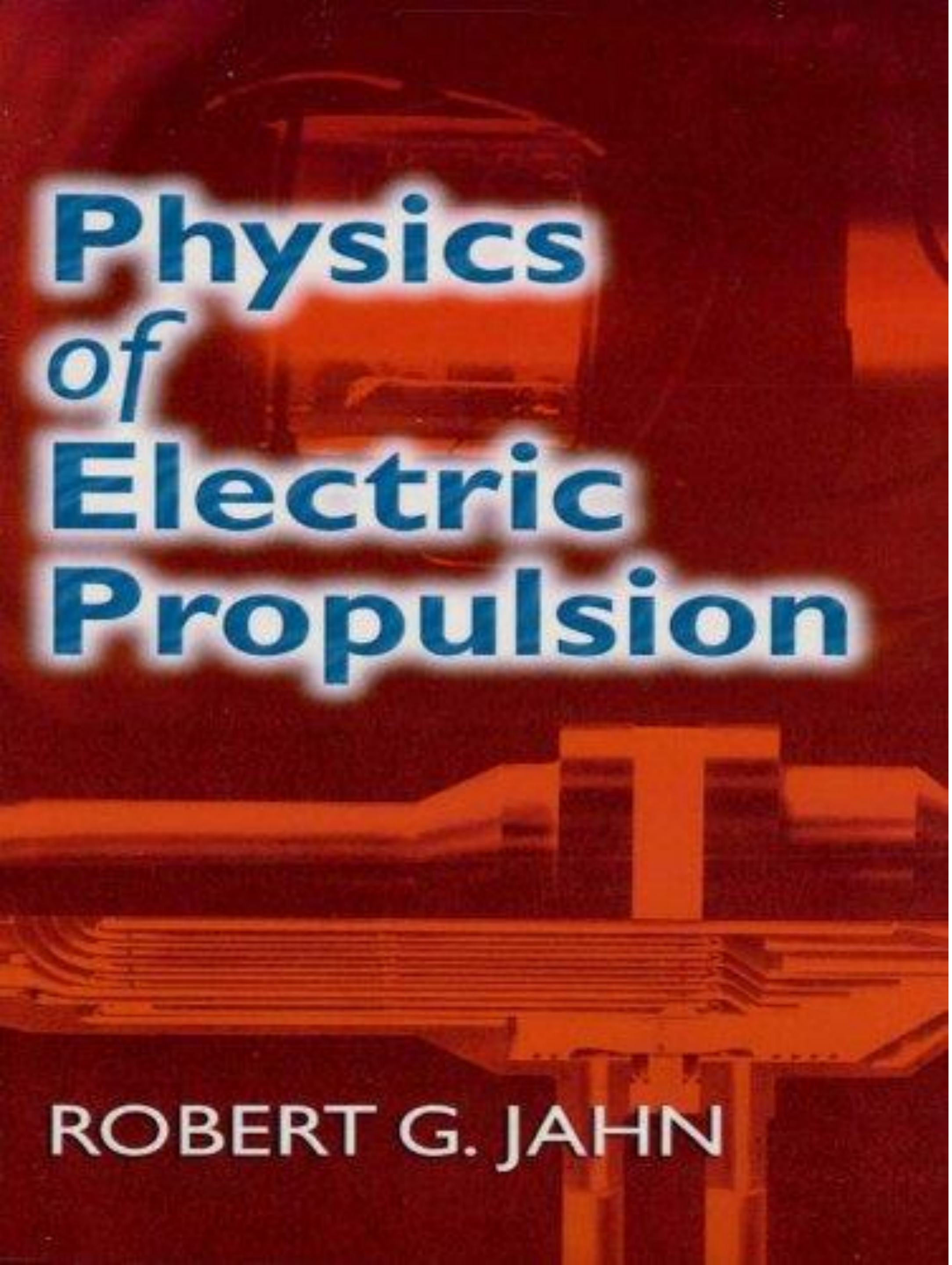
There is Kindle ver



by C. D. Brown

Chemical propulsion

- Mono-propellant
- Bi-propellant
- Solid rocket
- Cold-gas

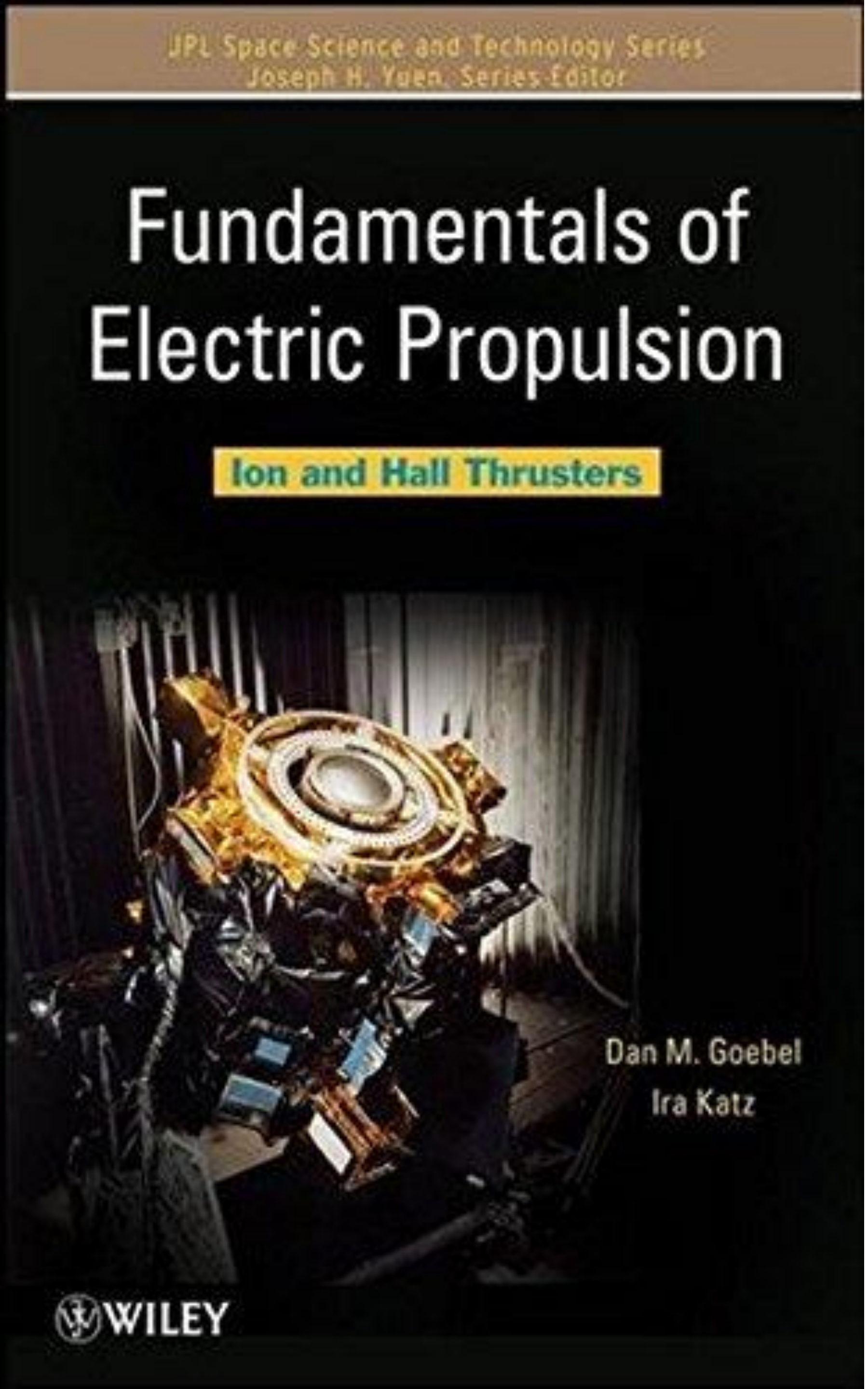


by R.G. Jahn

Classical & popular

Technologically Old, but long seller = good book

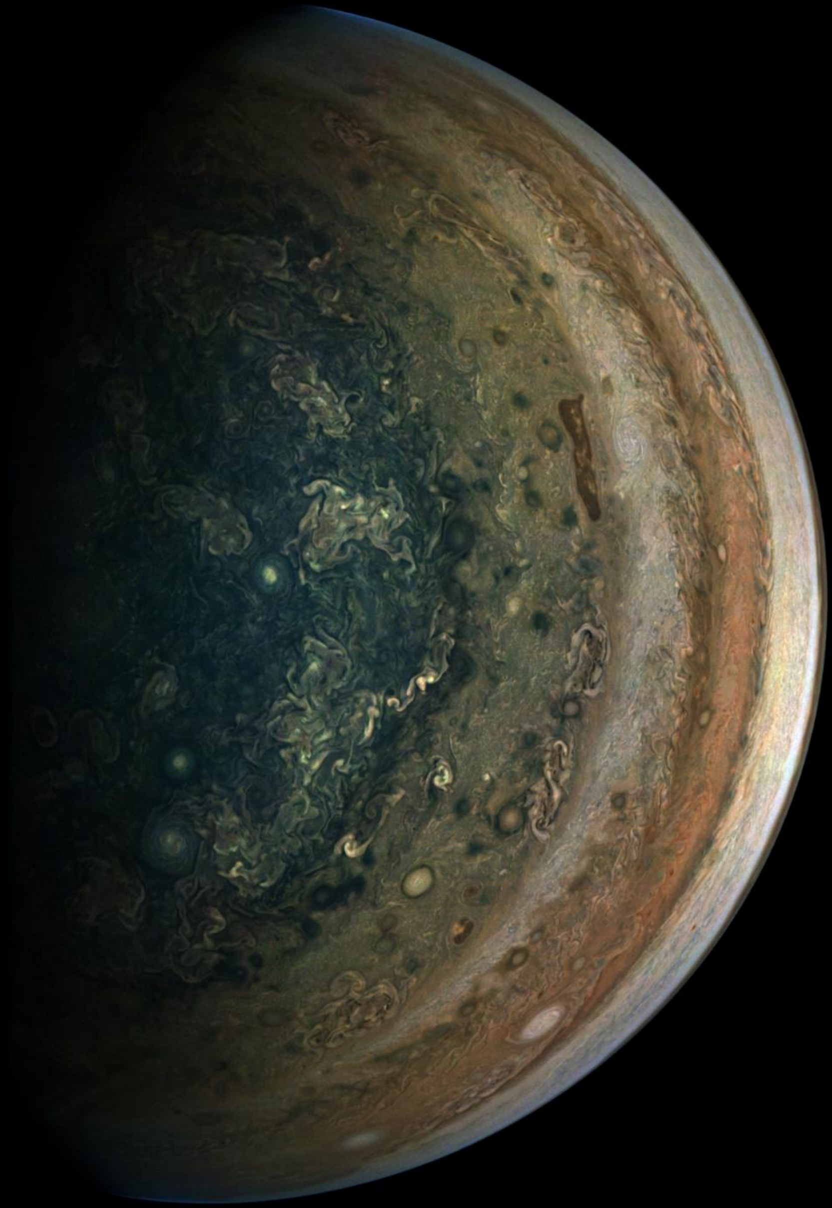
There are Paper back ver & Kindle ver



by D.M. Goebel & I. Katz

Technologically new

Focusing on ion/Hall thruster



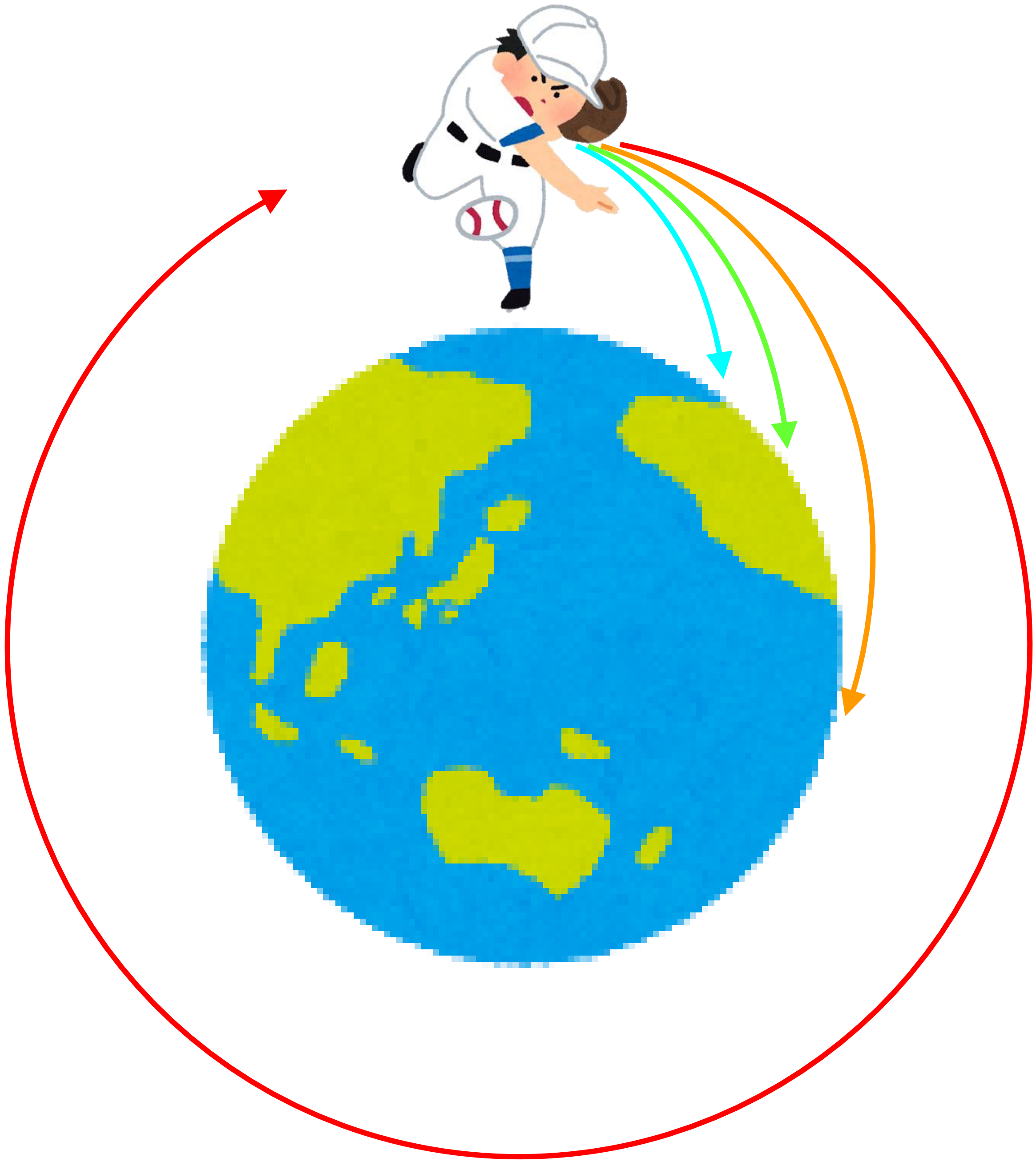
1: Fundamentals

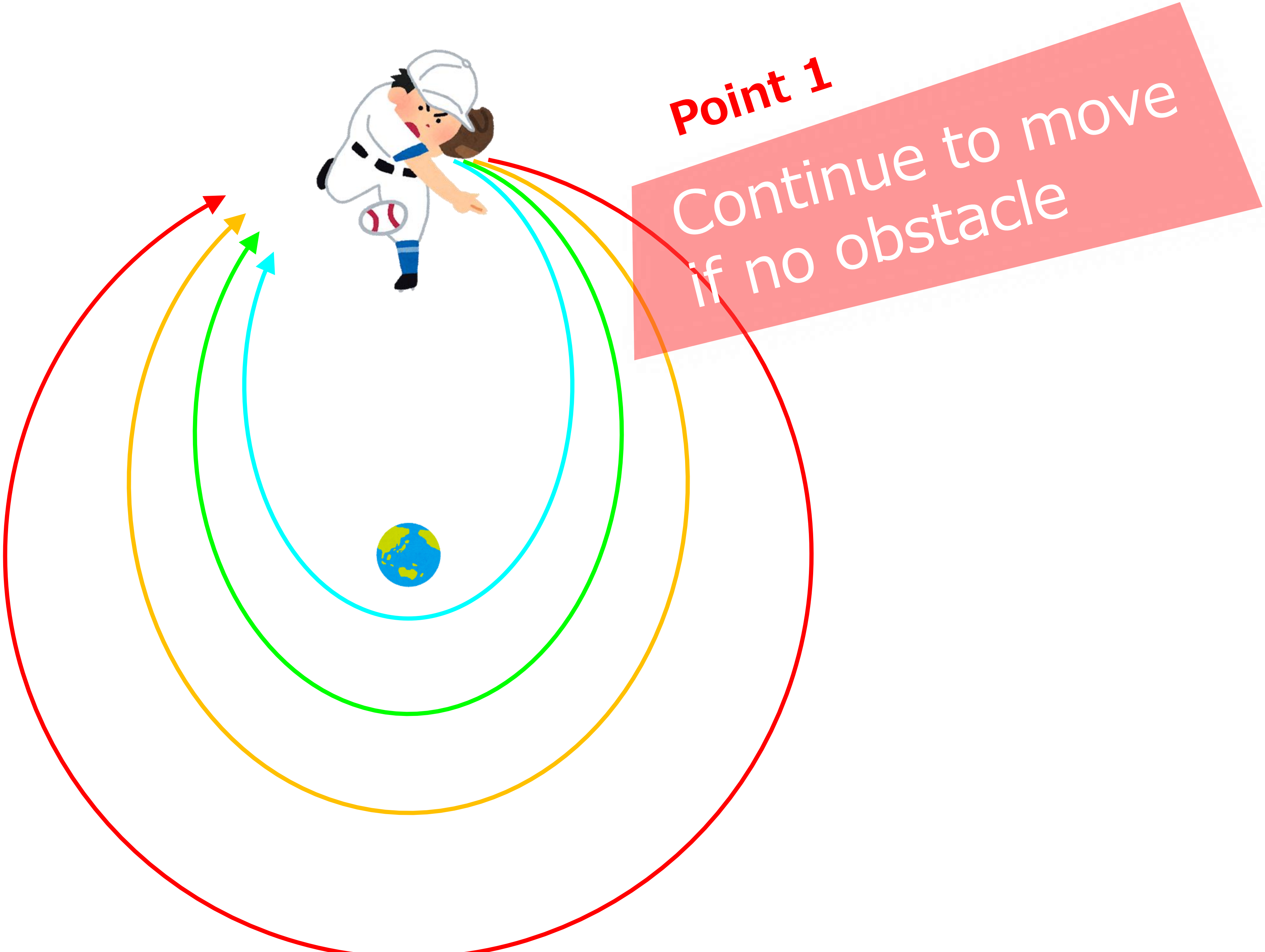
2: Chemical Propulsion

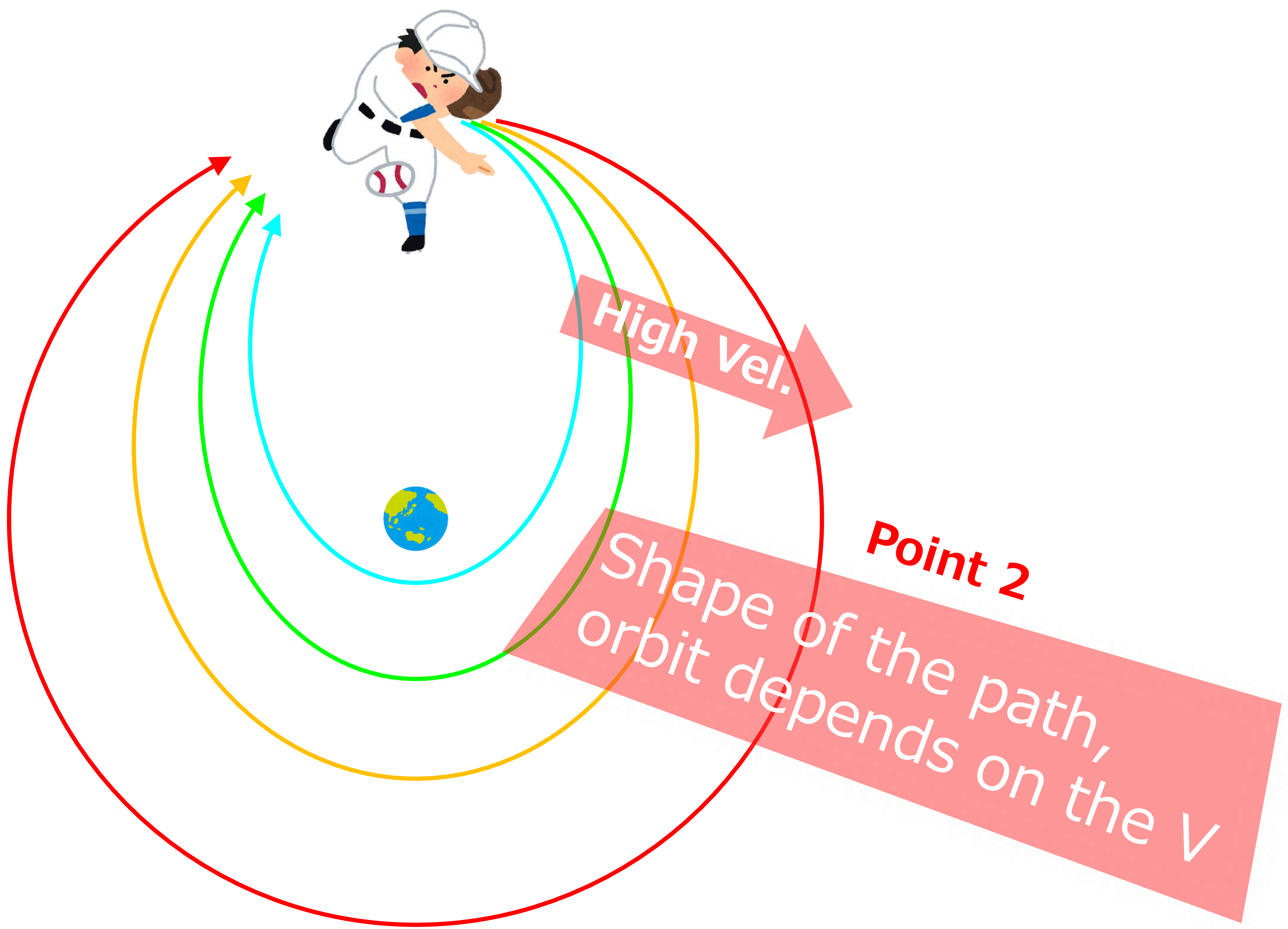
3: Electric Propulsion

4: Micropropulsion


Just falling
Going to the center by energy loss



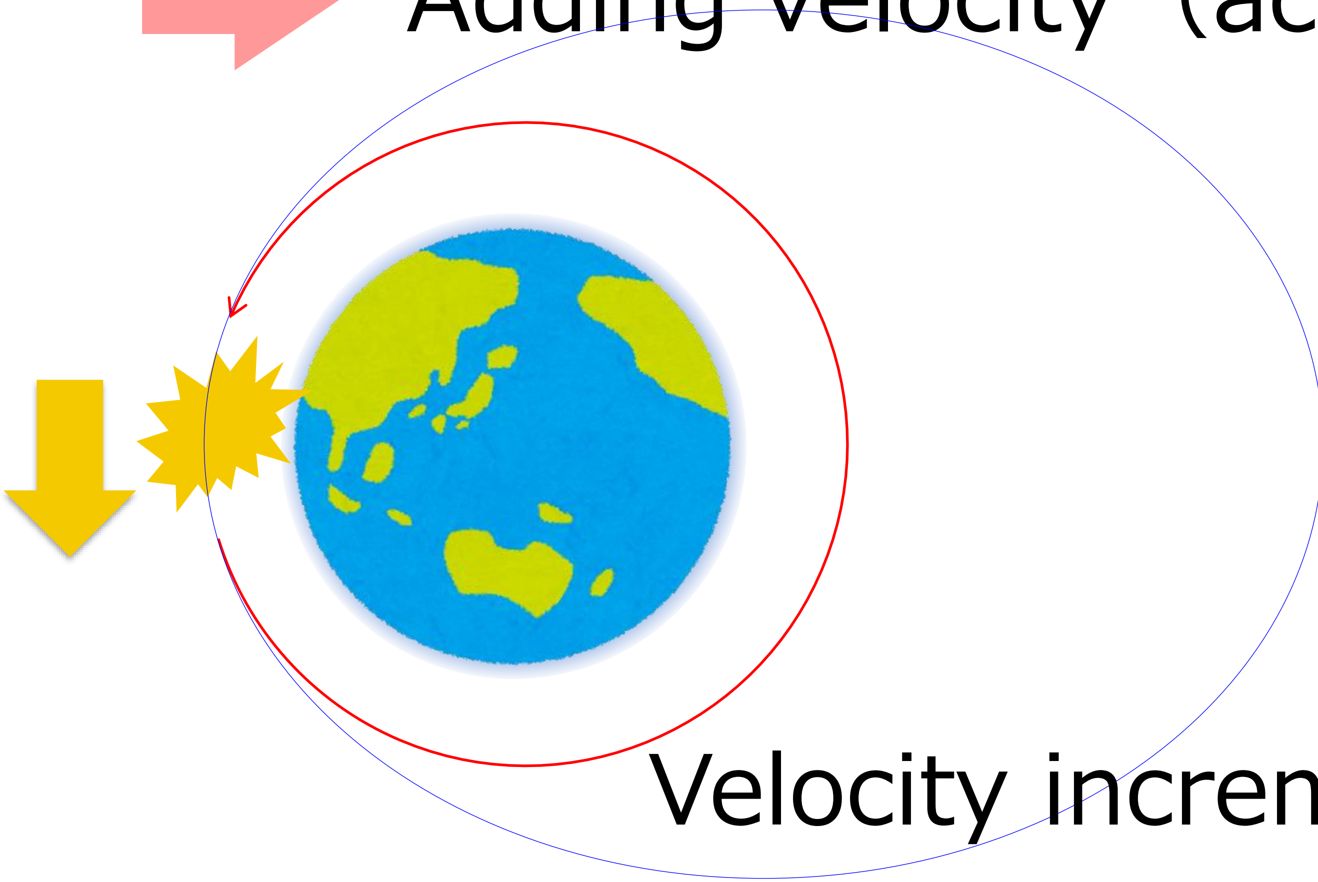

Point 1
Continue to move
if no obstacle


High Vel.
Point 2
Shape of the path,
orbit depends on the V

Velocity Increment: ΔV

How to change the orbit

⇒ Adding velocity (acceleration)



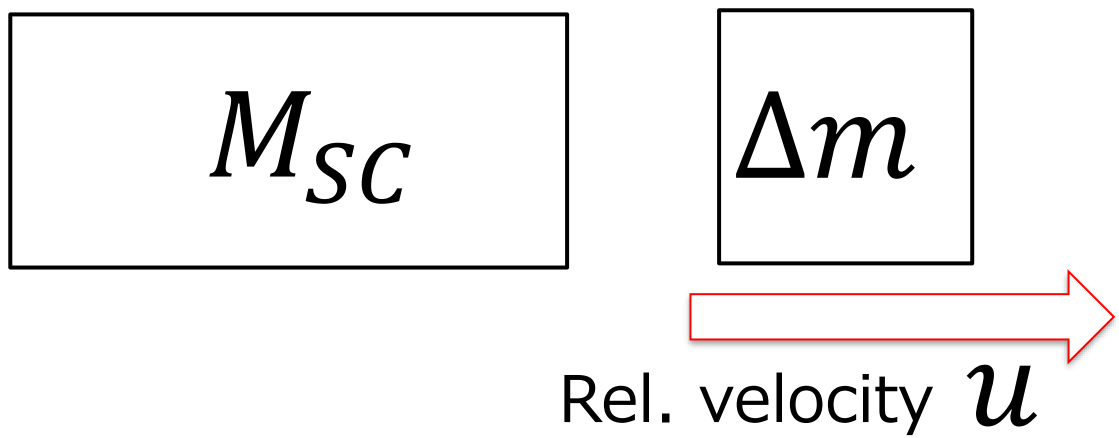
Velocity increment: ΔV


How to gain velocity?
Push something!
A315


Nothing
You need to bring something to push
©NASA
https://images.nasa.gov/details-iss040e012013.html

How does a rocket work?

Mass Δm is released from a spacecraft at a velocity u in time Δt



Impulse = Momentum increment

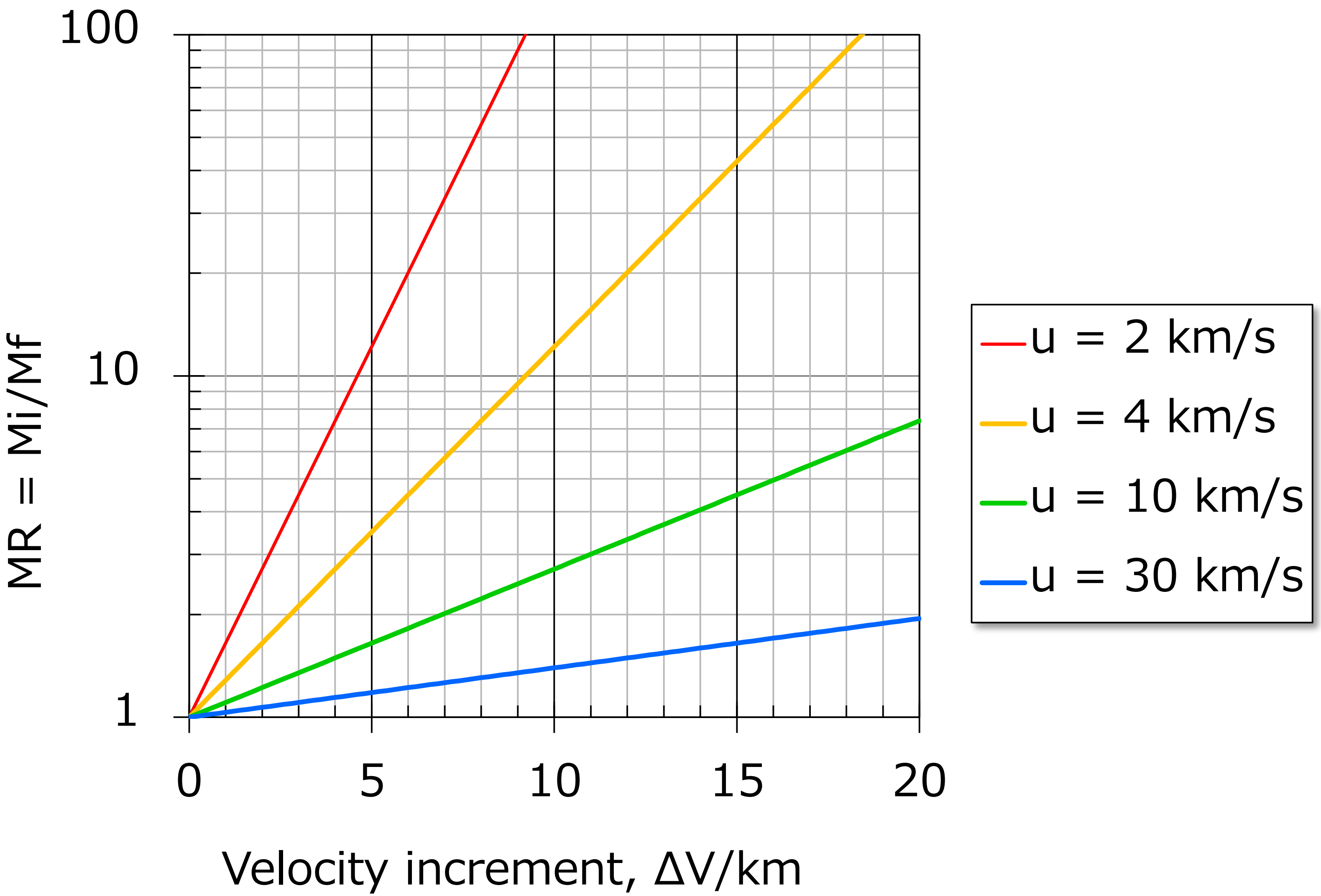
$$F\Delta t = \Delta m\, u$$

$$F = \dot{m}\, u$$: mass flow rate

World's Launch Vehicles

Engine	Launcher	Propellant	Ex Vel.	Thrust
