A Survey of Modern and Future Space Propulsion Methods

João Tiago da Silva Rodrigues Pinto

Instituto Superior Técnico, Universidade de Lisboa, Portugal

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Abstract

This thesis is the result of a survey of space propulsion methods, in the context of a fast manned mission to Mars. The capabilities of different technologies (chemical, non-chemical and advanced propulsion technologies) are explored to identify trends and evaluate their level of maturity. From the accessed literature, "rules of thumb" were found regarding the specific impulse and thrust-to-weight ratio of different propulsion technologies. Additionally, we compare both results and establish new "rules of thumb". To accomplish this, a database was made with data found in the "Web of Science" and in the NASA repository, A total of 249 space propulsion systems were identified, of which, 133 were chemicals, 90 non-chemicals and 23 advanced propulsion systems. With the information gathered in the database, 17 scatter plots were made. These plotted the specific impulse and the thrust-to-weight ratio as a function of different propulsion systems parameter of the different technologies. The results show that chemical propulsion is the more mature technology, however is limited to low specific impulse performances. Non-chemical propulsion offers improved performance over chemical systems, but the low maturity level of nuclear thermal propulsion systems and the low thrust-to-weight ratio of electrical propulsion. Advanced propulsion technologies are too far from present technological capabilities, the development of these systems would enable space missions scenarios unreachable with present technologies.

Keywords: Survey, Space Propulsion, Specific Impulse, Thrust-to-Weight Ratio

1. Introduction

A manned mission to Mars is one of the next major global objectives in space exploration. There are several new space propulsion technologies being developed promising improvements over the modern systems in use. In this work we make a survey on modern and future space propulsion methods, to evaluate their maturity and development trends to help accomplish a manned mission to Mars.

1.1. Impact of the Propulsion System on Vehicle Performance

There are several types of SPS. Most of them produce thrust T by ejecting propellants, stored in the vehicle. When combined and ignited they release enormous amounts of heat, the resulting thermodynamic energy from the expanded hot gas is then turned into kinetic energy using a convergent-divergent nozzle that accelerates the gas to supersonic velocities. By Newton's third law of motion, the hot exhaust leaving the nozzle with high speed applies an equal and opposite reaction to the vehicle, thus creating the accelerating force. Some Electric Propulsion (EP) systems, do not need to rely on the internal energy of chemical propellants, instead they use electric and/or magnetic fields to accelerate charged molecules or atoms, at very low densities, with the same effect [1]. Any vehicle that produces thrust by ejecting matter follows the same laws of momentum conservation. Assuming there are no external forces acting on the vehicle, the velocity for matter ejecting vehicles can be given as a function of the effective exhaust velocity c, the vehicle mass at ignition m_0 and its current mass m, as [1]

$$v = c \ln(m_0/m). \tag{1}$$

This is the Rocket Equation, as the vehicle expels propellant in one direction its velocity increases in the opposite. The more propellant expended, the greater the mass ratio m_0/m becomes and so does the vehicle velocity v. For a fixed amount of propellant expended, the vehicle velocity is directly proportional to the effective exhaust velocity c, defined as:

$$c = V_e - \frac{p_e - p_a}{\dot{m}} A_e. \tag{2}$$

The effective exhaust velocity is the important parameter of any mass ejection system, a higher number often indicates better engine overall performance. This parameter depends mainly on V_e, which is the velocity of the exhaust gas in relation to the vehicle. The second term of the equation includes the mass flow rate of the propellant $\dot{m}$, the effect of the ambient pressure p_a and the exhaust gas pressure p_e at the end of the nozzle with area A_e [2].

Optimal nozzle expansion is when $p_e = p_a$, as it happens when the vehicle is in vacuum and the exhaust gas is expanded to zero pressure. Assuming there are no external forces acting on the vehicle, the second term on the right of equation (2) equals zero and the effective exhaust velocity equals the exhaust velocity ($c = V_e$). In this conditions, if we start from zero velocity the final vehicle velocity depends only on how much of the vehicle is propellant and on the exhaust velocity. The vehicle can match it's own exhaust velocity if the mass ratio $m_0/m = e$ and even surpass it if the ratio is higher [1].

The effective exhaust velocity is usually stated as its equivalent, the specific impulse I_{sp}. This parameter is equal to the effective exhaust velocity divided by the standard Earth's surface acceleration of gravity g_0 ($I_{sp} = c \times g_0$), its unit "seconds" is the same in the imperial and metric systems. It can be treated as a measurement of the propellant efficiency, as it is the amount of momentum gained by the vehicle per sea level weight unit of propellant expended. A higher I_{sp} means smaller amounts of propellant needed to perform the same maneuver [3].

The total thrust force acting at the vehicle's center of mass T is given as:

$$F_{ext} + \dot{m}V_e - (p_e - p_a)A_e = T. \tag{3}$$

Here F_{ext} are the external forces acting on the vehicle. The second term is the *momentum thrust*, it's the product of the mass flow rate of propellant depleted with a velocity relative to the vehicle V_e, it is the biggest contributor to the vehicle's thrust. The third term is the *pressure thrust*, includes the effects of the atmosphere with pressure p_a and the pressure of the exhaust gas p_e. The thrust-to-weight ratio T/w gives the acceleration, in multiples of g_0, that the SPS is capable of giving to its own loaded propulsion system mass. For constant thrust, the acceleration of the vehicle increases as the propellant is burned and the vehicle mass decreases. Reaching its maximum right before the thrust termination. This parameter is useful in comparing different types of SPS and for identifying launch capability. A ratio above 1 is required to overcome Earth's gravity, otherwise the rocket will not lift [3].

1.2. SPS Types and Development

Each mission type can require very different types of propulsion systems to satisfy distinctive needs. Interplanetary manned missions need to be fast and safe to the crew, while robotic missions to the outer planets of the solar systems can endure continued low thrust for a long time in order to accelerate to the very high velocity required. In addition, along a given mission, the propulsion requirements can change dramatically, the lift-off requires a system which can provide a considerable amount of thrust in a very short time period, while station keeping requires small amounts of thrust over a long time period. As a result of this disparities there is no type of propulsion that will suit all mission classes or even all missions of the same type. It is therefore relevant to be able to differentiate and categorize the different types of SPS.

