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Assessment of Propulsion System Architectures for Green Propellants-based Orbital Stages

Alberto Sarritzu*[a], Felix Lauck[b], Lukas Werling[b], Angelo Pasini[a]

[a] *Department of Civil and Industrial Engineering, University of Pisa, Pisa, Italy*
[b] *Institute of Space Propulsion, German Aerospace Center (DLR), Lampoldshausen, Germany*

* Corresponding Author, alberto.sarritzu@ing.unipi.it

Abstract

Green Propulsion is a recurring trend in the space sector that has grown exponentially over the last decades. The researchers' shared goal is to find good alternatives to current liquid propellants, usually toxic and hard-to-manage during ground operations. The current toxic leading compounds are Hydrazine and its derivatives that covered and still cover a key role in the space propulsion arena: as a matter of fact, despite the well-known complications for incompatibilities with human health, and despite the dozens of proposed replacements, the propellants still have some advantages over many of the suggested alternatives and are commonly used. The main and natural application of green technologies is doubtlessly the in-space propulsion since the main features of long-term storability, stability and acceptable performance are a perfect match for engines working outside the atmosphere and far from the support of ground operations.

In this study, the identified most attractive technologies are evaluated on their applicability to upper stages. A specific class of systems, often referred to as kick-stages, are taken as reference. These systems are designed, as usually, to remain as light as possible to carry more payload, but concomitantly to be able to fulfil a very diverse type of missions. Between others: active space debris removal, multi-payload to multi-orbit delivery, in-orbit experiments with a few providers planning also the reusability and return to the ground. With such diverse and arduous purposes, it is clear that, in terms of propulsive system requirements, the challenges are many. The analysis expands on utilization of green technologies for these systems, outlining advantages and disadvantages in comparison with current concepts.

Particular focus is dedicated to the attainable performance with respect to required dry mass. In particular, it is analysed the different inert mass rate of various architectures considering also full-green-propellants-based designs that can offer synergies and advantages respect to classical ones.

Keywords: Green Propulsion, Hydrogen Peroxide, Upper Stage, Orbital Stage, Kick-Stage

Acronyms/Abbreviations

ACS – Attitude Control System, synonym of RCS
ECHA – European Chemical Agency
EIL – Energetic Ionic Liquid
GHS – Global Harmonized System
HTP – High Grade Hydrogen Peroxide
I_{sp} – Specific Impulse
I_{ssp} – System Specific Impulse
MMH – Monomethyl Hydrazine
NTO – Nitrogen Tetroxide
RCS – Reaction Control System
TRL – Technology Readiness Level
UDMH – Unsymmetrical Monomethyl Hydrazine

1. Introduction

The past few decades have seen a steep increase of space-related businesses and enterprises. The "new space" excitement fuelled the rise of dozens of businesses investing significant amount of money in the sector, even without a secure predicted economical return. The soaring enthusiasm toward space ventures benefits research and new developments, in a virtuous circle that is boosting the sector economy. As a matter of fact, the attempts of creating sustainable businesses based on access to space are many, and the number is still rising [1, 2].

In parallel with the renovated space sector excitement, it is important, however, to recognize existing issues. Space sustainability is a raising and important branch of research that deals with the sector issues connected to a possible misuse of existing technologies. The increasing awareness toward the issues is the first step to find a solution. The environmental impact of launchers [3], space debris mitigation [4], and the utilization of dangerous material such as toxic propellants [5] are between the most urgent matters to solve. The present study especially focuses on the last, but not least, issue: toxic propellants. Currently used compounds for in-space propulsion are well-known to be dangerous for human health and environment. While many alternatives are studied from decades, only a few technologies have reached orbit.

Section 2 quickly introduces the issue of toxic propellant and the state of the art of "green" technologies.

With the described space sector expansion, businesses are experiencing a parallel increment of the customer base, usually historically limited to national programmes. New customers are often viewed as new opportunities to develop novel capabilities and related services for both ground and in-space operations.

In this framework, many enterprises around the world are studying how to improve their customer services, especially the ones that can be provided in space. A class of upper stages, often referred to as kick-stages or orbital stages, is one of the proposed solutions to deal with current and arising trends and challenges in the sector. Section 3 explores this class of devices, chosen as reference systems for the study, exploring the possible business scenarios as well as the challenges that the development of such system faces.

Section 4 describes the possible propulsion system design alternatives for the reference system. It is shown how systems entirely based on green propellants may offer synergies and possible advantages respect to current state of the art toxic ones, but also shows how rarely tried concepts such as multi-mode propulsion systems are a perfect match to some green technologies.

Sections 5 analyses and compares the possible architectures, studying differences, advantages and disadvantages. The study shows how, especially at the beginning of the design, only looking at the propellant performances may not be significative enough to outline the real convenience of a system respect to another.

2. Past and Present Propellants: Green Propulsion

The propulsion system and its performances are doubtlessly at the base of any space mission success. The foundation of propulsion, especially for the chemical liquid branch, lay on the compounds that, releasing the chemical energy through reactions, create a high energy flow that correctly ejected generates thrust.

Since the onset of the space sector the research of the most suitable propellants and their combinations has been one of the most researched topics. Between the dozens of characteristics that a perfect candidate must have, two of the most valued features that are looked for in the perfect compounds are doubtlessly good storability and hypergolicity. These characteristics are key for any system to be capable to work in any situation with the least preparation procedures and especially able to work in the space environment.

Hypergolicity, defined as the property of a propellant combination to spontaneously ignite when in contact, has been deeply studied and hundreds of combinations have been tested experimentally to measure their capacity to ignite and their response time.

Around the 60's, hydrazine first and later its derivatives Unsymmetrical dimethylhydrazine (UDMH) and Monomethyl hydrazine (MMH) asserted their positions as lead candidates for their good storability and especially strong hypergolic performances when coupled with Nitrous Tetroxide as oxidizer. For applications that cannot involve cryogenic propellants such as in-space propulsion, Hydrazine and its derivatives have been, since then, the most utilized compounds.

Additional boost to Hydrazine utilization has been the development of the Shell 405 catalyst, capable to decompose the pure compound exothermically, making it a more than suitable match for monopropellant thrusters.

At the current state of the art, Hydrazines have been the leading propellants for more than 60 years and would probably remain in the podium if it was not for their mild toxicity, and their dangerous characteristics to human health and environment. The commonly coupled oxidizer, Nitrous Tetroxide (N_2O_4 or NTO), shows even more dangerous properties, being extremely toxic and particularly incompatible with humans and animal life.

Table 1 reports the risks posed by the utilization of the current leading compounds according to the labels by the Global Harmonized System (GHS) and the European Chemical Agency (ECHA, [6]).

