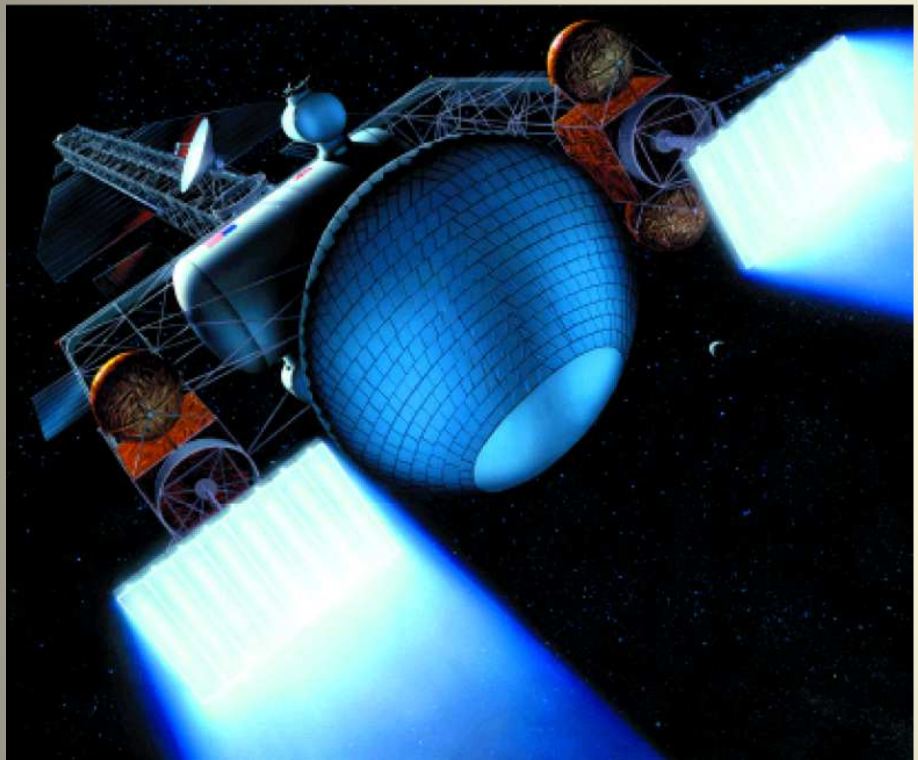
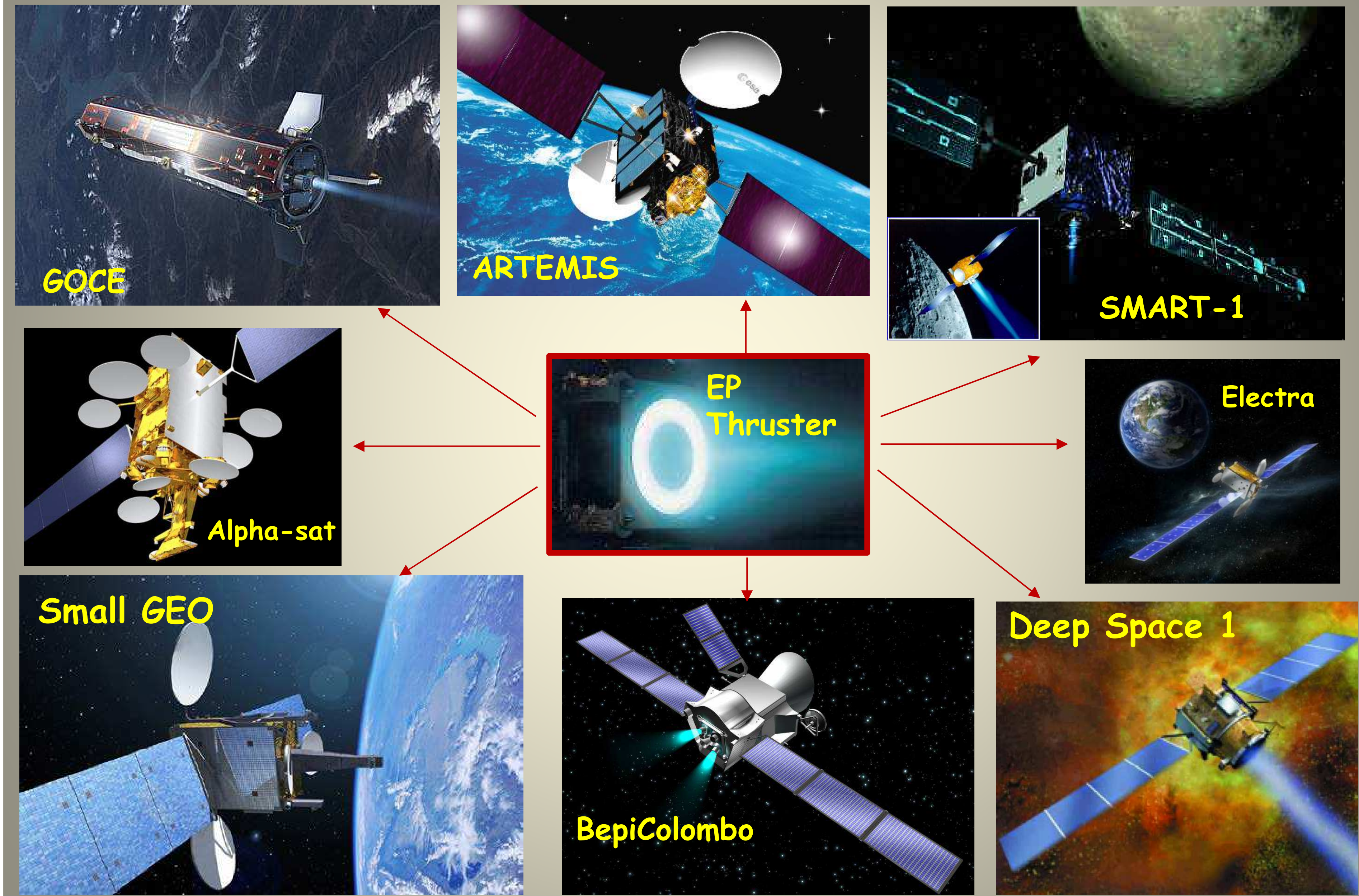
Electric Propulsion Survey: outlook on present and near future technologies / perspectives