One important definition is of the Technology Readiness Level (TRL). It is a measurement system used to determine the technical maturity of instruments and spacecraft sub-systems. It is defined by ISO standard 16290 on a scale of 1 to 9, with TRL-1 being the lowest and TRL-9 the highest level of maturity [4].

As the needs of each mission vary according to the phase they are in, we will separate SPS in their three main basic functions, this way we can understand better the capability of any given type of SPS to perform each function. The main basic functions of SPS can be divided as:

- Lifting the launch rocket and its payload from the surface of the Earth and delivering the payload into Low Earth Orbit (LEO). Generally, thrust is the important parameter. A T/w above 1 is required to launch from Earth's surface.
- Transfer payloads from LEO into more energetic orbits, such as interplanetary or interstellar, and retro-action while approaching the moon or a planet. The need to accelerate to very high velocities using less propellant makes the specific impulse the important parameter. Depending on the mission the T/w ratio requirement changes drastically. Some missions require variable thrust and engine restart capability.
- Small maneuvers and reaction control, this includes station keeping, docking maneuvers and spacecraft orientation. The necessary thrust depends on the vehicle mass and speed needed to perform the action, usually can be done with a low T/w ratio. An high I_{sp} is beneficial to reduce the required propellant mass. Some maneuvers often need thousands of thrust pulses, restarting and stopping is essential for systems performing this functions.

There are several ways to differentiate SPS categories. Following the *2015 NASA Technology Roadmap - TA2* [5], in this work we will categorize SPS as: chemical propulsion, non-chemical propulsion and advanced propulsion technologies, each of them having its own subcategories. Chemical propulsion converts the internal energy of the propellants into kinetic energy. The combustion of the propellants increases the temperature and pressure of the product gases which are then expanded in a converging-diverging nozzle to supersonic velocities, generating thrust. Chemical propulsion is the more mature technology and can reach T/w ratios superior to 100, presently is the only viable option for first stage engines. On the other hand, chemical propulsion is the lowest performance technology with a I_{sp} limited to several hundreds of seconds. This is due to the energy in chemical propulsion coming solely from the chemical reaction of the propellants. The highest possible I_{sp} is achieved when using energetic chemical reactions with low mass exhaust products. Chemical propulsion can be further classified according to the physical state of the propellant: solid, liquid, hybrid (solid + liquid) and gel [6].

To achieve high performance the energy cannot be exclusive out of chemical reactions. Non-chemical propulsion systems are those that use electrostatic, electromagnetic, field interactions, fission reactions, photon interactions, or externally supplied energy to accelerate a spacecraft. These propulsive technologies offer improved performances over chemical propulsion, however, the T/w ratio is usually very small [2]. Non-chemical propulsion can be further grouped into the following categories: electric propulsion, solar and drag sail propulsion, thermal propulsion and tether propulsion [5].

Advanced Propulsion Technologies are all concepts that are at TRL 3 or below. The development and breakthrough of this technologies could enable new types of space missions, today unreachable even with unlimited costs. This is achieved either by increasing the performance, or reducing propellant needs by reducing dry mass or mission velocity. This group of technologies include any basic principle or concepts formulated which are simply beyond present technical capabilities. The concepts are: beamed energy, advanced fission, fusion reactors and electromagnetic drive [5].

1.3. A Survey on Space Propulsion Systems

The performance of today propulsion systems makes manned planetary missions prohibitively long. In this work we analyze the different existing and proposed technologies in SPS with the objective to understand how to circumvent constraints to perform a fast transfer to Mars. In order to achieve this, the core of this work is divided into two main parts: the first is the construction of the database of SPS, and the second one is the analyses of the database, where we identify the trends in propulsion development and the performance capabilities of different technologies. The gathered data will help deduce if it is possible, and in what conditions, for each technology to carry out a transfer to Mars.

2. A SPS Database

In this work we built a database to analyse the evolution trends and evaluate performance capabilities of different technologies. The database will also be used to verify typical values of SPS types identified in the literature.

3. Rules of Thumb

We can analyse the gathered data to compare the "Rules of Thumb" (RT) found in the literature and that are supposedly typical values for SPS.

3.1. Rules of Thumb for Specific Impulse

- **RT1 - Chemical Propulsion Systems** values of I_{sp} around 170-468 s, typical values for system at SL with P_1 =6895 kPa and exit pressure = ambient pressure [3].
- **RT1a** - Typical values for I_{sp} of solid propulsion 170-220 s [2] [1].
- **RT1b** - Chemical bipropellant systems typical operating I_{sp} is about 300-468 s [8], depending on the propellant combination. Reference [9] gives representative values of contemporary and advanced chemical systems with a chamber pressure p_c = 6895 kPa and a nozzle area ratio $A_e/A_t = 81$.
- **RT1b.1** - Systems using NTO/MMH as propellants have a $I_{sp} = 317$ s [9]. This appears as a representative for storable bipropellant SPS as the different combinations have very similar I_{sp} capabilities [10].
- **RT1b.2** - Systems using LOX/LH_2 have $I_{sp} =$ 423 s [9].
- **RT1b.3** - Systems using LOX/RP-1 have $I_{sp} = 358$ s [9].
- **RT1b.4** - Systems using a LOX/CH_4 have $I_{sp} = 330$ s [9] [2].
- **RT2 - Electric Propulsion Systems** I_{sp} can go from 300 s to 12 000 s, depending on the type of technology used [9].
- **RT2a** - Electrothermal system typically have specific impulses ranging from 300 s up to 1200 s, depending on the technology [8].
- **RT2a.1** - Resistojets have a I_{sp} level typically between 300-400 s with an electrical power input of 0.5-1 kW and a thruster efficiency of 65-90 % [8, 9] [3].

