doi: 10.5028/jatm.v10.829 REVIEW ARTICLE

Space Propulsion: a Survey Study About Current and Future Technologies

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How to cite

Salgado MCV; Belderrain MCN; Devezas TC (2018) Space propulsion: a survey study about actual and future technologies J Aerosp Tecnol Manag, 10: e1118. doi: 10.5028/jatm.v10.829.

ABSTRACT: Current Space Launch Vehicles use chemical reactions (solid and liquid propellants) to achieve sufficient thrust to launch artifacts and humans into space. Propulsion technologies can be framed in three different categories: "escape propulsion", "in-space propulsion", and "deep space propulsion". The launch vehicles currently used for "escape propulsion" rely on mature technologies, which experienced only small incremental improvements over the last five decades, and breakthroughs for this kind of propulsion are not foreseen for the next two decades. This research gathered information on the main operational heavy-lift space launch vehicles with capacity over 5,000 kg that are used to reach GEO (Geostationary Earth Orbit) by the United States, Russia, Europe, China, Japan and India and compared their thrust capability. The results show that performance was improved mainly by adding boosters, increasing gross propellant weight, with larger diameter rocket motors and using more efficient liquid propellant pairs. Information regarding the frequency of published scientific articles and patents on Space Vehicles Propulsion Systems since the 1960s was also gathered, which demonstrates some progress in the last years, mainly in USA and Europe. "In-space" and "Deep space" spacecraft were also briefly examined in this article, resuming the main features of some new promising developments, mainly regarding the latter, which present prospects of significant technological advances; however, real progress in interplanetary missions will be possible only when technological breakthroughs towards other propulsion types become possible and feasible. So, two questions motivated the authors: why space propulsion development seems stagnant? Are there prospects for progress?

KEYWORDS: Space propulsion technology, Space vehicles, Liquid propellants, Solid propellants, Deep space propulsion, Rocket engines.

INTRODUCTION

Space flight is undoubtedly a remarkable and probably the most audacious human achievement of the 20th century. It started suddenly in the 1950s and grew explosively in the two following decades. During a period of more than fifty years of space flights, many things have changed. The Space Shuttle is a luxury ship compared to the Mercury capsules that carried the first American astronauts into space. Today there are few thousand satellites in orbit that form the backbone of Earth communications system; space probes have visited every planet of the solar system, as well as some asteroids and comets, and some were even sent outside the solar system. However, there is one thing that has not changed much: the way that rockets work, or, in other words, rocket propulsion, which is still chemical-based, like its predecessors that have put the Sputniks and Explorers into orbit in the late 1950s. While different fuels have been used, and current rocket engines are more technologically advanced than their early predecessors, the basic concepts involved are basically the same.

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Received: Nov. 01, 2016 | **Accepted:** Jun. 05, 2017

Section Editor: Ana Morais

The propulsion system of a rocket includes all the parts that make up the rocket engine: tanks, pumps, propellants, power head, and rocket nozzles. The function of the propulsion system is to produce thrust, which is the force that moves a rocket through air and space. Different propulsion systems generate thrust in different ways, but always through some application of Newton's third law of motion. In any propulsion system, a working fluid is accelerated and the reaction to this acceleration produces a force on the system. A general derivation of the thrust equation shows that the amount of thrust generated depends on the mass flow through the engine and the exit velocity of the gas.

Space propulsion technologies can be framed in three different categories: "escape propulsion" (from Earth surface to orbit), "in-space propulsion" (in orbit), and "deep space propulsion" (from orbit to outer space). The launch vehicles currently used for "escape propulsion" rely on very mature technologies, but for "in-space" and "deep space" vehicles, there are prospects of significant technological advances. According to Long (2012), chemical fuels are clearly inadequate for interstellar missions and new methods of propelling a vehicle through space should be invented.

The Euroconsult Report (2016) informs that global spending on space programs in 2014 has reached $66,5 billion. The report also presents the prospects of a new growth cycle in government space spending, which is expected to start soon and average 2.1% over the next eight years worldwide, reaching $81.4 billion by 2024.

Space program development has been on the rise during the past decade in an increasing number of countries, aiming to acquire independent assets to help their national, social, economic and technological development and contribute to their national defense and security programs. Space access budgets continued to increase over the past 5 years at a 10% Compound Annual Growth Rate (CAGR). Currently, the major difficulties of operating unmanned space missions are related to energy and propellant required for launch, transfer orbit, and maneuvering the satellite or spacecraft in orbit. Ongoing studies indicate that the area of greatest challenge has been identified to be propulsion. The main engines require improvement if reliability and cost goals are ever to be met. Johnson (2012) explains that there is no single propulsion technology that will benefit all missions or mission types.

Devezas *et al.* (2012) presented the worldwide space activities scenario during the last eighty years under the framework of the succeeding K-waves (Kondratieff waves), scrutinizing more than 7,500 space activity related events that occurred in the period 1930-2010. The authors showed that the intensity of these activities in the examined period evidenced a wave-like aspect, which matches very well the unfolding of the past 4th K-wave, and that there are signals that a new wave of space activities is under way following the path of the coming 5th k-wave. They also demonstrated that the space race that we have witnessed until now followed a natural growth process that reached a saturation point at the dawn of this century, and suggested that a new growth process in this field might be sprouting, with traits very different from the ones imagined by futurists and science fiction writers sixty years ago.

The projection of future of space programs from countries like the United States, Russia, Europe, China, Japan, India, South Korea, Iran and others, includes manned missions to secure a foothold on the Moon, reaching and intercepting asteroids that might threaten our planet, landing humans on Mars, accomplishing missions to Jupiter and other interplanetary travels in the period between 2015 and 2030, corresponding to the unfolding of the 5th K-wave. Undertaking such missions requires developing new space propulsion rocket engine systems. Space launch vehicles must be capable of reaching transfer orbits and detach from their spacecrafts, which, driven by new propulsion systems with high energy levels, will continue until the final destination. The research presented in this article was motivated by the search for answer to this critical question: are there available propulsion technologies ready to be used and/or to be developed on such short time span?

Modern literature of space technology often distinguishes the spacecraft propulsion according to the region of space foreseen for their movement, and more frequently, we find the following terms that represent these space regions, such as "In-Space", "Deep Space" and "Outer Space". There is no clear consensus about a name to designate propulsion in the region under the influence of Earth gravity located between the Earth surface and orbit, and for this reason the term "Escape Propulsion" was adopted by the authors for lack of a better alternative in the literature.

Recently, Johnson (2012) noted that "in-space" propulsion begins where the launch vehicle upper stage leaves off and starts performing the functions of primary propulsion, reaction control, station keeping, precision pointing, and orbital maneuvering. Figure 1 shows the definition of this space region. The term "escape propulsion" was adopted to describe the space between Earth surface and Earth orbit, and all propulsion technologies required by space missions when the space vehicle leaves the launch pad. The region beyond Earth gravitational influence, until the Geostationary Earth Orbit (GEO) at 35.786 km above Earth surface, is defined as "in-space", as shown in Fig. 1. "In-space" harbors all Earth monitoring systems, such as strategic communications assets, early warning, Earth observation, navigation, reconnaissance, surveillance and weather. After "in-space", or beyond GEO, in outer space, lies "deep space", encompassing interplanetary, interstellar, and intergalactic space.

The Inner Solar System contains the Sun and the inner planets – Mercury, Venus, Earth, Mars, and the asteroid belt. The Outer Solar System, which surrounds the Inner Solar System, contains the outer planets: Jupiter, Saturn, Uranus, Neptune and Pluto.