by Ing. Giovanni Matticari

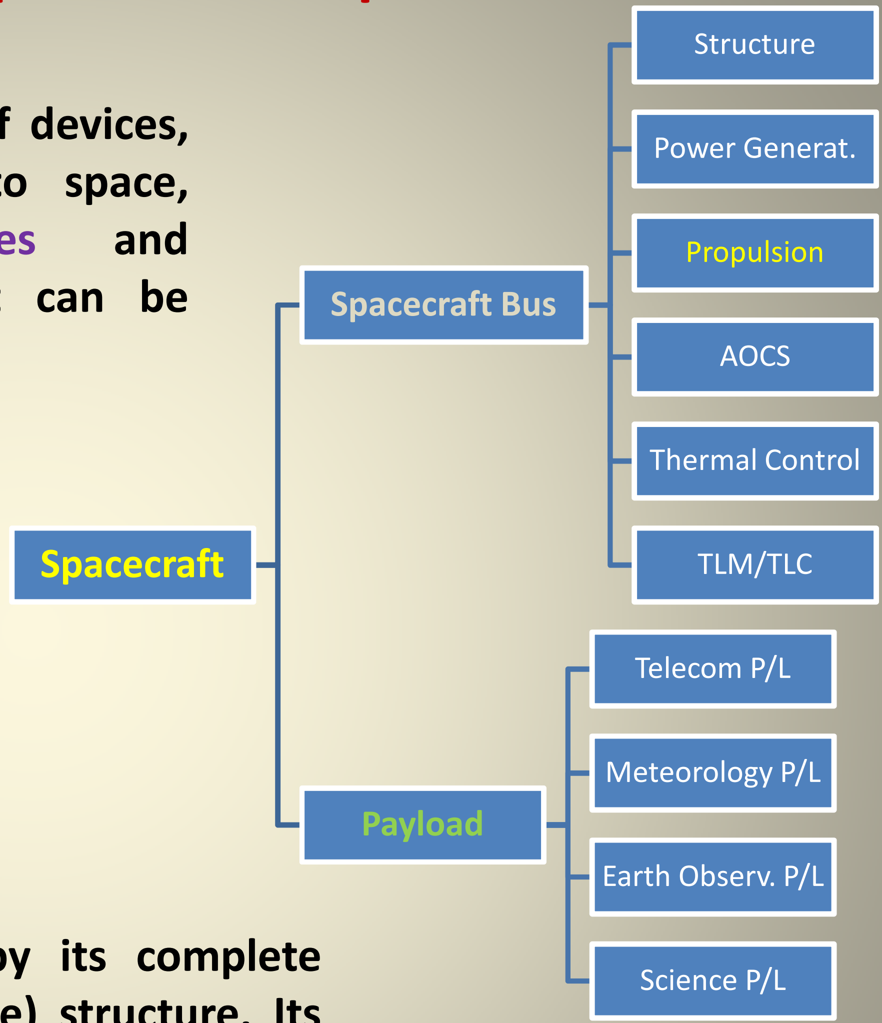
Electric Propulsion: a concrete reality on many S/C



Spacecraft and Spacecraft Propulsion

Spacecraft (S/C) is the collective name of devices, which are designed to be placed into space, comprising Earth orbiting satellites and interplanetary space probes. Spacecraft can be manned or unmanned.

The *Payload (P/L)* is the revenue-producing portion of a spacecraft load, e.g. passengers and cargo such as scientific experiments, TV transmitters, earth observation equipment like imaging instrumentation, etc.



Spacecraft Propulsion is characterized by its complete integration within the spacecraft (satellite) structure. Its function is to provide forces and torques in space to:

- transfer the spacecraft to the operational orbit/target (orbit acquisition)
- position the spacecraft (orbit control)
- orient the spacecraft (attitude control)

The Six Keplerian Elements of the S/C orbit

a = **Semi-major axis**: half of the line connecting the apogee with the perigee

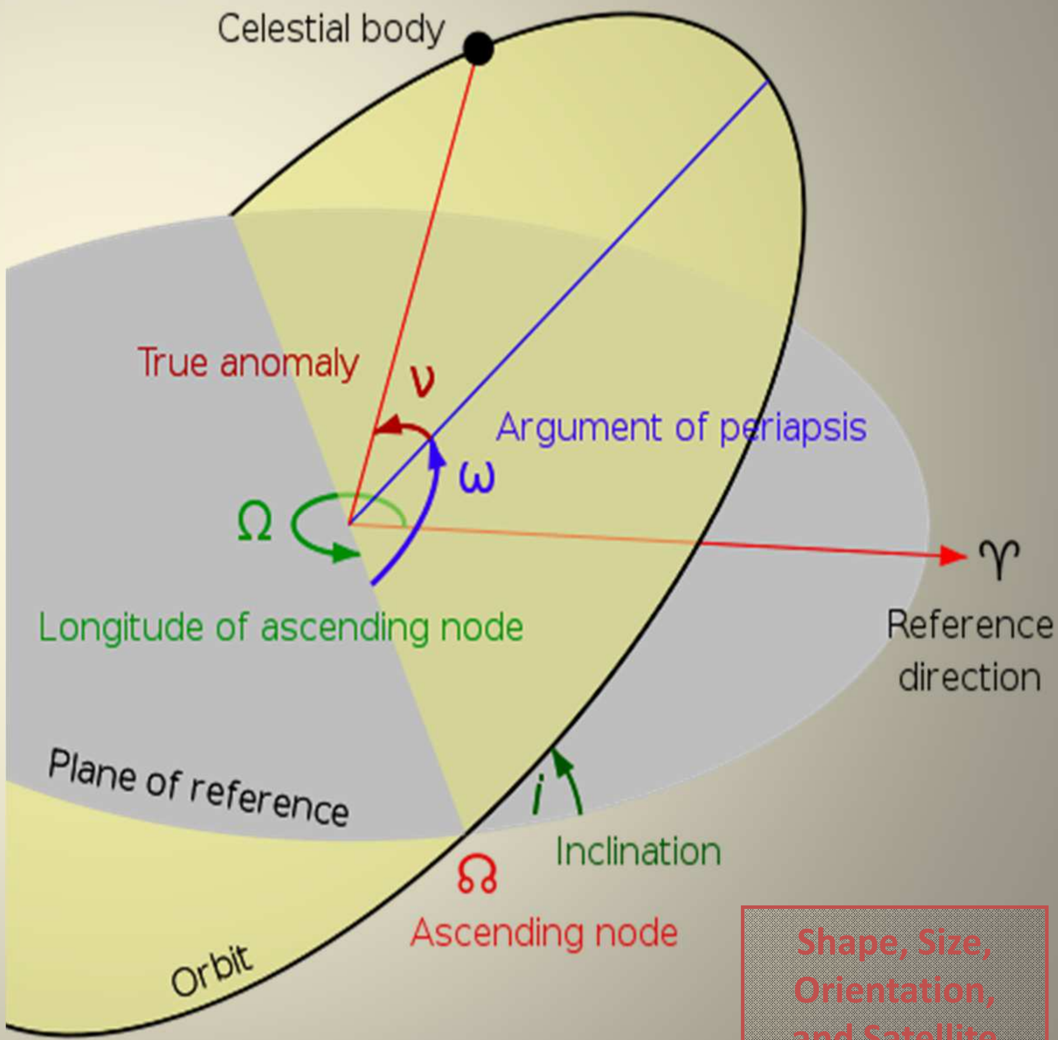
e = **Eccentricity**: defines the shape of the conic section (< 1,for an ellipse)