[1] In [7] says typical maximum I_{sp} for solid propulsion systems is 260 s.

[2] Reference [2] says current and conceptual propulsion systems using LOX/LH_2 have an I_{sp} = 455 s, while systems using LOX/LHC have an I_{sp} between 200-350 s.

[3] In [3] the typical I_{sp} is 200-350 s, this may be due to a smaller electrical power input.

- **RT2a.2** - Arcjets using hydrogen as propellant usually have I_{sp} about 900-1200 s, with typical power range in the 100 s of W [9], while systems using hydrazine have I_{sp} 500-600 s with electrical power input of 0.9-2.2 kW and 25-45 % thruster efficiency [8].
- **RT2b** - Electrostatic systems, or ion thrusters I_{sp} is frequently around 2500-3600 s, with electrical power input of 0.4-4.3 kW and a thruster efficiency from 40 % to 80 % [8] [4].
- **RT2c** - Electromagnetic systems can provide I_{sp} from 850 s to 12 000 s, depending on the technology employed [11].
- **RT2c.1** - Pulsed plasma thrusters have a I_{sp} between 850-1200 s, with the lowest electrical power input <200 kW, and lowest thruster efficiency 7-12 % [8] [5].
- **RT2c.2** - Hall effect thruster have a I_{sp} around 1500-2000 s, with a electrical power input level between 1.5-4.5 kW and thruster efficiency of 35-60 % [11].
- **RT2c.3** - Magnetoplasmadynamic thrusters are capable of delivering I_{sp} between 3000-12 000 s, depending on the electrical power input that can go from 100 kW to 1 MW [9] [6].
- **RT3 - Nuclear Thermal Propulsion System** using a nuclear solid core usually provide I_{sp} around 800-1000 s [9].
- **RT4 - Advanced Propulsion Systems** have the least amount of information, due to their theoretical nature and far reached technological developments needed.
- **RT4a** - Advanced fission SPS have I_{sp} around 2000-15 000 s [9].
- **RT4a.1** - Systems using a gas core have I_{sp} around 2000-7000 s [9].
- **RT4a.2** - Fission fragment propulsion are capable of providing a I_{sp} of 2000-5000 s [9].
- **RT4a.3** - External-pulsed plasma systems enjoy the highest I_{sp} of the advanced fission systems, are capable of 2500-15 000 s [9].
- **RT4b** - Fusion systems have I_{sp} that can go from 20 000 s to 10^6 s [9].

3.2. Rules of Thumb for Thrust-to-Weight Ratio

- **RT1 - Chemical Propulsion Systems** ratio of thrust force to the full propulsion system sea level weight up to 200 [3].
- **RT1a** - System using solid propellants have T/w ratio up to 200 [3].
- **RT1b** - Systems using liquid propellants have T/w capabilities limited to 200 [3].
- **RT2 - Electric Propulsion Systems** have T/w ratios usually between 10^{-6}-10^{-2} [3].
- **RT2a** - In the case of electrothermal systems the T/w ratio is usually comprehended between 10^{-4}-10^{-2} [3].
- **RT2a.1** - Resistojets T/w ratio is equal, usually about 10^{-4}-10^{-2} but can produce higher thrust levels of 200-1000 mN [3].
- **RT2a.2** - Arcjet have the lower thrust range between 200-300 mN and a T/w around 10^{-4}-10^{-2} [3].
- **RT2b** - Ion propulsion systems have low T/w ratio typically from 10^{-6} to 10^{-4} and a thrust range typically between 0.01 up to 500 mN [3] [7].
- **RT2c** - Electromagnetic systems have a T/w ratio that can go from 10^{-6} to 10^{-3} across all technologies, depending on the electrical power input [3, 11].
- **RT2c.1** - PPT systems usually have a small thrust range comprehended between 0.05-10 mN and a T/w ratio around 10^{-6} - 10^{-3} [3].
- **RT2c.2** - Current state-of-the-art HET have a thrust level usually of 10-50 mN and a T/w ratio capability of 10^{-6} - 10^{-3} [12].
- **RT2c.3** - MPD typical value of thrust level is 0.001-2000 mN with a T/w ratio usually from 10^{-6} up to 10^{-3} [12].
- **RT3 - Nuclear Thermal Propulsion** systems can reach T/w ratios up to 30 [11].
- **RT4 - Advanced Propulsion systems** - No information was found regarding the T/w of this type of systems.

4. Analyses and Results

4.1. Chemical Propulsion

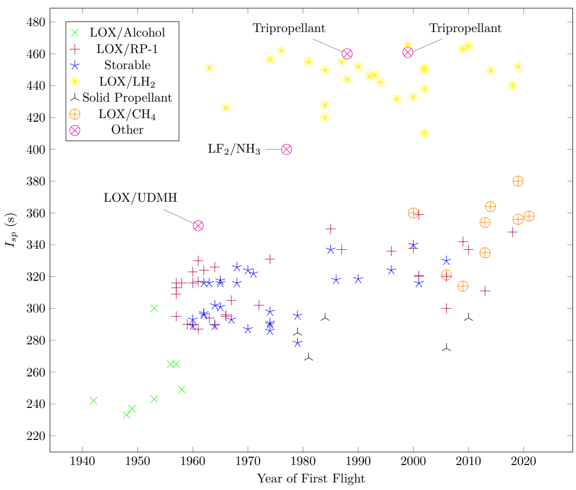

Figure 1: Vacuum I_{sp} plotted as a function of year of first flight, of chemical SPS

[4]In [3] the I_{sp} typical values are 1500-8000 s, while in [9] the given I_{sp} for this type of systems is 2000-10 000 s with electrical power inputs from W to 100 kW.

[5]In [3] the I_{sp} for PPT is around 600-2000 s, this may be due to lower electrical power input levels.

[6]Reference [3] gives more conservative typical values of I_{sp} around 2000-5000 s.