Distance (km)	Space	Events	Observation
0	Escape Propulsion	Earth	
50		End of stratosphere	
160	In-space	Beginning of Low Earth Orbit	
406		International Space Station	International Space Station at an orbital altitude between 330 and 410 km
2.000		End of Low Earth Orbit – beginning of Medium Earth Orbit	
20.000		GPS satellites	
35.786		End of Medium Earth Orbit – beginning of Geoestationary Earth Orbit Communications satelittes	
384.000	Deep-space	Moon	
1.500.000		Lagrangian point 1 Earth– Sun	Parking lot – where gravitational effects of Sun and Earth balance out
38.200.000		Venus	
55.700.000		Mars Curiosity rover – landed on Mars (August 2012)	
77.300.000		Mercury	
149.600.000		Sun	
588.390.000		Jupiter	
1.200.000.000		Saturn	
2.580.000.000		Uranus	
4.280.000.000		Pluto	
4.300.000.000		Neptune	
4.500.000.000		Outer solar system	
12.560.000.000		Termination shock	Wind of electrically charged particles becomes denser, hotter and slower
21.240.000.000		End of Heliosphere	

Figure 1. Boundaries of space regions.

This article describes the status of the technology for "escape propulsion" with solid, liquid, and green propellants, as well as hybrid propulsion, and for "in-space" and "deep space" propulsion with plasma propulsion and without propellants. It also tries to forecast the future development of propulsion technologies, identifying some futuristic projects such as Project Orion, Daedalus, Light Sail, Space Elevator, and VASIMR, indicating that the field of propulsion has many surprises to reveal us in the next 30 years for space exploration and interplanetary travel. This prospective study shows that advanced space programs are already planned for the near future (2030), including missions to the Moon, Mars, Jupiter, and beyond, which will need to use new space propulsion technologies. Figure 2 shows the comparation between the technologies used in each region of space.

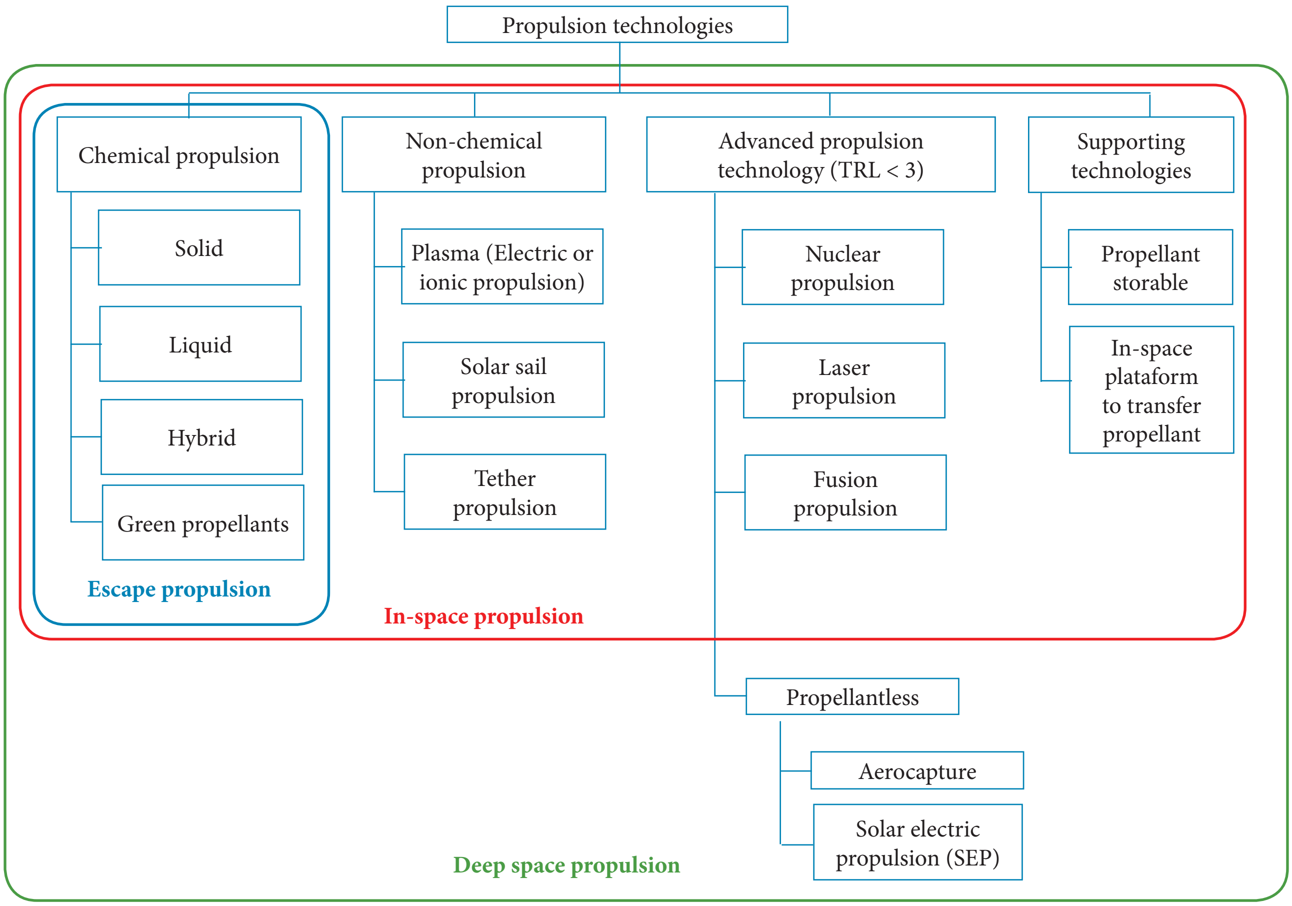

Figure 2. Technology area breakdown structure (adapted from Meyer *et al.* 2012).

ESCAPE PROPULSION

According to Caisso *et al.* (2009), in 1898, a Russian schoolteacher, Konstantin Tsiolkovsky (1857-1935) proposed the idea of space exploration using rockets. In 1903, Tsiolkovsky suggested the use of liquid propellants for rockets in order to acquire the necessary thrust. In the early 20th century, the American engineer Robert H. Goddard (1882-1945) conducted practical experiments with solid-propellant rockets. No one had ever built a successful liquid propellant rocket, as it was a much more difficult task than building solid propellant rockets: fuel and oxygen tanks, pumps, turbines and combustion chambers would be needed. Goddard achieved the first successful flight with a liquid propellant rocket on March 16, 1926 (Haeseler *et al.* 2004).

In the 1930s, the German engineer Wernher von Braun (1912-1977) was responsible for the design of the V2 ballistic missiles; however, von Braun was a researcher interested in manned space travel. He defended his PhD in 1934 and the title of his thesis was "Construction, Theoretical, and Experimental Solution to the Problem of the Liquid Propellant Rocket". After WWII, under the then secret "Operation Paperclip", von Braun and some select members of his rocket team were taken to the United States to work in the U.S. Space Program. The landing on the Moon in 1969 became possible through their efforts.

Until nowadays, the propulsion types used in launch vehicles to operate the "escape propulsion" region are variations of the chemical propulsion.

Rocket engines use mainly liquid propellants because of their higher efficiency and thrust. Rocket engines also use solid propellants, mainly in boosters, to improve thrust at takeoff and because, although less efficient, they have greater reliability, robustness and power, thus improving safety. The propulsion of rocket engines for launch vehicles takeoff from terrestrial platforms, ships or aircrafts, seems so far to be an established technology, with Technology Readiness Level (TRL) 9, as pointed out by Johnson (2012).

Technological advances in propulsion are steadily reducing costs and improving efficiency, reliability and safety, in order to keep up with satellite demand and maintain the competitiveness in space. Constant environmental concerns result to an increasing need for non-toxic propellants that do not harm life on the ground or in the atmosphere.