ν = **True anomaly**: The angle between perigee and satellite in the orbital plane, at a specific time

i = **Inclination**: The angle between the orbital and equatorial planes

Ω = **Right Ascension (longitude) of the ascending node**: The angle from the Vernal Equinox vector to the ascending node on the equatorial plane

ω = **Argument of perigee**: The angle measured between the ascending node and perigee

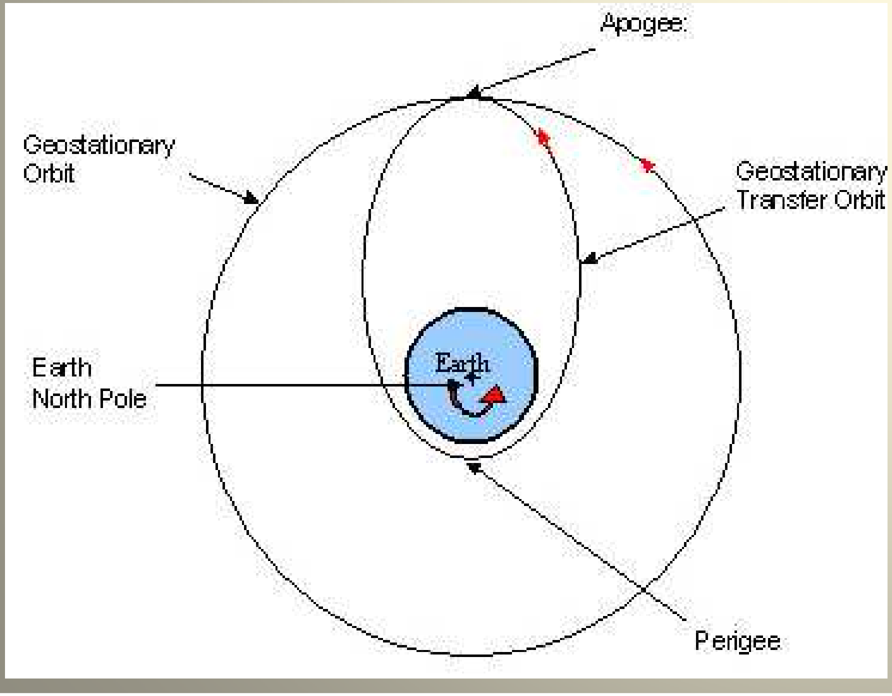


Shape, Size, Orientation, and Satellite Location.

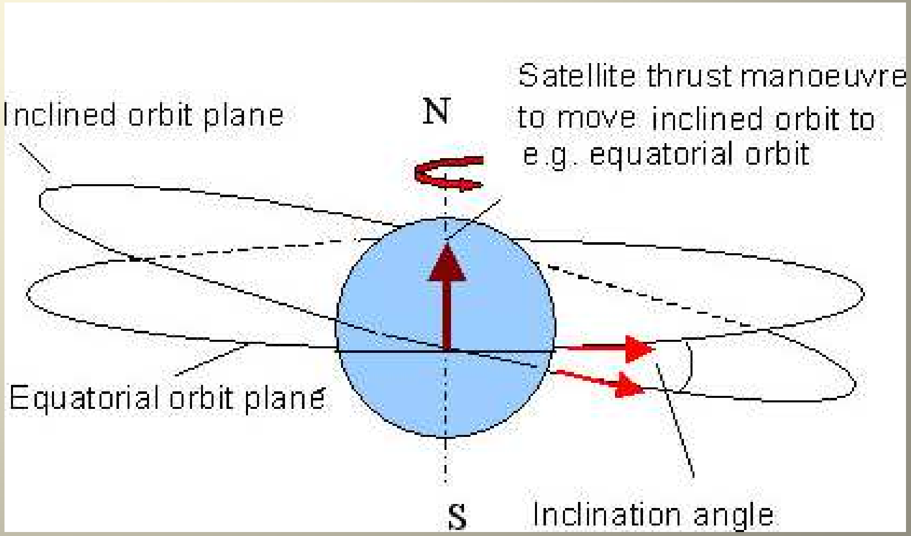
S/C Propulsion major features

- Very high velocity increment (ΔV) capability (up to many km/s)
- Low thrust levels (<1 mN to 500 N) with low acceleration levels
- Continuous and Pulsed operation
- Reliable, Accurate, Repeatable and Throttleable (only possible with Electric Propulsion)
- Minimum thrust exhaust impingement and contamination effects
- Last but not least: Cost effective

