Electric Propulsion for a Reusable Space Cargo

by
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1. Introduction

Electric Propulsion has several advantages against Chemical Propulsion. The most important is the save on fuel mass. For orbit transfer or interplanetary travel, the save on money can be very high. However, the burn time and electric power needed adds several constrains on the spacecraft mass, design and cost.
Using a Space Cargo propelled by an electric thruster would save mass and money on the satellite. Instead of using only once the solar panels and the thruster, they are used several times for different space missions. The spacecraft needs only to carry the propellant. Additionally, system engineering work is reduced.

2. Optimal Specific Impulse on Electric Propulsion

The basic rocket equation indicate that higher is the specific impulse, higher will be the ratio between the final mass and the initial mass:

$$\frac{M_f}{M_i} = e^{-\frac{\Delta V}{V_e}}$$

M_i - the initial mass
M_f - the final mass
ΔV – velocity increment
V_e – propellant exhaust velocity

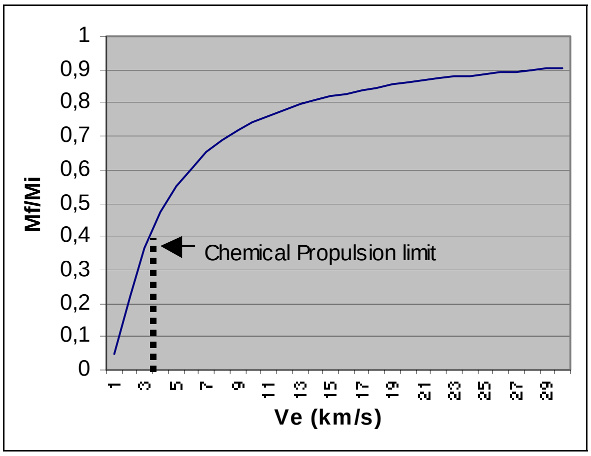


Fig. 1 – Fraction of final mass for ΔV= 3 km/s

When using an electric thruster, the power-plant mass is significant and has to be considered on the overall final mass. On Fig. 2, it is possible to see a simple schematic of the several contributions for the total mass of the spacecraft. No fuel is considered for the power-plant witch is true when using a system that converts solar radiation into electrical power.

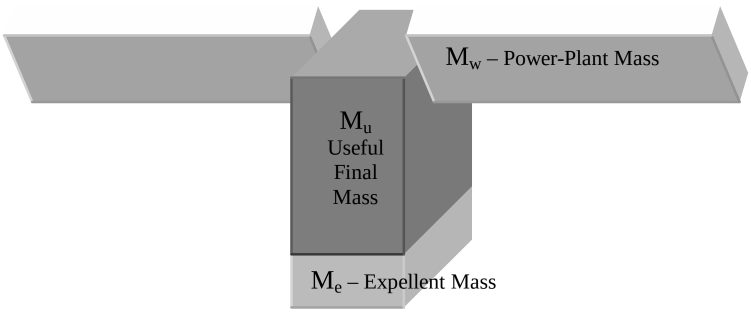


Fig. 2 - Schematic of the several contributions for the total mass of the spacecraft.

The total initial mass of the spacecraft is:

$M_s = M_u + M_e + M_w$

The power-plant mass depends strongly of the burn time T_b. If ones want a fast acceleration, more power is needed and then more mass . On the other hand, the sun energy can be used during more time. This means that a smaller power-plant can be used witch mean less mass. The equation that gives the ratio between the usable final mass and the initial mass is:

$$\frac{M_u}{M_s} = 1 - \frac{e^{\frac{\Delta V}{V_e}} - 1}{e^{\frac{\Delta V}{V_e}}} \left(1 + \frac{\alpha V_e^2}{2T_b} \right)$$

where α if the inverse specific power, the mass needed to produce one watt of power.

The Fig. 3 show the result of this equation for ΔV = 3km/s.

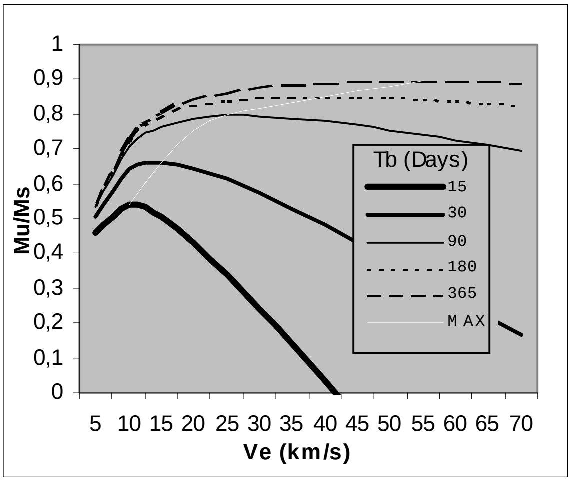


Fig. 3 – Fraction of final mass for ΔV= 3 km/s vs exhaust velocity.

Depending on the burn time, there is an optimal exhaust velocity. This will limit the maximum fraction of usable final mass. The white line indicates this value when time is changed. It is possible then to plot the optimal fraction of usable final mass versus the burn time (Fig. 4).