[7]In [11] the typical T/w ratio is around 10^{-5}-10^{-4}.

Figure 1 shows the vacuum I_{sp} for all chemical SPS in function of the year of the first flight. As expected by RT1b the highest I_{sp} of all chemical propulsion systems are achieved by SPS using LOX/LH_2 as propellants, with a specific impulse between 430-465 s.

Storable propellants SPS have values around 280 s to 340 s, when analysing only contemporary SPS the range of specific impulse decreases, with all systems providing I_{sp} between 310 s to 340 s. SPS using LOX/RP-1 have slightly higher specific impulse capabilities than those using storable propellants, with the I_{sp} of contemporary SPS around 300 s to 360 s. Solid propellant systems have specific impulse capabilities different than those given by RT1a. With the specific impulse around 260 s to 300 s. In the last twenty years, methane (CH_4) saw an increased interest as a possible solution for both manned and unmanned missions to Mars. With the I_{sp} values about 310 s to 380 s, can achieve higher performance than systems using storable or LOX/RP-1 as propellants. Even though it grants lower performance than LOX/LH_2, liquid methane is approximately six times more dense than liquid hydrogen, meaning the fuel tanks can be smaller. Figure 2 shows the influence of the chamber pressure p_c on the vacuum specific impulse of chemical SPS. Across all sub-types of chemical propulsion there is a positive weak relation between the increase of p_c and the I_{sp} provided by the SPS. Increasing the chamber pressure as a positive influence on the exhaust velocity and consequently on the specific impulse.

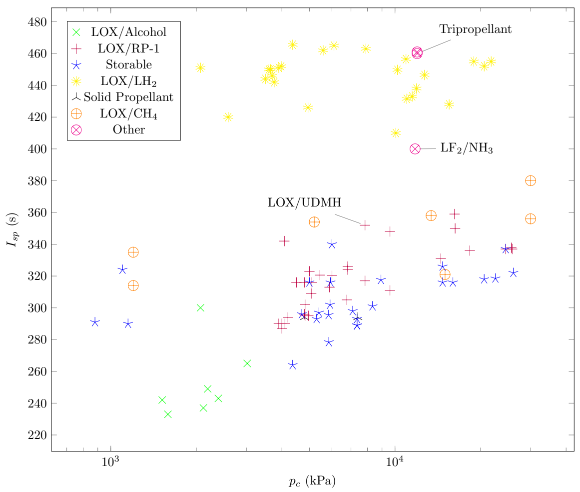

Figure 2: Vacuum I_{sp} plotted as a function of chamber pressure, of chemical SPS

Figure 3 shows chemical SPS vacuum specific impulse plotted against the nozzle area ratio. The plot contains all Chemical SPS with vacuum thrust and A_e/A_t. The nozzle area ratio has an impact on the exit pressure of the nozzle. The bigger the ratio, the more expanded the gas is in the nozzle, and the closer the exit nozzle pressure gets to 0. As expected across all types of chemical SPS, the I_{sp} increases with A_e/A_t.

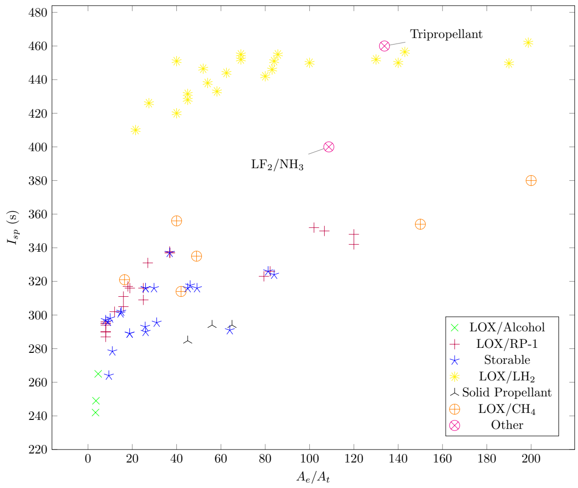

Figure 3: Vacuum I_{sp} plotted as a function of nozzle area ratio, of chemical SPS

From figures 1-3 the NRT relative to specific impulse of chemical propulsion systems can be extrapolated:

- **NRT1 - Chemical Propulsion Systems** values for vacuum I_{sp} of conceptual SPS are typically between 260-470 s.
- **NRT1a** - Solid propellant SPS have a vacuum I_{sp} around 260-300 s.
- **NRT1b** - Chemical bipropellant conceptual systems typical operating vacuum I_{sp} is about 300-470 s.
- **NRT1b.1** - Systems using a combination of storable propellants have a I_{sp} between 310-350 s.
- **NRT1b.2** - Systems using LOX/LH_2 have I_{sp} around 410-470 s.
- **NRT1b.3** - Systems using LOX/RP-1 have I_{sp} about 300-360 s.
- **NRT1b.4** - Systems using a LOX/CH_4 have I_{sp} among 310-380 s.

Figure 4 shows the vacuum I_{sp} plotted as a function of T/w. In all sub types of chemical propulsion, with the exception of systems using LOX/Alcohol as propellants, increasing the I_{sp} has a negative impact in the T/w. This is expected when optimizing a SPS trade between specific impulse and thrust-to-weight ratio must be done. This is demonstrated by plots 3 and 6, where we can see the opposite effect of increasing A_e/A_t. The development of I_{sp} results in a decrease of T/w. In figure 5, a strong correlation between T/w and p_c is identified. Again we see some outliners, these can be explained by the