F1	Saturn V	LOX/RP-1	**3.0 km/s**	7.7 MN
RD-107	Soyuz	LOX/RP-1	**3.1 km/s**	1.0 MN
RD-264	Dnepr	N2O4/UDMH	**3.2 km/s**	4.5 MN
SSME	Shuttle	LOX/LH2	**4.5 km/s**	2.2 MN
LE7A	H2A	LOX/LH2	**4.3 km/s**	1.1 MN
Vulcain2	Arian 5	LOX/LH2	**4.3 km/s**	1.3 MN
SSRB	Shuttle	Composite	**2.7 km/s**	13.8 MN
SRB-A	H2A	Composite	**2.8 km/s**	2.3 MN
M-V-1	M-V	Composite	**2.8 km/s**	2.4 MN

Exhaust velocity is a key



Propulsion = Energy converter

(Any → Kinetic energy)

Chemical propulsion

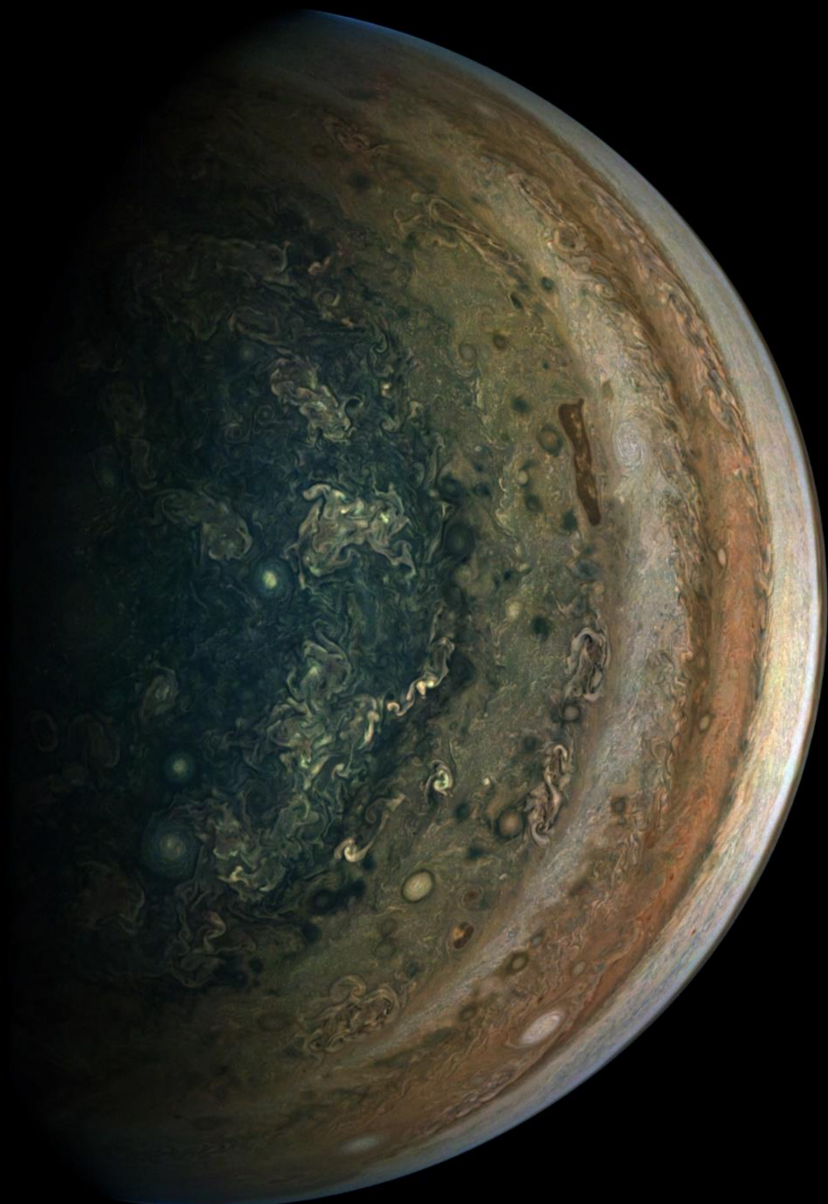
Chemical E → Kinetic E

Exhaust velocity : 1 – 4 km/s

Electric propulsion

Electric E → Kinetic E

Exhaust : 10 – 50 km/s



1: Fundamentals

2: Chemical Propulsion

3: Electric Propulsion

4: Micropropulsion

Chemical Propulsion; Processes

Chemical energy

By combustion

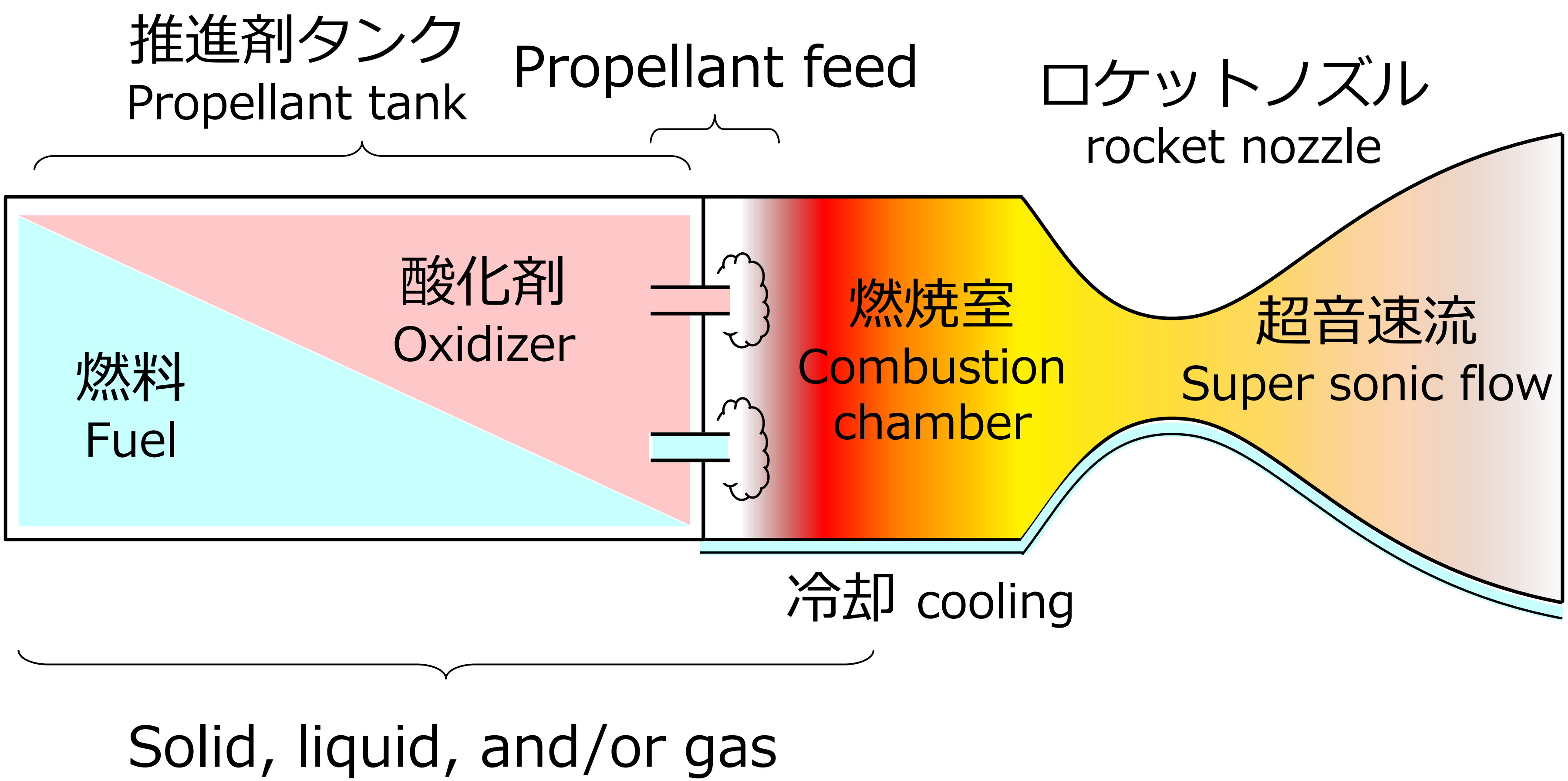
Thermal energy

Nozzle theory

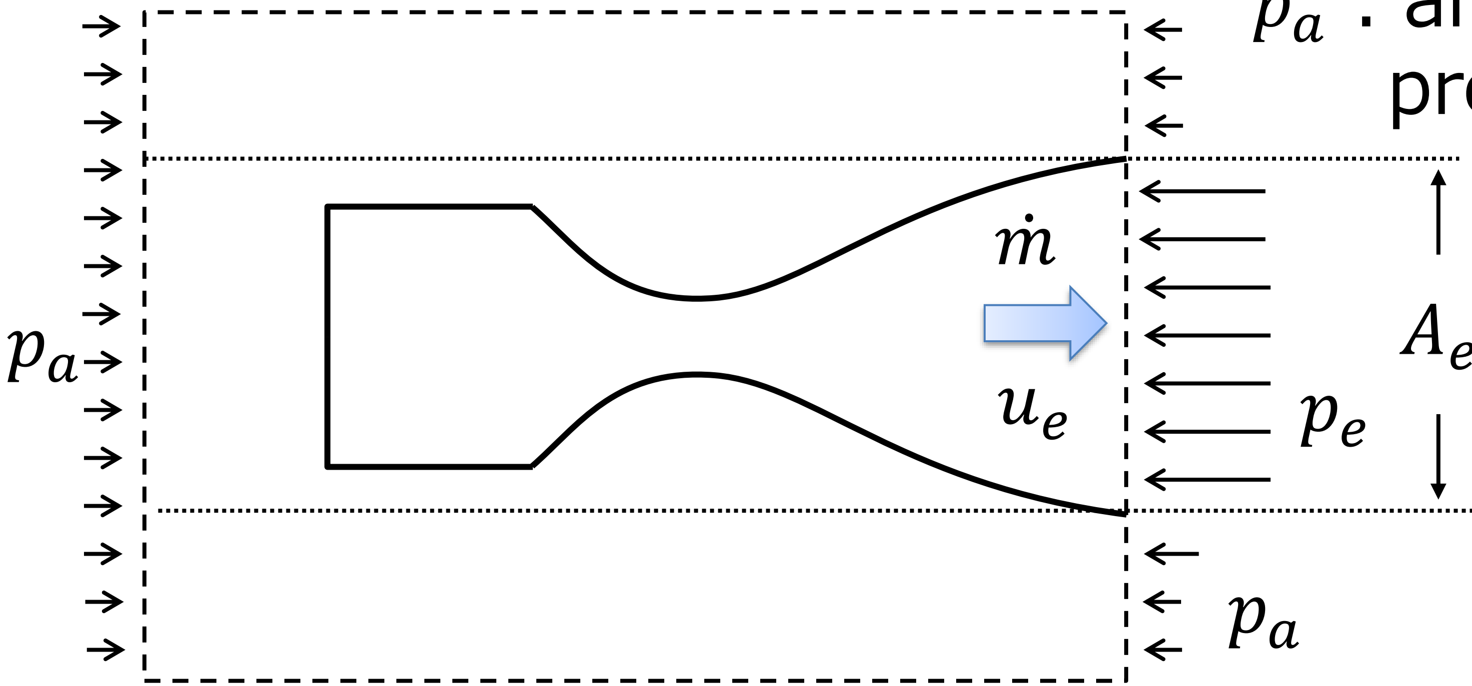
By a rocket-nozzle

Kinetic energy

Chemical Propulsion; Overview



Pressure thrust



Pressure difference of the front and back sides applies another thrust:

$$F = \dot{m} u_e + (p_e - p_a) A_e$$

Effective Exhaust Velocity

$$F = \dot{m}u_e + (p_e - p_a)A_e$$

⋯Actual "exhaust velocity" is not enough

Introducing a new velocity: Effective Exhaust Velocity

$$c \equiv \frac{F}{\dot{m}}$$

Specific Impulse

$$I_{sp} \equiv \frac{F}{\dot{m}g} = \frac{FT}{\dot{m}Tg} = \frac{I}{Mg}$$

"g" is just by custom.