Hydrazine	**MMH**	**UDMH**	**NTO**
Category 3	Category 2	Category 2	Category 1

Category 1	Substances with high acute toxicity. Fatal if swallowed, in contact with skin or inhaled, even at the lowest doses.
Category 2	Substances with high acute toxicity. Fatal if swallowed, in contact with skin or inhaled, at mild exposure.
Category 3	Substances with mild acute toxicity. Toxic if swallowed, in contact with skin or inhaled.
Category 4	Substances with mild acute toxicity. Harmful if swallowed, in contact with skin or inhaled.
Category 5	Substances with relatively low acute toxicity but which, under certain circumstances, may nevertheless pose a hazard to vulnerable populations

Table 1 - Hydrazines Risks according to the GHS and ECHA [7, 8]

Managing such toxic compounds is difficult and expensive in terms of both money and time, requiring particular care to be moved and loaded into their final tanks. The propellant loading procedure must happen, for security reasons, as one of the final integration steps. If toxic and dangerous propellants are involved, the procedures are complicated and long, necessitating of dedicated trained teams and the use of invasive protective equipment such as the Hazmat Suites shown in Figure 1.

Figure 1 - Fuelling procedure requiring Hazmat suites for Messenger mission - credit NASA, public domain

For clear reasons, finding good replacements for Hydrazines is, now from decades, a goal that many research centres, companies and other entities around the world have embraced. Such replacements are usually referred to as “Green Propellants”.

2.1 Green Propellants

Despite the incredible amount of research on the topic, there is still not a clear and shared definition of the “Greenness” of a new compound to be included in the green propellants’ family. Currently, in Europe Hydrazines are enlisted in the list of concerning substances by the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation [9], with the implicit meaning that they may be banned for use in the coming years, despite the almost unanimous requests for exceptions from European national Space Agencies and industries [10].
Research considers “green” almost any compound that can be seen as a potential substitute of hydrazine, with investigations in the past years focusing on three main pillars:

- Performance
- Storability
- Health & Safety

Some candidate compounds excel in one or more fields, but still only a very few have reached a technology maturity high enough to become a proper option for satellite operators.

2.1.1 Green Propulsion technologies

As mentioned, it is possible finding in literature a multitude of studies on green propellants. The research is often funded by Space Agencies that, recognizing in the problem the opportunity of new developments, have nudged and boosted the progress of new compounds.
Businesses, on their side, have benefited of the money given from Space Agencies to develop their own products, but nonetheless only a few of them have reached a TRL above 4-5, and often only thanks to National Agencies efforts.

Being the research very variegate, the number of technologies developed is long.
The selection of the most promising technologies to develop and integrate in future systems is, by itself, a hard task. The technologies maturity level is only partially public, and it is difficult discerning the best option without having a clear and broad point of view.
A selection of the most promising technologies, reported with their estimated maturity level and performances, is shown in Table 2 for Monopropellant systems and in Table 3 for Bipropellant systems [11, 12]. The TRL is always a very subjective measure to the real advancement of a technology. While the propellants characteristics may be fixed and with very high TRL, the related system could still be at very early stages, encountering for instance issues still to be solved, such as stable ignition or combustion temperature.

Propellant	**TRL**	**I_{sp}**
Hydrazine	High	239 s
AF-M315E	High	266 s
SHP-163	High	276 s
HNP225	High	213 s
FLP-106	Med-High	254 s
LMP-103s	High	252 s
H_2O_2 monopropellant 98% (HTP)	Med-High	170 s
Nitrous Oxide/Hydrocarbon monopropellant blends	Low-Med	300 s
Gel Propulsion	Low	200-300 s
Nitrous Oxide monopropellant	Med	<180s

Table 2 - Promising Monopropellant Technologies Properties – The TRL is delicate to evaluate

Propellant Couples	**TRL**	**I_{sp}**
MMH/NTO	High	330 s
Kerosene + H_2O_2	Med-High	315 s
Ethanol + H_2O_2	Med-High	305 s
Self-pressurizing Hydrocarbon + N_2O	Med	>280 s
Energetic Ionic Liquid + H_2O_2	Low-Med	315 s
Gelled Propellants + H_2O_2	Low	>300 s

Table 3 - Promising Bipropellant Technologies Properties – The TRL is delicate to evaluate

Considering only the maturity level or only the performances in the selection process is essentially wrong and could lead to problematic results. A generic selection process is complex and should consider the many parameters involved, including features such as Health and Safety, Availability and Cost Reduction of new and past compounds. Furthermore, the selection criteria and especially the performances may be measured using different parameters, changing dramatically the appeal of different technologies. This fact is very often utilized by companies or researchers to boost their products. Different studies [11, 13] propose fully requirements-based approach to analyse the different candidates utilizing a multi-level criteria selection. Such methods can reveal to be very useful to select the best alternative despite being time and effort-requiring, especially during the early phases of design.

Generically speaking, the current most promising technologies for monopropellant usage are doubtlessly Energetic Ionic Liquids (EILs). This class of compounds can be tailored to different characteristics, and some of the formulations have already been or are being demonstrated in space missions by America (AF-M315E, now called ASCENT), Europe (ADN compounds) and Japan (SHP and HP series). The other compounds show either low technology readiness level or low performance, especially the "pure" substances such as Nitrous Oxide and Hydrogen Peroxide.

There is, however, a specific feature of the latter mentioned "pure" compounds that completely change their attractiveness: they are also oxidizers considered "green" for bipropellant systems. Hydrogen Peroxide is the only non-toxic and non-cryogenic oxidizer at ambient conditions with modest performances, and during the selection process of the most suitable alternative, this is a very important characteristic to consider. It is to be noticed also that the long term storage (years) of Hydrogen Peroxide presents challenges for its decomposition characteristics.

As regarding bipropellant technologies, the current research focuses on two main technologies: High Grade Hydrogen Peroxide coupled with a suitable fuel and the so-called self-pressurising systems.

There are many companies around the world developing and testing engines based on the coupling between various hydrocarbons and HTP, but in this study it is put emphasis on the advantages of new technologies, in particular the use of Energetic Ionic Liquids in bipropellant mode. The reference utilized in this analysis is the Energetic Ionic Liquid called HIP_11, currently developed by the German Aerospace Centre (DLR Lampoldshausen) [14, 15, 16]. The motivations behind the choice are the fuel characteristics and its innovation, better described in Section 4.1.3.

The second promising candidate for bipropellant systems is the self-pressurising technology. It is based on the coupling between compounds with very high vapour pressure, that hence do not require a separate pressurizing system. Example of these compounds are Ethane or Ethylene or Propene as fuels and Nitrous Oxide as Oxidizer. Such compounds are studied by years, both in bipropellant mode and monopropellant mode as pre-mixed blends. The reference example of these technology used in the present analysis is HyNox, also in development at the German Aerospace Centre (DLR Lampoldshausen) [17, 18, 19]. Such compounds are promising and challenging, having to solve issues such as bi-phase injection, external ignition and high combustion temperature, but are nonetheless leading candidates for future systems. Its promised compactness is doubtlessly one of the major advantages for future use in Orbital Stages, more characteristics are described in Section 4.1.3.

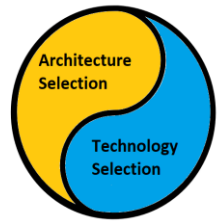


Figure 2 - Architecture and Technologies selection should be part of the same analysis

In the following sections it will be analysed how the technology selection can be strongly influenced by the chosen architecture of the system. It is recognized how some candidate technologies can offer synergies if applied to specific architectures that may result in overall better performances compared to other, at first look better, options. The analysis focuses on the puzzle of choosing the best technology for a defined architecture or fixing the best technology and build the architecture by consequence. The dilemma remains one of the major trade-offs to complete at the early phases of any study.