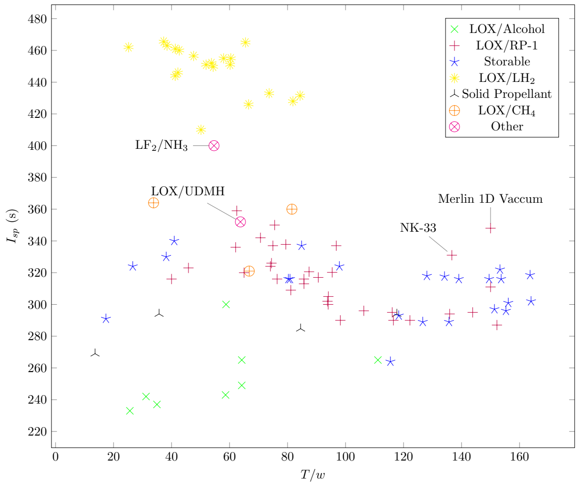

Figure 4: Vacuum I_{sp} plotted as a function of T/w, of chemical SPS

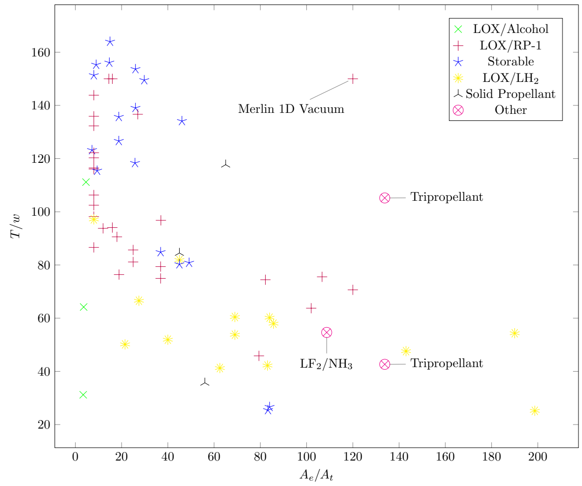

Figure 6: Vacuum T/w plotted as a function of nozzle area ratio, of chemical SPS

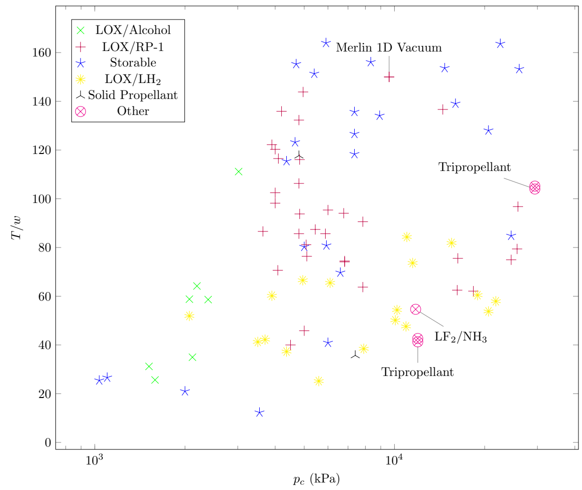

Figure 5: Vacuum T/w plotted as a function of chamber pressure, of chemical SPS

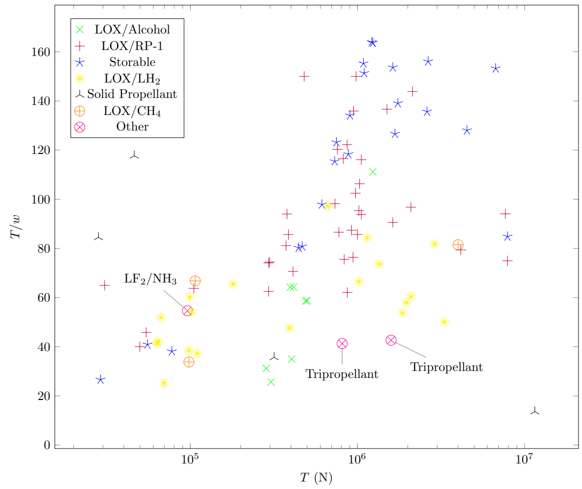

Figure 7: Vacuum T/w plotted as a function of thrust, of chemical SPS

purpose of the SPS, engines doing first stage usually are built with focus on development of thrust in determinant of specific impulse. Figure 6 shows the thrust-to-weight ratio of the SPS plotted as a function of the nozzle area ratio. Contrary to figure 3, where an increase in A_e/A_t helped the development of the specific impulse. The increase of the nozzle adds extra weight, this has a toll on the thrust-to-weight ratio. Excluding the propellant combination the area ratio is the parameter with biggest influence in the T/w. A big difference in values happens around $A_e/A_t = 40$. The majority of the SPS with $A_e/A_t < 40$ have a T/w between 70 and 160, while systems with $A_e/A_t > 40$ have a T/w between 20 and 70. Systems designed for low altitude operations have nozzle area ratio below 30, while systems for high altitudes have the ratio generally above 40. Figure 7 displays the T/w plotted as a function of the thrust it can produce. This can help understand how well the thrust-to-weight ratio of SPS scale with size. There is a weak link between the increase of thrust and the increase of T/w.

With the exception of solid motors, there is a clear step on what acceleration the SPS has. For thrust bellow 10^5 N, the T/w is limited to values below 70, while systems with an order of magnitude higher, 10^6 N, can reach a T/w of 160.

A new set of values of T/w can be deduced from figures 4-7 relative to the capabilities of different propellant combinations. The NRT relative to thrust-to-weight ratio of chemical propulsion systems are as follows:

- **NRT1 - Chemical Propulsion Systems** values for T/w vary from 20 up to 170.
- **NRT1a** - Solid propellant SPS have a T/w below 120.

- **NRT1b** - Chemical bipropellant systems have values for T/w up to 170.
- **NRT1b.1** - Systems using a combination of storable propellants have a T/w usually between 80-170.
- **NRT1b.2** - Systems using LOX/LH_2 have a T/w around 30-100.
- **NRT1b.3** - Systems using LOX/RP-1 have T/w about 60-150.
- **NRT1b.4** - Systems using a LOX/CH_4 have T/w among 30-80.