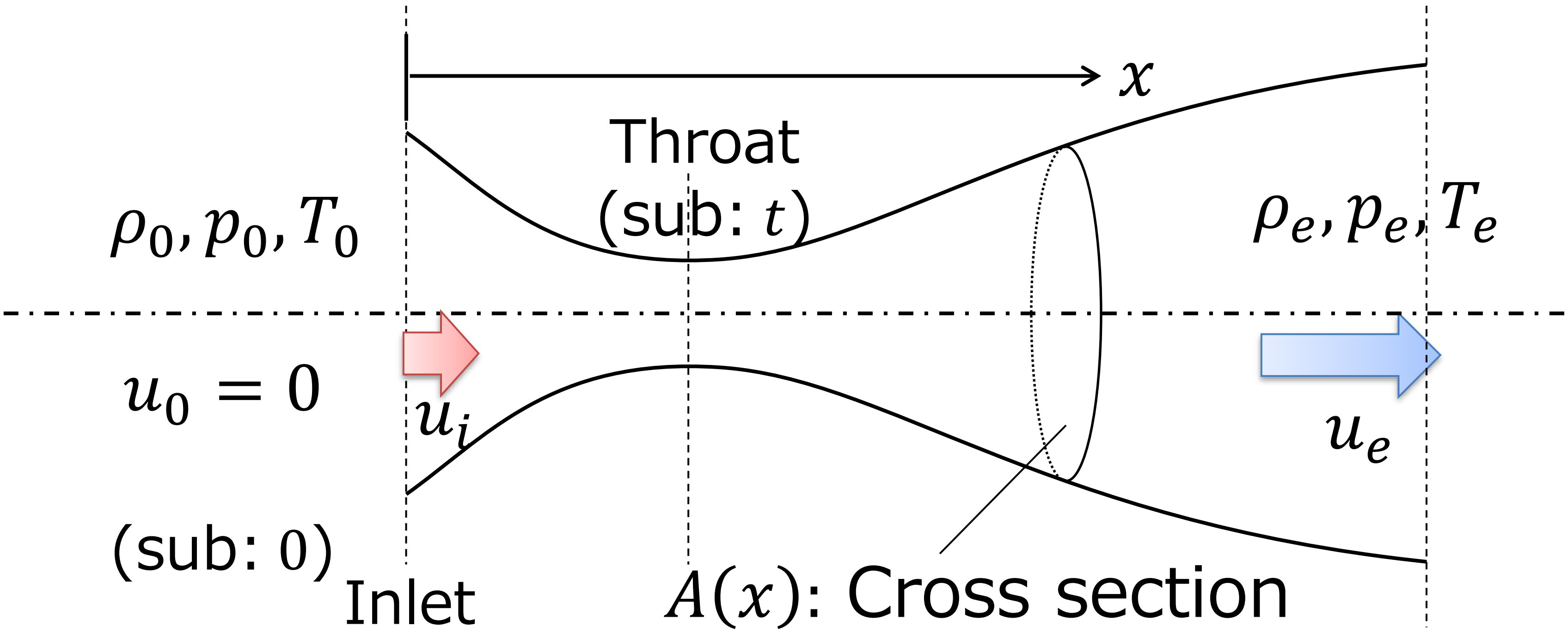
$$c = gI_{sp}$$ (think about 10 times diff.)

e.g.

$c = 4000$ m/s $I_{sp} = 408$ s

$c = 30000$ m/s $I_{sp} = 3060$ s

Rocket Nozzle; Quasi-1D&Isotropic



Flow parameters
- $\rho = \rho(x)$: Density
- $u = u(x)$: Velocity
- $p = p(x)$: Pressure
- $T = T(x)$: Temperature

Government Equations

Mass conservation

$$d(\rho u A) = 0 \quad \cdots \textbf{Eq.(1)}$$

Momentum conservation

$$d(\rho u^2 A) = -A dp \quad \cdots \textbf{Eq.(2)}$$

Energy conservation

$$c_v dT + p d\left(\frac{1}{\rho}\right) = 0 \quad \cdots \textbf{Eq.(3)}$$

Equation of state

$$p = R\rho T \quad \cdots \textbf{Eq.(4)}$$

⇔

Unknowns

$$u = u(x)$$
$$\rho = \rho(x)$$
$$p = p(x)$$
$$T = T(x)$$

Rocket-nozzle thrust

$$F = \dot{m}u_e + (p_e - p_a)A_e$$

$$= A_t p_0 \sqrt{\frac{2\gamma^2}{\gamma - 1}\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}\left\{1 - \left(\frac{p_e}{p_0}\right)^{\frac{\gamma-1}{\gamma}}\right\}} + (p_e - p_a)A_e$$

$$= A_t p_0 C_F$$

$$C_F = \sqrt{\frac{2\gamma^2}{\gamma - 1}\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}\left\{1 - \left(\frac{p_e}{p_0}\right)^{\frac{\gamma-1}{\gamma}}\right\}} + \left(\frac{p_e}{p_0} - \frac{p_a}{p_0}\right)\frac{A_e}{A_t}$$

C_F : Thrust coefficient, 推力係数

Depending on the aperture ratio and gas type

Expressing the acceleration of the gas by the nozzle

Exit Pressure & Aperture Ratio

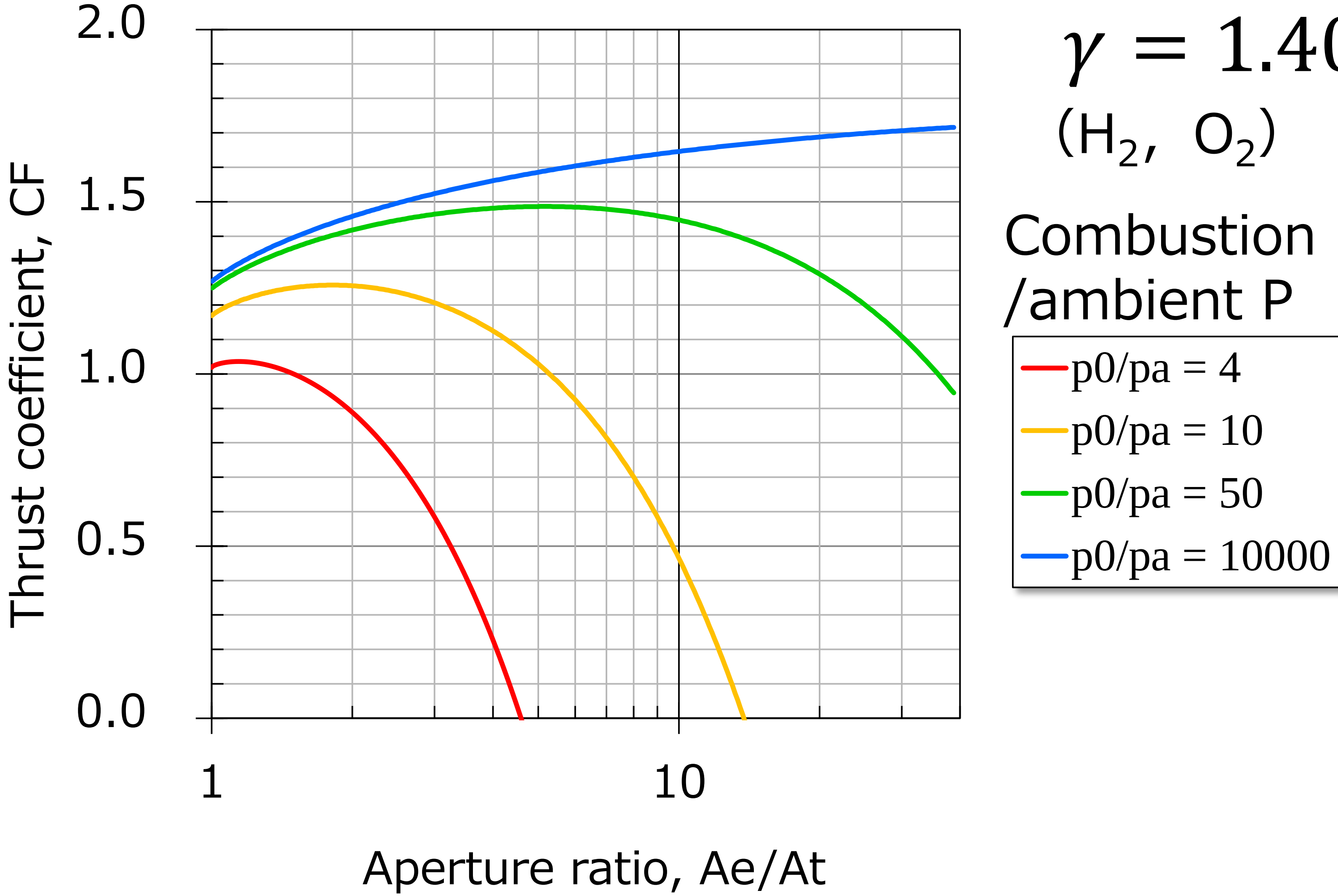
Mass conservation between throat and exit

$$A_t p_0 \sqrt{\frac{\gamma}{RT_0}} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{2(\gamma-1)}} = \rho_e u_e A_e$$

$$u_e = \sqrt{\frac{2\gamma}{\gamma - 1} RT_0 \left\{ 1 - \left(\frac{p_e}{p_0} \right)^{\frac{\gamma-1}{\gamma}} \right\}}$$

$$\frac{A_t}{A_e} = \left(\frac{\gamma + 1}{2} \right)^{\frac{1}{\gamma-1}} \left(\frac{p_e}{p_0} \right)^{\frac{1}{\gamma}} \sqrt{\frac{\gamma + 1}{\gamma - 1} \left\{ 1 - \left(\frac{p_e}{p_0} \right)^{\frac{\gamma-1}{\gamma}} \right\}}$$

Thrust Coefficient



$\gamma = 1.40$

(H_2, O_2)

Combustion P /ambient P

Rocket Thrust

$$
\begin{aligned}
F &= \dot{m}u_e + (p_e - p_a)A_e \\
&= A_t p_0 C_F \\
&= \dot{m} c^* C_F
\end{aligned}
$$

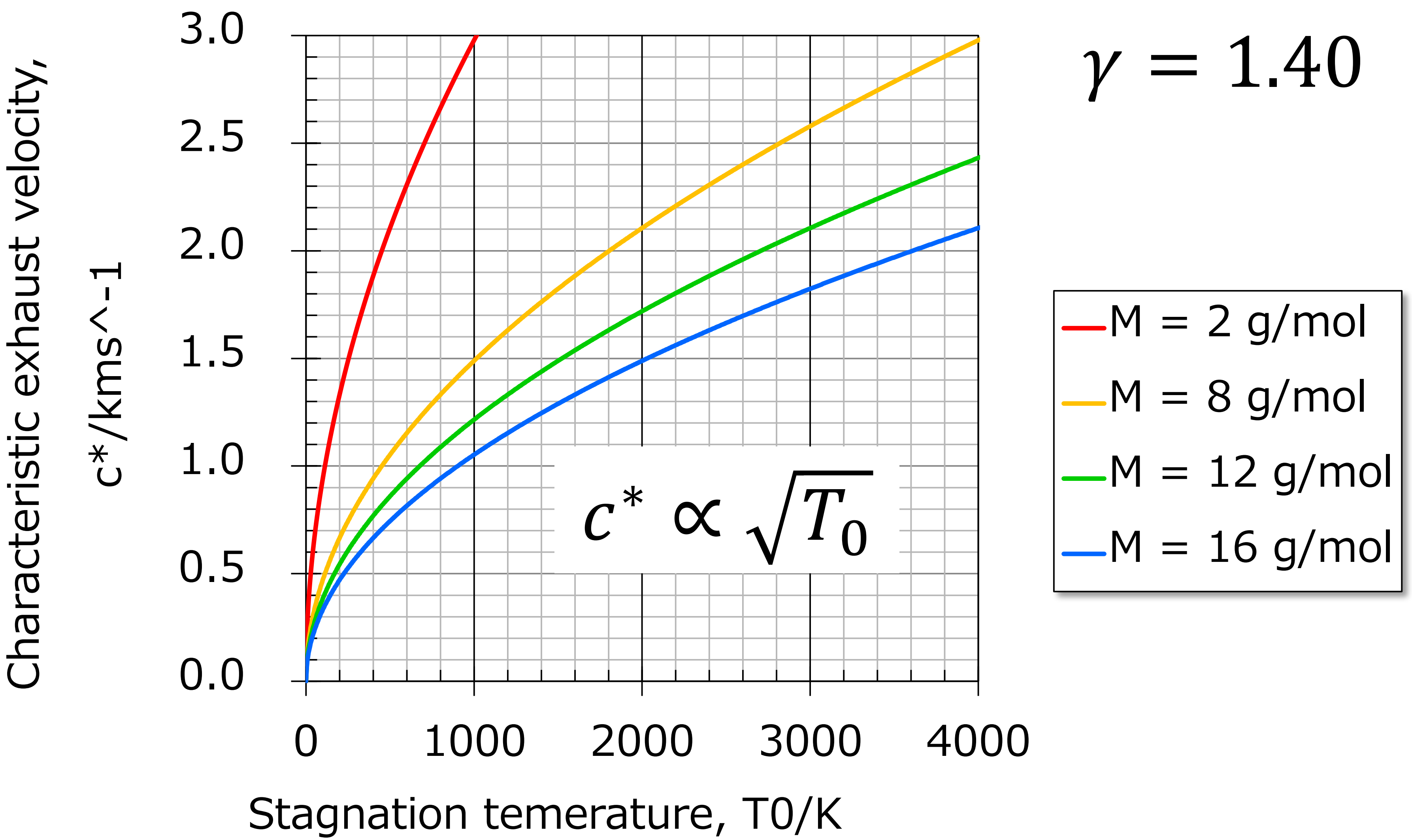
$$
c^* \equiv \frac{A_t p_0}{\dot{m}} = \sqrt{\frac{RT_0}{\gamma}\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{\gamma-1}}}
$$

c* : Characteristic velocity (c star)，特性速度

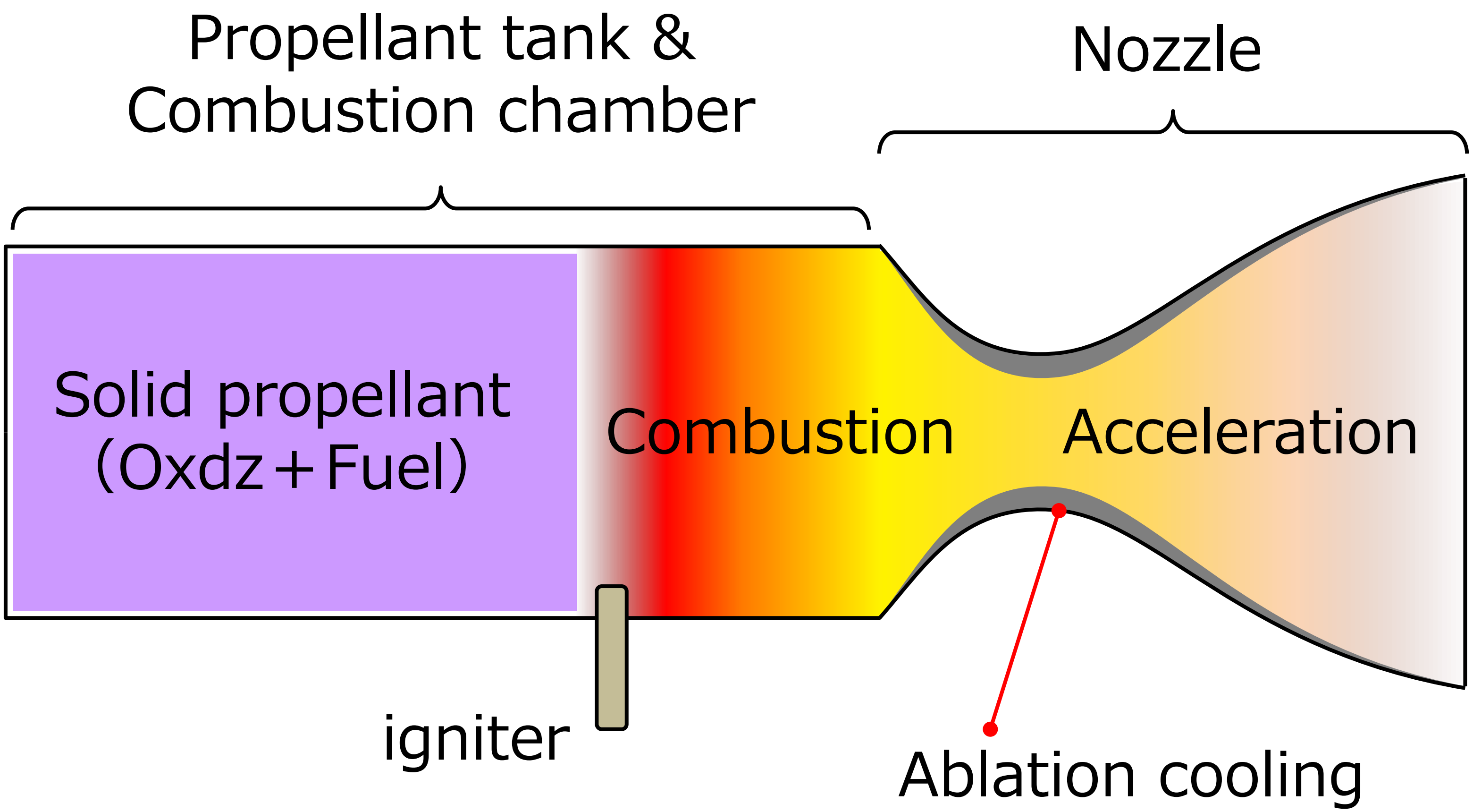
Depending on the temperature and gas type

Expressing the performance of combustion chamber

Characteristic Velocity



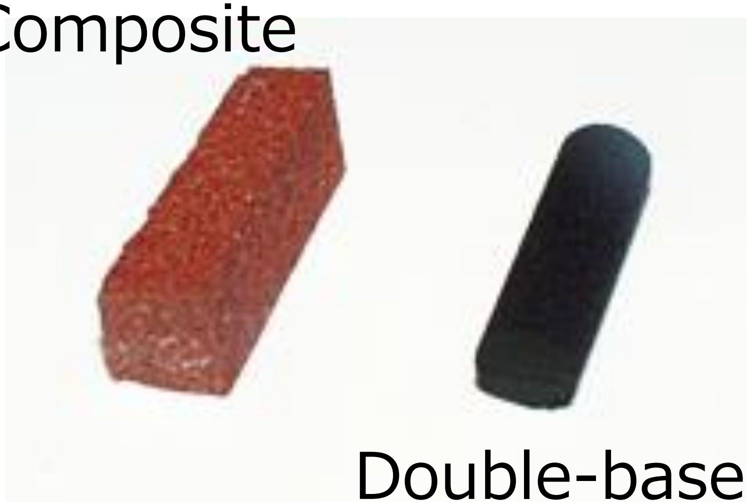
Solid motor; Structure



Double-based propellant

Nitroglycerin（NG, $C_3H_5(ONO_2)_3$）：Fuel&Oxidizer
→Liquid, Plasticizer, High reactivity, O rich

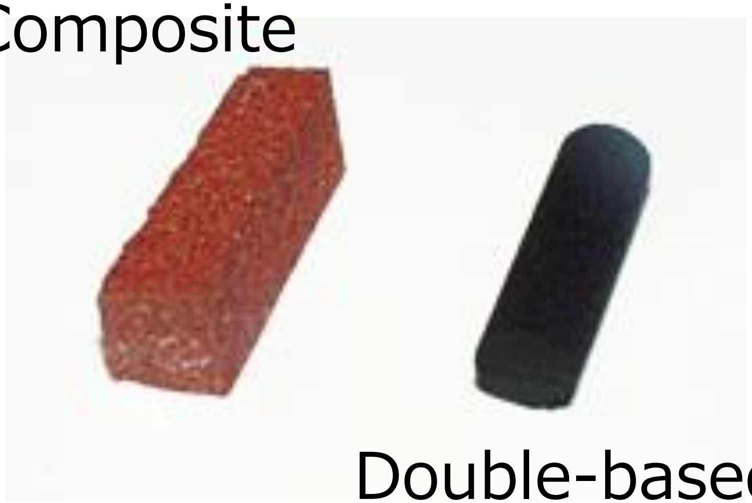
Nitrocellulose（NC , $C_{12}H_{14}(ONO_2)_6O_4$）：Fuel&Oxidizer
→Solide, Binder, Stable, F rich