3. Reference system: The raise of kick-stages

The focus of the study is the assessment of different technologies and architectures for a specific class of upper stages, generically referred to as kick-stages.

The definition of "upper stage" is very broad and can include second stages as well as interplanetary transfer stages. The current analysis uses a specific class of devices as reference system, currently being developed by many entities around the world. The analysed class answers to different names, the most utilized are kick-stages, orbital transfer stages or tug stages, and the first name of the list is used in this paper to refer to such devices.

The basic idea and purpose of the selected systems is to extend current launcher capabilities, introducing features such as multi-orbit precise delivery, docking, multi payload delivery and more in general to deal with the arising challenges of on-orbit servicing. In general, such systems' goal is to walk the extra mile performing

the tasks that until now are deemed impossible or are directly subsidized to the payload.
The motive behind the origin of such systems is directly related with current and future trends in the space sector. The many ventures entering the sector see the current challenges as opportunities, and what now seems hard to accomplish, may soon become reality. In particular, the "space services" portfolio, expected to grow in the next few years, includes very diverse missions such as multi-payloads to multi-orbits delivery, in-space logistic, on-orbit servicing and refuelling, active space debris removal and constellations deployment.

3.1 Access to space

Access to space is often reduced to the mere initial Earth-to-Orbit phase. The initial stages are certainly the most critical, and for clear reasons in the past decades a great amount of research has been spent to increase the technologies capabilities. It is, however, only a part of the story. Once in space, payloads must be placed in their selected working orbit, task not trivial and that depends on a multitude of factors.
Generically speaking, what is commonly referred to as Access to Space can be split into two strongly interconnected phases:

- Access to space
- Orbit Insertion

For payload owners, the first phase is solved finding a way to reach space through one of the launchers available in the market. If the payload is big enough, the best option for a generic customer could be to book an entire launch, selecting the best launcher depending on the required capabilities. The option is out of reach for many operators for economical and logistic reasons. The widespread common practice is a shared launch, in order to divide the costs and risks with other customers.
Another often utilized custom is the practice called *piggy backing*. The practice consists into a hitchhiker-style passage to space, usually utilized by small payloads to exploit the available volume and mass left by bigger payloads in the fairings, benefitting a possibly cheaper ride at the expense of the delivery to a generic orbit.

The described scenarios implicitly require the satellites and payloads to have an active propulsion system on board capable to perform one or more manoeuvres to arrive to their destination orbit and overcome the second challenge: Orbit Insertion.

While current launchers technologies normalized the first phase, creating a market where it is "easy" accessing space, the capabilities of upper stages in the last few years only marginally improved the Orbit Injection phase. The services of precise multi-payloads or multi-orbits deliveries are very seldomly guaranteed unless under specific conditions, and never together.

It is common for upper stage technologies to offer passages to Low Earth Orbits (LEO) or generic insertions into what are called transfer orbits for higher orbits destinations. The common practice is justified by both economic and technological motivations.

- The vast majority of payloads are inserted in LEO, and only a very few payloads every year travel further to higher orbits or interplanetary missions. It is sensible, hence, optimizing technologies for the most requested and especially rewarding operations.
- Technology-wise, reaching Geostationary Orbits (GEO), Geosynchronous Orbits (GSO), Medium Earth Orbits (MEO) or Interplanetary orbits, requires multiple firings of the propulsion system separated by long hours of coasting, complex orbital adjustments, and a very long overall mission duration.
  Upper stage engines are often based on the design of the main stage engines optimized for vacuum use and hence are, almost always, based on cryogenic propellants, equipped with turbopumps and designed to be ignited only once or maximum a few times, and always during short mission duration.

There is a clear trend between launch providers and companies to move towards a more flexible range of offered services in space.
The strategies followed range from the enhancement of existing upper stages, making them more versatile and able to fulfil a more diverse number of missions, to the addition of a further stage to the launcher to accomplish more ambitious goals. The last stage is the so-called kick-stage, and it can be provided by the same launching company or by other ventures, with the common promise of performing missions otherwise impossible.
Table 4 shows the companies that are developing, or have already developed, devices with similar purposes to the above described. The table does not make distinction between chemical-based or electric-based propulsion, nor between the target orbits.

Company	**Device name**	**Location**
Avio	Space Rider [20]	EU
Ariane Group	Astris & Lunanova [21]	EU
Rocket Factory	Orbital Stage [22]	EU
Exolaunch	Reliant [23]	EU
The Exploration Company	Nyx [24]	EU
Skyrora	Space Tug [25]	UK
Rocket Lab	Kick Stage [26]	NZ – US
MOOG	SL-OMV [27]	US
Andrew Space	Sherpa Tug [28]	US

Launcher	Orbiter [29]	US
Momentus Space	Vigoride [30]	US
Northrop Grumman	MEV [31]	US
Impulse Space	Impulse Space [32]	US
Starfish Space	Otter [33]	US
Astroscale	ELSA [34]	Japan

Table 4 – Devices developed or in development around the world to deal with on-orbit servicing

It is reasonable expecting more venture pursuing the same or similar objectives if their business will reveal to be sustainable and rewarding, especially with the raising number of micro launchers and customer base in the market. The following sections enter more in detail on the possible economical motivations and technical challenges behind such devices, taking as example the delivery of a few satellites to GEO.

3.2 On-Orbit Servicing

It comes naturally that a device capable of pursuing missions such as delivery of multi payloads to far orbits would also have the capacity to achieve many and diverse tasks, especially the ones connected with the generic name of On-Orbit Servicing.
The sector is predicted to skyrocket in the next few years, with billions of investments almost by any sector. The kick-stage can, doubtlessly, be considered an enabler for this kind of services.
There are many proposals to use such devices in many ways, such as On-Orbit repairs and maintenance, refuelling, orbiting tanks, astronauts support and others *in situ* operations [35].
It is not discussed here the viability and sustainability of the offered services, but it is undeniable that the trend of the sector is promising and there will be new developments in the next few years.

3.3 Kick-Stage Possible Business Scenario analysis – Pre-life services

The following section describes a possible utilization of the kick-stage: the multi-payload delivery to far orbits such as GEO, MEO or Lagrangian points orbits, starting from the businesses needs and evolving on the strategies. It is described a pre-operation service, but it will be clear to the reader its applicability to post-operation services such as re-fuelling or decommissioning.