4.2. EP Analyses

Figures 8 and 10 display the vacuum I_{sp} as a function of the thruster efficiency, and electrical power input of the EP gathered in the database, respectively. Figure 8 displays the vacuum specific im-

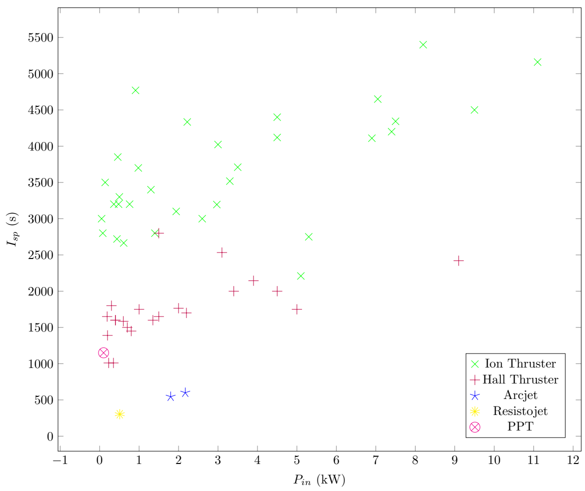

Figure 8: Vacuum I_{sp} plotted as a function of input power, of EP

pulse as a function of the P_{in}. The exhaust velocity, and by consequence the specific impulse, is a function of the square root of the electrical power input. The plot verifies the equation, across all subtypes of EP there is a positive non-linear correlation between the variables. Some outliners were expected, as the thruster efficiency and the mass flow rate of the propellant also impact the development of I_{sp}. Figure 9 gives the vacuum I_{sp} plotted in function of the thruster efficiency η.

The data displayed for ion thrusters seem to show more of a linear correlation between the variables in question, as for the rest of EP technologies not enough information was available. For a constant P_{in} the thrust and the specific impulse are inversely proportional. A possible explanation for the linear increase is that, increasing the I_{sp} passed 3000 s is less impactful than increasing the thrust. The displayed ion thrusters are mainly used for small maneuvers and reaction control. Figure 10 displays vacuum I_{sp} in function of the T/w ratio. Unlike

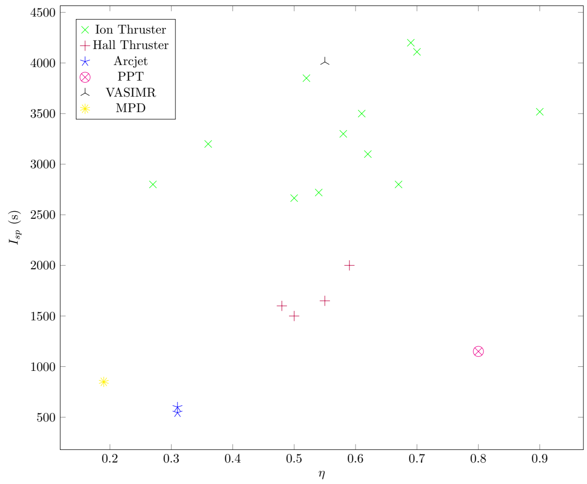

Figure 9: Vacuum I_{sp} plotted as a function of thruster efficiency, of EP

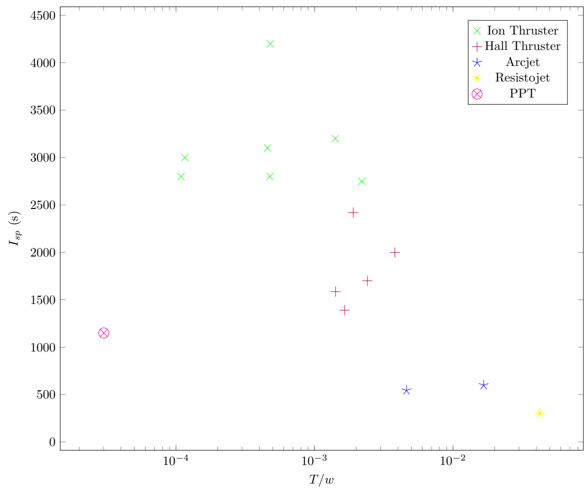

Figure 10: Vacuum I_{sp} plotted as a function of T/w, of EP

what we saw in figure 4, T/w does not seem to have an impact on the specific impulse inside one sub-type of EP, as different P_{in} and η have a major impact in both the I_{sp} a T/w. Electrothermal systems are the systems with lower I_{sp} but capable of achieving the highest T/w of EP, in the opposite side, ion thrusters have the highest I_{sp} capabilities of EP but the lower T/w.

From figures 8-10, the different I_{sp} capabilities and trends for EP technologies are presented. Both electrothermal systems, arcjet and resistojet, have the lower I_{sp}. Electrostatic or ion thrusters achieve the highest I_{sp} of all types of EP considered. Although this type of SPS has the capability of reaching values superior to 10 000 s (as is the case of the NASA Interstellar), most systems using this technology deliver between 2500 s and 5500 s of specific impulse. Electromagnetic thrusters have different capabilities depending on the technology used. Hall effect thrusters are the most discussed in the bibliography out of all types of electromagnetic thrusters, most HET have a level of I_{sp} comprehended between 1000-3000 s.

The big limitation of EP is the electrical power available in space and its weight. Therefore, if MW class powers are achieved, it would result in a significant improvement of I_{sp}. Also, if the specific power (or power-to-mass ratio) is increased the T/w capabilities of EP would also improve.

From figures 8-10 the NRT relative to specific impulse of EP can be extrapolated:

- **NRT2 - Electric Propulsion Systems** I_{sp} can go from 300 s to 14 000 s, depending on the type of technology used. [9].
- **NRT2a** - Electrothermal system typically have specific impulses ranging from 300 s up to 600 s, depending on the type of electrothermal system used.
- **NRT2a.1** - Resistojets have a I_{sp} level around 300 s.
- **NRT2a.2** - Arcjets have I_{sp} about 500-600 s.
- **NRT2b** - Electrostatic systems, or ion thrusters I_{sp} is often comprehended around 2500-4500 s, with electrical power input up to 10 kW and a thruster efficiency from 40 % to 70 %. When the P_{in} is scaled up to 30 kW these systems can reach values up to 14 000 s of specific impulse.
- **NRT2c** - Electromagnetic systems can provide I_{sp} from 1000 s to 4000 s, depending on the technology employed and the electrical power input.
- **NRT2c.1** - PPT have a I_{sp} around 1150 s.
- **NRT2c.2** - Hall effect thruster have a I_{sp} between 1000-3000 s, most systems with an electrical power input level up to 5 kW and thruster efficiency of 50-60 %.
- **NRT2c.3** - MPD thruster have a I_{sp} around 850 s at 150 kN power level.
- **NRT2c.4** - VASIMR have a I_{sp} around 4000 s.