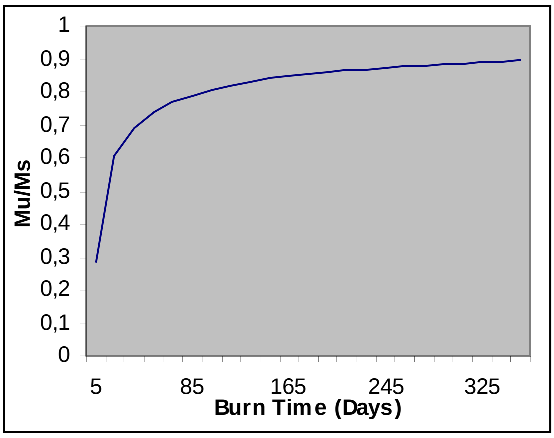


Fig. 4 – Fraction of final mass for ΔV= 3 km/s vs burn time.

Two options can be considered. The first one is to adapt the burn time to the power-plant mass needed for the mission. This means that the power-plant energy is used on a first phase to perform the orbit transfer and then, on a second phase, to supply the spacecraft for the mission objectives. The disadvantage is that the duration of the manoeuvre can reach several months.
The second option is to adapt the power-plant mass to the wished duration of the manoeuvre. The disadvantage is that after the orbit transfer, an excess of power is available witch means that initial mass and cost is higher than on the first option.
Spacecraft design try to meet a way between these two options but often the final design is close to the first option. For some missions, it is not possible to use electric propulsion because of the constrain on time.

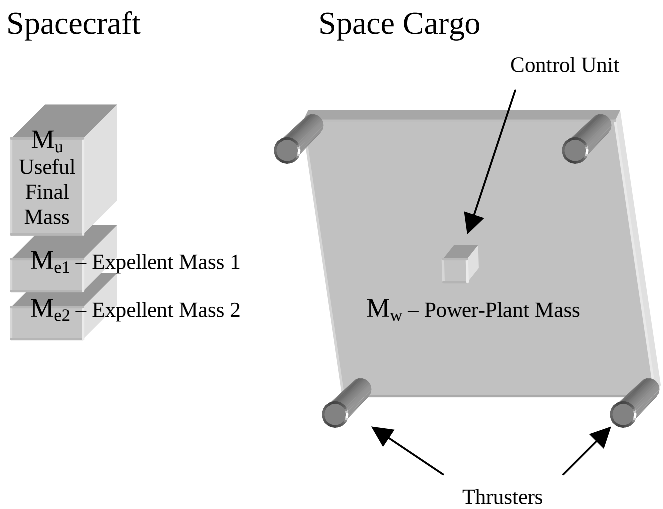
3. Reusable Space Cargo Concept

As it was seen, if one want to decrease the burn time, a waste of power-plant will arise. However, this “waste” could be used again for other spacecrafts. This means that they don’t need to carry on board the power-plant for the propulsion system. This is the main idea of the Space Cargo concept.
The Space Cargo consist not only on a reusable power-plant but on a whole space transportation system that it is used more than once. The subsystem that the customer spacecraft save are the following:

- power-plant
- electric thrusters
- attitude and orbit control system during transfer (including save on processor, sensor, software, etc)

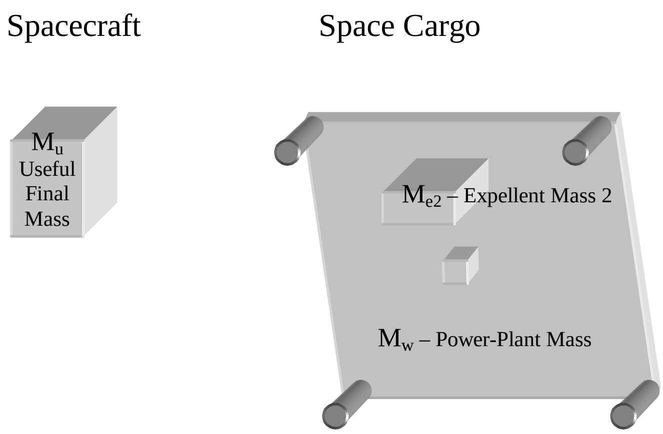
The only thing that the customer need to bring is the fuel for the transfer. Of course, because the Space Cargo need to come back to the original orbit, the fuel will be higher than for a normal electric propulsion transfer. However, because fuel becomes a small part of the total mass, the overall balance is positive. Just above, we present a schematic of the Space Cargo concept.