Miniaturization of technologies is doubtlessly one of the most relevant drivers of the huge space sector expansion of the last few decades. It is very common seeing pictures showing the increase in number of objects in orbit, especially in LEO. Mega Constellations of thousands of satellites, deployed at dozens per launch are saturating the market and space of low orbits. It is a matter of time when ventures will start looking at further orbits, currently less utilized because expensive and difficult to reach.
MEO, GEO and HEO (Medium, Geostationary and Heliocentric) orbits, being harder to reach, have been until now a privilege of governments, telecommunication and television companies with high budgets. Revenues from the telecommunication satellites account for billions of dollars, but the rate of payloads to GEO remains small. One of the motivations is the extreme complexity of the spacecrafts with these destinations and the intrinsically connected cost.
Satellites directed to these orbits are carefully built and tested for long periods, requiring many expensive extra checks. Their high cost is justified only by the long duration of their missions, with an estimated operation time spanning from a few years to slightly more than a decade.
The main reason of the satellites' end of operations is not, however, some type of malfunctioning or their becoming too old to work, but instead *they stop operating because they run out of propellant*, crucial to remain in orbit with the correct orientation. GEO satellites do not necessitate of big amounts of propellant during operations, being their only manoeuvres some corrections in attitude and orbit, but any drop of it is, nonetheless, very valuable for the operating company. The return of investment for the companies is strongly correlated with the length of such systems operativity, and hence to the propulsion system.
The volume and mass of propellant that such satellites can bring in orbit is very limited; the contributing factors are many, but the most important is the physical volume and mass allowed by the launcher capabilities. The satellites are already very heavy and loaded with big amount of propellant, but they utilize the great majority of it to enter the operating orbit, and only a smaller portion to maintain the position.

The generic tasks of a satellite propulsion system can be summarized as orbit injection and attitude control or station keeping. The former represents the obvious first step for the beginning of operations, while the latter is a necessary effort for the correct system activities.
Currently, the orbit injection alone requires several tons of propellants.
Big satellites in far orbits are, for this reason, quickly switching from chemical to electric propulsion, in order to reduce the big masses required by chemical rockets and their propellants. The use of electric propulsion is appealing because the thrusters allow an extremely efficient use of the propellant, reducing the required mass and volume. The advantages come, however, with a price to pay. Firstly, the thrusters require more electrical power than the usual budget to operate, hence additional payload. Secondly, electric thrusters generate low thrust levels and need a long time before they can insert the

spacecraft in their final destination. For instance, the usual time to arrive to a GEO stable orbit from a GTO using only electric propulsion is around 4 months. This time, for a telecommunication satellite, is a delay in the start of operations, time that if spent in orbit could start generating revenue.

The kick-stage, as a system, promise to relieve the orbit injection burden from the satellite operators, offering it as a service. The service, of course, would be far from being priceless, but from the satellite operators' point of view, such system would offer very valuable features:

- Availability of more mass to be utilized for additional payload or for more propellant to remain more time in orbit,
- Satellites size reduction, not needing anymore full tanks and big and heavy propulsion systems to perform high ΔV manoeuvres.
- Relief of the duty of orbit insertion.
- Relief of the mission analysis and control for the first, critical, phases.

The only critical occupations for the satellite operator would be the initial and end of operations once already in orbit, the remaining would be taken care by the kick-stage services. The customer of a kick-stage operations would pay for a shift of risk and related services.

The described example is only one possible use-case scenario of the kick-stage. The idea behind such systems is to design them to be as versatile as possible, making them able to perform a very diverse range of missions, and the capabilities described above could enable them.

3.4 Kick-Stage Challenges – Operator Point of View

The kick-stage does, of course, come with specific challenges to face, directly correlated with the type of missions they are designed to accomplish.

Being one of the main purposes the versatility, the system should be flexible to accommodate different requirements while remaining robust and reliable.

Some of the main challenges that a system like a kick-stage will need to face are:

- The mission analysis is an even more critical than usual phase. Its optimization could lead to big saving in total mass and propulsion system requirements. In particular, the utilization of non-conventional orbits could support the problem of multi-payload to multi-orbit delivery. The problem is not trivial and has been mathematically studied for years, known as the salesman problem.
- The propellant budget needed to perform the target missions is voluminous. For delivery of payloads to GEO, the ΔV required exceed the few km/s. The logistics and integration of the upper stage must be closely analysed, and the best technology to save volume and mass should be considered.
- Reliability – the system should demonstrate exceeding levels of reliability to be trusted by customers to transport their precious payloads. The decommissioning of such devices must be considered as well, to not occupy the orbits with undesired objects.

The design of the device, and especially the propulsive system, could lead to new developments. The propulsion system is usually designed for a specific target mission, and the mission analysis tries to accommodate its requirements using what is available. If the propulsion system is flexible enough, the process could work in both directions, with new missions enabled by the on-board characteristics and vice versa.

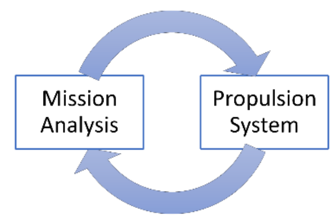


Figure 3 – Mission analysis and Propulsion System Design Loop

As described in the next sections, an accurate design and utilization of new technologies such as green propellants could lead to savings in inert mass such as the thrusters itself, the tanks, lines, valves and the entire propulsion system.

4. In-Space Propulsion systems

The propulsive system is especially crucial for a correct and efficient operation of any spacecraft operations. One of the main purposes of the kick-stage is to alleviate the burden of complex propulsion systems from the payloads, and hence the requirements of its own system result, by cascade, more stringent and complex.

A generic propulsion system is usually designed to accomplish two functions: perform the principal manoeuvres for apogee or perigee orbit insertion and control the device attitude and orientation. The two tasks are commonly performed by two separated Sub-Systems, hereby referred to as Main Engine and Reaction Control System. In the present study it is not analysed the Electric Propulsion case.

Main engines have the task of inserting the spacecraft into transfer or final orbit. Their operation is crucial to reach destination. The engines are usually high thrust, in the order of hundreds or thousands of Newtons-force, to reduce the burning time and validate the classical approximation of impulse manoeuvres during mission analysis. Ignition of such thrusters is usually limited in number of events, but the burning time can be long, exceeding the hundreds of seconds. The ΔV budget of these engines is usually very high, having to perform orbital movements, and hence their performance must be closely analysed to reduce the propellant utilization. While clustering of engines has been utilized in the past, it is usually preferred the use of a single bigger engine that results in higher efficiency and smaller overall mass.

Attitude and Reaction Control Systems (ACS or RCS) are the other key part of any spacecraft propulsion system. As stated by the name, the main purpose is to give the satellite a way to control its positioning in space correcting the orbit, changing the orientation and especially counteracting orbit or attitude perturbations. Perturbations are, unfortunately, unavoidable in space and can derive from extremely diverse sources such as solar wind, gravity corrections, collisions avoidance, thrust misalignments, mathematical models approximations. It is not rare for attitude control systems to be integrated with other devices such as momentum wheels that actively act on the stability of the spacecraft, but such devices necessitate, for physical reasons, to be desaturated by thrusters, that need to also cover this task. RCS thrusters must be able to operate during long periods of time, their ignitions can be frequent. The thrust level required by these thrusters is usually low, in the order of a few Newtons-force to some hundreds, depending on the spacecraft size and on the distance between the application point and the device centre of gravity (arm). The ΔV requirements of these engines is very limited, depending on the spacecraft's mission length. Their operations often require very short firings called pulses to finely act on perturbations.

