

SESA 6071

Spacecraft Propulsion

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Definitions

| | | | |
|-----------|--------------------------------------|-----------|---|
| I_t | Total Impulse (Ns) | I_{sp} | Specific Impulse (s) |
| F | Rocket Thrust (N) | g_0 | Standard Gravitational Accel (m/s^2) |
| \dot{m} | Propellant mass flow rate (kg/s) | m_p | Expelled propellant mass (kg) |
| c | Effective exhaust velocity (m/s) | η_T | Power Conversion Efficiency |
| P_{in} | Input Power (W) | m | Spacecraft or launch vehicle mass (kg) |
| α | Specific power plant mass (kg/W) | M_{pow} | Power plant mass (kg) |

1. Lecture 1

1.1. What is Rocket Propulsion

Propulsion itself is the **act of changing the motion of a body**, typically by using newtons third law and it can be classified in various types of ways. A more colloquial way of defining rocket propulsion is as **mass drivers**, throwing out mass one way to yield an acceleration in the other.

1.2. Rocket Propulsion Family Tree

In **Figure 1** the rocket propulsion types are grouped by the energy source.

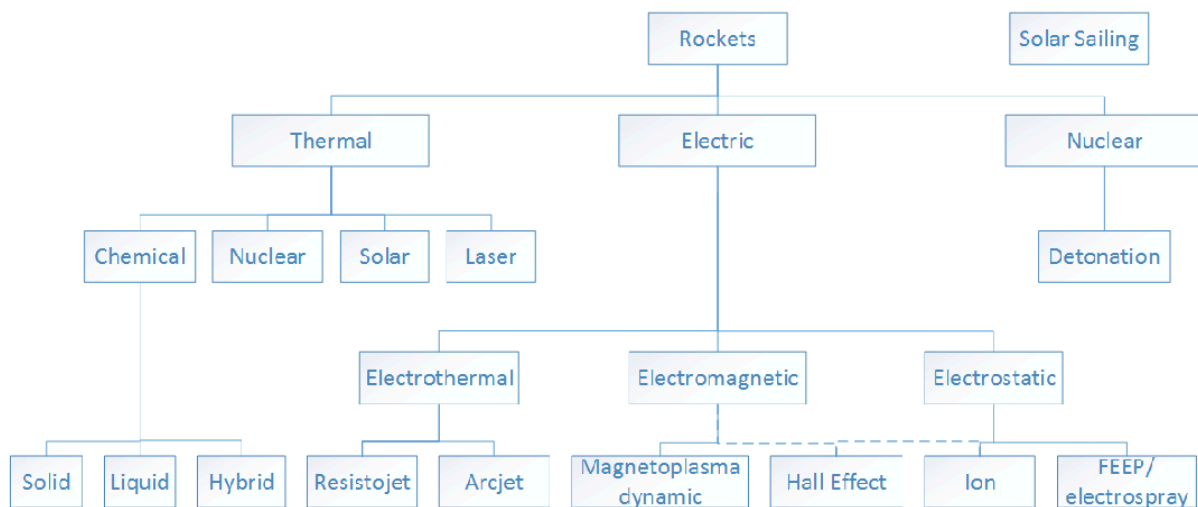


Figure 1: Flowchart of the rocket propulsion family tree

1.2.1. Chemical Rockets

These utilize either a chemical reaction or decomposition to generate energy. Gas is heated to between **700°C - 1300°C** and to speeds between **1.5 km/s - 4.5 km/s**. These require a **fuel and oxidizer** and come in the following types:

- **Solid:** Fuel and oxidizer mixed within into a solid grain which cannot stop burning once ignited. feature **high thrust with low performance**.
- **Liquid:** Burn a liquid fuel and oxidizer allowing for repeated firings and variable thrust. Feature **high performance and thrust with high complexity**.
- **Hybrid:** Have a liquid oxidizer but a solid fuel allowing for better performance than solid with lower complexity.

1.2.2. Electric Rockets

These use electrical energy to generate thrust without utilizing combustion. Typically have very high exhaust velocities (**~ 60,000 m/s**) and therefore **very high performance** at the costs of **high complexities and very low thrust**. The four distinct groups are:

- **Electrothermal:** Uses electrical energy to heat a propellant (Resistojet). Are **simple to build** at the cost of **low thrust**.
- **Electrostatic:** Uses electrical energy to accelerate ionized fuel across an electric fields. Feature **good performance** at the cost of **being expensive and low thrust**.
- **Electromagnetic:** Accelerates an ionized fuel using a magnetic field. Fall issue to **low efficiency unless power input is high**.
- **Hall Effect Thruster:** Uses a mixture of both electrostatic and electromagnetic propulsion methods to accelerate propellant. These are the most **commonly used**.