Example of Orbit Change: Transfer the S/C from the GTO to the GEO

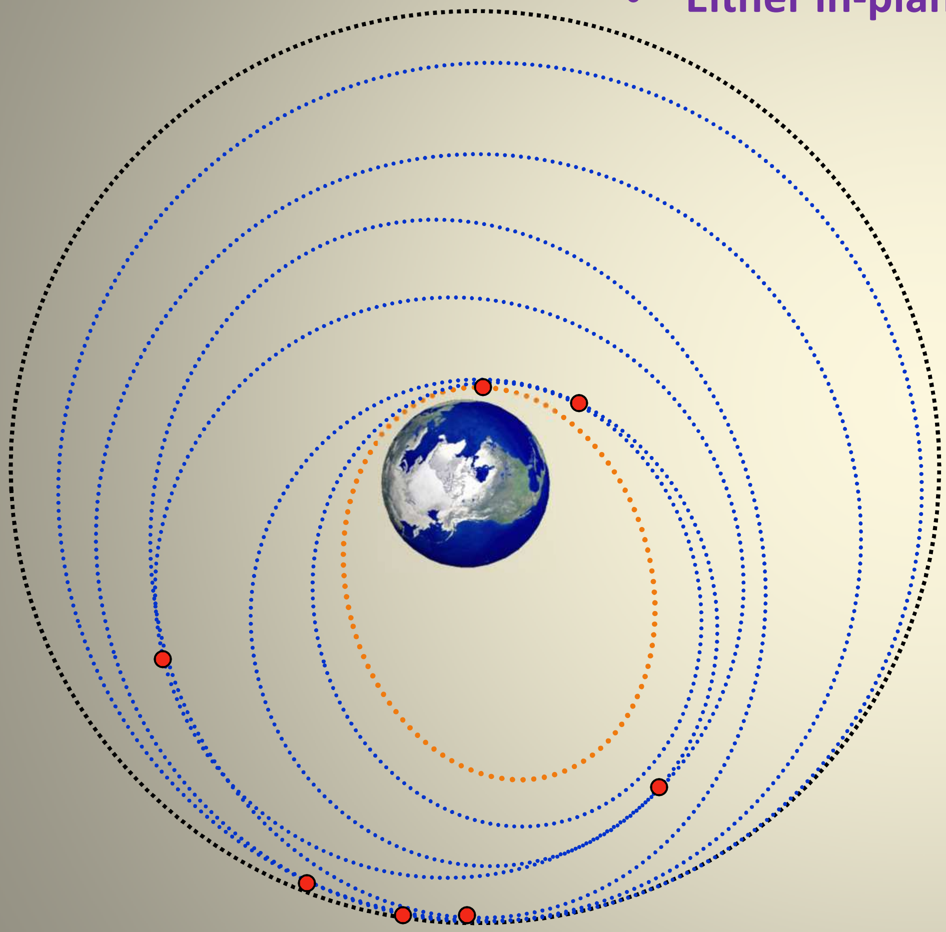


Example of Orbit Control: Orbit Plane correction maneuver

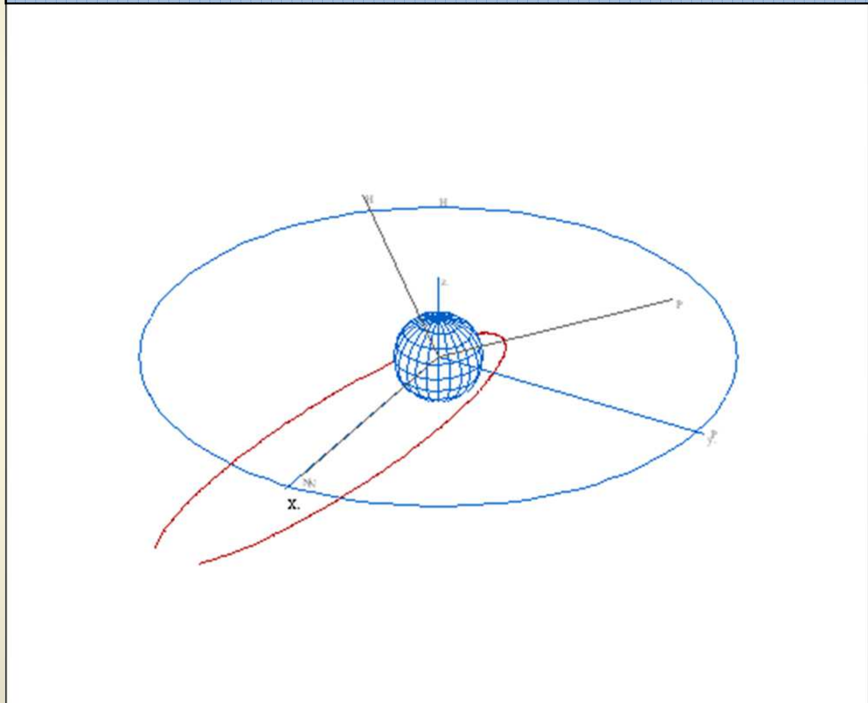


Low Thrust (< 1 N) Orbit Transfer

- **Thrusting in the orbit plane** will change ***a*** and ***e***
- **Out-of-plane thrusting** will change ***i*** and Ω
- **Either in-plane or out-of-plane thrusting** can change ω



A series of plane and altitude changes



Continuous Electric Engine Ppropulsion.

PROs: Lower propulsion system mass. Same system used for orbital maintenance.
CONs: Weeks or even months to reach final orbit. Van Allen Radiation belts.