Main Engine System	**Reaction Control System**
High Thrust	Low Thrust
Limited Ignition events	Frequent Ignition Events
Pulsed mode not necessary	Pulsed mode considered a strong advantage
High ΔV budget	Limited ΔV budget, depends on the mission length

Table 5 – Main characteristics of Propulsion Sub-Systems

From the brief introduction, while the main engine is important for the beginning of mission, the RCS has an equal or even more crucial significance for successful in-space operations.

Spacecrafts and upper stages are physically stabilized in two ways: full three-axis stabilization or spinning one-axis stabilization. The advantages and disadvantages of the two methods are not discussed in detail. The important factors to consider is that while the latter require a smaller number of thrusters to perform the control, it is more suitable for orbiting satellites with requirements of continuously face a target like the Earth. The former method gives full freedom of movements and is more suitable for devices like transfer or kick stages. For the reference system, it is crucial having the capability of managing the attitude to accomplish missions such as payloads release and dockings.

Three-axis stabilized spacecrafts require a relatively high number of thrusters arranged so that the torques they apply to the structure are pure couples without translational component, even though the latter capability may be required in some applications. Exact number of thrusters depends on the system design, capabilities required, system shape and finally level of redundancy required. Figure 4 shows a generic minimum-number configurations. The thrusters are arranged so that they apply torques to the spacecraft as pure couples, without translational component.

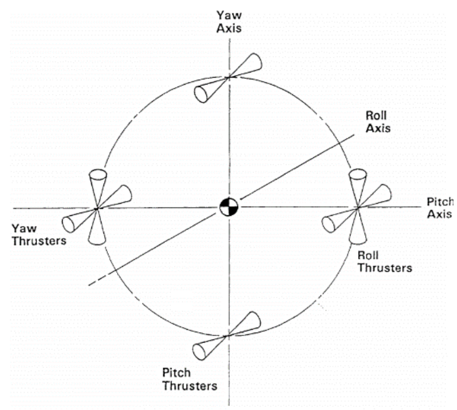


Figure 4 – Minimum number of thrusters configuration for a three-axis stabilized system.
Source and credit **[36]**

It is possible decreasing the overall number with some clever design choices, not analysed in the present study.

4.1 Architectures

Although the overall propulsion system is composed by two sub-systems with almost independent tasks, it is very frequent, especially for big spacecrafts and stages, to have many common components between the Main engine(s) and the RCS to save mass and volume.

The allocation of common components and how they interact is what is defined 'Architecture' in this study.

The architecture analysis and the selection of the best one is a very complex topic that requires some considerations.

4.1.1 Propellants considerations

Before a detailed description of the different possible architectures, a few considerations are necessary

regarding the propellants currently utilized and their properties.
As mentioned in Section 2, the almost totality of spacecrafts currently in orbit with chemical propulsion systems on board use Hydrazine or its derivatives (MMH and UDMH) and Nitrogen Tetroxide (NTO) as propellants.
It is useful understanding some characteristics of the propellants and their utilization modes.
Pure Hydrazine can be utilized in both monopropellant and bipropellant modes. Its use in bipropellant mode as fuel is possible but it has very little flying heritage even though the option has been extensively studied. During the missions that adopted this solution, Hydrazine's tanks needed to be heated up because of its high freezing point. There are options off-the-shelf available for such systems but Hydrazine as fuel is less stable than MMH or UDMH and its combustion is more unstable and historically avoided. Moreover, its high freezing point makes it unsuitable for long missions. An important example of system based on Hydrazine used in dual mode (monopropellant and bipropellant) is the Mars Global Surveyor [37]. Pure Hydrazine has also been used in the past in some forms of Electric Propulsion, especially electrospray and arcjet [38].

Hydrazine's derivatives, MMH and UDMH, at contrary, can be utilized only in bipropellant mode, usually coupled with NTO. Their chemical formulations have carbon chains that would concur to the possibility of system clogging, and the catalysts do not decompose them reliably. They have never been used in Electric Propulsion mode.

As regarding green propellants described in Section 2, the great majority of compounds can work only at a single mode with some golden exceptions: Hydrogen Peroxide and Nitrous Oxide. Hydrogen Peroxide is doubtlessly the most prominent green oxidizer, and the only compound that can be used both in mono and bipropellant chemical modes, although with limited performance. Nitrous Oxide could be decomposed and used as monopropellant as hydrogen peroxide, but it shows very high decomposition temperature that degrades very quickly the catalytic bed. It has, at the current state of the art, not extensively studied at the same level of HTP.
While Hydrocarbons cannot be used as monopropellants nor in electric propulsion modes, Energetic Ionic Liquids, by nature, should be compatible to be used as propellants for some types of electric propulsion. The development of this capability for specific compound requires more research and technologies advancements.

With such premises, the propellants characteristics clearly imposes strong limits on the architecture selection. Table 6 shows a summary of the different propellants' modes compatibilities.

Propellant	Monopropellant Mode	Bipropellant Mode	EP Mode
Hydrazine	YES	YES	YES
MMH	NO	YES	NO
UDMH	NO	YES	NO
HTP (98%)	YES	YES	NO
N_2O	YES	YES	NO
Hydrocarbons	NO	YES	NO
EILs	YES*	YES	YES*

Table 6 – Propellants and Propulsion Modes compatibility. *Depends on the compound, more research needed

Main engines, requiring high thrust and high performances, are usually based on bipropellants systems, while RCS, needing lower levels of thrust, do not have this limitation. There are many cases of Main Engines based on monopropellant systems, although none of them are upper stages.
The entire Architecture topic could be extended with the use of promising new technologies such as Electric Pump to increase performances. Although considered a promising development, it is not analysed in the present study.

4.1.2 Existing Architectures

Most of the prime space thrusters' suppliers provide ready, off-the-shelf, propulsion systems architectures for in-space operations.
The most common architectures are the only-monopropellant system (Figure 5) and the only-bipropellant system (Figure 6). The two architectures, hereby referred to as Architecture 1 and 2 respectively, have long fly heritage and are widespread in a big number of satellites and spacecrafts.

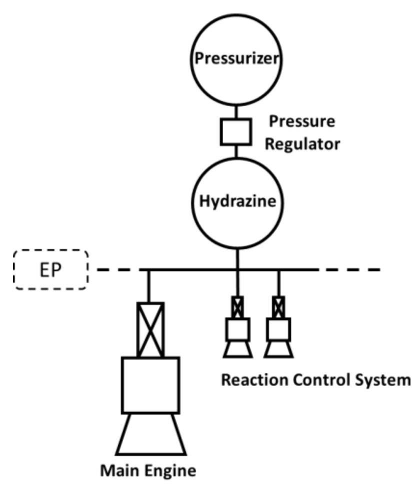


Figure 5 - Architecture 1: Only-Monopropellant System, often operated in blow-down mode

The clear advantage of the only-monopropellant architecture (Architecture 1) is doubtlessly its simplicity: the thrusters are easy to operate, there are few failure points. These systems are typically based on pure hydrazine for its outstanding flight heritage and performance in monopropellant mode. Their applications are usually left for RCS operations, with optional electric propellers (Electrospray) included in the design, but could include the main engine sub-system, that however remains limited in performance. The system has never flown based on other monopropellants, mainly because of the long-term storability issues of Hydrogen Peroxide.