1.2.3. Nuclear Rockets

Broadly speaking there are two types of nuclear rockets, these are:

- **Nuclear Detonation:** Use the shockwave produced when nuclear bombs are detonated to produce thrust (Orion Drive). **High performance and thrust** but are **very dangerous and have limited testing**.
- **Nuclear Thermal:** Uses the heat energy produced during nuclear fission to heat a propellant (typically hydrogen) which is then exhausted. These have **high performance and thrust** but are **dangerous and have limited testing**.

1.2.4. Solar and Laser Rockets

These systems use large diameter telescopes to focus in a laser or solar radiation to heat up a propellant. These systems feature **high theoretical performance and moderate thrust** but are **very complex and lack any real testing**.

1.2.5. Solar Sails

These systems use no propellant at all and instead produce thrust through the momentum gained when a photon is incident on the sail. These systems feature **good performance with no fuel** but fall victim to **low thrust and engineering complexity**.

1.3. Rocket Propulsion Applications

Instead of grouping together rocket propulsion methods using the energy source, the rocket application can also be used, for example:

- **High Thrust/Maneuverability:** Typically have the cost of **low performance** and use **chemical or solid** propulsion methods.
- **High Performance:** Typically have the cost of **low thrust** and use **electrical** propulsion methods.
- **Balanced Thrust and Performance:** Typically the middle ground is **nuclear thermal**.

2. Lecture 2

2.1. Definitions and Fundamentals

To develop an empirical measure of performance we should first consider **Eq. 1**.

$$I_t = \int_0^t F \, dt \quad (1)$$

Where:

- I_t : Total Impulse (Ns)
- F : Thrust Force (N)
- t : Burn Duration (s)

Note that for **Eq. 1**, if F is constant then the equation simplified to $I_t = Ft$. A more useful measure of performance for rocket engines is shown in **Eq. 2**.

$$I_{sp} = \frac{\int_0^t F \, dt}{g_0 \int_0^t \dot{m} \, dt} = \frac{I_t}{g_0 \int_0^t \dot{m} \, dt} \quad (2)$$

Where:

- I_{sp} : Specific Impulse (s)
- g_0 : Standard Gravitational Accel (m/s^2) = $9.81 \, m/s^2$
- \dot{m} : Propellant mass flow rate (kg/s)

There is no concrete reason on why g_0 is present in this equation, however one common theory is that it allows I_{sp} to be in seconds instead of featuring a length unit which would eliminate any error in conversion from metric to imperial. If F and \dot{m} are both constant over the t then **Eq. 2** simplifies to **Eq. 3**.

$$I_{sp} = \frac{I_t}{g_0 m_p} \quad (3)$$

Where:

- m_p : Expelled propellant mass (kg) = $\dot{m}t$

Another useful parameter for defining engine performance is shown in **Eq. 4**.

$$c = \frac{F}{\dot{m}} \quad (4)$$

Where:

- c : Effective exhaust velocity (m/s)

The exhaust velocity is called as such as the **velocity profile of the exhaust is not uniform**, this is most seen in chemical rockets due to the **no slip condition** but is slightly seen in electrical rockets too. Rearranging all of the previous equations together yields a definition for I_{sp} in terms of c .

$$I_{sp} = \frac{c}{g_0} \quad (5)$$

Typical I_{sp} values for the rocket engine types defined in the previous lecture are shown in **Table 1**.

| Rocket Engine Type | $I_{sp}(s)$ | Thrust (N) | Efficiency | Propellant |
|------------------------------|-------------|-----------------|------------|-----------------------------|
| Chemical bi-propellant | 200 - 450 | $\leq 10MN$ | 0.8 | Liquid or Solid Propellents |
| Chemical mono-propellant | 150 - 250 | 0.03 - 100 | 0.9 | N_2H_4 |
| Thermal Nuclear Fission | 500 - 860 | $\leq 10MN$ | 0.5 | H_2 |
| Resistojet - electrothermal | 150 - 350 | 0.01 - 10 | 0.4 | N_2H_4 , NH_3 , H_2 |
| Ion Thruster - electrostatic | 1500-8000 | $10^{-5} - 0.5$ | 0.65 | Xe |
| Hall Effect Thruster | 1500-2000 | $10^{-5} - 2$ | 0.55 | Xe |

Table 1: Typical values of I_{sp}

2.2. Maximum Chemical Performance

A typical chemical reaction used in chemical rockets is combustion shown in **Eq. 6**.