Propellant Consumption and Specific Impulse

Thrust force *F* (N) is generated by expelling mass (propellant) from the S/C at high velocity ⟹

$$F = \dot{m} v_e \qquad F = -m\frac{dv}{dt}$$

Propellant Quantity M_{pr}(Kg) required for a S/C **velocity change Δ*V* (m/s)**

$\dot{m}$ = rate of propellent mass ejection (kg/s)
v_e = effective exhaust velocity (m/s)
M_{SC} = initial S/C Mass (Kg)

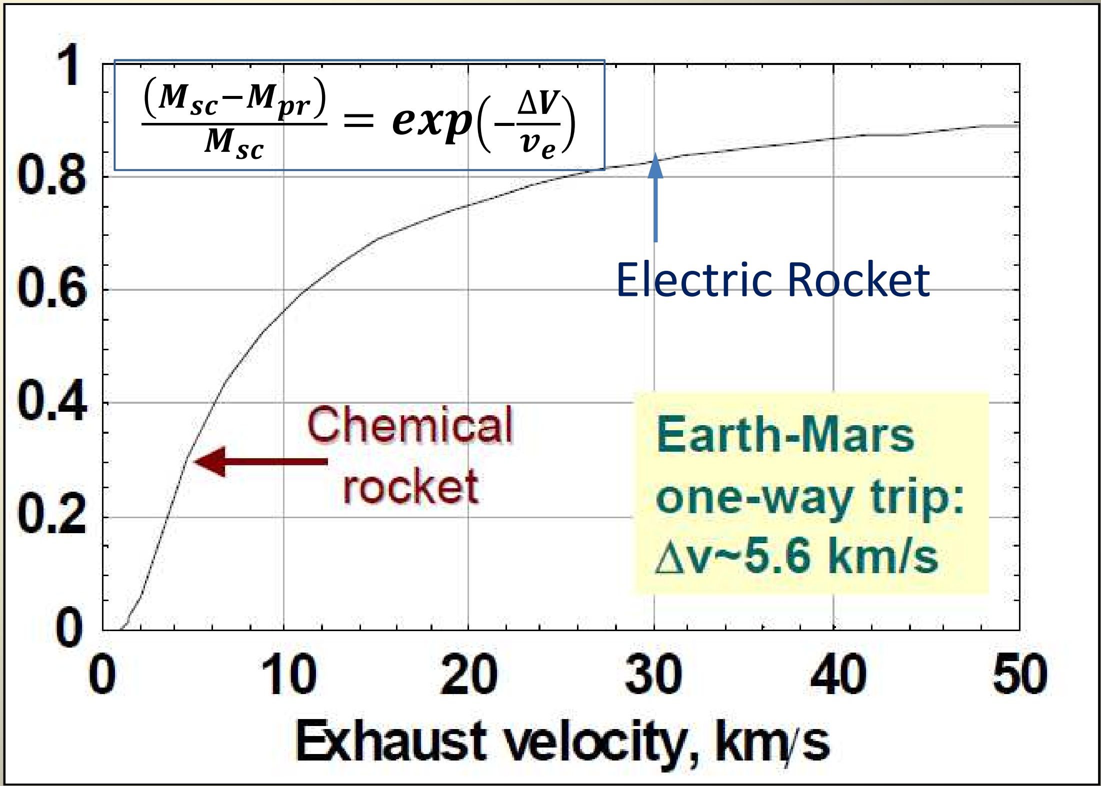
$$M_{pr} = M_{sc}\left[1 - exp\left(-\frac{\Delta V}{v_e}\right)\right]$$

Totale Impulse I_{tot} (Ns) associated to a certain mass of propellant M_{pr} is given by:

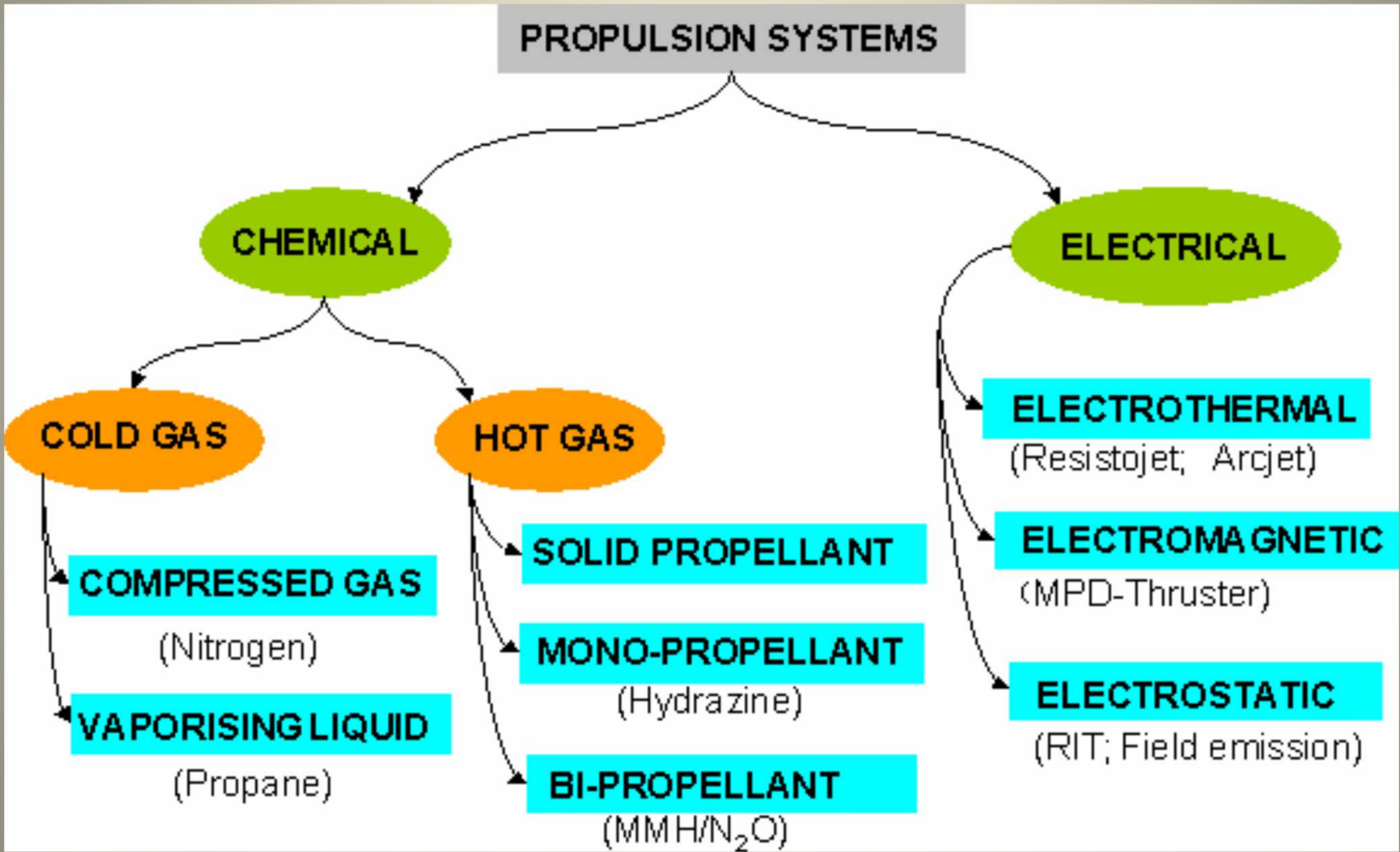
$$I_{tot} = \int_0^{\tau} F dt = v_e \int_0^{M_{pr}} dm = v_e M_{pr}$$