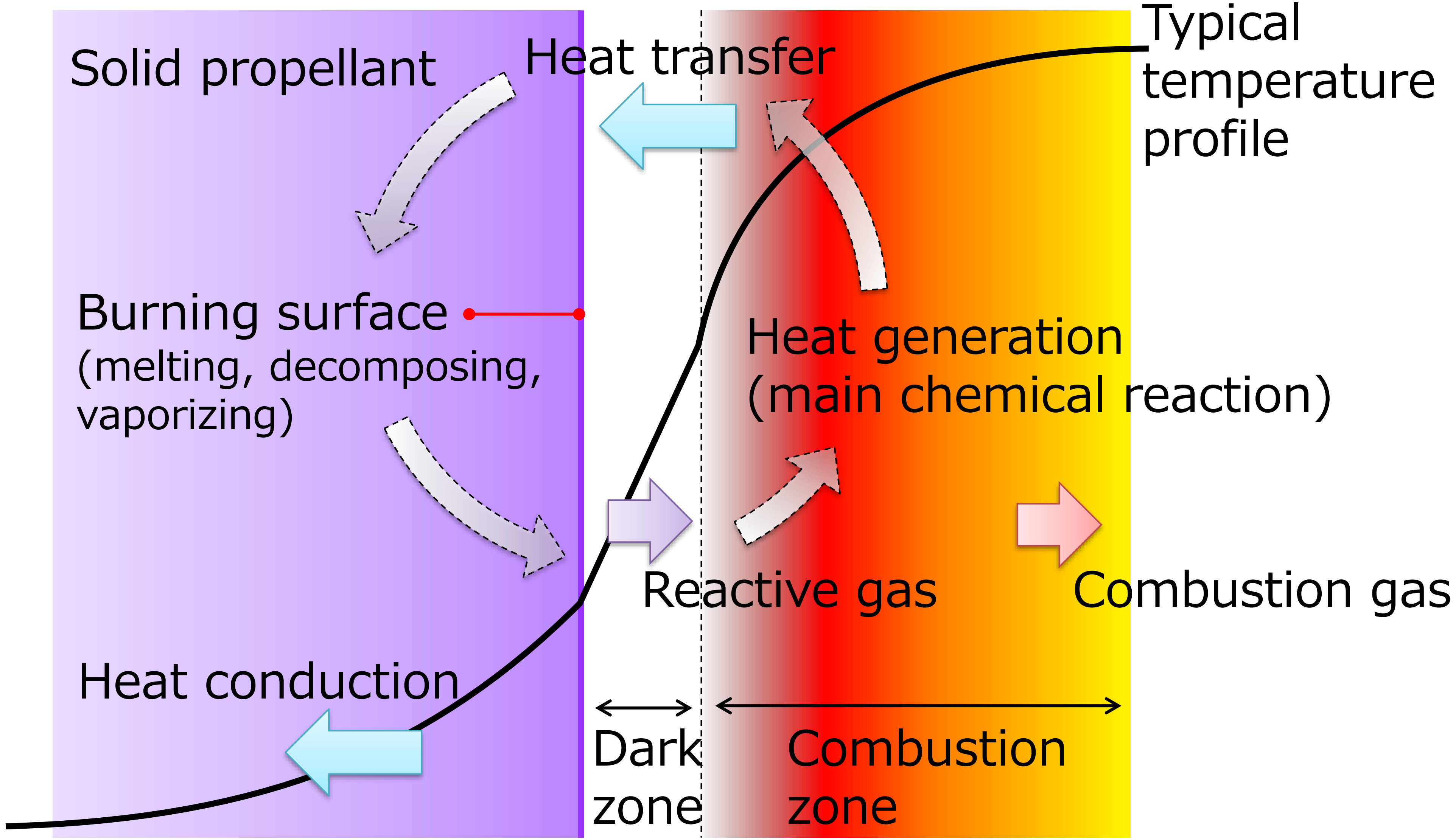
Composite Propellant

Oxdzr : Ammonium perchlorate（AP）, etc

Fuel : Polymer, Binder, Polyvinyl Chloride（PVC）,
Hydroxyl-terminated polybutadiene (HTPB) ,
Powdered metal (Al)



Combustion structure (DB)



Burning Rate and Burning Area

Gas exhausted from the nozzle

$$\dot{m}_t = \frac{A_t P_c}{c^*}$$

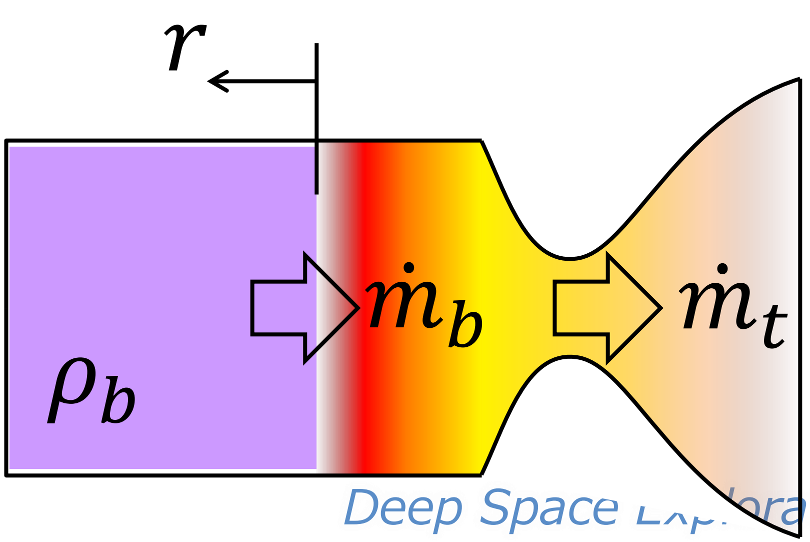
Gas generated by combustion

$$\dot{m}_b = \rho_b A_b r$$

Balance

$$\dot{m}_t = \dot{m}_b$$

$$P_c = \rho_b r c^* \frac{A_b}{A_t}$$

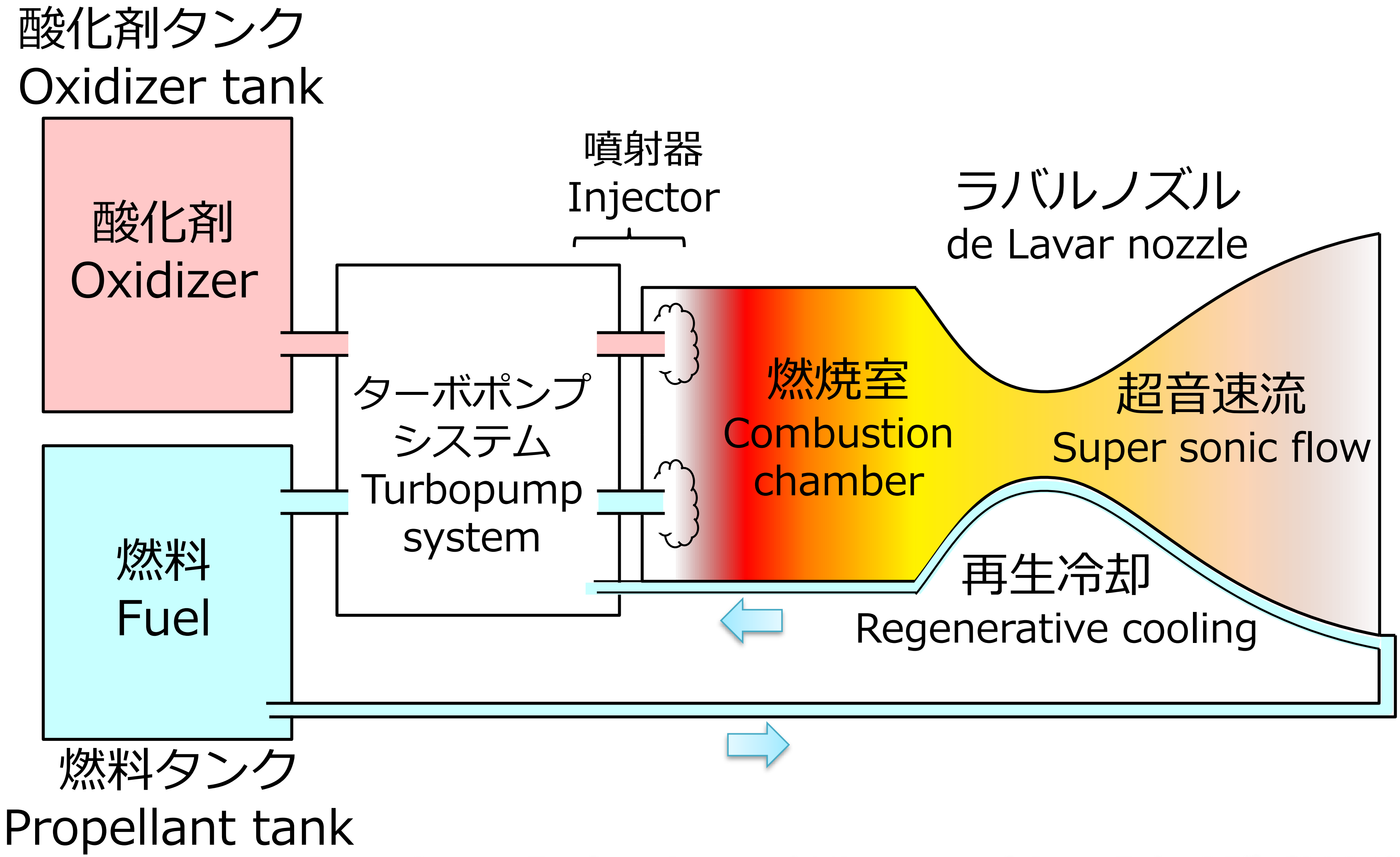


r: Burning rate (e.g. cm/s)

A_b: Burning area

ρ_b: Solid propellant density

Liquid Engine; Structure



Oxidizer

Oxygen（O_2）

Boiling point 90 K→ specific gravity 1.14

LOX: Liquid Oxygen

The most popular as oxidizer

Nitrogen tetroxide, NTO（N_2O_4） ≅ MON

Boiling point 294 K→ specific gravity 1.45

Popular by good storability

Hydrogen peroxide（H_2O_2）

Can be reacted using a catalyst

Red fuming nitric acid（RFNA: HNO_3+NO_2(5-20%)）

Higher E than HNO_3. High toxicity

Fuel

Hydrogen（H2）

Boiling point 20 K→Specific G 0.07（low density)
Flammable in air
Low molecular mass, and high Isp

Hydrocarbon-based fuel (Kerosene, RP-1)

RP-1: highly refined for rocket engine
Boiling point 500 K, SG 0.81（289K)
Good availability and good handling ability

Hydrazine（N2H4: CH1.97）, MMH, UDMH

Boiling point 387 K, SG 1.02（293K)
Toxic, spontaneous combustion in air
Reaction using a catalyst (mono-propellant)

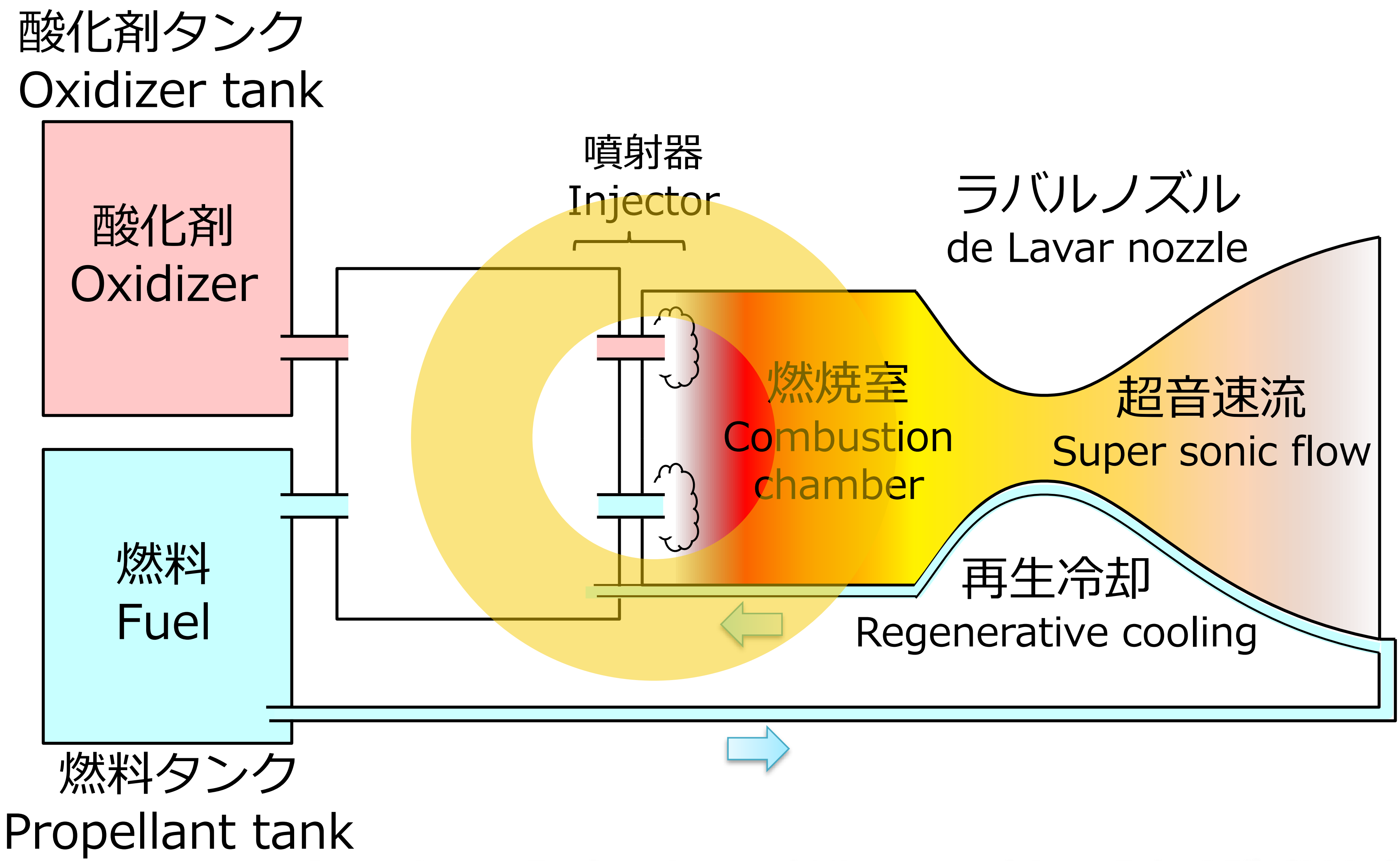
MMH: Monomethylhydrazine

UDMH: unsymmetrical dimethylhydrazine

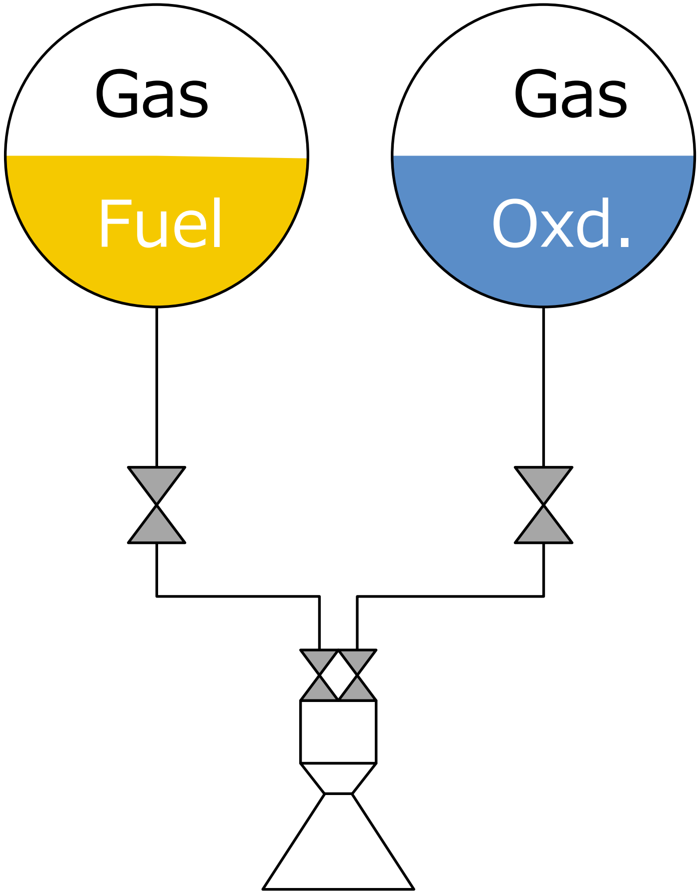
C. Propulsion of Space Probes

	Fuel	Oxd.	#	Thrust/N
Bepicolombo (MPO)	MMH	N_2O_4	8	5 & 22
Hayabusa1/2	Hydrazine	N_2O_4	8	20
Mars Global Surveyor	Hydrazine	N_2O_4	13	4.4 & 600
Galileo	MMH	N_2O_4	13	10 & 400
Shuttle RCS	MMH	N_2O_4	44	110 & 3870
Viking Orbiter	MMH	N_2O_4	1	1330