Combustion as shown in **Eq. 6** is an exothermic reaction as the energy of the reactants is more than the energy of the products, allowing for an excess of energy after the reaction. To estimate an effective upper limit to the energy released during combustion, the bond energies shown in **Table 2** can be used.

| Chemical | Bond Energy (kJ/mol) |
|----------|--------------------------|
| H_2 | 436 |
| O_2 | 498 |
| H_2O | 428 |
| | 498.7 |

Table 2: Respective bond energies of reactants and products in combustion.

Note that there are two bond energies in **Table 2** due to the OH and the OH - H bonds. The maximum energy can be calculated and are shown in **Figure 2**.

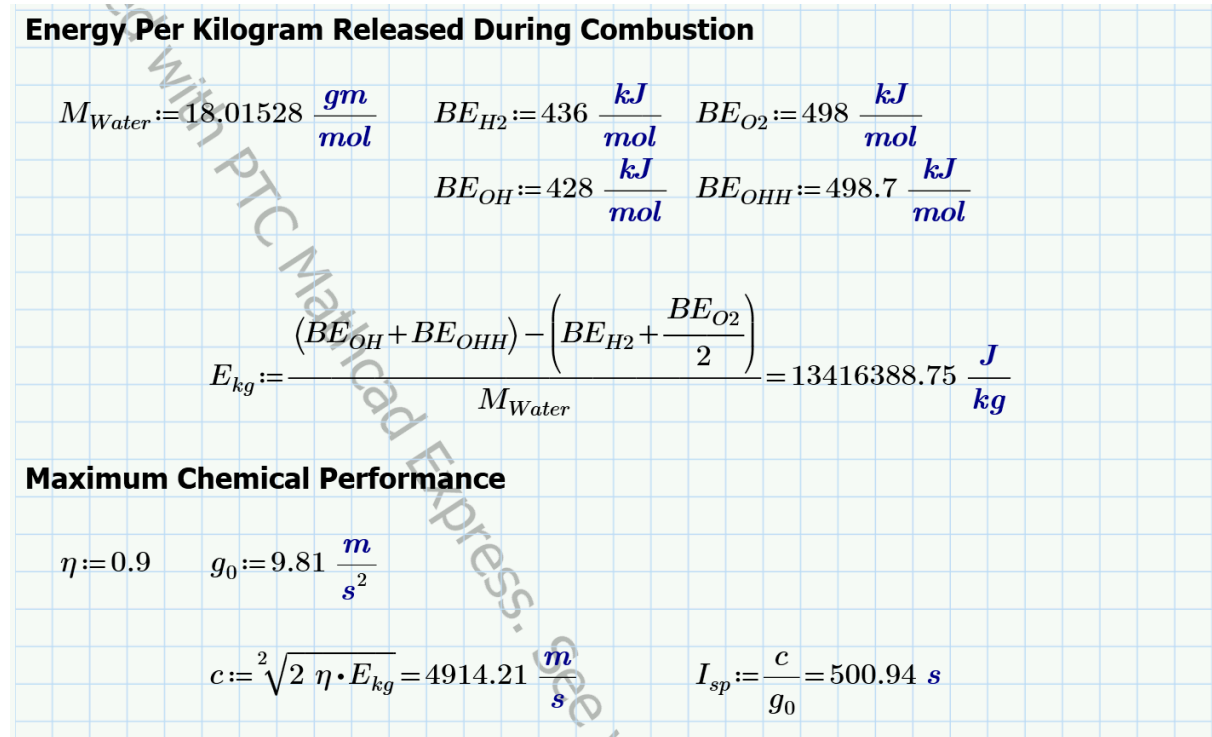


Figure 2: Calculations for maximum chemical rocket engine performance

Note that in this calculation, the bond energy of oxygen is halved as per **Eq. 6** and the equation for effective exhaust velocity comes from the kinetic energy equation and noting that $E_{kg} = Energy/mass$.

2.3. Comparative Electric Performance

To compare the efficiency of chemical propulsion to electric propulsion consider an electrostatic propulsion system shown in **Figure 3**.

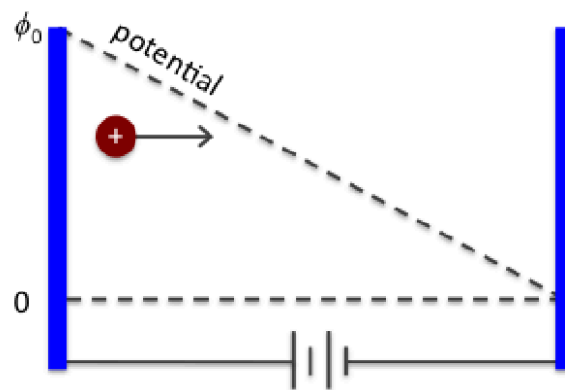


Figure 3: Basic principle of an electrostatic propulsion system.