CHEMICAL PROPULSION

Solid fuel propulsion

In a solid rocket fuel grain, all the components required for vigorous combustion are mixed together and packed into a solid cylinder, as shown in Fig. 3, into one substance. Once the combustion starts, it proceeds until all the propellant is exhausted. There will be an oxidizer (usually a salt such as ammonium perchlorate or potassium nitrate), a fuel (HTPB – Hydroxyl Terminated Polybutadiene) or some other solid hydrocarbon and an accelerant (sulphur, powdered aluminium, or other easily oxidized metal). When lit, the fuel grain will burn energetically, releasing a large volume of hot gases that are used to provide thrust (SPA… 2014).

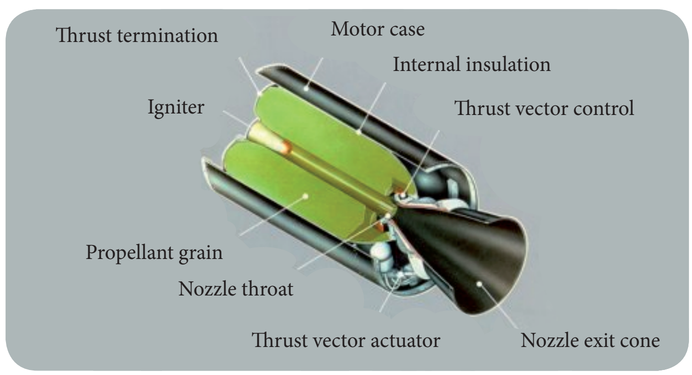

Figure 3. Solid rocket engine (SPA… 2014).

The more sophisticated solid rockets are used as launch boosters on various vehicles including the retired Space Shuttle, Delta IV, Atlas V, Ariane 5, and in intercontinental ballistic missiles. Specific impulses from solid rockets are not as high as liquid fueled rockets, but ease of use, short preparation time, and relative simplicity of construction make them the rocket of choice for the widest variety of applications. Solid rockets are much easier to handle and can stay idle for years before firing.

Casting the fuel grain port in different configurations, as shown in Fig. 4, can yield different burn characteristics. Star configurations tend to be popular for a relatively even burn.

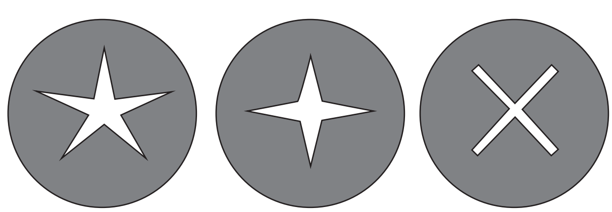

Figure 4. Grain fuel configurations (SPA… 2014).

The mixing and preparation of large fuel grains is difficult, highly technical, and dangerous. A solid rocket fuel is, by definition, an explosive. For optimum performance and reliability, the fuel grain mixture must be composed of very fine particles very evenly mixed. During the mixing and casting process, the mixtures are very unstable and dangerous. Massive explosions have occurred during manufacture of solid rocket fuel grains. The biggest drawback of solid rockets for manned use is that they cannot be controlled or switched off once they are lit. Aborts are impossible after ignition (SPA… 2014).

Liquid fuel propulsion

Propellant is comprised of two composites: fuel and oxidizer, as shown in Fig. 5. They are stored separately in tanks in liquid phase and are pumped into the nozzle combustion chamber where burning occurs. Engine can stop the combustion and the thrust by turning off propellant flow. Liquid rockets tend to be heavier and more complex because of the pumps and storage tanks.

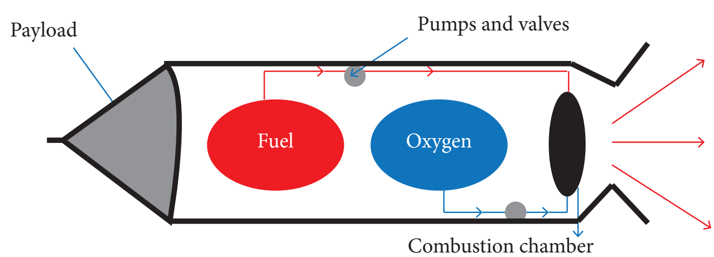

Figure 5. Draft of liquid propulsion rocket (SPA… 2012b).

Hybrid propulsion

As the name implies, "hybrids" are a cross between other types of rocket motor, in particular, liquid fueled rockets and solid fuel rockets. They were conceived to overcome the complexities of liquid bi-propellant engines and the lack of controllability of solid rocket motors (Fig. 6).

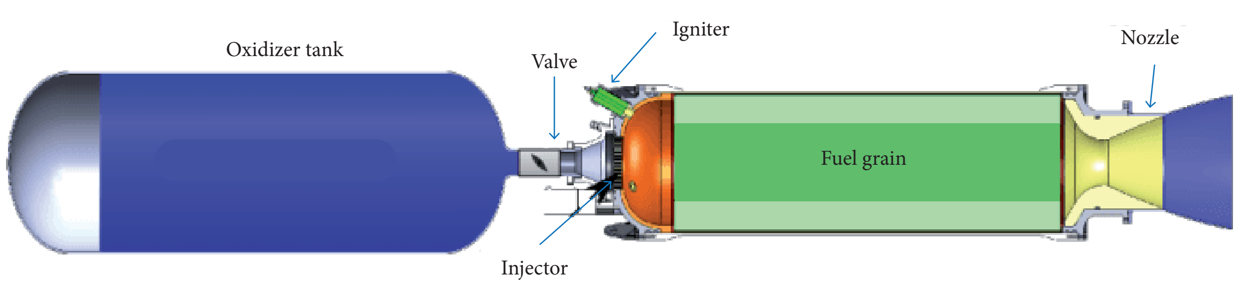

Figure 6. Hybrid engine (credit to Jonny Dyer to SPA… 2014).

One of the substances is solid, usually the fuel, while the gaseous propellant, stored in the oxidizer tank, as shown in Fig. 6, is injected into the solid. The oxidizer is admitted through a small orifice (injector) at the input end, an igniter (pyrotechnic or electrical) is used to start the burn, and the oxidizer consumes the surface of the fuel grain.

The basic idea is to inject a liquid oxidizer into a fuel grain that consists only of fuel, and that cannot sustain combustion on its own. The motor is controlled (throttled up and down or shut off) by controlling the flow of liquid oxidizer into the combustion chamber. Typically, the combustion chamber is a long cylinder lined with a fuel composed of hydrocarbons (HTPB, kerosene, plastics of various types, amongst many other possibilities).

The main advantage of these engines is that their performance is high, similar to that of solid propellant, and combustion can be moderated, stopped, or even restarted, similar to liquid propellant. However, it is difficult to achieve very large thrusts, and thus, hybrid propellant engines are rarely built.

Green propellants

According to Gohardani *et al.* (2014), currently, toxic and carcinogenic hydrazine propellants are commonly used in spacecraft propulsion. These propellants impose distinctive environmental challenges and consequential hazardous conditions.

Green Propellants is a general name for a family of propellants, being used in liquid, solid, hybrid, mono or bipropellant engines, which satisfy certain requirements such as low toxicity, low pollution, good storability, wide material compatibility and good performance (Haeseler *et al.* 2004). The main expectations of green propellants (cost, complexity and environmental pollution reduction) can serve as criteria to identify a large number of green propellants: low toxicity, that reduce operation hazards and safety precautions during handling and storage; low environmental impact, that reduce ground atmospheric and space pollution; reduced production and operational costs due to reduced toxicity and complexity and good performance when mass-specific and volume-specific performance is considered. Gohardani *et al.* (2014) said that, with an increasing level of future space activities and applications, the significance of greener space propulsion becomes even more pronounced.