Phase 1: RENDEZ-VOUS



Phase 2: TRANSFER
(using fuel M_{e1})

Phase 3: UNDOCKING
(fuel M_{e1} consumed)



Phase 4: RETURN TO INITIAL ORBIT
(Using fuel M_{e2})

Phase 5: RENDEZ-VOUS
(with a new spacecraft that will supply more fuel)

Considering this mission architecture, the total initial spacecraft mass is:

$$M_s = M_u + M_{e1} + M_{e2}$$

Now, without the power-plant mass, the following equation arise:

$$\frac{M_u}{M_s} = 1 - \frac{\left(1 - e^{\frac{\Delta V}{V_e}}\right)\left(1 + \frac{\alpha V_e^2}{2T_b}\left(e^{\frac{\Delta V}{V_e}} - 1\right)\right)}{\left(\frac{\alpha V_e^2}{2T_b} - 1\right)e^{\frac{\Delta V}{V_e}} - \frac{\alpha V_e^2}{2T_b}}$$

If we compare this fraction mass with the one we get for a normal electric propulsion, we will have a net additional gain as presented on Fig. 5.

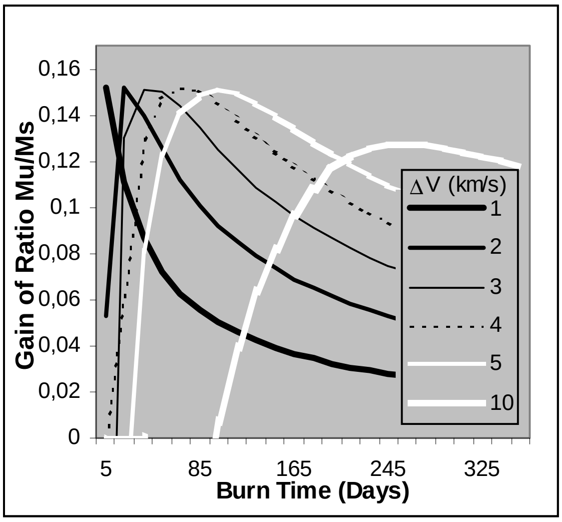


Fig. 5 – Additional gain on the fraction of usable final mass velocity.

For most ΔV, the maximum gain is around 15%. Here again, the time burn is an important factor. A zero gain on mass fraction will lead on time gain as showed on Fig. 6 by the white arrows. Significant save on time can be achieved without decreasing the final usable mass.

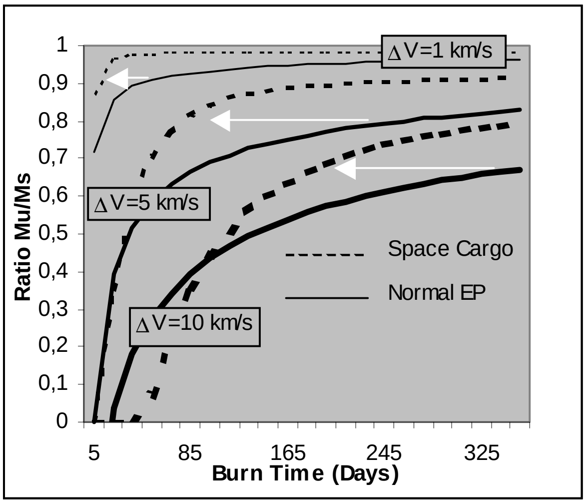


Fig. 6 – Space Cargo and Normal Electric Propulsion mass fraction versus burn time.

4. Mission Applications

The benefits of the Electrical Space Cargo may be applied to several kind of missions:

- LEO to GEO
- Inclination change
- GEO to LEO for repair / maintenance
- Deorbit
- Earth - Moon transfer
- Earth - Mars transfer

The use of the International Space Station for the maintenance or repair of the Electrical Space Cargo may be envisaged.

As an example we will study the transfer of a satellite from a LEO (300 km) orbit to a higher orbit (3 000 km). The satellite total mass is 1000 kg.

Chemical Propulsion

The necessary ΔV is around 1,2 km/s. This will lead 670 kg of usable final mass.

Electric Propulsion

If we constrain the burn time to 20 days, the optimal exhaust velocity is around 15 km/s and the final usable mass is 820 kg.

Electrical Space Cargo utilization

The orbit transfer has the same path however the optimal exhaust velocity is 60 km/s and the final usable mass is 950 kg.
But if one needs a fast manoeuvre without changing the mass fraction, the time burn can decrease to 5 days using an exhaust velocity of 15 km/s.

5. Conclusion

The Electric Space Cargo concept reveal to have several advantages for mass and time save. However, the main benefit is essentially economic. The customer may save complex design and material cost avoiding:

- deployable solar panels
- electric thurster
- attitude and navigation hardware/software specially developed for the manoeuvre

However some special improvements has to be made for the developpement and utilization of a Electric Space Cargo, mainly:

- Less degradation on materials (thruster, solar panels, processors)
- huge and ligth structures
- light rendez-vous devices

Further benefits will come if electric thrusters with variable specific impulse are developped. When the Space Cargo is coming to the orginal orbit (without the spacecraft), there’s no time constrain. This means that less fuel is necessary if the specific impulse may be raised.
On the other hand, transfer from LEO to GEO implies passing through the Van Allen Belt. If the specific impulse may be decreased during this phase of the transfer, less time will be needed and less radiation will come.
The Moon and Mars exploration will also need the use of a Electric Space Cargo

6. Bibliography

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