Specific Impulse I_s (sec) is the impulse delivered per **weight unit of propellant**

$$I_s = v_e/g_0 \qquad I_s = \frac{F}{\dot{m} g_0}$$

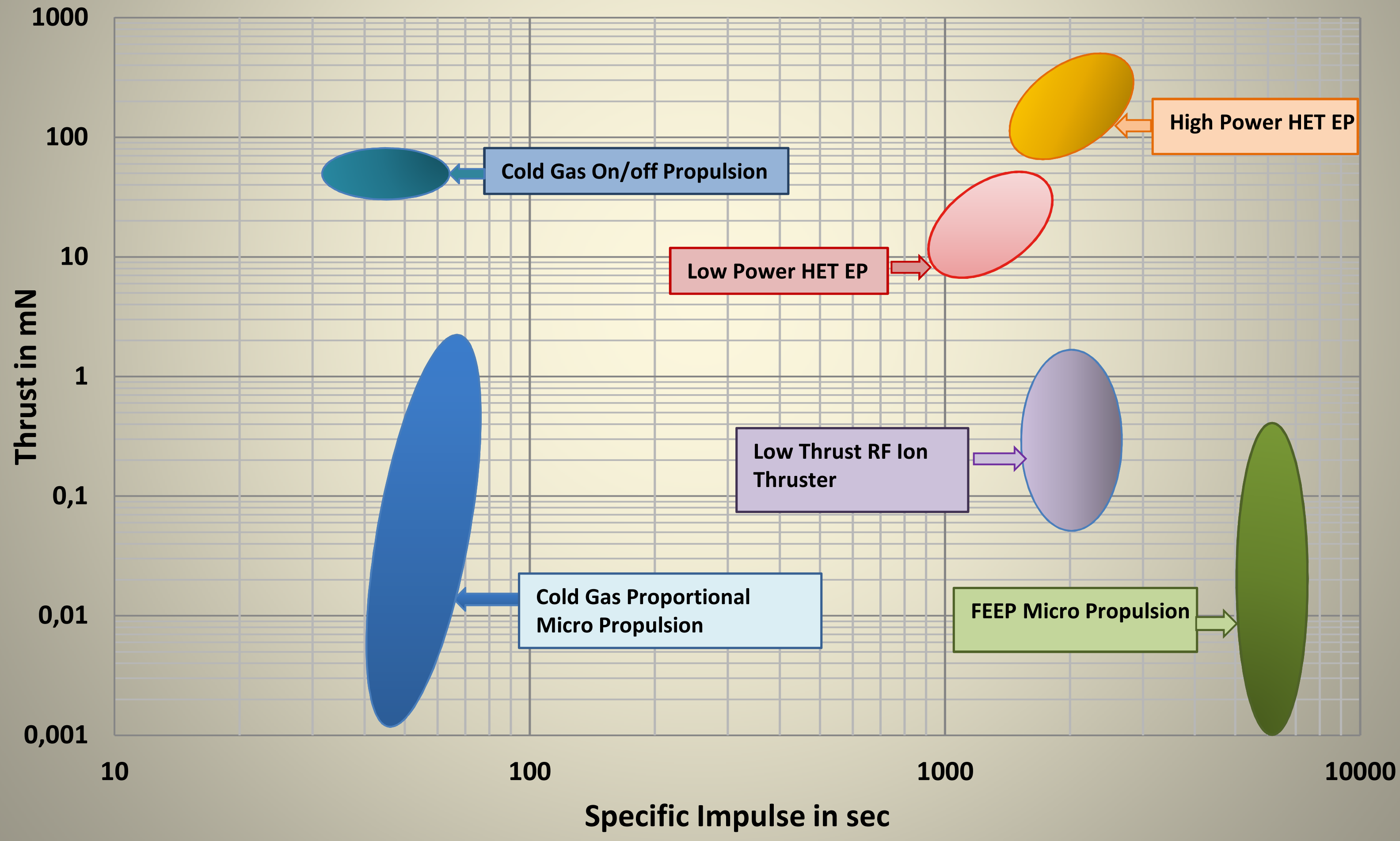


Propulsion Systems classified according to the type Energy Source

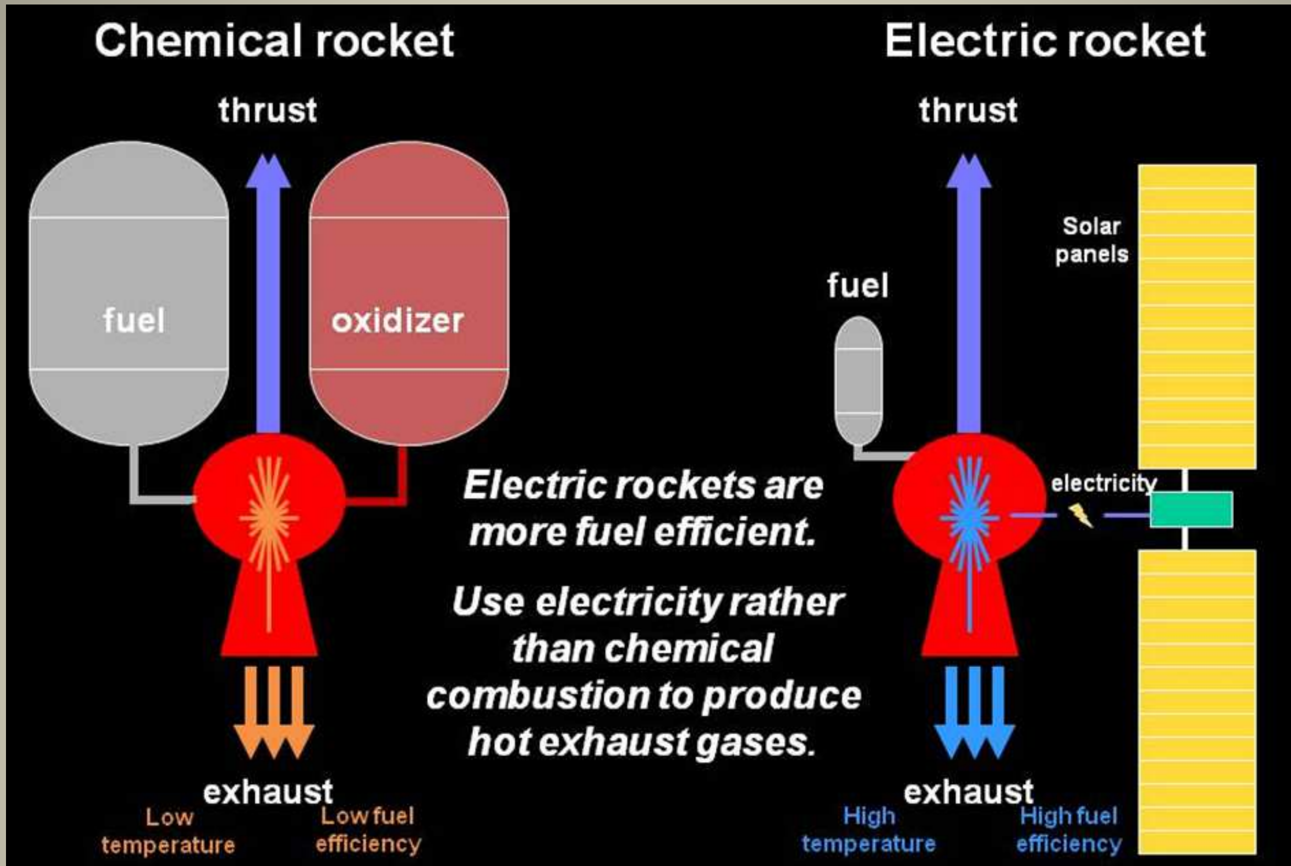


Some S/C Propulsion S/S with direct involvement of Italian Industry

The lower is the specific Impulse the higher is the Propellent Consumption
For EP: The higher is the specific Impulse the higher is the Power Consumption (at a fixed thust level)



Chemical and Electric Propulsion principles



Chemical Propulsion

The energy to produce thrust is stored in the propellant, which is released by chemical reactions

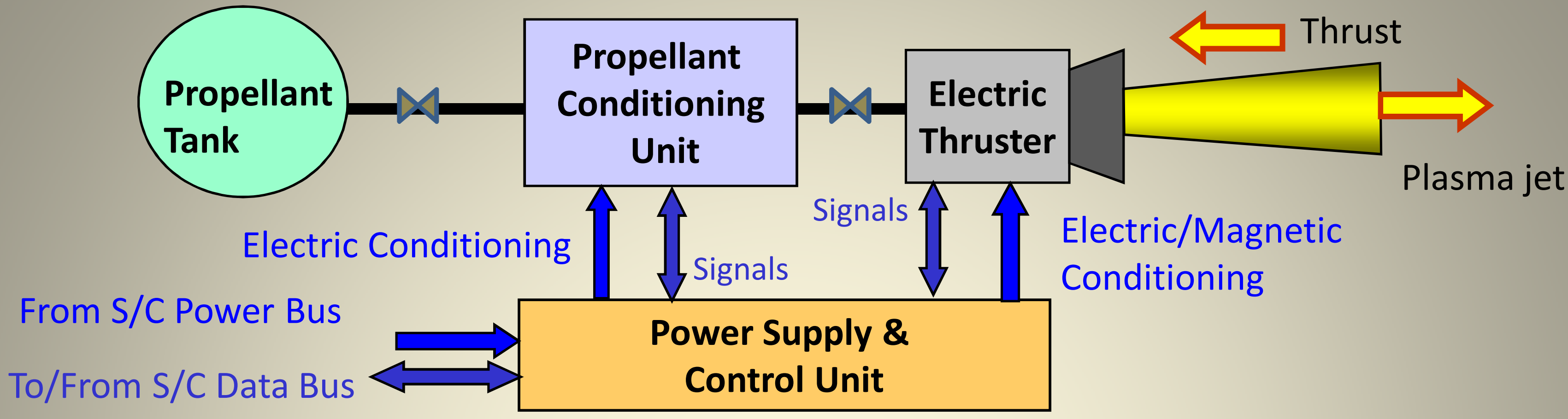
the propellant is then accelerated by expanding it in form of gas through a nozzle

Electric Propulsion

The propellant physical status (temperature, ionization, kinetic energy) is modified by using Electric Power, in order to generate a Thrust

Propellant acceleration is achieved by electrical heating and/or by Electrical and Magnetic body forces

Electric Propulsion main advantages



Replacing **Chemical propulsion** systems with **Electric Propulsion** systems can provide substantial benefits, such as:

- achieve **Drastic reduction of the propellant** necessary to fulfil the mission
  - saving in the launch costs,
  - increase of the payload mass ratio
  - extension of the operational mission
- **Adjust and control the thrust** level - also in **real time** - within a rather wide thrust range
- possibility to implement **autonomous navigation strategy** using the he EP as actuator of the control strategy