IN-SPACE PROPULSION

The beginning of the space region that can be characterized as "in-space" propulsion is the point where the launch vehicle upper stage leaves off, and starts performing the functions of primary propulsion, reaction control, station keeping, precision pointing, and orbital maneuvering (Johnson 2012). The main engines used "in-space" provide the primary propulsive force for orbit transfer, interplanetary trajectories and planetary landing and ascent. Action control and orbital maneuvering systems provide the propulsive force needed for maintaining orbit, position control, station keeping, and spacecraft attitude control. New "in-space" propulsion technologies development will result in improvements in thrust levels, power, specific mass (or specific power), volume, system mass, system complexity, operational complexity, commonality with other spacecraft systems, manufacturability, durability, and, of course, cost. "In-space", defined as the region between Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO), as shown in Fig. 1, includes all Earth monitoring systems, such as communications strategic assets, early warning, Earth observation, navigation, reconnaissance, surveillance and weather.

The technologies used in satellite launch vehicles or spacecrafts operating in "in-space" are mainly chemical propulsion-based, such as in espace propulsion, but research and use of other propulsion types are increasing.

NON-CHEMICAL PROPULSION

Plasma propulsion (electric or ionic propulsion)

According to Szelecka (2016), plasma engines are used for space propulsion as an alternative to chemical thrusters. Due to the high exhaust velocity of the propellant, they are more efficient for long-distance interplanetary space missions than their conventional counterparts. Plasma is an electrically neutral gas (helium neon or xenon), in which all the positive and negative charges from neutral atoms, electrons, negatively and positively charged ions, come up to scratch. Plasma is the basis of every electric or ionic propulsion. Ion propulsion is one of the latest advances in spaceflight propulsion. Rather than ejecting a relatively large amount of mass over a short period of time to create thrust, an ion propulsion engine ejects individual atoms at velocities 5 to 30 times higher than traditional engines, over a much longer period of time (days, weeks, or longer). This type of thrust eventually will propel the spacecraft to much larger velocities than that obtained by traditional engines. Ion propulsion is currently one of the best answers to long distance missions, and, ironically, is also very well-suited for small attitude adjustment thrusting, because of the extremely low impulse of the thrust. Figure 7 illustrates how ion propulsion systems works. Ions must be created before they can be expelled. To do this, a plasma (typically xenon, because it is relatively stable and is over 4 times heavier than air) is bombarded with electrons emitted from a cathode. When an electron strikes a xenon atom, it knocks away one of the atom's electrons, resulting in a positively charged xenon ion. An electric field is created in the rear of the xenon chamber using a pair of positively and negatively charged metal grids. The xenon atom accelerates through this electric field, and is ejected from the spacecraft imparting an equal and opposite force to the spacecraft as it leaves. To prevent the ion from being attracted back to the spacecraft (and therefore negating any thrust it provided) a stream of electrons is directed into the exhaust to neutralize the ions.

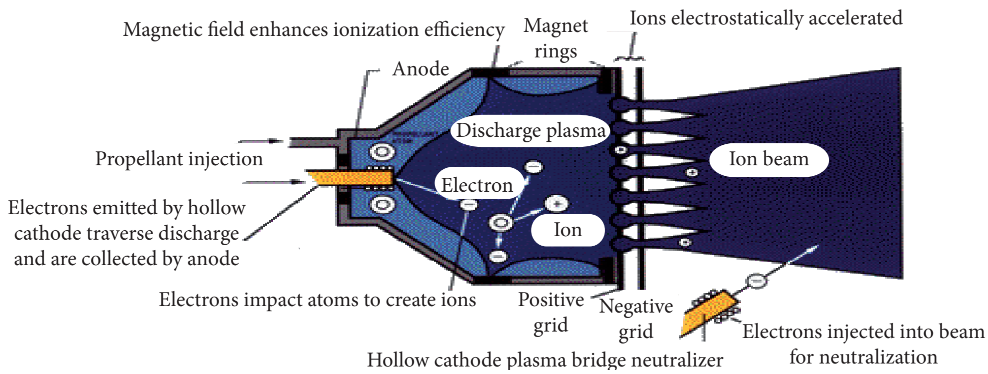

Figure 7. Plasma propulsion engine (NASA 2008).

Solar sail propulsion

The solar sail is another concept of propulsion. It is basically a big photon reflector surface. The power source for the solar sail is the Sun and it is external to the vehicle (Sutton, 2000). Solar sail propulsion uses sunlight to propel vehicles through space by reflecting solar photons from a large, mirror-like sail made of a lightweight, highly reflective material. According to Johnson *et al.* (2011), solar sail propulsion utilizes the solar radiation pressure exerted by the momentum transfer of reflected light. The integrated effect of a large number of photons is required to generate an appreciable momentum transfer; therefore, a large sail area is required. Since acceleration is inversely proportional to mass for a given thrust force, the mass of the sailcraft must be kept to a minimum. Figure 8 illustrates how the solar radiation pressure is utilized for propulsion. Incident rays of sunlight reflect off the solar sail at an angle θ with respect to the sail normal direction. Assuming specular reflection from a perfectly flat sail membrane, there will be two components of force, one in the direction of the incident sunlight and the second in a direction normal to the incident rays. When the force vectors are summed, the components tangent to the sail surface cancel and the components normal to the surface add to produce the thrust force in the direction normal to the sail surface.

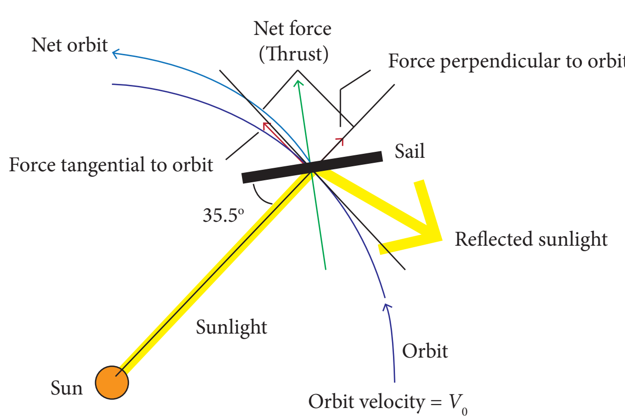

Figure 8. Solar sail propulsion (Johnson *et al.* 2011).

Tether propulsion

The tether propulsion consists of a long, thin wire deployed from an orbiting satellite or vehicle. The movement of a wire through a magnetic field produces an electrical current. The current in the wire produces a magnetic field around the wire, which interacts with the Earth magnetic field. The force exerted on the tether by Earth magnetic field can be used to raise or lower a satellite orbit, depending on the direction of the current. Researchers at the Marshall Center are also investigating the use of electrodynamic tethers for future scientific missions to Jupiter and its moons. In theory, electrodynamic tether propulsion could be used in the proximity of any planet with a significant magnetosphere, like Jupiter, as shown in Fig. 9.

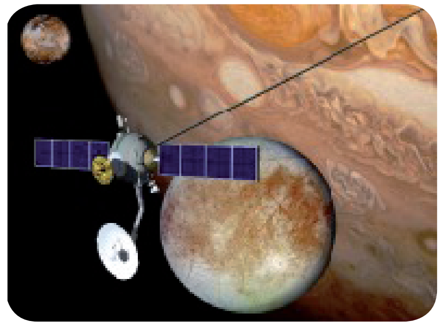

Figure 9. Electrodynamic tether propulsion – a thin power wire (NASA 2014).