Liquid Engine; Structure



Blow Down Feed System



High pressure gas
Inside the tanks

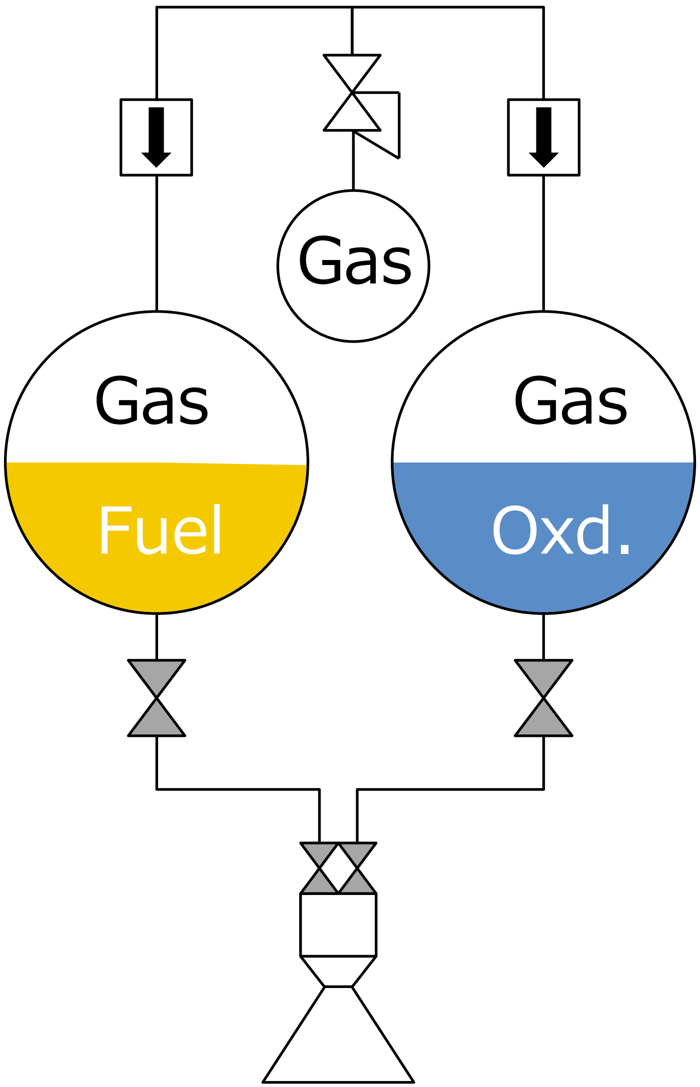
↓

Pressure change
By the gas usage

↓

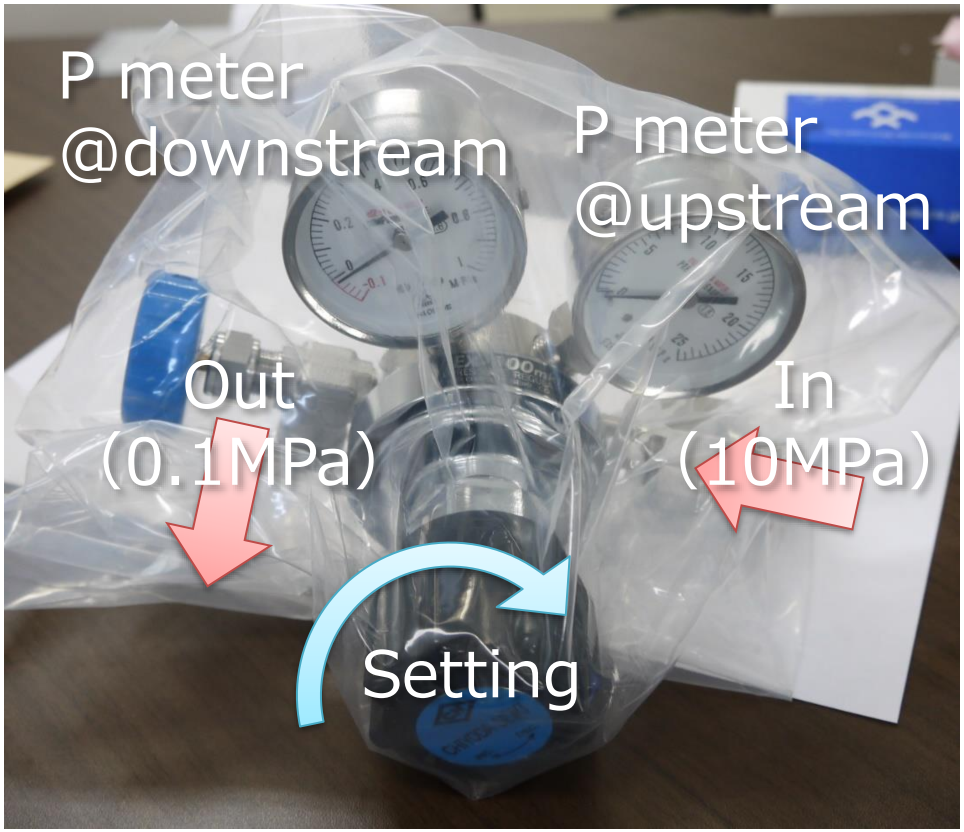
Change of the flow rate

Gas Pressure Regulator System

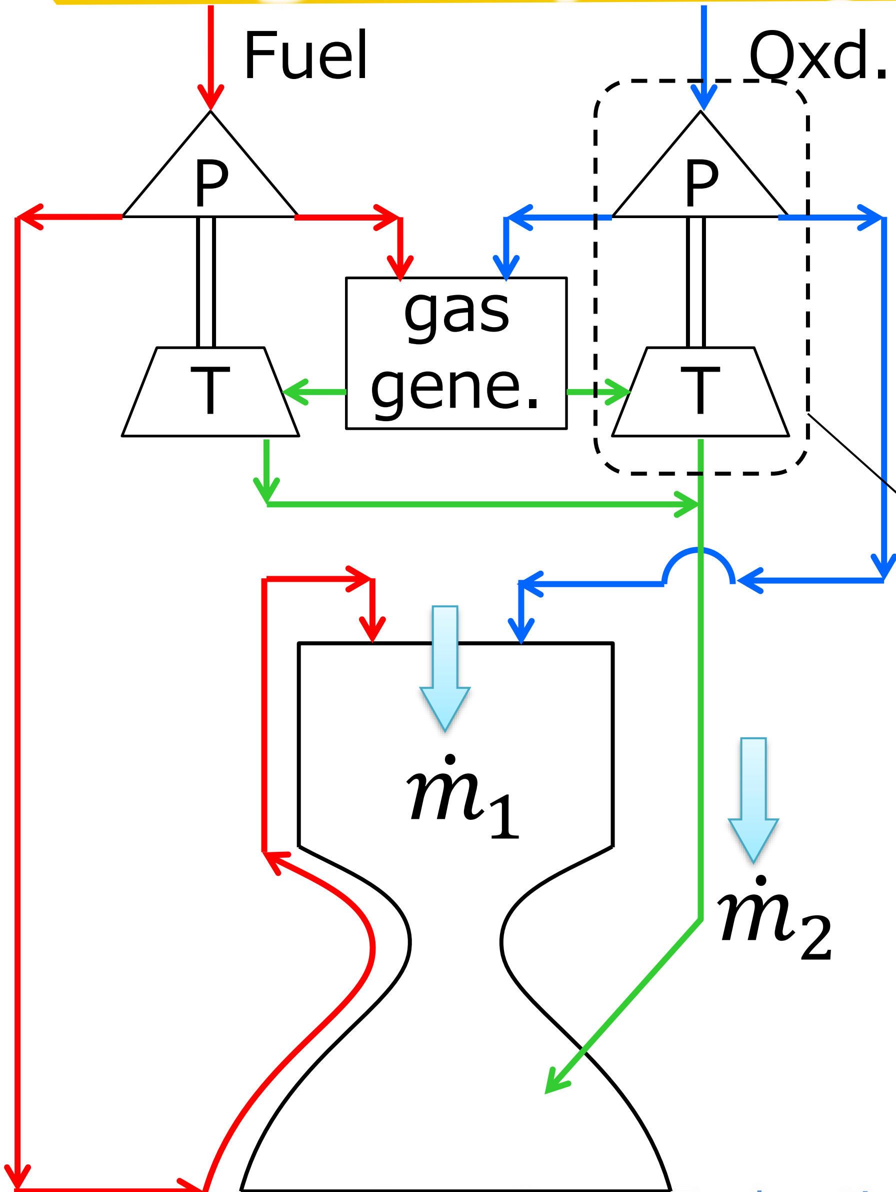


Pressure regulator

Reducing the input pressure of a fluid to a desired value at its output.



Engine Cycle System

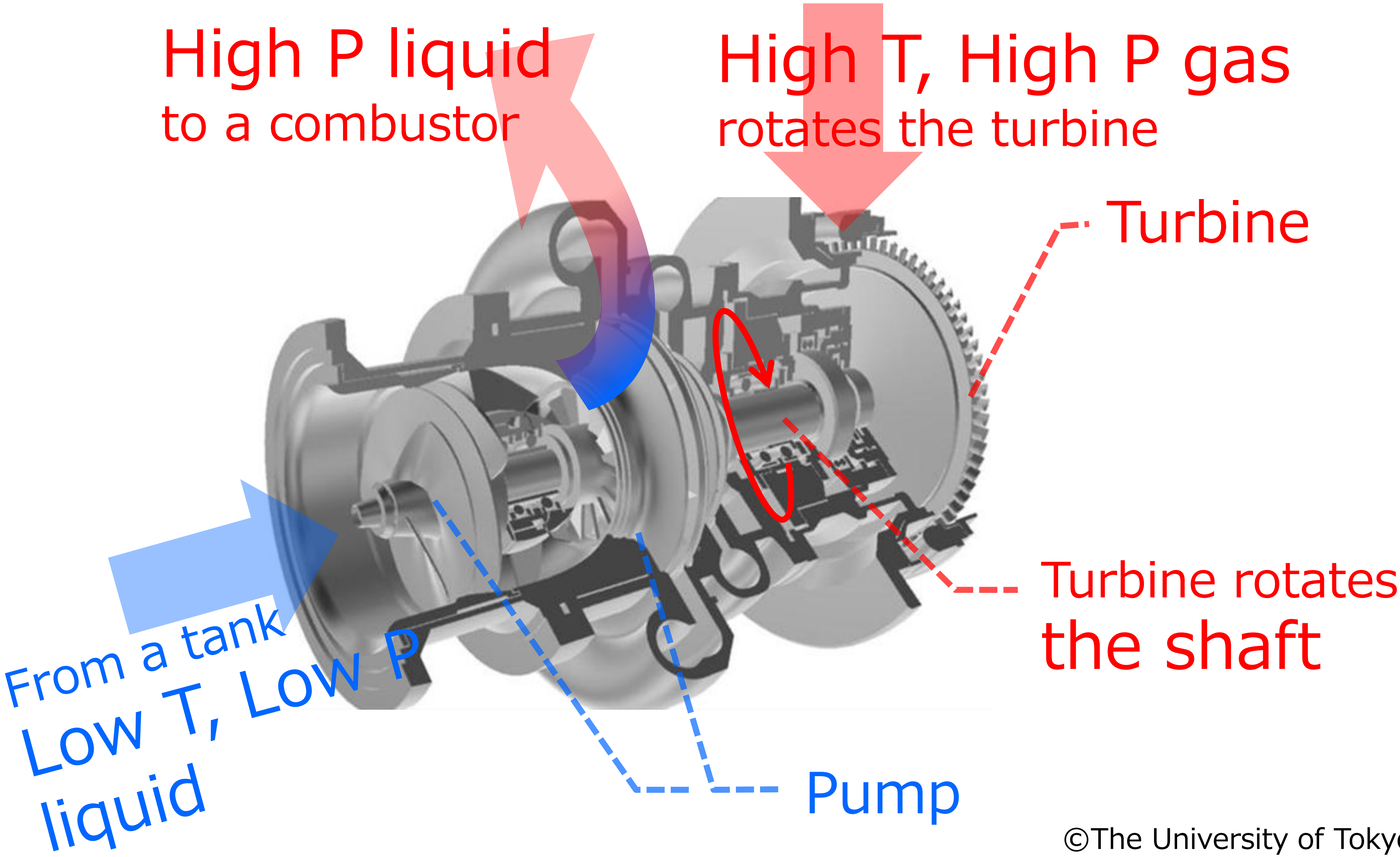


e.g. Gas generator Cycle

Pump and Turbine

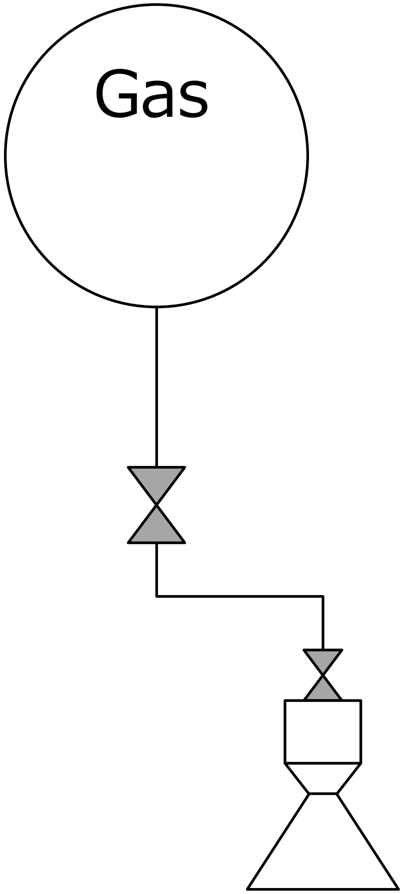
Turbopump

Turbopump



High P liquid
to a combustor
High T, High P gas
rotates the turbine
Turbine
Turbine rotates
the shaft
From a tank
Low T, Low P
liquid
Pump

Cold-gas Jet Thruster

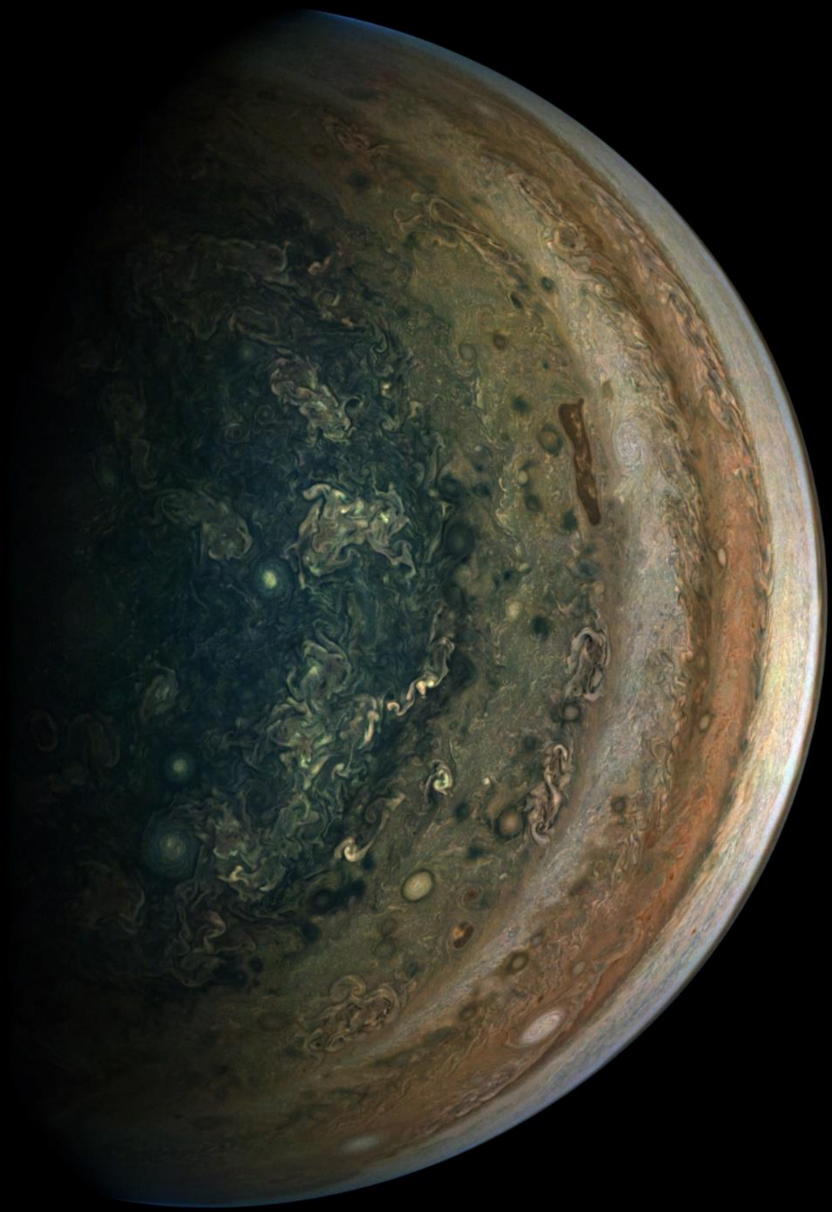


The simplest thruster

Cold-gas Jet Thruster

Reliability
Simplicity

Poor performance
I_{sp}: 24 s



1: Fundamentals

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4: Micropropulsion

CP (Chemical E → Kinetic E)

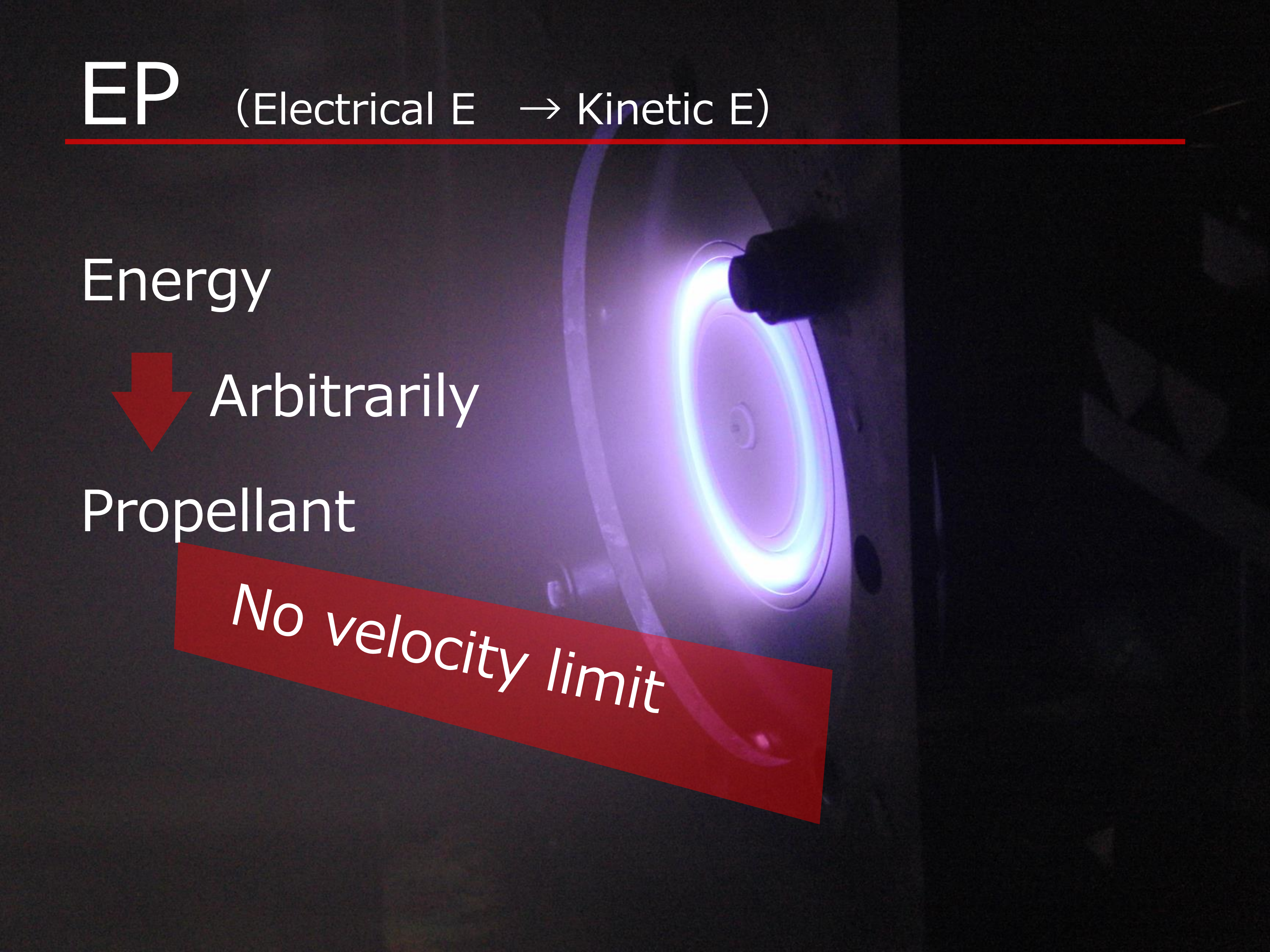
$H_2 + O = H_2O + 241$ kJ/mol

18 g

$$\frac{1}{2}\dot{m}u_e^2 = E$$

$$\Rightarrow u_e = 5\,\mathrm{km/s}$$

Mass & energy are coupled → Velocity limit
Actual limit: about 4.5 km/s


EP (Electrical E → Kinetic E)
Energy
Arbitrarily
Propellant
No velocity limit

Exhaust velocity can be increased
by electric propulsion

↓

Possible:
Over 90% payload for $\Delta V = 10$ km/s
(e.g. 100 km/s propulsion for Jupiter)

But, it’s not an all-rounder

↓

Small thrust（～ 0.1 N）

Long operation time（～ 1 year）

By solar array panel
(limited)

$$\eta P = \frac{1}{2}\dot{m}u_e^2$$

Energy conversion eff.

Energy conservation

By solar array panel
(limited)

$$\eta P = \frac{1}{2}\dot{m}u_e^2 = \frac{1}{2}\underline{F u_e}$$

Constant

Energy conversion eff.

High velocity &
Low thrust

By solar array panel
(limited)

$$\eta P T = \frac{1}{2} F u_e T = \frac{1}{2} M_{sc} \Delta V u_e$$

Energy conversion eff.

Operation time

High velocity &
Long time

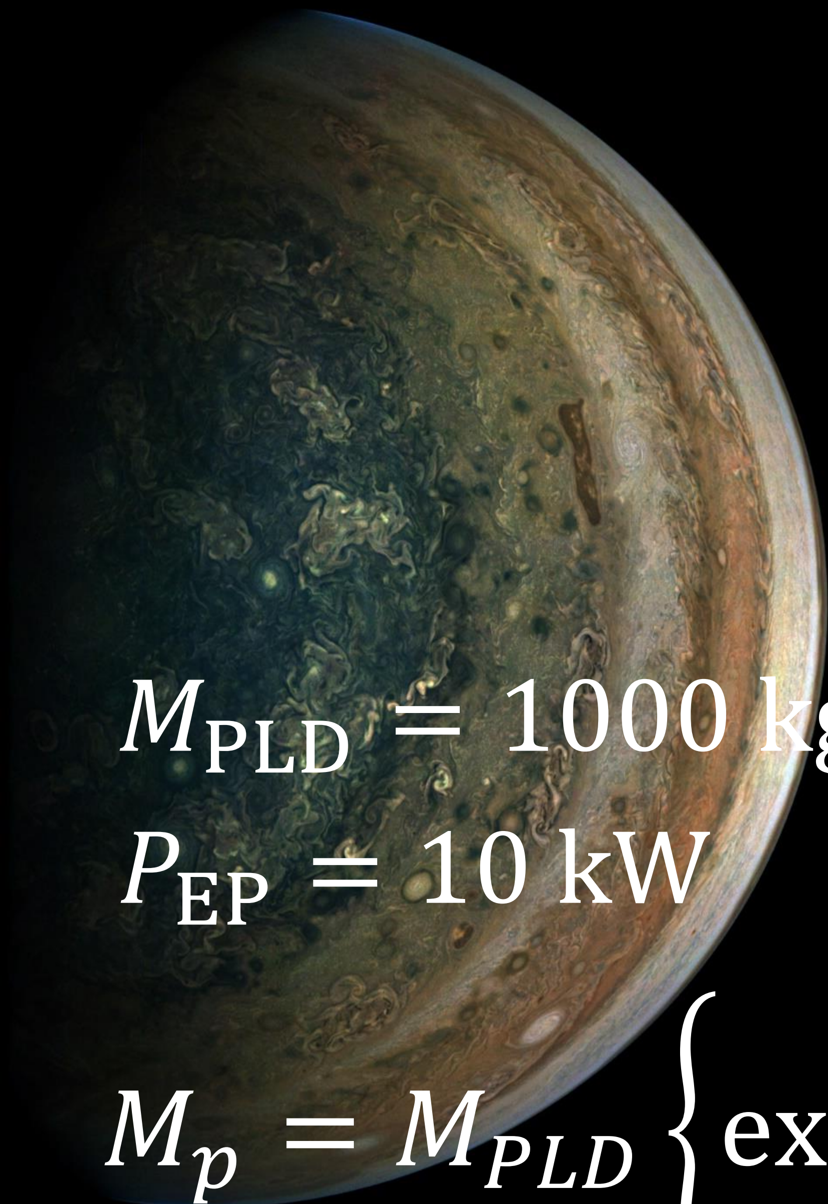
Q: Higher ex. velocity, better?

A : NO

Why ?