Electric Propulsion System Mass and optimum I_S (v_e)

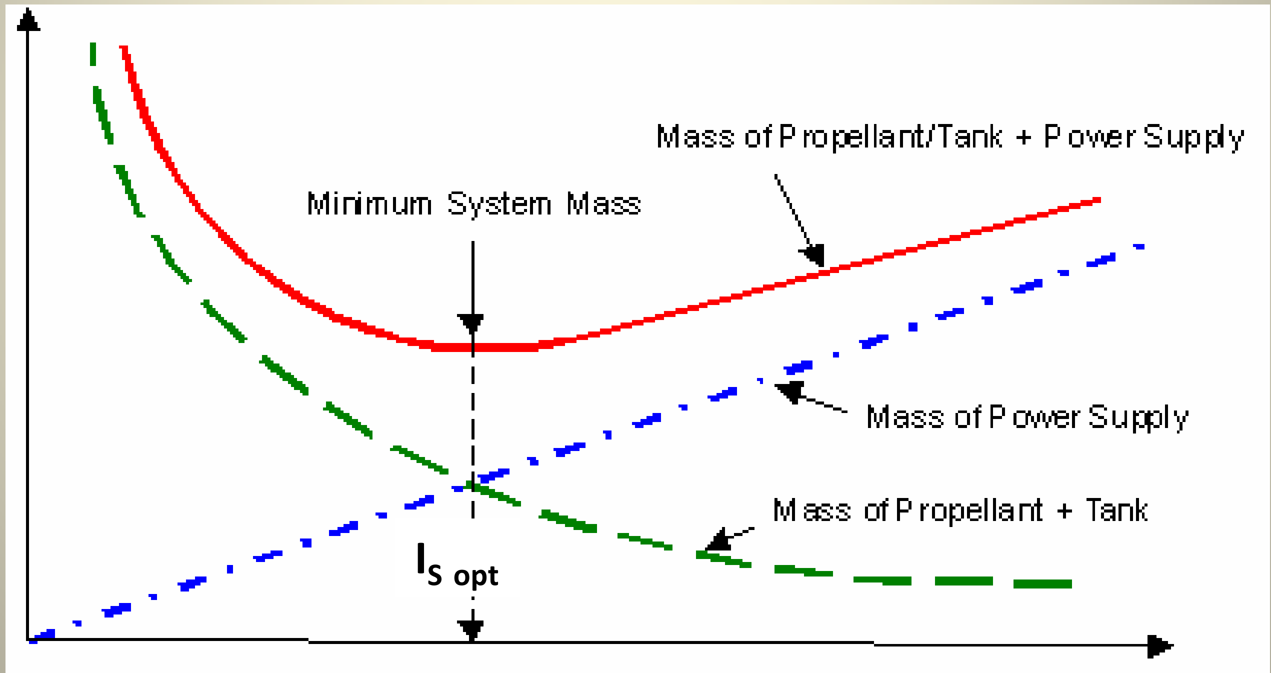
Propellant + Tank Mass + **Power Supply & Control Unit + Thruster/s** = **Electric Propulsion System Mass**

Decrases when increasing the I_S

Increases when increasing the I_S

Achieves a minimum for an optimum I_S

EP System Mass



Specific Impulse (I_S)

The point of intersection of the two curves determines the minimum of the EP system mass by $I_{S\ opt}$ resulting in a *maximum value of mass available to the payload*.

Electric Propulsion Types

Electric Propulsion Devices can be grouped into 3 major classes:

Electrothermal Thrusters
Use electrical energy to heat the propellant that is then expanded in a nozzle to produce thrust (enthalpy into kinetic energy conversion)

- *Resistojet*
- *Arcjet*
- *Electrothermal hydrazine*
- *Microwave electrothermal*
- *Pulsed electrothermal*

low conversion efficiency from the thermal to the kinetic energy.

Electrostatic Thrusters
use electric fields for accelarating the ionized particles of a gaseous propellenant

- *Gridded Ion Engines*
  - *Electron Bombardment (DC)*
  - *Radiofrequency or Microwave*
- *Hall Effect:*
  - *SPT*
  - *TAL*
- *HEMPT*
- *Colloid*
- *Field Emission (FEEP)*

Electromagnetic Thrusters
Use the combined action of electric and magnetic fields for producing body forces that directly accelerate the plasma

- *Magnetoplasmadynamic*
  - *Self-field*
  - *Applied-field*
- *Pulsed plasma*
- *Helicon plasma*
- *Inductive pulsed plasma*
- *Electron-cyclotron-resonance*
- *Variable specific-impulse plasma*

Most "popular" Electric Thrusters features

	Electrothermal		Electrostatic				Electromagnetic	
	Resistojet (NH_3)	Arcjet (N_2H_4)	Hall	Ion	HEMPT	FEEP	MPD	PPT
Propellant	NH_3, N_2H_4	NH_3, N_2H_4, H_2	Xe, Ar, Kr	Xe, Ar, Kr	Xe, Ar, Kr	Cs (In)	H_2	Teflon
Power Range (W)	500 to 1500	200 to 2000	300 to 8000	200 to 5000	1000 to 8000	<1 to 30	10 K to > 500 K	1 to 200
Specific Impulse (s)	300 -400	500-700	1400 to 2500	2000 to 4000	2000 to > 3000	6000	2000 to 5000	800 to 1200
Thruster Efficiency	80%	35%	40 to 55%	50 to 65%	50 to 55%	80%	30 to 50%	10-15%
Plume Divergence	< 20°	< 20°	30-40°	> 15°	40-45°	< 20° (x) < 40° (y)		
Status	Flown	Flown	Flown	Flown	Ready to Fly	Ready to Fly	Engineer.	Flown
Typical Mission	Orbit Control Orbit Insersion	Orbit Control	Orbit Control Orbit Raising	Orbit Control Orbit Raising	Orbit Control Orbit Raising	Attitude Control Fine Pointing	High ΔV Cruising	Attitude Control