ADVANCED PROPULSION TECHNOLOGIES

Fusion propulsion

Miernik *et al.* (2011) describe how fusion-based nuclear propulsion has the potential to enable fast interplanetary transportation. A fusion reaction occurs when two atoms of hydrogen collide to create a larger helium-4 atom, releasing energy. Fusion, according to Long (2012), is the combination of two light isotopes to release energy. The enormous amount of energy created from those reactions is ejected from the engine to provide thrust. Using this type of propulsion system, a spacecraft could reach Mars in just about three months while it would take at least seven using conventional rockets.

Laser propulsion

Laser propulsion is a form of beam-powered propulsion where the energy source is a remote (usually ground-based) laser system and separate from the reaction mass. This form of propulsion differs from a conventional chemical rocket where both energy and reaction mass come from the solid or liquid propellants carried on board the vehicle.

Nuclear propulsion

Nuclear rockets can be used only outside Earth's atmosphere, to avoid any possibility of radioactive contamination. The possibilities that nuclear energy offers to space missions were recognized even before the discovery of nuclear fission and its use makes such missions possible, hence becoming of fundamental importance. Available technology includes both solar and nuclear thermal sources that heat hydrogen propellant to achieve high specific impulse. Of these two, only nuclear thermal propulsion is rated as a high-priority technology. Nuclear Thermal Rockets (NTR) are high-thrust propulsion systems with the potential to achieve twice the specific impulse of the best liquid hydrogen/oxygen chemical rockets.

DEEP SPACE PROPULSION

For "deep space" missions, such as missions to the outer planets of our solar system, the propellant energy and mass requirements tend to be higher than for missions closer to Earth due to the higher spacecraft speed required to reduce mission duration, lower solar intensity, maneuvers involved and the generally heavier spacecraft. In many missions, natural orbits around the sun, called Hohmann trajectories, are used to send the spacecrafts from Earth orbit to target orbit with a minimum expenditure of energy. Planet movement and gravity are also used to accelerate the spacecraft without consuming energy. However, these missions last a long time. Future manned mission duration must be kept to a minimum and the most direct path is to be adopted. This requires higher energy consumption and propellant quantity. With chemical rockets and existing technologies, these missions are almost impossible.

The types of propulsion used to operate the "in-space propulsion" region are variations of the chemical, such as used in escape propulsion and in-space propulsion, non-chemical, like used in-space propulsion, and advanced propulsion. Most of these technologies are still under development and are not yet considered as mature technologies. Nuclear propulsion, laser propulsion, fusion propulsion is the same propulsion types, like in-space propulsion.

PROPELLANTLESS

Aerocapture

Aerocapture technique uses a planet or a moon atmosphere to accomplish a quick, near propellantless orbit capture of a space vehicle, and place it in the desired orbit. Atmosphere is used as a brake to slow down a spacecraft, converting its kinetic energy into thermal energy.

Aerocapture, according to Anderson *et al.* (2010), is the process of entering the atmosphere of a target body to practically eliminate the chemical propulsion requirements of orbit capture. Aerocapture is the next step beyond aerobraking, which relies on multiple passes high in the atmosphere using the spacecraft's drag to reduce orbital energy. Aerobraking has been used at Mars on multiple orbiter missions, as shown in Fig. 10. Aerocapture maximizes the benefit from the atmosphere by capturing in a single pass (Fig.11).

The maneuver starts with the spacecraft arriving with a hyperbolic trajectory into the celestial body atmosphere. The atmospheric friction slows it down and places it into an elliptical orbit. Onboard thrusters are then used to circularize the orbit, as shown in Fig. 12.

NASA technologists are developing ways to place robotic space vehicles into long-duration scientific orbits around distant Solar System destinations without the need for the heavy fuel loads that have historically limited vehicle performance, mission duration, and mass available for science payloads.

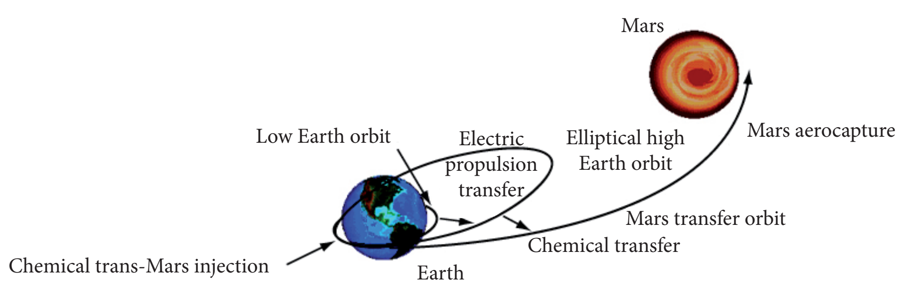

Figure 10. Mars transfer orbit.

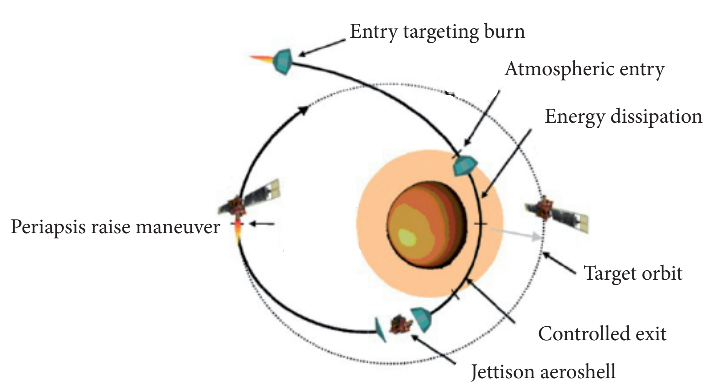

Figure 11. Aerocapture maneuver (Anderson *et al.* 2010).

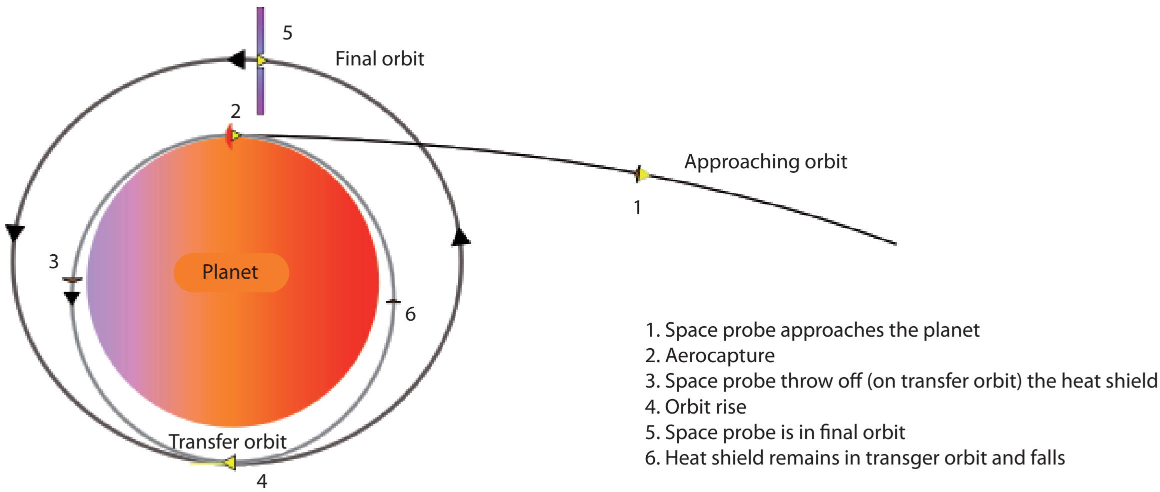

Figure 12. Aerocapture (Stanek 1992).