If the available power is limited,
the operation time is too long.

$$\Delta V = 13\ \mathrm{km/s}$$

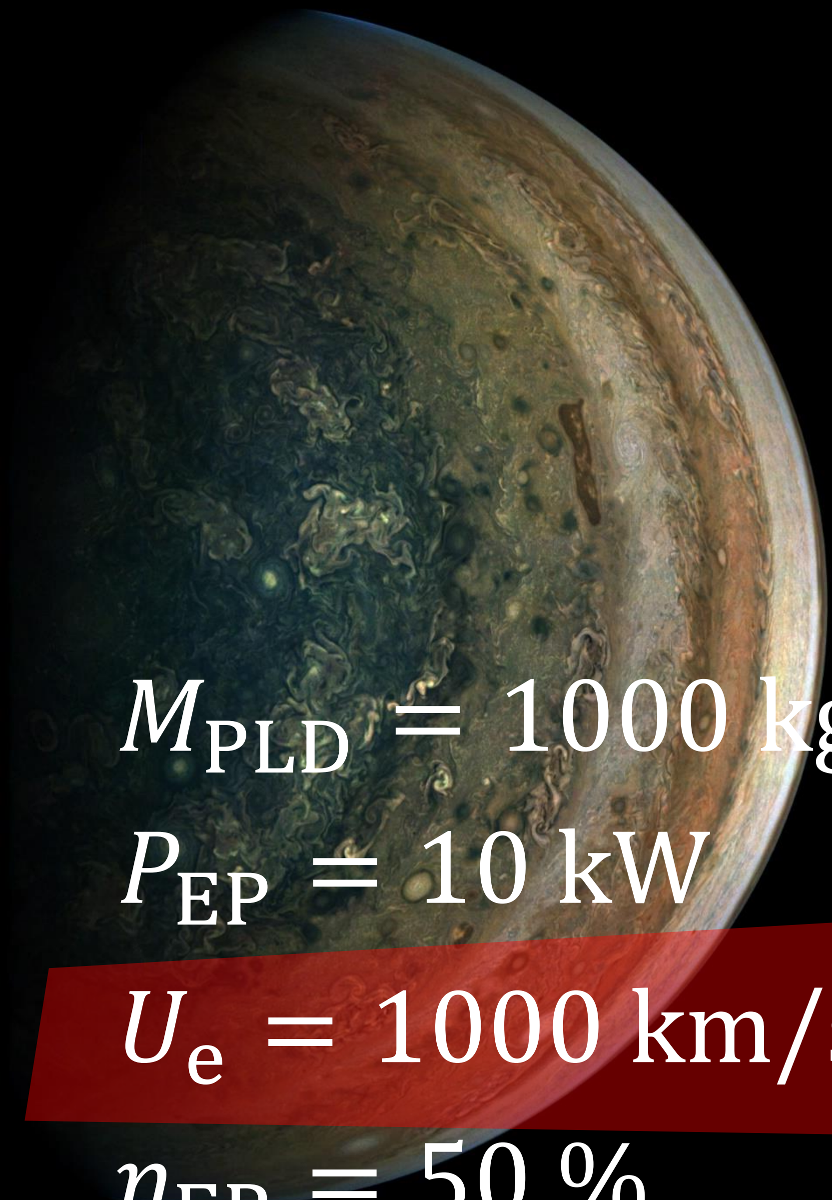


$$M_{\mathrm{PLD}} = 1000\ \mathrm{kg}$$

$$P_{\mathrm{EP}} = 10\ \mathrm{kW}$$

$$M_p = M_{PLD}\left\{\exp\left(\frac{\Delta V}{u}\right) - 1\right\}$$

$$\Delta V = 13 \text{ km/s}$$



$$M_{\text{PLD}} = 1000 \text{ kg}$$

$$P_{\text{EP}} = 10 \text{ kW}$$

$$U_{\text{e}} = 1000 \text{ km/s}$$

$$\eta_{\text{EP}} = 50 \text{ \%}$$

images-assets.nasa.gov/image/PIA22690/PIA22690~orig.jpg

By solar array panel
(limited)

$$\eta P T = \frac{1}{2} F u_e T = \frac{1}{2} M_{sc} \Delta V u_e$$

Energy conversion eff.

Operation time

High velocity &
Long time

$M_{\mathrm{PLD}} = 1000\ \mathrm{kg}$

$P_{\mathrm{EP}} = 10\ \mathrm{kW}$

$U_{\mathrm{e}} = 1000\ \mathrm{km/s}$

$\eta_{\mathrm{EP}} = 50\ \%$

$F_{\mathrm{EP}} = 10\ \mathrm{mN}$

$\dot{m}_{EP} = 10\ \mathrm{\mu g/s}$

$M_{\mathrm{EP}} = 13\ \mathrm{kg}$

$$\tau_{\mathrm{EP}} = 41\ \mathrm{year}$$

$M_{\mathrm{PLD}} = 1000\ \mathrm{kg}$

$P_{\mathrm{EP}} = 10\ \mathrm{kW}$

$U_{\mathrm{e}} = 30\ \mathrm{km/s}$

$\eta_{\mathrm{EP}} = 50\ \%$

$F_{\mathrm{EP}} = 0.3\ \mathrm{N}$

$\dot{m}_{EP} = 10\ \mathrm{mg/s}$

$M_{\mathrm{EP}} = 542\ \mathrm{kg}$

$$\tau_{\mathrm{EP}} = 1.5\ \mathrm{year}$$

$M_{\mathrm{PLD}} = 1000\ \mathrm{kg}$

$P_{\mathrm{EP}} = 1000\ \mathrm{W}$

$U_{\mathrm{e}} = 10\ \mathrm{km/s}$

$\eta_{\mathrm{EP}} = 50\ \%$

$F_{\mathrm{EP}} = 1\ \mathrm{N}$

$\dot{m}_{EP} = 0.1\ \mathrm{g/s}$

$M_{\mathrm{EP}} = 2670\ \mathrm{kg}$

$$\tau_{\mathrm{EP}} = 0.8\ \mathrm{year}$$

$M_{\mathrm{PLD}} = 1000\ \mathrm{kg}$

By CP

$U_{\mathrm{e}} = 2.5\ \mathrm{km/s}$

$M_{\mathrm{EP}} = 180{,}000\ \mathrm{kg}$

Operation time: 10 min.

Flying time: 2-6 years

Q: Higher ex. velocity, better?

A : NO

Why ?
Even if you increase the power to shorten the operation time,
Solar array mass increases more than the propellant reduction.

$M_{\mathrm{PLD}} = 1000 \text{ kg}$

$P_{\mathrm{EP}} = 10 \text{ kW}$

$U_{\mathrm{e}} = 30 \text{ km/s}$

$\eta_{\mathrm{EP}} = 50\ \%$

$F_{\mathrm{EP}} = 0.3 \text{ N}$

$\dot{m}_{EP} = 10 \text{ mg/s}$

$M_{\mathrm{EP}} = 542 \text{ kg}$

$$\tau_{\mathrm{EP}} = 1.5 \text{ year}$$

$M_{\mathrm{PLD}} = 1000\ \mathrm{kg}$

$P_{\mathrm{EP}} = 300\ \mathrm{kW}$

$U_{\mathrm{e}} = 1000\ \mathrm{km/s}$

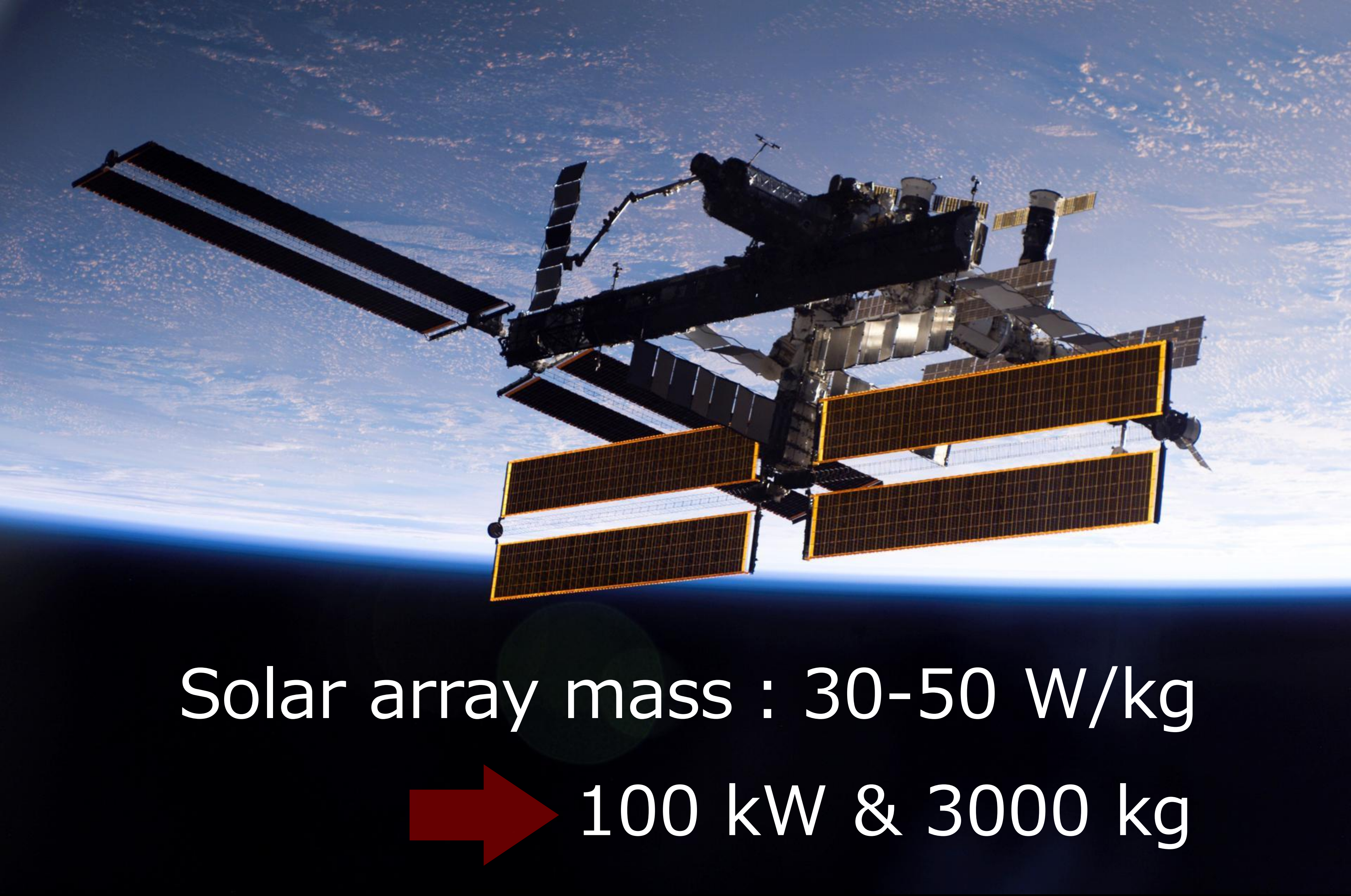
$\eta_{\mathrm{EP}} = 50\ \%$

$F_{\mathrm{EP}} = 0.3\ \mathrm{N}$

$\dot{m}_{EP} = 0.3\ \mathrm{mg/s}$

$M_{\mathrm{EP}} = 13\ \mathrm{kg}$

$$\tau_{\mathrm{EP}} = 1.4\ \mathrm{year}$$



Solar array mass : 30-50 W/kg

→ 100 kW & 3000 kg

$M_{\mathrm{PLD}} = 1000\ \mathrm{kg}$

$P_{\mathrm{EP}} = 300\ \mathrm{kW}$

$U_{\mathrm{e}} = 1000\ \mathrm{km/s}$

$\eta_{\mathrm{EP}} = 50\ \%$

$F_{\mathrm{EP}} = 0.3\ \mathrm{N}$

$\dot{m}_{EP} = 0.3\ \mathrm{mg/s}$

$M_{\mathrm{EP}} = 13\ \mathrm{kg}$

$\tau_{\mathrm{EP}} = 1.4\ \mathrm{year}$

$M_{\mathrm{SAP}} = 9{,}900\ \mathrm{kg}$

Optimum exhaust velocity

Thrust Efficiency $\eta_{\rm th} = \dfrac{\dot{m}_{\rm prop} V_{\rm e}^2}{2P_{\rm s}}$

$P_{\rm s}$: Available Power

Specific power of solar cell panels

$\alpha = P_{\rm s}/m_{\rm panel}$ (W/kg)

$\beta = m_{\rm panel}/P_{\rm s}$ (kg/W)

Typical $\beta = 0.05$ kg/W

Propellant consumption rate

$\dot{m}_{\rm prop} = m_{\rm prop}/\tau$

τ: Transfer Time

$$m_i = m_{pay} + \beta P_S + m_{prop}$$

Optimum exhaust velocity

$$\frac{m_{pay}}{m_i} = 1 - \frac{\beta P_s}{m_i} - \frac{m_{prop}}{m_i}$$

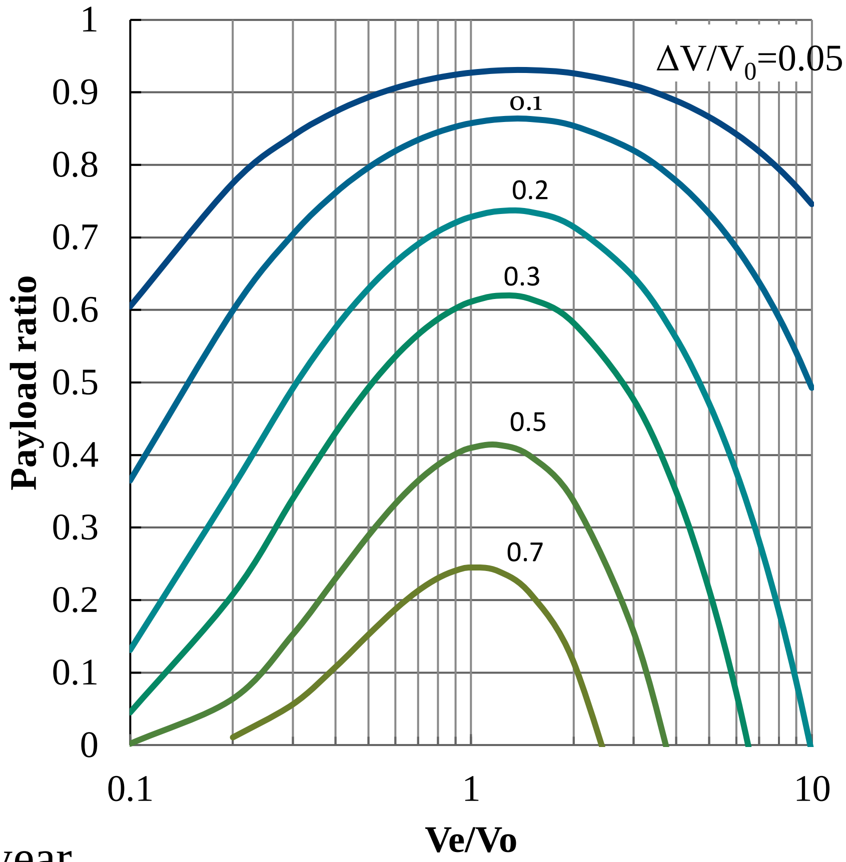
$$= 1 - \frac{m_{prop}}{m_i}\left(\frac{\beta P_s}{\dot{m}_{prop}\tau} + 1\right)$$

$$= 1 - \left(1 - \exp\left(\frac{-\Delta V}{V_e}\right)\right)\left(\frac{\beta V_e^2}{2\eta_{th}\tau} + 1\right)$$

$$= \exp\left(\frac{-\Delta V}{V_e}\right) - \frac{\beta V_e^2}{2\eta_{th}\tau}\left\{1 - \exp\left(\frac{-\Delta V}{V_e}\right)\right\}$$

$$V_{e,opt} \approx V_0 = \sqrt{\eta_{th}\tau/\beta}$$

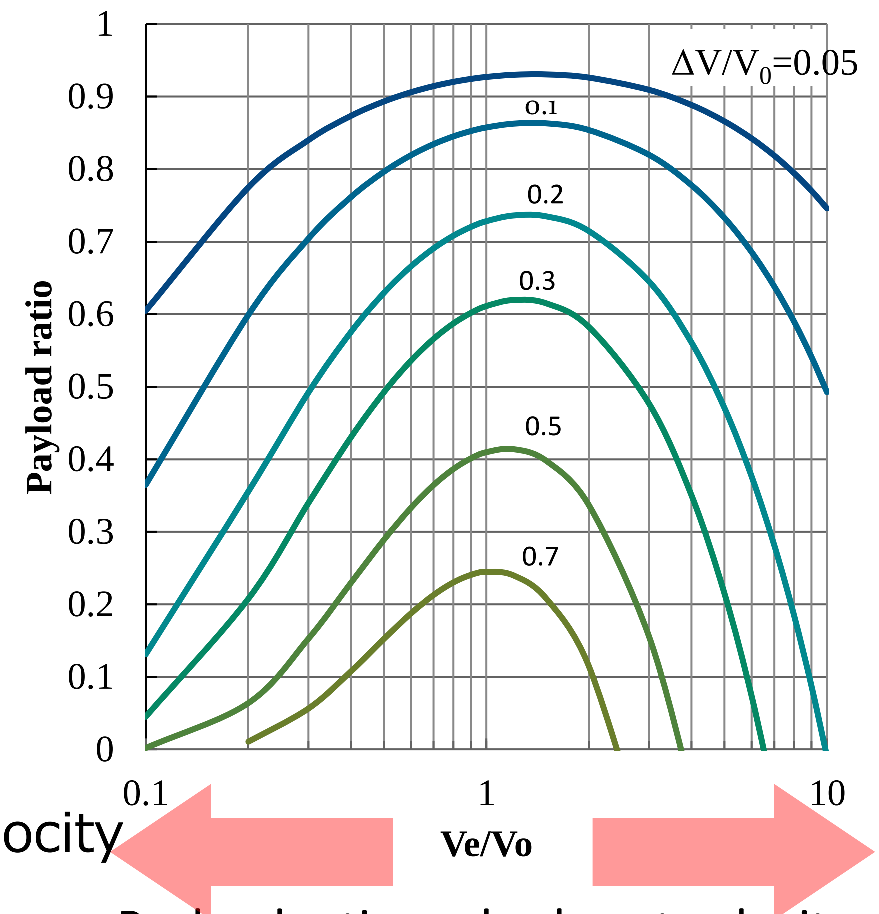
$V_{e,opt} \approx$ 10km/s for 30 days, 33km/s for 1 year.



Payload ratio and exhaust velocity

Optimum exhaust velocity

Propellant is
too heavy
due too low velocity



Power sources are
too heavy
due too high velocity

Payload ratio and exhaust velocity

Category of EP

ETA: Eletrothermal Acceleration

Electric energy → Thermal E → Kinetic energy

Joule heat **Nozzle**

ESA: Electrostatic Acceleration

Electric energy → Kinetic energy

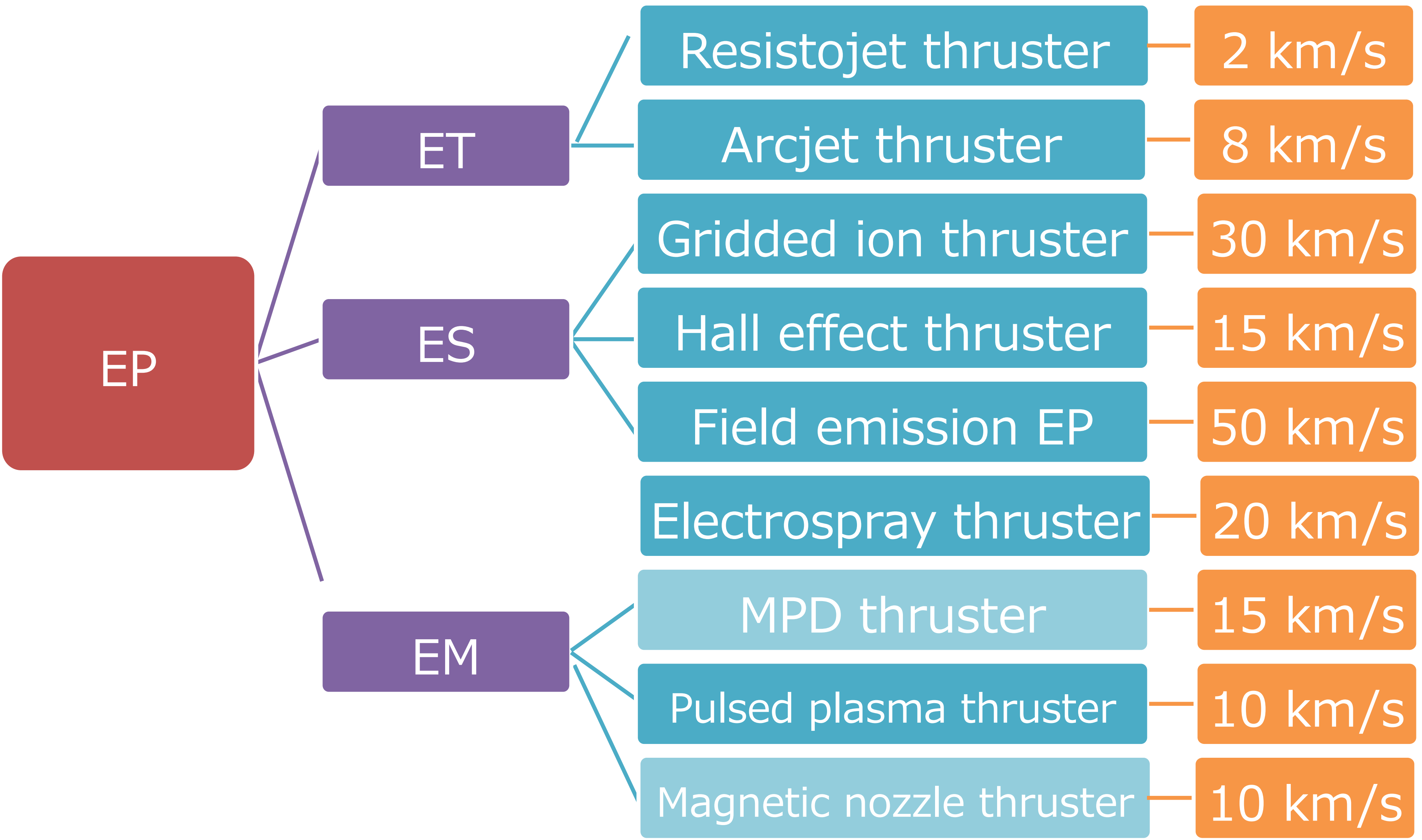
Electrostatic force（Coulomb force)