The only-bipropellant system (Architecture 2) is doubtlessly the most common, offered by all the main thrusters' manufacturers. It is sometimes referred to as Unified Propulsion System. It is based on the coupling between MMH (or for older systems UDMH) and NTO. The propellants combination is doubtlessly the most common and widespread for in-space operations. It offers outstanding performances, good storability and good re-ignition capabilities. It is, as introduced in Section 2, toxic and their loading procedure associated costs are one of the main pushes to green propulsion research.

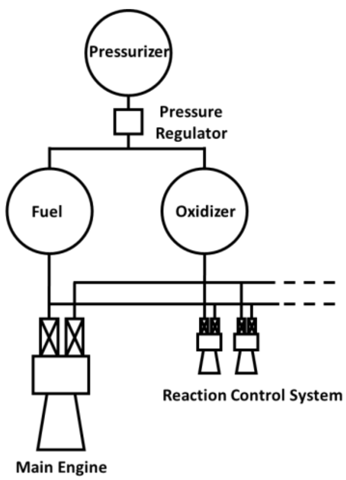


Figure 6 - Architecture 2: Only-Bipropellant System

A major disadvantage of Architecture 2 is the use of bipropellant thrusters for RCS applications. These thrusters do not work well during transients and short firings, losing most of their performances gain. Their operations are not as performant in pulsed mode as in continuous mode, and their entire configuration, including their intrinsic larger volumes and mass, appear almost under-utilized for the small ΔV required by the RCS.

It is recognised that the development of small bipropellant engines in the last few decades has led to optimized systems, with minimal weight and very good performance, and especially available off-the-shelf.

Both existing Architectures could, with some effort, be converted to green propellants. It is to be recognized that these systems were developed in many decades for specific compounds, and it is impossible requiring from the new substances to perform or work without differences.

4.1.3 Green Propellants-based Architecture

In this study are introduced two additional Architectures based on green propellants and their characteristics. As briefly mentioned, systems based on hydrazine in multi-mode propulsion have been studied in the past because they show clear advantages in terms of mass and performance. Hydrazine, however, showed to not be the correct candidate for these systems.

The first proposed architecture is based on the use of High-Grade Hydrogen Peroxide (HTP, 98% volume on water) as oxidizer for a high performant and high thrust main engine and in monopropellant mode for the smaller RCS thrusters. The Dual-Mode system, hereby referred to as Architecture 3 is shown in Figure **7**.

For the Main Engine, the fuel selection would require a dedicated trade-off. Currently, many companies in the sector are studying the coupling of various hydrocarbons with HTP, with particular focus on Kerosene (RP-1) and Ethanol. For the present study it is selected a fuel still in early-phases of research but that appear promising and especially could offer clear advantages architecture-wise: HIP_11. HIP_11 is an Energetic Ionic Liquid currently being tested by DLR. Its performances, when coupled with HTP, appear to be only slightly lower than MMH/NTO, it is hypergolic and denser than the toxic combination, being hence more efficient volume-wise. Together with a few other EILs in development around the world, it is doubtlessly one of the most promising technologies both for a switch from toxic combinations to cleaner ones and for new designs.

The peculiarity of the technology architecture-wise is that, by nature, Energetic Ionic Liquids could be suitable to be used also as propellants for Electric Thrusters. The development of such engines would require more research, but it is nonetheless a possibility to consider to furtherly increase the capabilities of a system based on this class of fuels.

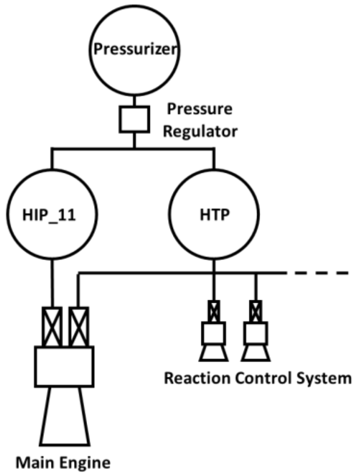


Figure 7 – Architecture 3: Dual-Mode Propulsion System

Architecture 3 shows clear advantages on the RCS side, where the reduced number of lines, valves and components could improve its reliability. The performances of RCS thrusters are lower, being the HTP specific impulse lower than other propellants, but the next section shows how, for low ΔV budgets, the overall system could become advantageous.
The Electric Propulsion option, although mentioned, is not considered since it would require completely new developments currently not pursued.

The last architecture proposed in the study is the self-pressurized system, shown in Figure 8. The system is based on the coupling between fuels and oxidizers with very high vapour pressure, that hence show self-pressurizing characteristics. Example of these compounds are Ethane or Ethylene as fuels and Nitrous Oxide as Oxidizer.
The clear potential of these compounds is the mass saving from the complete absence of pressurization system at the price of heavier storing tanks. The reference technology is HyNox, in development at the German Aerospace Centre (DLR Lampoldshausen).

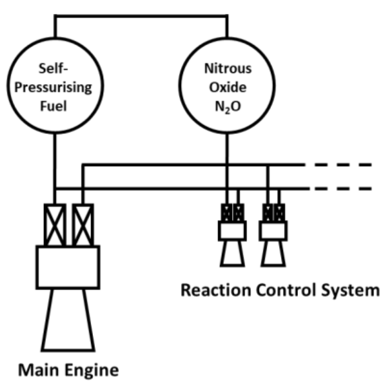


Figure 8 - Architecture 4: Self-Pressurizing System

A non-negligible advantage of Architecture 4 is that both fuel and oxidizer could be used as cold-flow thrusters in case of extreme need and for short and very precise manoeuvres. The efficiency of these manoeuvres would be very low but roughly predictable, and extremely simple and easy to operate. The flexibility of the system is undeniable. A possible drawback, where research is focusing at the current state of the art, is the bi-phase injection and the very high combustion temperature and the necessary presence of an ignition device. To overcome the issues there are many solutions in progress, including active nozzle cooling with regenerative cooling, that however require higher inert mass. The latter characteristic is considered in the following section when the architectures are compared.