Solar Electric Propulsion

Solar electric propulsion (SEP) uses solar power to ionize and accelerate heavy propellants, as inputs to a low thrust, fuel efficient, Ion propulsion system (IPS). The necessary electrical power comes from arrays of photovoltaic cells, so the technology is also called solar-electric propulsion. Ejecting mass at extremely high speed is the action that causes the reaction of the spacecraft accelerating in the opposite direction. The exhaust velocity of the ions is much higher than the chemical rocket exhaust velocity and that is the main reason for its higher performance.

The low thrust level of ion engines means that they must run for a long time to accelerate the spacecraft to its desired velocity. Ion engines are the most efficient fuel rockets used in space today, roughly ten times more efficient than conventional chemical rocket engines.

Johnson *et al.* (2013) have shown a roadmap with the top ten technical challenges for “in space” propulsion systems identified and prioritized by National Aeronautics and Space Administration (NASA) based on perceived mission needs or potential impact on future “in-space” transportation systems. These challenges were then categorized into near (present to 2016), mid (2017-2022), and long-term (2023-2028) time frames, as presented in Table 1, representing the point at which Technology Readiness Level 6 (TRL-6) is expected to be achieved.

Table 1. Challenges for escape and in-space propulsion systems (Johnson *et al.* 2013).

Rank	Description	Timeframe
1	Power processing units (PPUs) for ion, hall, and other electric propulsion systems	Present to 2016
2	Long-term in-space cryogenic propellant storage and transfer	2017-2022
3	High power class solar electric propulsion scalable to megawatt (MW) class nuclear electric propulsion	2017-2022
4	Advanced in-space cryogenic engines and supporting components	2017-2022
5	Development and presentation of Microelectromechanical Systems (MEMS)	Present to 2016
6	Demonstrating large (over 1000 m^2) solar sail equipped in-space vehicle	Present to 2016
7	Nuclear Thermal Propulsion (NTP) components and systems	2023-2028
8	Advanced space storable propellants	2017-2022
9	Long-life (> 1 year) electrodynamic tether propulsion system in Low Earth Orbit (LEO)	Present to 2016
10	Advanced in-space propulsion technologies (TRL < 3) to enable a robust technology portfolio for future missions	2023-2028

Historically, these propellants have not been applied beyond upper stages because of the inherent difficulties associated with their long-term storage. Furthermore, numerous concepts for advanced propulsion technologies, such as electric propulsion, are commonly used for station keeping on commercial communications satellites and for prime propulsion on some scientific missions because they have significantly higher ISP (specific impulse) values. Several of these technologies offer performance that is significantly better than that achievable with chemical propulsion. This roadmap describes the portfolio of "in-space" propulsion technologies that could meet future space science and exploration needs. There is no single propulsion technology that will benefit all missions' types. The requirements for "in-space" propulsion vary widely depending upon the intended application.

LAUNCH FAILURES

Sackheim (2006) researched the causes of launch vehicle failures in the period between 1980 and 1999, and has identified propulsion failures as the leading cause. In the present research, we extrapolated the search for failure causes to September 2016, concluding also that propulsion continued to be the main source of failures, with 58% of all failures, surpassing all the other systems that comprise a satellite launch vehicle, as shown in Table 2. The high rate of propulsion failures indicates that, despite being considered a mature technology, it is still necessary to continue looking for ways to make it safer and more reliable.

Table 2. Causes of launch vehicle failures on systems 1980-Sept/2016 (adapted from Sackheim 2006).

Country	Propulsion	Avionics	Separation	Electrical	Structural	Other	Unknown	Total by country
USA	22	4	10	1	1	3	3	44
Russia	49	3	2			8	19	81
Europe	8	1						9
China	6	1			2		1	10
Japan	3		1			1		5
India	3	2	1	1		1		8
Failures	91	11	14	2	3	13	23	157
	58%	7%	9%	1%	2%	8%	15%	100%

INTENSITY OF RESEARCH ACTIVITY

The number of scientific publications on space propulsion as indexed by Scopus is shown in Fig. 13. As can be seen, the number of publications started to grow significantly after 1993, which sounds as an indicator of the research growth in the field of space propulsion. The same conclusion can be inferred by the growing number of patents, whose growth is also pronounced ten years later (as of 2003). This increase in publications and patents implies in increasing investment in scientific research, and somehow this fact coincides with the increase in the space field budget between 2000 until 2009, as published in the Euroconsult Report (2010).

The scientific interest in this field confirms the need to develop new technologies for space propulsion. However, after 2011 we can observe a slight slowdown in the number of publications in this area. This may be a signal of the absence of revolutionary alternatives or significant discoveries, resulting in research budget restrictions and consequently in reduction of publications by the scientific community, especially in countries that invest in space technology, which are presented in Fig. 14.

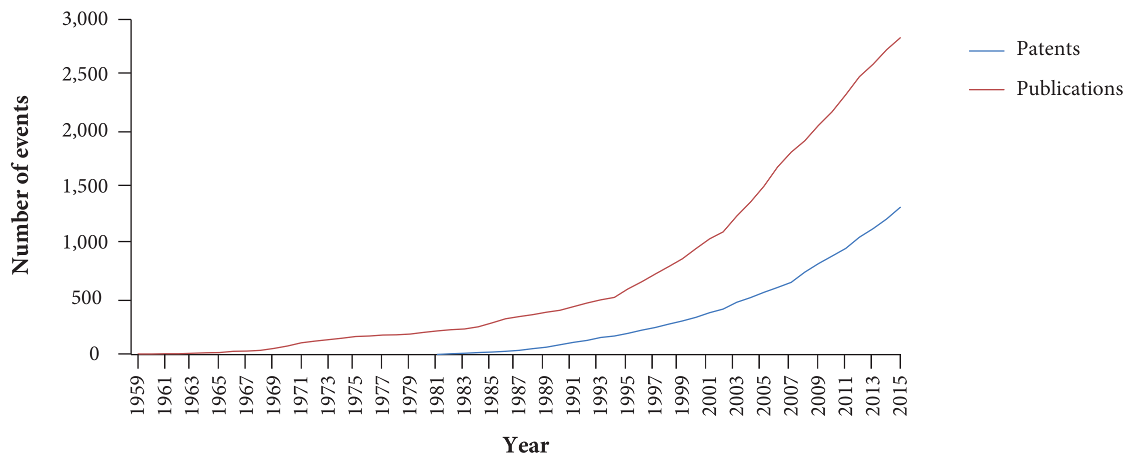

Figure 13. Publications and patents per year on "Space Vehicles Propulsion Systems" indexed in Scopus.

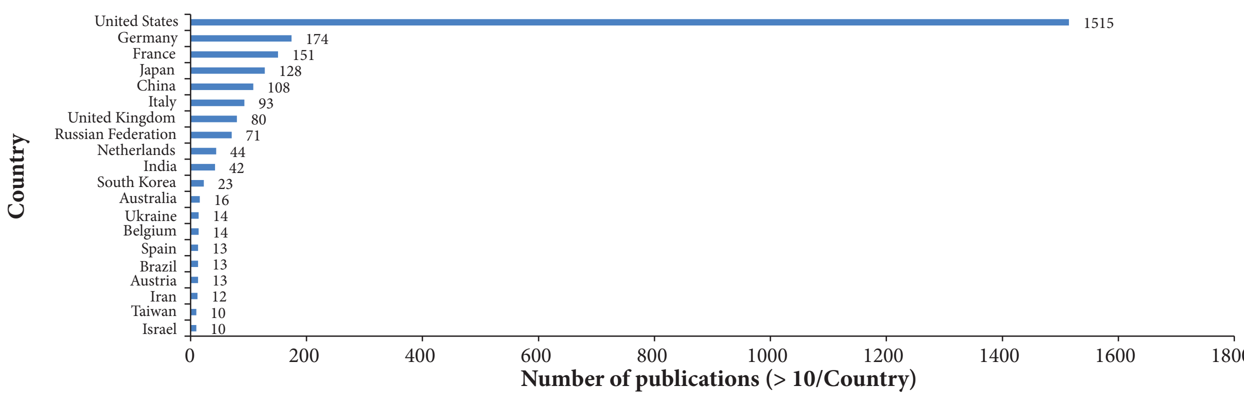

Figure 14. Number of publications on "Space Vehicles Propulsion Systems", by country, in the period 1959-2015, as indexed by Scopus.