A charged ion (assumed for these calculations to be a water ion) enters an electric field which causes it be accelerated to the more negative (lower potential) plate. By setting the electric potential energy gained by the ion equal to the kinetic energy ($\eta E_p = E_k$) then the I_{sp} can be calculated, shown in **Figure 4**.

Voltage Required for an Isp of 500s Using Ionized Water

$$\begin{aligned}
 M_{\text{Water}} &:= 18.01528 \frac{\text{gm}}{\text{mol}} & \eta &:= 0.9 & g_0 &:= 9.81 \frac{\text{m}}{\text{s}^2} & N_a &:= 6.023 \cdot 10^{23} \text{mol}^{-1} \\
 I_{sp} &:= 500 \text{ s} & q &:= 1.6 \cdot 10^{-19} \text{ C} \\
 V &:= \frac{\frac{1}{2} \frac{M_{\text{Water}}}{N_a} (I_{sp} \cdot g_0)^2}{\eta \cdot q} = 2.5 \text{ V}
 \end{aligned}$$

Figure 4: Comparative electrical propulsion system voltage calculations.

As shown in **Figure 4** the voltage required to match the performance of a chemical system is very low and easily achievable, in reality electrostatic systems can achieve efficiencies in excess of 10,000s.

2.4. Nuclear Performance

To estimate the performance of a thermal nuclear rocket engine, Uranium-235 fission is considered, where the energy released in one fission event is immediately transferred to a water molecule, this calculation is shown in **Figure 5**.

Energy Transferred to One Water Molecule During One Nuclear Fission Event

$$\begin{aligned}
 E_{U235} &:= 180 \text{ MeV} = (2.88 \cdot 10^{-11}) \text{ J} & M_{\text{Water}} &:= 18.01528 \frac{\text{gm}}{\text{mol}} & N_a &:= 6.023 \cdot 10^{23} \text{mol}^{-1} \\
 m_{\text{Water}} &:= \frac{M_{\text{Water}}}{N_a} = 0 \text{ kg} & & \leftarrow \text{is } 2.99 \times 10^{-26} \text{ but is too small for mathcad to show} \\
 E_{kg} &:= \frac{E_{U235}}{m_{\text{Water}}} = (9.63 \cdot 10^{14}) \frac{\text{J}}{\text{kg}}
 \end{aligned}$$

Performance of a Nuclear Thermal System

$$\begin{aligned}
 \eta &:= 0.9 & g_0 &:= 9.81 \frac{\text{m}}{\text{s}^2} \\
 c &:= \sqrt{2 \eta \cdot E_{kg}} = 41631151.15 \frac{\text{m}}{\text{s}} & I_{sp} &:= \frac{c}{g_0} = (4.24 \cdot 10^6) \text{ s}
 \end{aligned}$$

Figure 5: Maximum nuclear thermal propulsive system performance.

Note that this I_{sp} is a theoretical upper limit and in reality the true performance is much lower and is limited by material limits due to heat.

2.5. Definitions and Fundamentals Cont.

For propulsion systems, efficiency can be defined in terms of the fraction of source power that is converted to jet power, this efficiency is shown in **Eq. 7**.

$$\eta_T = \frac{\dot{m}c^2}{2P_{in}} \quad (7.1)$$

$$P_{in} = \frac{\dot{m}c^2}{2\eta_T} = \frac{Fc}{2\eta_T} \quad (7.2)$$

$$\frac{P_{in}}{m} = \frac{F}{m} \frac{c}{2\eta_T} = a \frac{c}{2\eta_T} \quad (7.3)$$

Where:

- η_T : Power conversion efficiency
- P_{in} : Input or Source power (W)
- a : Acceleration (m/s^2)
- m : Spacecraft mass (kg)

Note that for electrical systems P_{in} , the power must come from a source e.g., solar panel array. **Eq. 7** Also shows that **for a fixed specific power: ($\frac{P_{in}}{m}$) a high effective exhaust speed (c) means a low acceleration.** It is also useful to define a specific power plant mass as shown in **Eq. 8**.

$$\alpha = \frac{M_{pow}}{P_{in}} \quad (8)$$

Where:

- α : Specific power plant mass (kg/W)
- M_{pow} : Power plant mass (kg)