5. Architectures Analysis

The comparison of different architectures is, as any trade-off process, complex and multi-disciplinary.
In this study it is performed a preliminary comparison in terms of mass saving.
Being the reference system an upper stage, it is by itself a payload for the previous stages and any little saving of mass accumulates and could be assigned to other precious cargo. As described in Section 3, some of the reference system purposes are to accomplish precise orbits insertion and being utilized as carrier for other systems, hence any mass saving would allow to transport more payload and generate more revenue.
The propulsive system is at the foundation of the system, and it is likely to take a big portion of the total upper stage mass. The focus of any propulsive technology selection usually remains on the I_{sp}. The parameter is, of course, key to select the most performant technology but unfortunately not always reflects the real complexity of the topic. While it is a good and reliable method to understand the efficiency of a propellant, it does not consider the differences in terms of mass requirements that some technologies require. A good example is electric propulsion: propellants show very high values of I_{sp}, but to understand the real properties of a thruster it is necessary knowing also at least the operative power required to operate. The latter corresponds to additional necessary mass to operate that must be considered in the comparison of propellants.
A good method to perform a more detailed analysis is to look at a parameter called System Specific Impulse (I_{SSP}). The parameter was introduced in the late 90s' by Dr Peter Erichsen [39, 40] as a method to compare very different propulsion systems considering the entire mass envelope instead of only the propellant efficiency.
The parameter is defined as:

$$I_{SSP} = \frac{I_{TOT}}{m_{PS}} = I_{SP}\ \frac{m_P}{m_{PS}}$$

The use of system specific impulse to compare different propellants for a defined system helps including in the analysis different contributions peculiar of some technologies. For example, additional necessary mass can derive from cooling for excessive combustion temperature, storing pressure, additional lines, reliability. For a correct estimation of the I_{SSP} it is necessary a deep understanding of the mission requirements, together with the size and dimensions of the system. While it is possible estimating many of the parameters during the preliminary mission analysis, in this study it is not selected a reference case and hence the I_{SSP} is not directly calculated. It is, however, estimated how the different architectures may be convenient in various situations.

5.1 Comparison methodology

As mentioned, the comparison of the various architectures is performed in terms of overall propulsion system mass. In general, the mass of the entire upper stage (m_0) can be divided into propulsive system mass (m_{PS}), structural mass (m_{struct}) and Payload mass (m_{PL}).
It is common putting the mass of the propulsion system inside the structural mass and analysing only the propellant mass, but the focus of the study is the analysis of the propulsion system in its entirety.

$$m_0 = m_{PS} + m_{struct} + m_{PL}$$

The propulsion system mass fraction is defined as:

$$F_{PS} = \frac{m_{PS}}{m_0}$$

The propulsion system mass can be divided into three contributions: propellant mass (m_P), tanking and pressurizing system (m_{PSS}) and the remaining, called here hardware mass (m_{HW}).

$$m_{PS} = m_P + m_{PSS} + m_{HW} = m_P + m_{inert}$$

The first term is the impulse-generating mass, while the sum of the second two terms is hereby referred to as inert mass, necessary mass that does not directly generate thrust but is fundamental for the working of the system.
The scope of any good design would be *to maximize the impulse-generating mass while reducing the inert mass as much as possible*. Reducing the inert mass without denting the system performances or reliability is an arduous task. Propellant mass, tanking and pressurization system (m_P + m_{PSS}) are very hardly decreasable without diminishing the performances of the system, but the remaining mass (m_{HW}) can be improved with a smart utilization of resources for some missions, for instance by introducing system architectures that share components and lines or based on multi-mode propulsion. It is useful also defining a few other important parameters connected to the propulsion system: the propellant mass fraction, f_p, and the inert mass fraction, f_{inert}.

$$f_P = \frac{m_P}{m_{PS}}$$

$$f_{inert} = \frac{m_{PSS} + m_{HW}}{m_{PS}} = \frac{m_{inert}}{m_{PS}}$$

The most efficient mass-wise overall systems are those that utilize a relevant amount of propellant. For such engines, the propellant mass fraction, f_p, that can be converted into impulse is very close to 1 because the propellant mass is the biggest contributor to the overall system mass. Main engines are the best representatives of systems with f_p very close to 1, having to burn tons of propellants. A very efficient bi-propellant system that must perform long firings, although heavy, is justified by its utilization purpose.

At contrary, reaction control systems usually have short operations in time, especially for Upper Stages. Having to control the attitude of the device for limited amount of time, not exceeding the few weeks or months depending on the mission, they need a very limited ΔV budget. These systems have higher inert mass fraction, with values of f_{inert} reaching values up to 0.7, meaning that only 30% of their overall mass is propellant [37]. For such systems, any possible reduction of inert mass would be very beneficial.
The study of the different architectures points towards the reduction of inert masses, especially those connected with the RCS.
For the analysis, the common rocket equation is written in its form:

$$m_p = m_0 (1 - e^{-\frac{\Delta V}{g\, I_{sp}}})$$

Using the mass relationships defined above, the relation becomes:

$$\frac{m_{ps}}{m_0} = \frac{m_{inert}}{m_0} + (1 - e^{-\frac{\Delta V}{g\, I_{sp}}})$$

The latter relationship can be re-written as:

$$\frac{m_{ps}}{m_0} = F_{PS} f_{inert} + (1 - e^{-\frac{\Delta V}{g\, I_{sp}}})$$

In the following paragraph, the different architectures described are compared using their different values of inert mass. A very precise calculation of the inert mass would require a detailed mission analysis scenario, and some parameters are, hence, estimated.

5.2 Architectures Comparison

In the present study, the reference system is an orbital vehicle that must be capable of a very broad range of missions, mostly relying on the propulsion system. Some assumptions are, hence, taken. The propulsion system, during the comparison, is supposed to take the great part of the overall mass budget of the upper stage and its value is initially fixed to 60% ($F_{PS} = 0.6$).
The two sub-systems, Main Engine and RCS, are analysed separately. During the analysis it is assumed that the 90% of the initial overall propulsive system mass is assigned to the Main Engine sub-system while the remaining to the RCS.

$$F_{PS-Main\ Engine} = 0.6 * 0.9 = 0.54$$
$$F_{PS-RCS} = 0.6 * 0.1 = 0.06$$

The comparison is made in terms of ΔV budget of the different architectures, considering that they have different hardware, or inert, initial masses.
The inert mass savings of the different architectures and the values utilized as performances are summarized in Table 7.

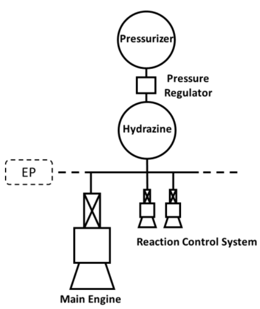
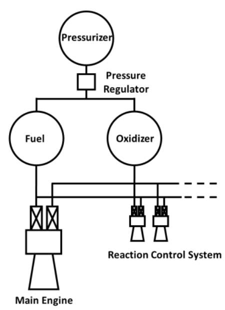
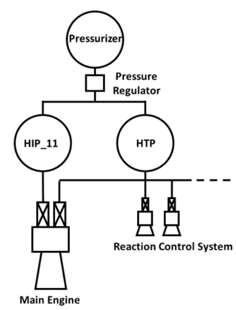
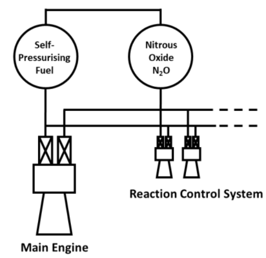
	Architecture 1	**Architecture 2**	**Architecture 3**	**Architecture 4**
				
Main Engine	f_{inert} = 0.05 I_{sp}= 235 s	f_{inert} = 0.1 I_{sp}= 330 s	f_{inert} = 0.1 I_{sp}= 310 s	f_{inert} = 0.1 I_{sp}= 300 s
RCS	f_{inert} = 0.3 I_{sp}= 235 s	f_{inert} = 0.5 I_{sp}= 290 s	f_{inert} = 0.3 I_{sp}= 180 s	f_{inert} = 0.4 I_{sp}= 270 s