MAIN EXPENDABLE LAUNCH VEHICLE OPERATIONAL CAPABILITY TO GEOSTATIONARY EARTH ORBIT

Expendable Launch Vehicles (ELV) are used once. The U.S. Space Transportation System (STS), *i.e.*, Space Shuttle, was designed as a reusable system to reach LEO. Most of its components are refurbished and reused multiple times. The space shuttle was a partially reusable vehicle used by NASA as a satellite launcher, spacecraft for manned missions in orbit and device repairs and refueling the International Space Station. The space shuttle was first released in 1981 and performed its last mission in 2011, when STS was deactivated.

A sampling of operational launch vehicles (ELV) that are of interest to interplanetary mission follows. One useful performance measure for comparison among launch vehicles is the amount of mass they can lift to Geostationary Transfer Orbit (GTO). Table 3 shows the categories of LV used in this study.

The following sections (and respective Figs. 15-20) analyze the launch vehicle thrust capacity evolution, considering the leading countries in space area, such as Europe, USA, Russia, Japan, China and India. Data extracted from Spacerockets (2012a).

Table 4 below shows the propellants types used in different launch vehicles, which are identified in the sequence of graphs exhibited in Figs. 15 to 20.

Table 3. Launch vehicle categories (Devezas *et al.* 2012).

Launch vehicle by category	
Category	**Payload lift capacity to LEO**
Small	< 2,000 kg
Medium	≥ 2,000 kg < 10,000 kg
Mid-heavy	≥ 10,000 kg < 20,000 kg
Heavy	≥ 20.000 kg

Table 4. Propellants.

Propellants	Type	Description
CTPB	Solid	Carboxyl-Terminated Polybutadiene
HTPB	Solid	Hydroxyl-Terminated Polybutadiene
HEF-20	Solid	High-Energy Fuel – equivalent to CTPB
PBAN	Solid	Polybutadiene-Acrylic Acid-Acrylonitrile Terpolymer
LOx	Liquid	Liquid Oxygen
LH_2	Liquid	Liquid Hydrogen
N_2O_4	Liquid	Nitrogen Tetroxide
UH 25	Liquid	75% UDMH and 25% Hydrazine Hydrate
UDMH	Liquid	Unsymmetrical Dimethyl Hydrazine
MMH	Liquid	Monomethyl Hydrazine
KEROSENE	Liquid	Kerosene
IRFNA	Liquid	Inhibited Red Fuming Nitric Acid (HNO_3+14% N_2O_4 + 1.5-2.5% H_2O + 0.6% HF)
AEROZINE 50	Liquid	50% Hydrazine and 50% UDMH
WFNA	Liquid	White Fuming Nitric Acid
MON	Liquid	Mixed Oxides of Nitrogen

ARIANE 5 (EUROPE)

The first launch of a rocket of the Ariane family happened in 1979 and Ariane launchers 1, 2 and 3 operated until 1986. The three launchers were slightly different. The first and third stages of Ariane 2 and 3 were longer than those of Ariane 1, while Ariane 3 had strap-on boosters containing liquid or solid propellant, making it the most flexible and powerful of the three and capable of launching a payload of 1.7 tons. Ariane 4 was extremely versatile. The first stage could hold two or four strap-on boosters, or none at all. This means that it could lift into GEO satellites weighing from 2.0 t to nearly 4.3 t, almost three times as much as Ariane-3. During its working life, Ariane 4 captured 50% of the market in commercial satellite launching, showing that Europe can more than hold its own in the commercial launch field.

Created as the first commercial space transportation company in 1980, Arianespace is now responsible for the production, operation and marketing of the Ariane 5 launchers. Arianespace serves more than half of the global market for spacecraft launches to Geostationary Transfer Orbit (GTO). The first Ariane 5 launch happened in 1999, followed by more 66 successful launchings. All Ariane 5 versions have a central core stage attached to two solid boosters. On top of this, different upper stage configurations are integrated. Ariane 5 Generic+ was designed to improve the initial Ariane 5 version performance and respond to a shift in market demand. A set of small but important changes have been introduced on a limited number of launchers, with the goal of increasing thrust as show in Fig. 15. These changes include: replacing the aluminum structure of Vehicle Equipment Bay (VEB) with a lighter composite version; a new separation system for VEB and main stage to reduce the separation shock; new electrical equipment and components.

Figure 15 shows the thrust evolution since Ariane 1 and how engine type and new propellant pairs improved the new model efficiency. Since 2003, Ariane 5 has been upgraded for increased reliability and liftoff capability, and is expected to remain one of the world's principal launch vehicles in the foreseeable future.

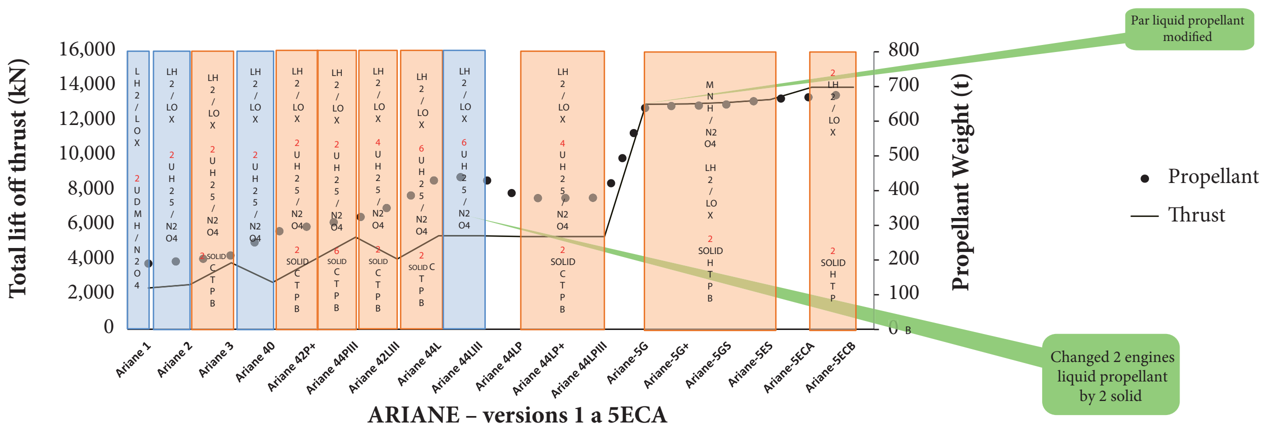

Figure 15. Thrust evolution and propellant types by engine, Space Launch Ariane family.

As will be shown in the next sections, there are now important developments being performed by other leading space faring nations, what will imply in a ferocious competition. The Chinese Long March; Atlas, Delta and Falcon-9 of the US; GSLV III and H-II manufactured in India and Japan, respectively; and the mighty Russian Soyuz-2 are all excellent and reliable mid-heavy launch rockets that will compete with Ariane 5.