EMA: Electromagnetic Acceleration

Electric energy → Kinetic energy

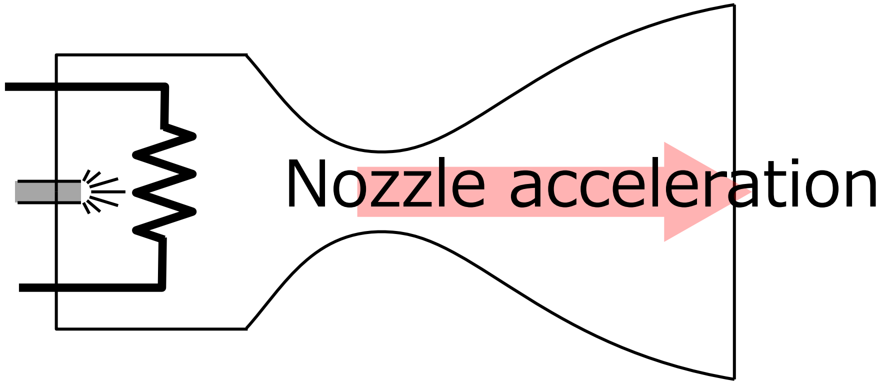
Electromagnetic force（Lorentz force)

EP Thrusters



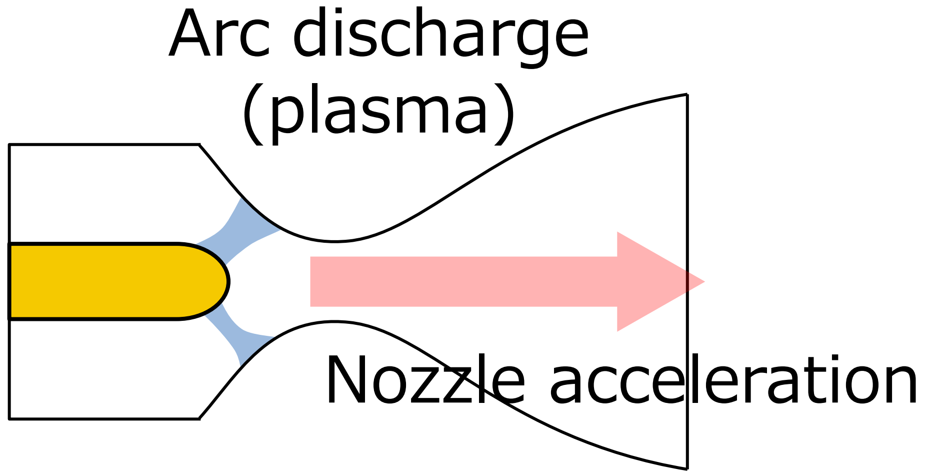
Resistojet thruster

Application: many
Working fluid: hot gas
W.F. generation: resistive heating
Acceleration: nozzle
Exhaust velocity (typical): 1 – 5 km/s
Power (typical): 10 W – 2 kW



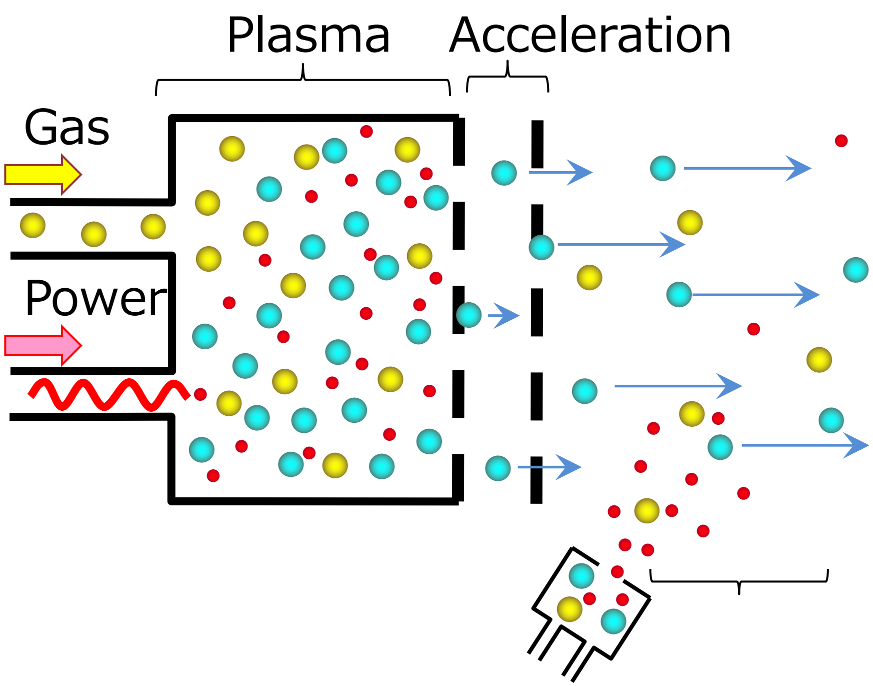
Arcjet thruster

Application: many
Working fluid: plasma
W.F. generation: arc discharge
Acceleration: nozzle
Exhaust velocity (typical): 5 – 10 km/s
Power (typical): 1 – 2 kW



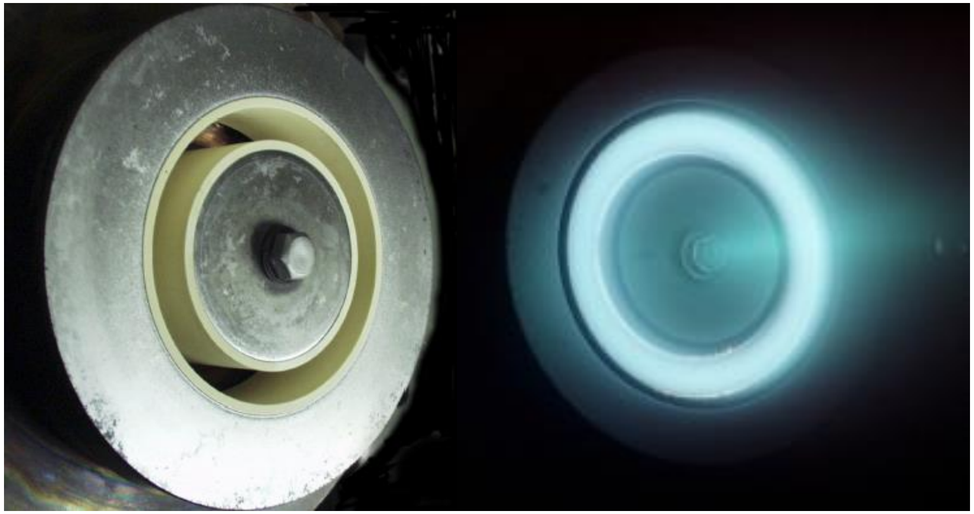
Gridded ion thruster

Application: many
Working fluid: plasma
W.F. generation: DC-discharge, RF, microwave
Acceleration: Electrostatic, 1 kV
Exhaust velocity (typical): 30 km/s
Power (typical): 0.5 – 2.0 kW



Hall effect thruster

Application: many
Working fluid: plasma
W.F. generation: DC-discharge
Acceleration: Electrostatic, 300 V
Exhaust velocity (typical): 15 km/s
Power (typical): 0.5 – 2.0 kW



Field emission electric propulsion

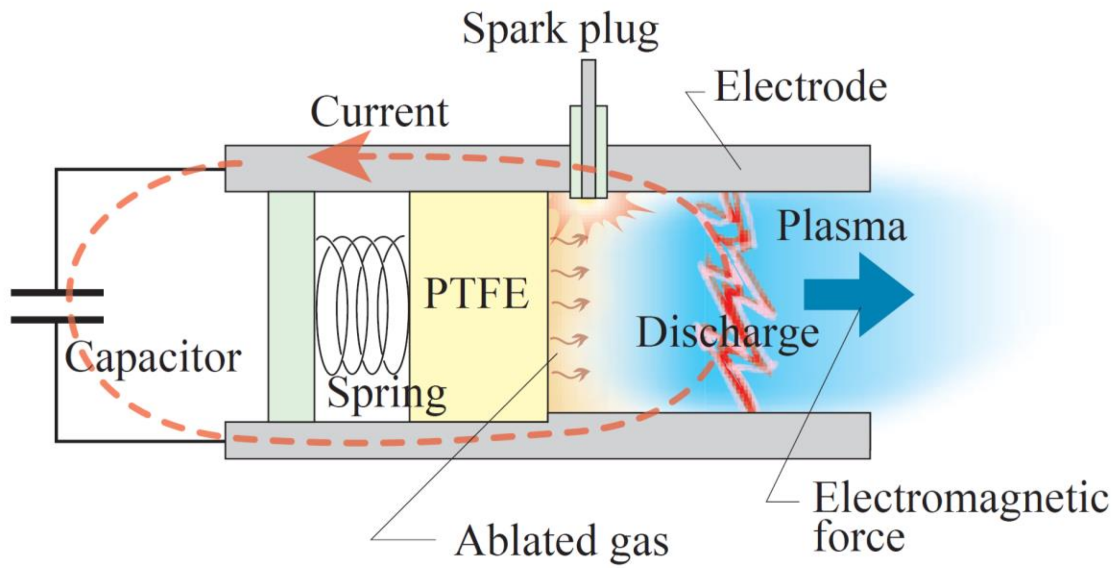
Application: 20 in space
Working fluid: ionized liquid metal
W.F. generation: field emission
Acceleration: Electrostatic, 10 kV
Exhaust velocity (typical): 50 km/s
Power (typical): 40 W

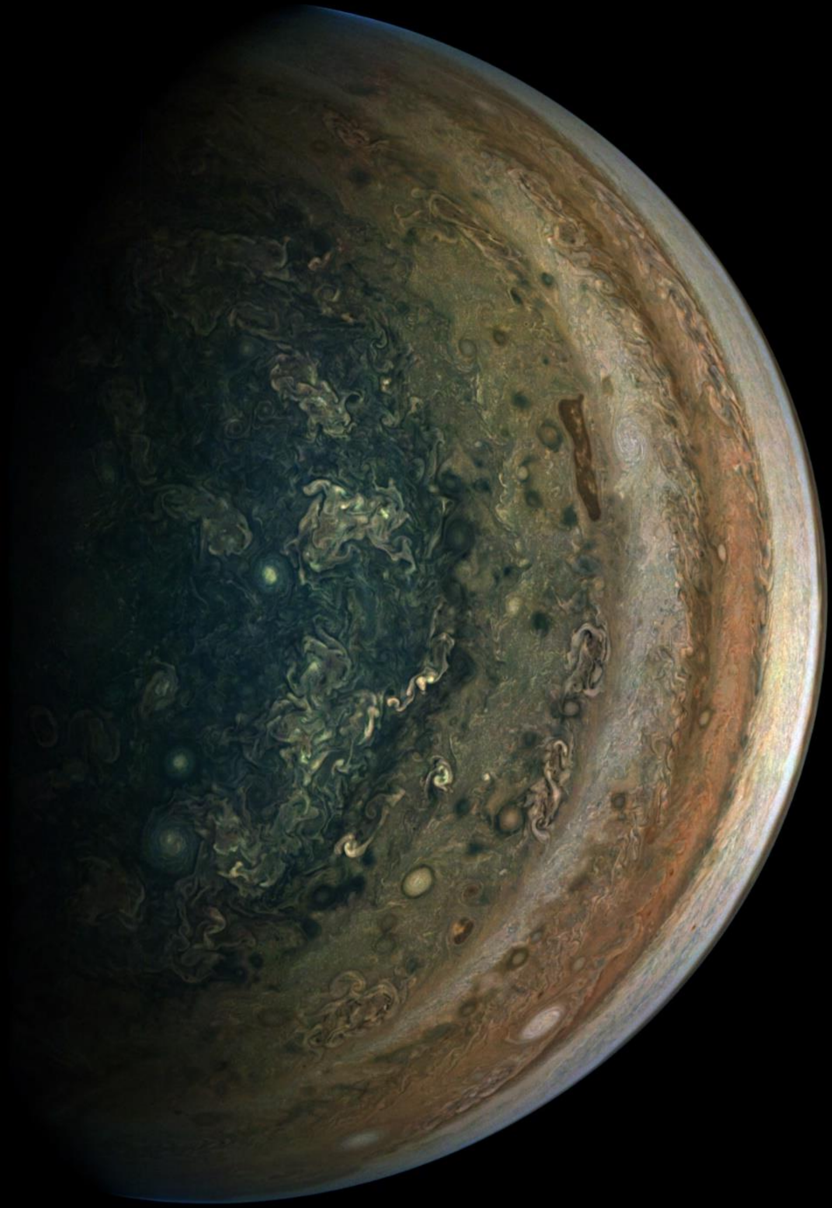
Electrospray thruster

Application: a few demonstrations
Working fluid: ionized/droplet ionic liquid
W.F. generation: field emission/Tayler-cone
Acceleration: electrostatic, 1-3 kV
Exhaust velocity (typical): 10-20 km/s
Power (typical): 5 W

Pulsed plasma thruster

Application: several demonstrations
Working fluid: plasma
W.F. generation: pulsed arc discharge
Acceleration: electromagnetic/electrothermal, 1-3 kV
Exhaust velocity (typical): 5-20 km/s
Power (typical): 10 W





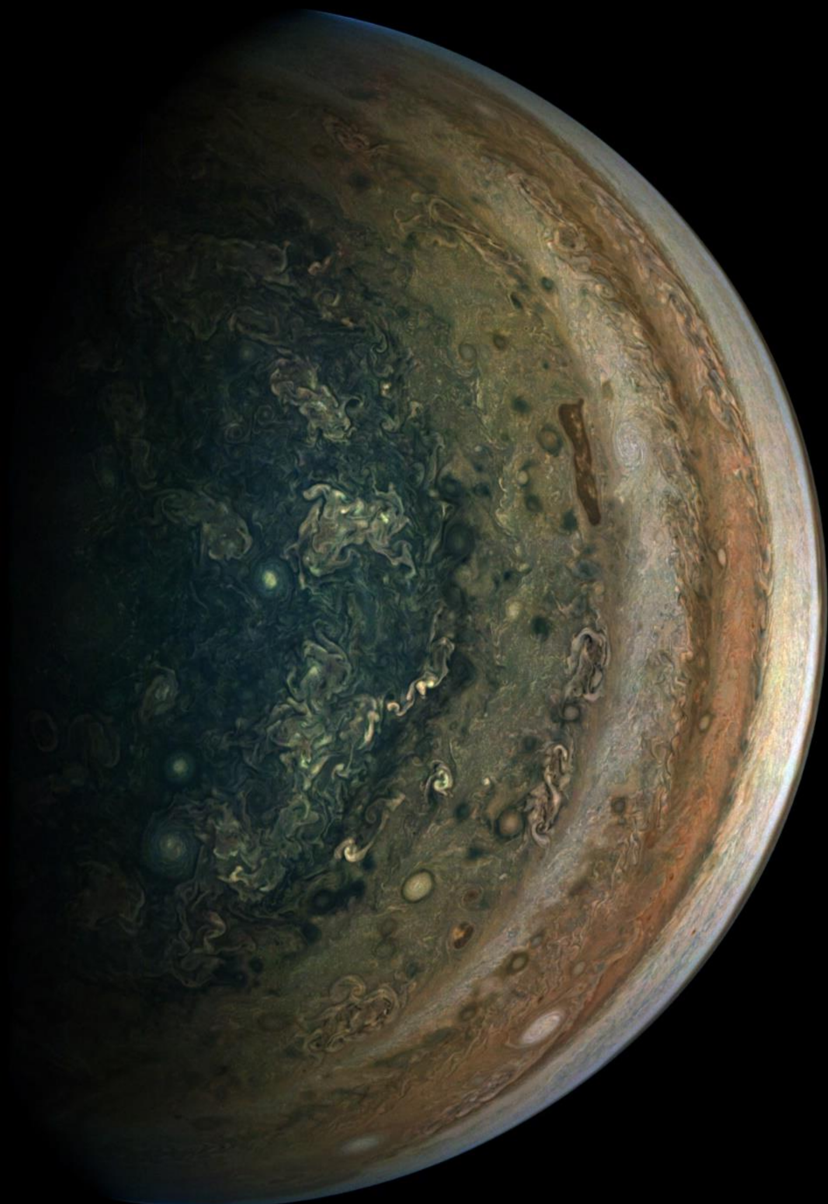
1: Fundamentals
2: Chemical Propulsion
3: Electric Propulsion

4: Micropropulsion

What is micropropulsion?

Just Small

There are difficulties in miniaturization of technology. The performance becomes lower (it’s nature, unavoidable). If you are a developer, it’s a big challenge, but if you are a user, what you do is to select the suitable one.



1: Fundamentals

2: Chemical Propulsion

3: Electric Propulsion

4: Micropropulsion

4.A: Key words

4.B: How to choose?

4.C: Recent trend

4.D: Pickup

1.Different roles

I. High specific impulse

II. Multiaxis thrust

III. High thrust

Orbit transfer

Drag compensation

Unloading

Rendezvous

Insertion
Escaping

Landing

Emergency

Miniaturization as system

Still small-satellites have little resource

2.Unified propulsion

PROCYON:

Ion thruster

+

Cold-gas thruster

By gas-sharing

ArgoMoon:

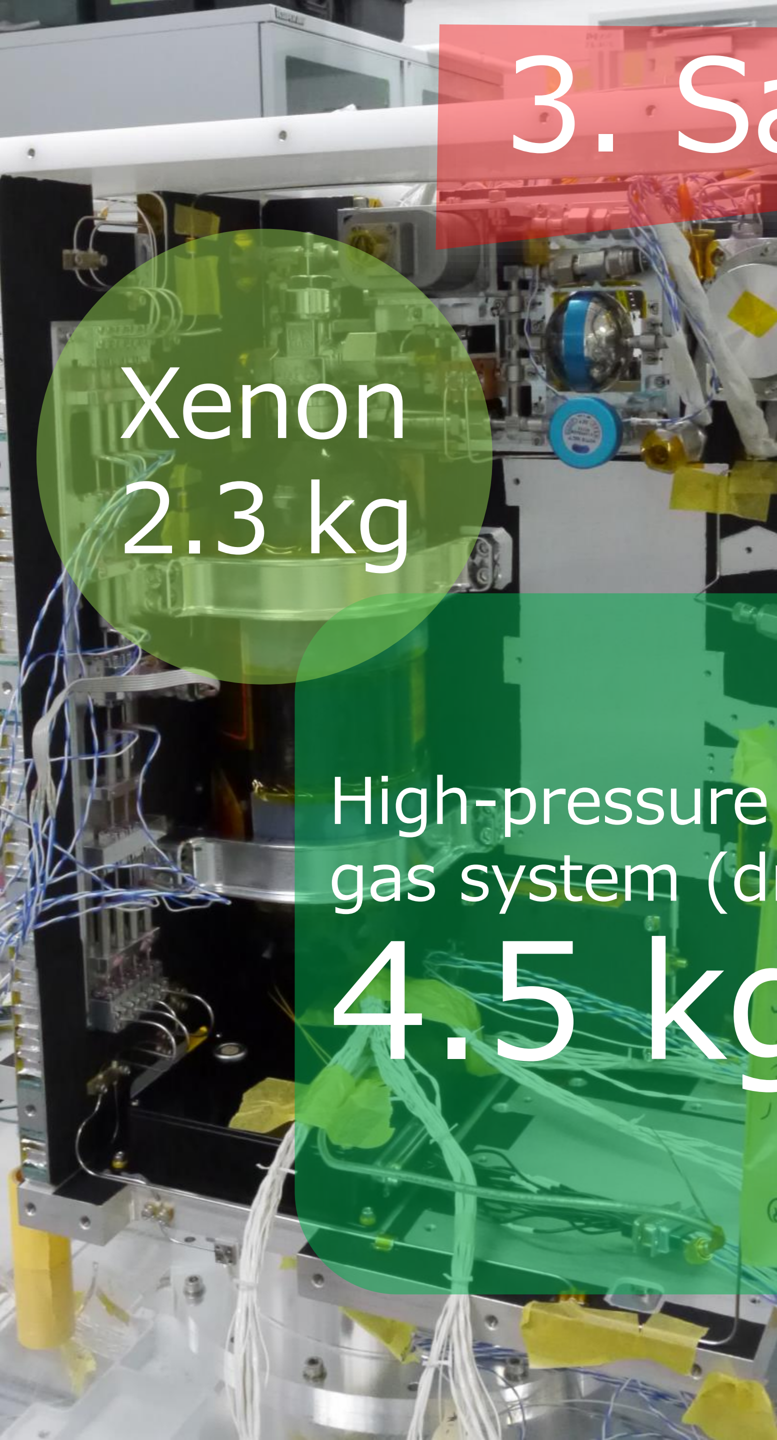
Green-mono

+

Cold-gas thruster

By plenum-gas usage

3. Safety



Xenon
2.3 kg

High-pressure
gas system (dry)
4.5 kg

vs. Regulation

vs. Safety review

Are there many choices?

Yes, too many

Some are really good thrusters.
Some are different from the data sheet.
Some may not work at all…

Which should you choose?

Enough information?

- ✓ NOT only performance, but principle, photo, dimensions, etc. are important.
- ✓ Is that principle feasible?
- ✓ Was it measured? How?
- ✓ Do they publish it at conferences/journals?

What is getting attention ?