Figure 11 gives the T/w of EP as a function of the electrical power input. There is a positive correlation between the plotted variables, increasing the P_{in} has a positive consequence to the T/w ratio. Some out-liners were expected, as for a constant P_{in} the specific impulse in inversely proportional to the T/w.

Figure 12 displays the T/w ratio as a function of η. The thruster efficiency is a measurement of how efficiently the electrical power and propellant are used in the production of thrust [3]. Although not enough data was found for the majority of the systems to confirm this, ion thrusters have a strong positive correlation, with the increase of the thruster efficiency there is an increase in T/w.

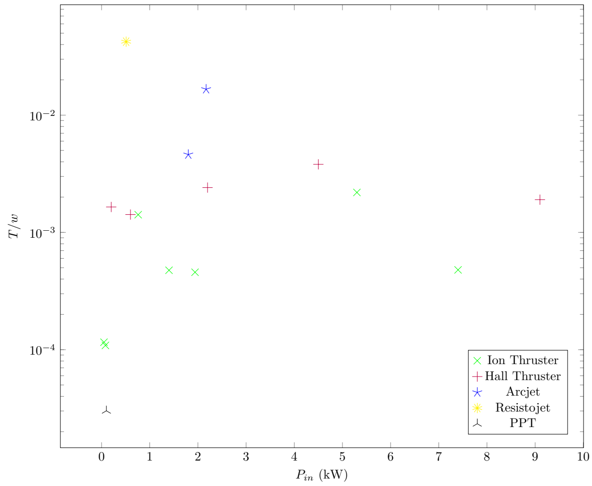

Figure 11: Vacuum T/w plotted as a function of input power, of EP

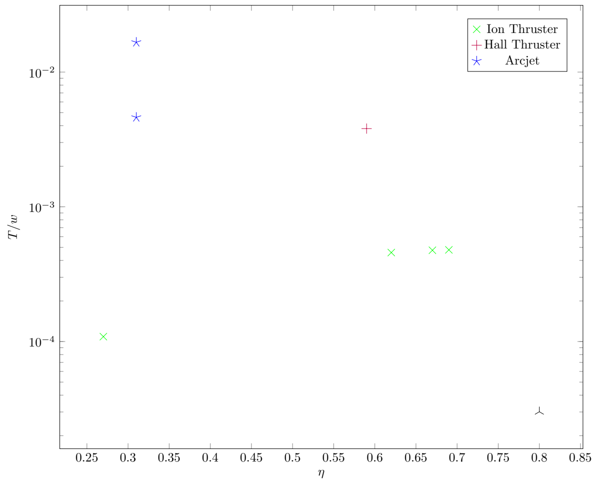

Figure 12: Vacuum T/w plotted as a function of thruster efficiency, of EP

From figures 11 and 12 the NRT relative to thrust-to-weight ratio of EP can be extrapolated:

- **NRT2 - Electric Propulsion Systems** T/w can go from 10^{-5} up to 10^{-1}, depending on the type of technology used.
- **NRT2a** - Electrothermal system typically have thrust-to-weight ratio ranging from 10^{-3} up to 10^{-1}, depending on the type of electrothermal system used.
- **NRT2a.1** - Resistojet have a T/w level around 5×10^{-1}.
- **NRT2a.2** - Arcjets have T/w comprehended between 10^{-2}-10^{-3}.
- **NRT2b** - Electrostatic systems, or ion thrusters T/w is comprehended around 10^{-4}-10^{-3}.
- **NRT2c** - Electromagnetic systems can provide

T/w from 10^{-5} to 10^{-3}, depending on the technology employed.

- **NRT2c.1** - PPT have a T/w around 3×10^{-5}.
- **NRT2c.2** - Hall effect thruster have a T/w between 10^{-3}-10^{-2}.

4.3. Nuclear Thermal Propulsion Analyses

Figure 13 displays the vacuum I_{sp} as a function of the T/w, of NTP systems. The I_{sp} across all systems are very similar, ranging from 700 and 1000 s. There is a big difference in the T/w capabilities of the systems. NTP are the only systems off all non-chemical technologies capable of delivering a thrust-to-weight ratio of the propulsion system above one. From figure 13 the NRT relative to thrust-to-weight

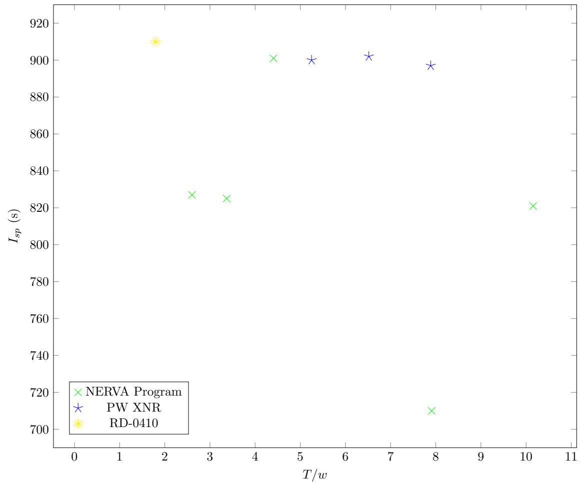

Figure 13: Vacuum I_{sp} plotted as a function of T/w, of NTP

ratio and the specific impulse of NTP can be extrapolated:

- **NRT3 - Nuclear Thermal Propulsion System** using a nuclear solid core usually provide I_{sp} around 700-1000 s and a T/w up to 30.