Table 7 - Architectures comparison and associated values of propulsive systems inert mass and performance

5.2.1 Main Engine sub-system considerations

For the Main Engine sub-system, the comparison of the different Architectures on the ΔV budget is shown in Figure 9. The curves do not start from the origin because the inert mass is considered in the equation. The inert mass value shifts the curves, reducing the propellant mass storable in the system and hence the attainable ΔV. For big engines, the inert mass is, regardless on the technology, small respect to the mass contribution given by the propellant. The sub-system main purpose is to perform high ΔV manoeuvres, up to several km/s, and the propellant is the biggest contributor to the overall system performances. Because of this, the efficiency of the propellant itself becomes a crucial factor to consider when selecting the best technology. It is clear, hence, that the systems with higher I_{sp} must be preferred to attain the desired values of ΔV. It is also clear why Architecture 1 is not suitable for many applications. Its attainable ΔV values are lower than the other candidate technologies at parity of mass and the difference increases with the ΔV requirement. While it would be the natural choice for ΔV under 300 m/s, for any higher budget manoeuvres it would result in bigger required mass for the excess propellant.

For a propulsion system that targets to occupy the 60% of the overall orbital stage mass, the attainable ΔV overcomes the 2 km/s, for more requiring manoeuvres a larger portion of the stage mass would be required.
For a propulsion system that targets the propulsive system mass fractions assumed above, the attainable ΔV overcomes the 2 km/s for most of the propulsive systems. For missions that include manoeuvres with higher ΔV requirements, a larger portion of the stage mass must be assigned to the propulsive system.

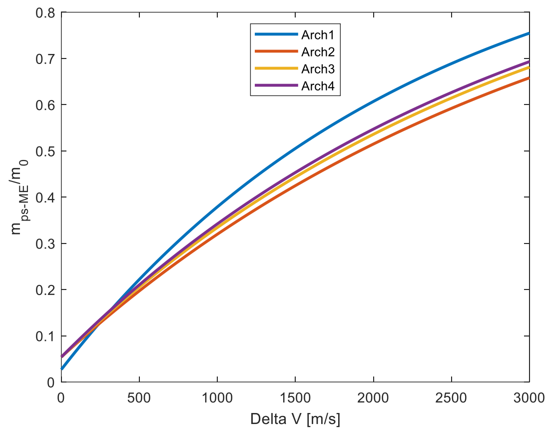


Figure 9 - Architectures Comparison for Main Engine Sub-System

The other architectures have very similar properties, being their performances very close. The variability connected to performances is greater on the increasing of ΔV required, and the low values of inert mass fractions do not influence.

5.2.2 RCS sub-system considerations

The comparison for the RCS propulsion system is more variegate. The system, as described in Section 3, is by its nature less efficient mass-wise than the Main Engine. Its firings are frequent but for very short burning times, and the ΔV budget during the entire mission is very limited and strongly dependent on the mission duration. As comparison, the ΔV requirement for station keeping of a spacecraft in GEO orbit does not exceed the few dozens of m/s per year.

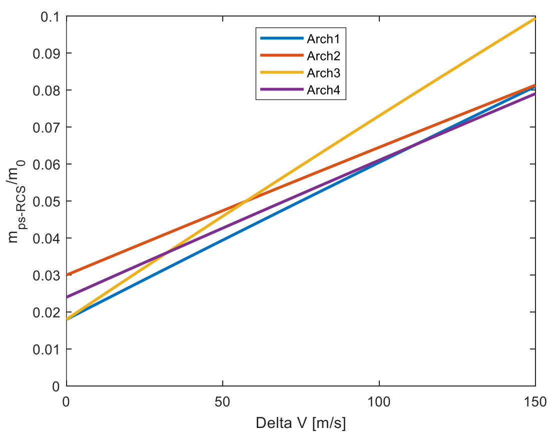


Figure 10 - Architectures Comparison for RCS Sub-System

The comparison of the different architectures is shown in Figure 10.

The different starting points of the various curves are resulting from the distinct values of inert mass of each technology. Monopropellant engines show a net advantage respect to bipropellant engines because their inert mass is lower, but the gap is quickly filled by the difference in performances.
The importance of the gap depends primarily on the mission analysis. Excluding Architecture 1, shown to not be suitable for Main Engine requirements, the other design that is based on Monopropellant RCS is Architecture 3, based on HTP. The low performances of the propellant show how the architecture quickly becomes unsuitable at increasing of ΔV, but for missions with low requirements it is convenient.
The Architecture 4, based on self-pressurizing propellants, has an intermediate value of inert mass, being heavier for some characteristics but not having the entire pressurizing system. The high performances of the propellants allow it to be quickly convenient respect to the monopropellant Architecture 3 for high ΔV, and almost always convenient than the toxic Architecture 2 for ΔV up to 190 m/s.

5.2.3 Overall Propulsion System

It is shown how different architectures, based on similar technologies, may offer some advantages in terms of involved masses. It is to be recognized that the selection of the best architecture is a complex trade-off, for which other parameters must be considered.
Between others:

- Complexity: How difficult is a system to build, how many components compose it and the broad availability of such components.
- Reliability: The concept is strictly correlated with the complexity of a system and includes considerations on the failure points, operating conditions and burning time.
- Redundancy: Orbital Stages always have a level of overlapping between capabilities, and for instance the RCS often has more engines than the minimum number to be able to operate also in case of a partial system failure. Redundancy automatically implies an increment of inert mass.

6. Conclusions

The study analysed the new class of orbital vehicles, currently in development in various organization around the world, called kick-stage. Their business may reveal profitable, and if this will be the case many more entities will luckily attempt to reproduce it. The market and the increasing customer base may benefit from the development of such a versatile device, and the possible uses are several and in expansion with the sector called on-orbit servicing.

Green propulsion is a very commonly research topic in the propulsion niche, but nonetheless the application of new technologies has been lacking. With the "New Space" excitement, it is crucial to utilize at best new technologies that reduce costs and possible harm to human life. The analysis of various possible architectures for the kick stage compares existing designs based on toxic compounds with new ones built on green technologies. The outcomes based on the inert masses comparison show how these "new" architectures are promising and may show clear advantages.

The technologies, being still in development, need further efforts to reach a maturity level that would allow their commercialization. The effort is usually taken by entities only through strong pushes from national agencies, and very often, especially in Europe, new systems designs are still based on toxic combinations, with a switch to greener option only planned for the future.

The complete replacement of Hydrazine is currently a far horizon, and it would be not advantageous in many applications. As a matter of fact, for big spacecrafts in far orbits that necessitate good performances in a long time span, it is doubtlessly the best candidate compared to any green propulsion technology. On the other hand for other technologies such as orbital and kick stages, designed to operate in time spans shorter than a few months, green propulsion could offer clear advantages.

The study shows how *design for green propulsion technologies can be more beneficial than switching to them later*. Technologies need time and money to develop and often the path is difficult to predict, without growing with the very stringent constraints deriving from the mere substitution.

Acknowledgements

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Figure 11 - ASCenSIon Project Logo

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