The best place to check the trend of small satellites:

Small Satellite Conference

- ✓ More industry side rather than academic
- ✓ Single-session presentation & huge exhibition
  - ✓ ⇨ Severe selection ⇨ good index
- ✓ SSC2020 was online

Propulsion topics at SSC-2019/2020

Green mono-propellant thruster x2

Electric propulsion x3

Hybrid thruster x2

Cold-gas thruster x2

Propulsion topics at SSC-2019/2020

- ✓ High thrust
- ✓ Safety

Green mono-propellant thruster x2

- ✓ High ΔV
- ✓ Safety

Electric propulsion x3

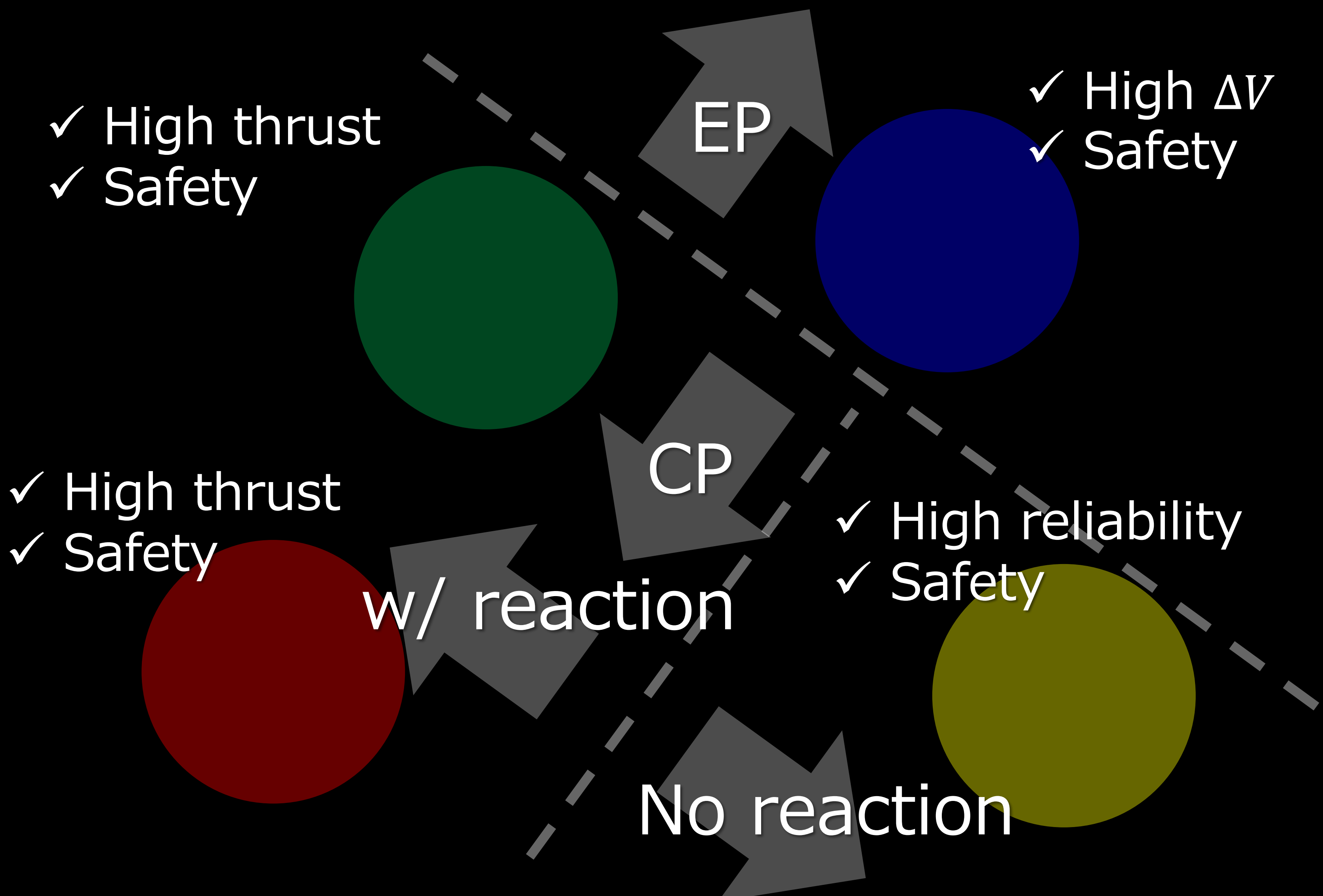
- ✓ High thrust
- ✓ Safety

Hybrid thruster x2

- ✓ High reliability
- ✓ Safety

Cold-gas thruster x2

Different ability by different type



“Safety” is the KEY

✓ High thrust
✓ Safety

Green mono-propellant thruster

✓ High ΔV
✓ Safety

Electric propulsion

✓ High thrust
✓ Safety

Hybrid thruster

✓ High reliability
✓ Safety

Cold-gas thruster

Degree of “Safety” is different

- AF-M315E = NH_3OHNO_3, etc
- LMP-103S = $NH_4(NO_2)_2N$, etc

✓ Safety

Green mono-propellant thruster

Electric propulsion

✓ Safety

- Water
- Teflon
- Indium

✓ Safety

Hybrid thruster

- ABS + Gas O_2
- ABS + O_2/N_2O

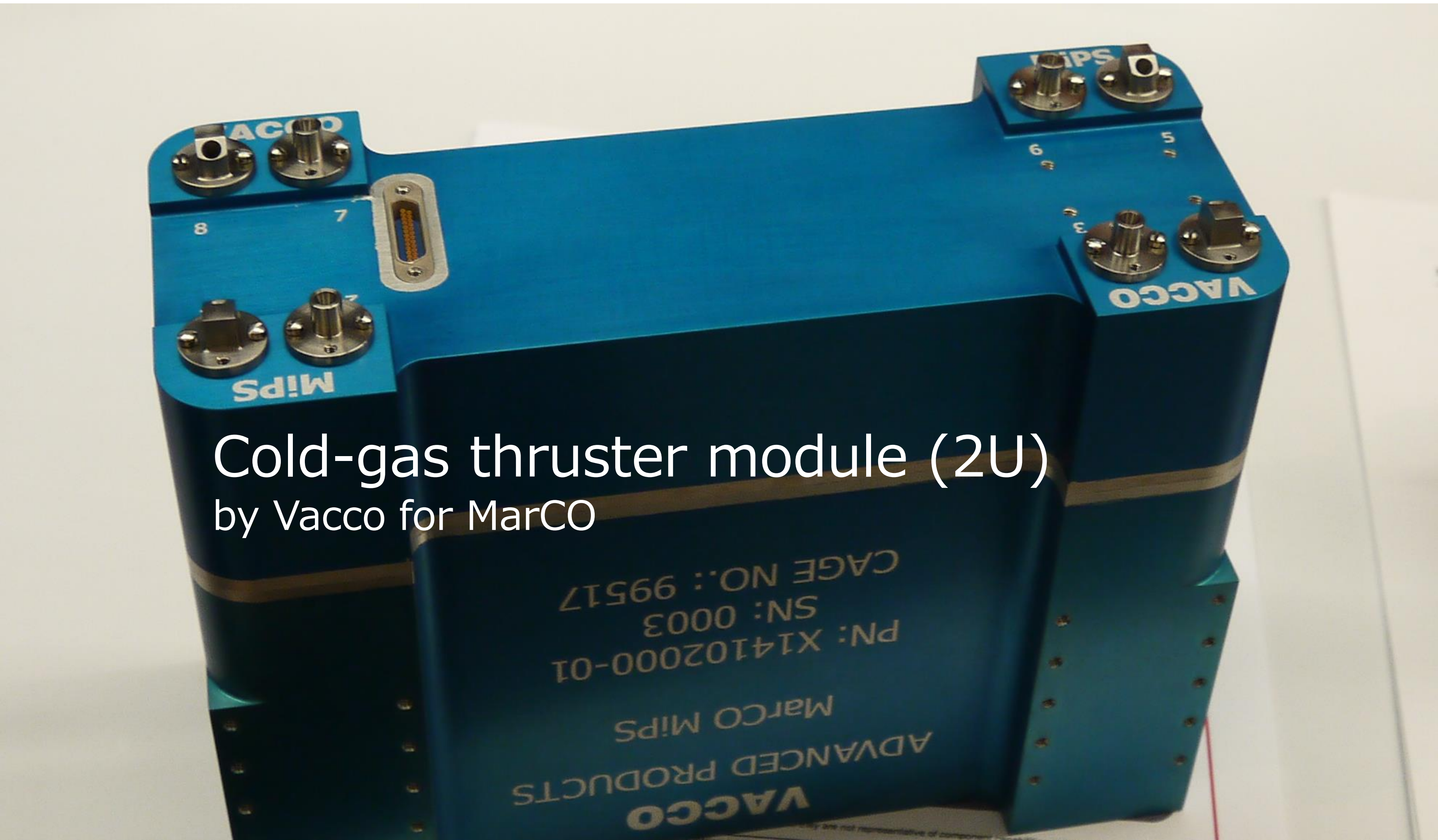
✓ Safety

Cold-gas thruster

- Indium
- Pressurized gas

MarCO

has a multiaxis-thruster system using cold-gas (R134a).



Cold-gas thruster module (2U)
by Vacco for MarCO

FEEP

By ENPULSION

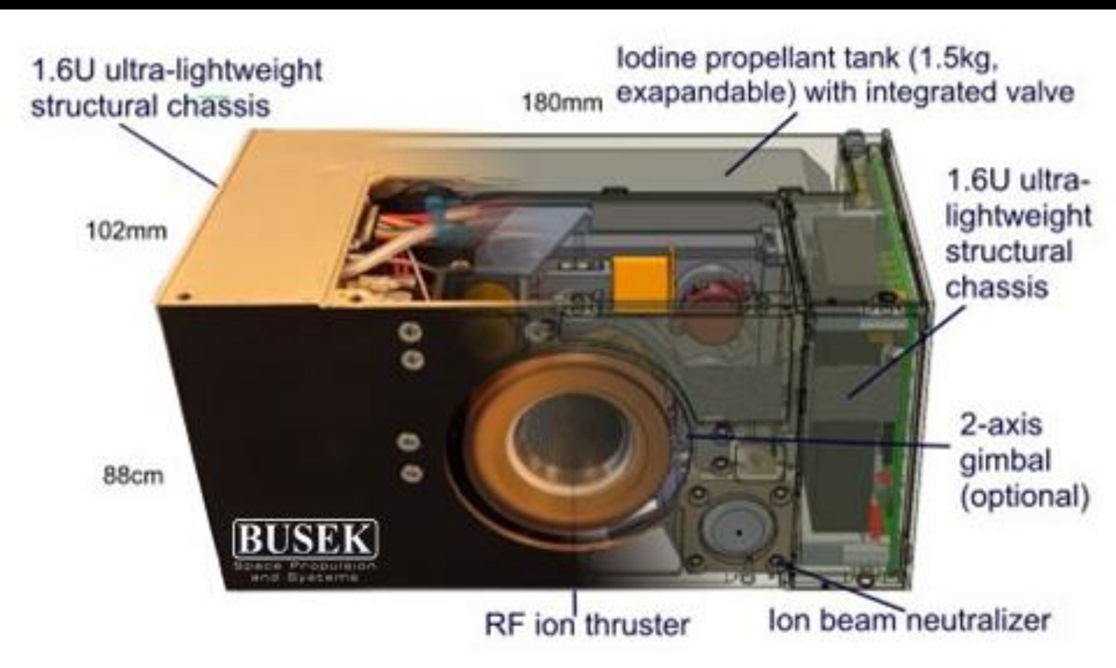
- Indium
- 0.9 kg, 40 W, 5000 Ns, 0.35 mN, 2000 s
- Operation in 2018 April !!

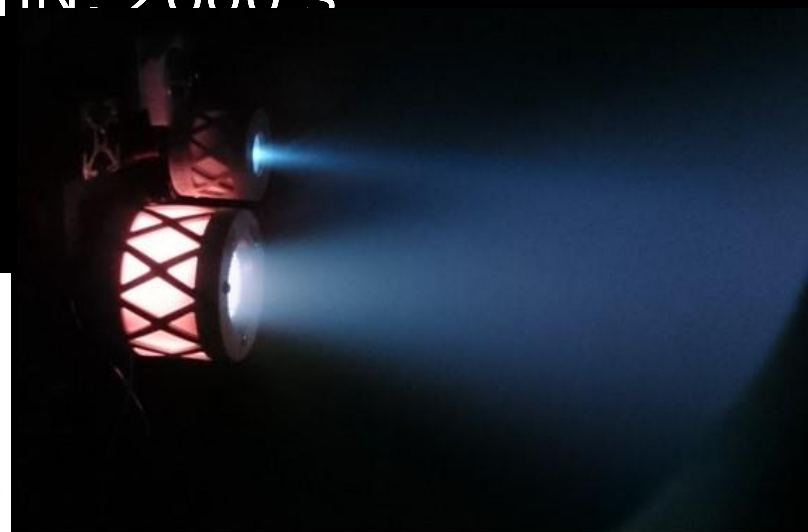
ENPULSION NANO

Iodine ion thruster; BIT-3

By Busek Co. Inc.

- iodine
- 3.0 kg, 80 W, 40000 Ns, 1.24 mN, 2600 s
- Planned in 2019 by SLS-EM1



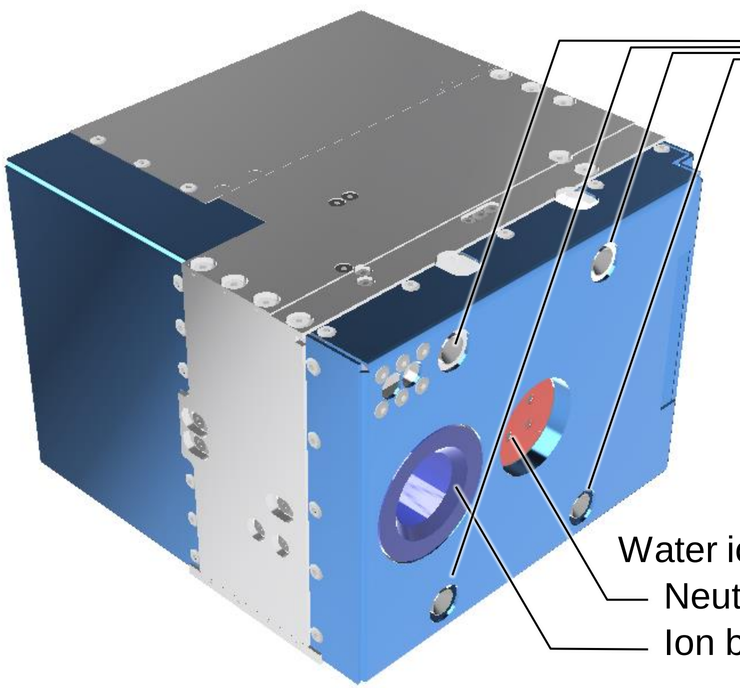


(C) BUSEK

Water Unified Propulsion

By Pale Blue Inc.

- Water ion thruster & Water Resistojet thruster
- Size 90x90x123 mm^3, <2.2 kg, Water < 0.3 kg
- IT: 300 μN, 600 s, T: 1 mN, 70 s x4
- Planned in 2022 by JAXA Innovative Program-3

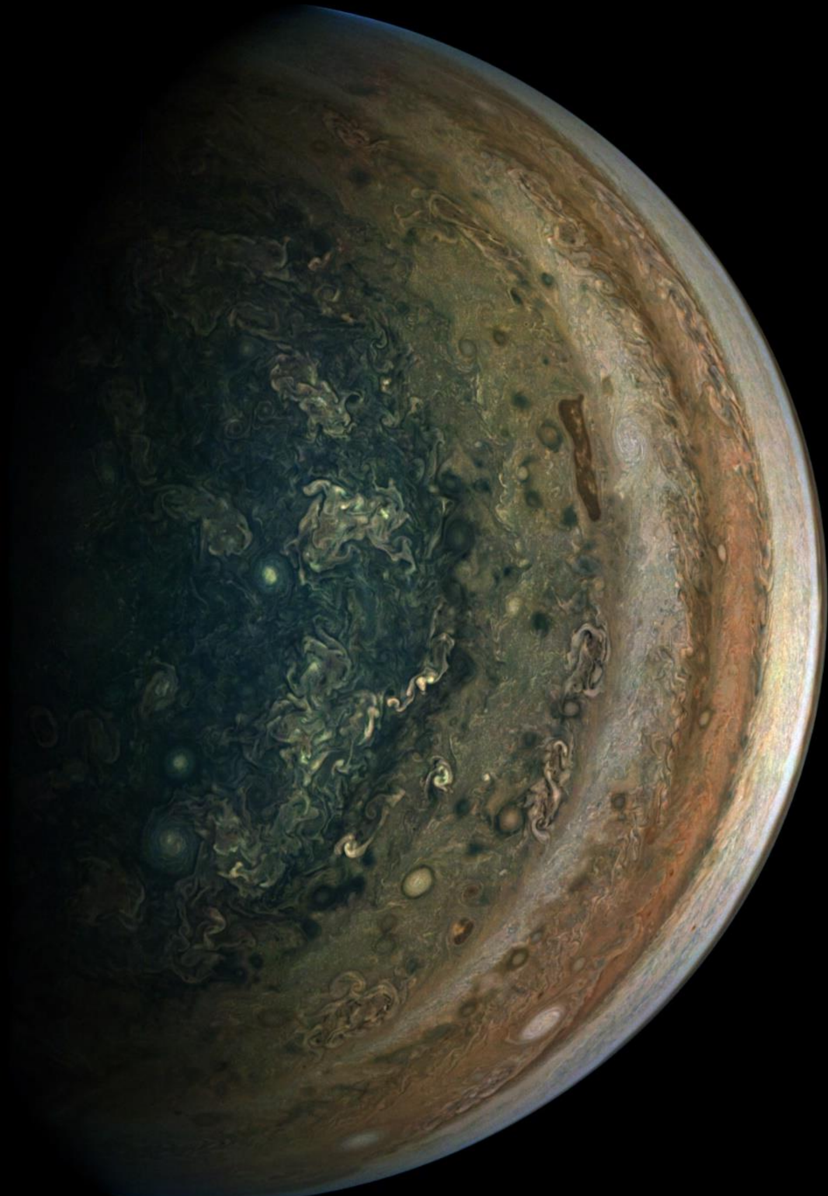


Water propulsion system		
Size	$< 90 \times 90 \times 123$ mm^3	
Mass	< 2.2 kg (wet) & < 0.3 kg (water)	
Mode	Ion thruster	Resistojet
Head #	1	4
Power	< 30 W	< 5 W
Thrust	300 μN	1 mN
*I*sp	600 s	70 s

Thruster name		Size U	N –	Total Impulse Ns	Power W
Aerospace	MEMS	0.18	5	7	NA
U of Texas	Custom	0.40	1	56	2
SFL	CNAPS	1.58	4	106	4
MIT	SiEPS	0.20	1	116	2
Busek	BET-100	0.40	1	175	6
Busek	μ-resistojet	4.00	4	8	6
			1	240	15
Busek	μPPT	0.50	1	252	2
GWU	μCAT	0.20	4	570	10
Vacco	MarCO prop.	1.50	8	755	15
CUA/Vacco	CHIPS	1.60	1	814	30
			4	511	NA
Hyperion	PM200	1.00	1	920	6
Aerojet RD	MPS-130	1.00	4	1200	17
Tethers U	HYDROS-C	2.00	1	2150	20
Phase Four	RFT	1.00	1	2200	100
Enpulsion	IFM Nano T	1.00	1	5000	40
U of Tokyo	Unified W water	3.00	1	5100	47
			4	870	19
Busek	BIT-3	1.60	1	20600	56

Thruster name		Size U	N -	Propellant -	Thrust mN
Aerospace	MEMS	0.18	5	HFC236fa	100.0
U of Texas	Custom	0.40	1	HFC236fa	110.0
SFL	CNAPS	1.58	4	SF_6	50.0
MIT	SiEPS	0.20	1	EMI-BF_4	0.1
Busek	BET-100	0.40	1	EMI-Im	0.1
Busek	μ-resistojet	4.00	4	Ammonia	0.5
			1		10.0
Busek	μPPT	0.50	1	PTFE	0.5
GWU	μCAT	0.20	4	Nickel	0.0
Vacco	MarCO prop.	1.50	8	HFC236fa	25.0
CUA/Vacco	CHIPS	1.60	1	R134a	30.0
			4		18.0
Hyperion	PM200	1.00	1	Propane/N_2O	500.0
Aerojet RD	MPS-130	1.00	4	AF-M315E	1.3
Tethers U	HYDROS-C	2.00	1	Water	1.2
Phase Four	RFT	1.00	1	Xenon	5.2
Enpulsion	IFM Nano T	1.00	1	Indium	0.4
U of Tokyo	Unified W water	3.00	1	Water	0.3
			4		3.9
Busek	BIT-3	1.60	1	Iodine	0.7

Thruster name		Size	N	Propellant	GHS	NFPA		
		U	-	-	#	B	R	Y
Aerospace	MEMS	0.18	5	HFC236fa	4, 7	1	0	1
U of Texas	Custom	0.40	1	HFC236fa	4, 7	1	0	1
SFL	CNAPS	1.58	4	SF_6	4	2	0	0
MIT	SiEPS	0.20	1	EMI-BF_4	7	3	1	0
Busek	BET-100	0.40	1	EMI-Im	6	2	1	0
Busek	μ-resistojet	4.00	4 / 1	Ammonia	4, 5, 7, 9	3	0	0
Busek	μPPT	0.50	1	PTFE	NC	1	0	0
GWU	μCAT	0.20	4	Nickel	2, 7, 8	2	1	0
Vacco	MarCO prop.	1.50	8	HFC236fa	4, 7	1	0	1
CUA/Vacco	CHIPS	1.60	1 / 4	R134a	4	2	1	0
Hyperion	PM200	1.00	1	Propane/N_2O	2, 3, 4	2	4	0
Aerojet RD	MPS-130	1.00	4	AF-M315E	1, 6, 7, 8	3	0	0
Tethers U	HYDROS-C	2.00	1	Water	NC	0	0	0
Phase Four	RFT	1.00	1	Xenon	4	0	0	0
Enpulsion	IFM Nano T	1.00	1	Indium	8	2	0	0
U of Tokyo	Unified W water	3.00	1 / 4	Water	NC	0	0	0
Busek	BIT-3	1.60	1	Iodine	5, 6, 7, 9	3	0	0



Thank you