4.4. Advanced Propulsion System Analyses

Figure 14 displays the vacuum specific impulse as a function of the vacuum thrust, of advanced propulsion technologies. Data relative to the thrust-to-weight ratio is essential to understand the capabilities of these concepts, however it is difficult to identify relevant and accessible literature. There seems to be no correlation between the thrust and specific impulse across all technologies displayed in figure 14. The highest I_{sp} is achieved by the two different fusion reactor concepts, inertial confinement fusion (ICF) and magnetic confinement fusion (MCF). ICF systems specific impulse range between 10^4 s to 10^6 s, while MCF are around 10^6 s. This is two orders of magnitude greater than any EP system described in the accessed literature. Advanced

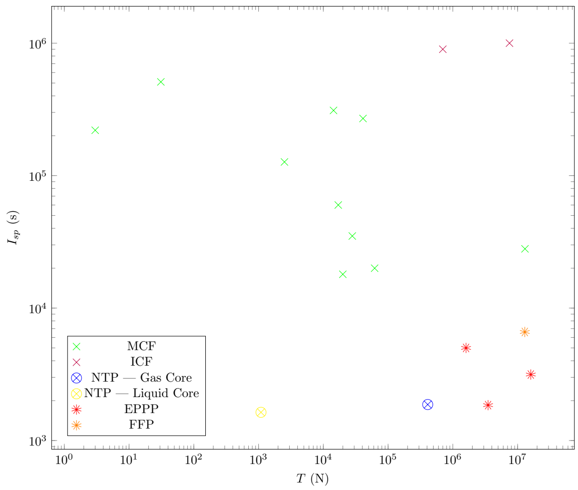

Figure 14: Vacuum I_{sp} plotted as a function of T, of Advanced Propulsion Systems

fission technologies have relatively lower I_{sp} capabilities, around 10^3 s to 10^4 s, comparable to the values obtained of electrostatic and electromagnetic systems.

From figure 14 the NRT relative to the specific impulse of advanced propulsion technologies can be extrapolated:

- **NRT4 - Advanced Propulsion Systems** vacuum I_{sp} ranges between 2000 s and 10^6 s.
- **NRT4a** - Advanced fission SPS have I_{sp} around 2000 s to 10^4 s.
- **NRT4a.1** - Systems using a gas core have I_{sp} around 2000 s.
- **NRT4a.2** - Fission fragment propulsion are capable of providing a I_{sp} of 6600 s.
- **NRT4a.3** - External-pulsed plasma systems are capable of providing I_{sp} between 10^3 s and 10^4 s.
- **NRT4a.4** - Systems using a liquid core have I_{sp} around 2000 s.
- **NRT4b** - Fusion systems have I_{sp} that can go from 10^4 s to 10^6 s.
- **NRT4b.1** - Magnetic confinement fusion concepts I_{sp} ranges from 10^4 s to 10^6 s.
- **NRT4b.2** - Inertial confinement fusion specific impulse is around 10^6 s.

5. Conclusions

We analysed the NRT relative to specific impulse of chemical propulsion, with the RT from the literature. Here, it was detected a discrepancy relative to solid propellant systems, where the values of NRT1a are larger than those of RT1a by a factor of 1.5. This discrepancy can be explained due to a lack of data relative to military application in the database. For the different types of liquid propellant combinations, RT1b.1-RT1b.4 give representative values of specific impulse for contemporary chemical systems, with a chamber pressure $p_c = 6895$ kPa and a nozzle area ratio $A_e/A_t = 81$. In figures 2 and 3 we plotted I_{sp} as a function of p_c and A_e/A_t, respectively. The identified range of values for all liquid propellant combinations of chemical propulsion systems, are in the spectrum given by the RT.

As for the T/w ratio of chemical propulsion, no RT were found relative to different propellant combinations. Sutton refers in [3, p. 39] the typical values for solid and liquid chemical propellant systems are $T/w < 200$. From figures 4-7 we identified NRT, relative to different propellant combinations of chemical SPS. Storable propellants have the highest T/w of chemical SPS gathered in the database, with $T/w < 170$. Systems using the propellant combination LOX/RP-1 achieve values of $T/w < 150$. As for LOX/CH_4 and LOX/LH_2 propellant combinations, both have similar capabilities, $T/w < 80$.

Electric propulsion has a lower maturity level compared to chemical propulsion. The identification of trends is harder in this type of SPS because there is a lack of information relative to the majority of EP technologies, with the exception of ion and hall effect thrusters. This was most impactful on the evaluation of the T/w ratio. Also, the I_{sp} and T/w performance depends on the electrical power input available P_{in}. The values identified in NRT2 are relative to power levels up to a few tens of kW, with the progressive increase of the available electrical power levels in space, the maximum values of the EP are bound to increase.

Nuclear Thermal Propulsion (NTP), is a technology with a lower maturity level (TRL ≤ 6) in comparison to Chemical Propulsion and some types of Electrical Propulsion (ion and hall effect thrusters). The values identified in NRT3 are very similar to the values of RT3. The analysed systems have a specific impulse between 700 s and 1000 s with a $T/w < 30$. The performance of this technology surpasses chemical propulsion capabilities, but since it never had the same amount of investment (as a result of the dangers associated with using nuclear fuels), its capabilities were never utilized. If this technology reaches the level of maturity and security of chemical propulsion, it's expected to be a viable alternative to chemical propulsion [13].

Regarding Advanced Propulsion Technologies, the extrapolated NRT4 values are theoretical, as are the RT4 identified in literature. These values have to be thought as expected values, since these technologies development and maturity are very low (TRL < 3). As a result, it is difficult to analyse them. However, we can recognize that a development in one of these concepts, and if the theoretical values become a reality, would enable missions that, with the today's existing technical capabilities, are unreachable.

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