ATLAS V AND DELTA IV (UNITED STATES)

The Atlas rocket family began its life in 1957 as the first successful Intercontinental Ballistic Missile (ICBM) launched by the United States, created by Lockheed Martin. On February 20, 1962, the Friendship 7 Mercury spacecraft, carrying the first American astronaut John Glenn, was launched on an Atlas Agena rocket. Atlas launch vehicles launched more than 100 scientific missions from 1960 to 1978, which delivered the first close-up photographs of another planet. Atlas-Centaurs launched the Pioneer deep space probes in the early 1970s, which sent back information on Saturn, Jupiter, and the farthest reaches of the solar system. Space Launch Complex 41 at the Kennedy Space Center (KSC), where Viking 1 and 2, and Voyager 1 and 2 began their journeys, has become the Atlas V launch facility.

The Atlas V rocket is an expendable launch vehicle formerly built by Lockheed Martin. It is now built by the Lockheed Martin-Boeing joint venture, United Launch Alliance. Aerojet develops and manufactures the Atlas V boosters. The rocket, built in Decatur, Alabama, consists of a first stage powered by kerosene and liquid oxygen, which uses a Russian made RD-180 engine, and a liquid hydrogen-liquid oxygen powered Centaur upper stage. Some configurations also use strap-on booster rockets. Together these components are referred to as the Atlas launch vehicle (Johnson 2012). Figure 16 shows the thrust evolution since Atlas LV-3C Centaur, and how engine type and new propellant pairs improved efficiency in successive models.

Delta rockets have been built and launched since 1960. Delta origins go back to the Thor intermediate-range ballistic missile, which was developed in the mid-1950s for the U.S. Air Force. Known as the "workhorse" of the launch industry, Delta is a family of two or three-stage liquid propelled ELVs that use multiple strap-on solid rocket boosters in various configurations. Originally made by McDonnell Douglas, it is now produced and launched by the Boeing and Lockheed Martin joint venture, United Launch Alliance (ULA). Figure 17 shows the thrust evolution since Delta A and how engine type and new propellant pairs improved efficiency in successive models.

Delta IV was developed in partnership with the U.S. Air Force EELV program and is the most advanced family of Delta rockets (Johnson 2012). Delta IV blends advanced and proven technology to launch virtually any medium-to-heavy size payload to space. Delta launch record (307 flights as of July 2004) includes Earth orbiters and interplanetary missions dating back to 1960. Space Launch Complex 37, a historic Saturn-1 launch pad at the KSC, has become the Delta-IV launch facility.

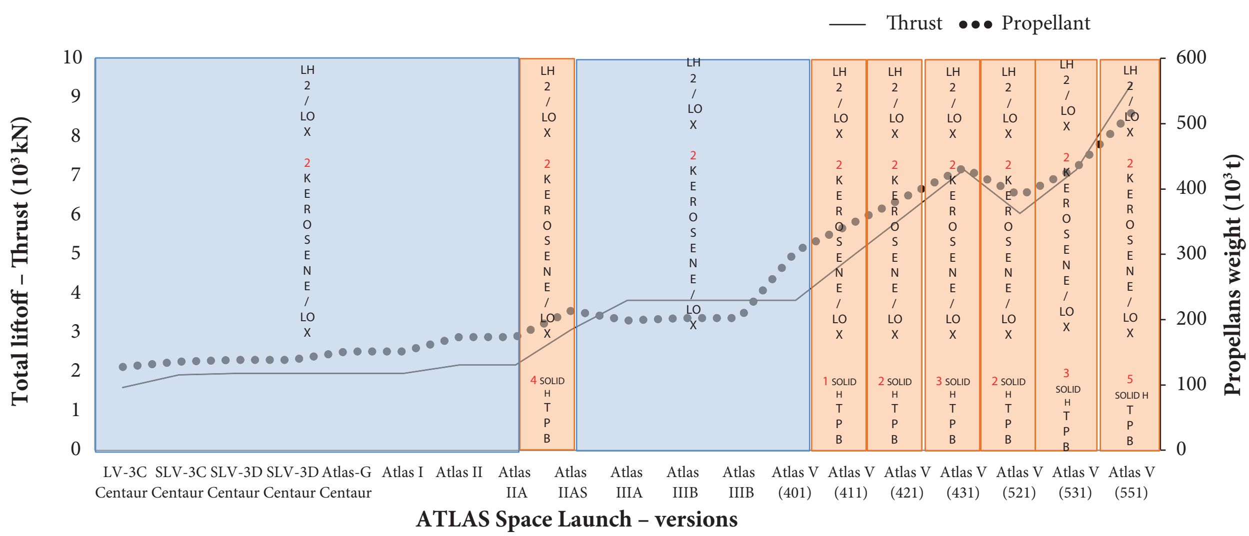

Figure 16. Thrust evolution and propellant types by engine, Space Launch Atlas family.

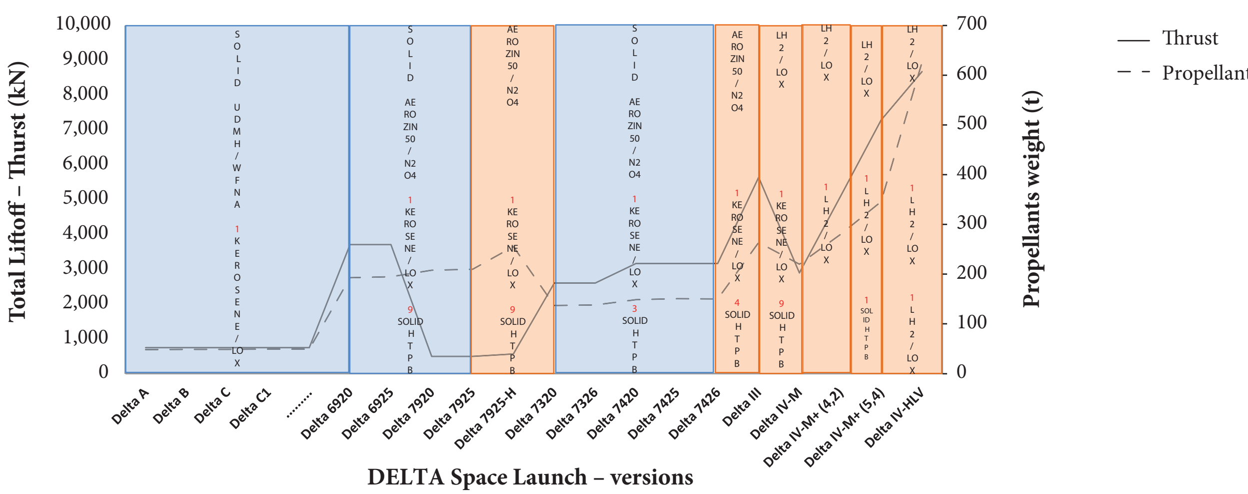

Figure 17. Thrust evolution and propellant types by engine, Space Launch Delta family.

PROTON (RUSSIA)

The Proton launch vehicle was developed in the 1960s as a two-stage intercontinental ballistic missile capable of lofting the heaviest Russian arsenal warheads. The heavy lifting capability of the Proton was appealing to the leaders of Russia space program as they prepared to compete against the US in the race to the Moon (Johnson 2012).

Figure 18 shows the evolution of the Proton and how engine type and new propellant pairs improved the new model efficiency. It is a liquid-propellant ELV, capable of placing 20,000 kg into LEO, originally developed by the Soviet CIS Interkosmos. It is launched from the Baikonur Cosmodrome in Kazakhstan, with launch services marketed by International Launch Services (a company formed in 1995 by Lockheed Martin, Khrunichev Enterprises and NPO Energies). With an outstanding reliability record and over 200 launches, the Proton is the largest Russian launch vehicle in operational service. It is used as a three-stage vehicle primarily to launch large space station type payloads into LEO and in a four-stage configuration to launch spacecrafts into GTO and interplanetary trajectories. The Proton launch vehicle family has become the principal heavy launcher of the Russian space program and one of the premier launch vehicles in the world.

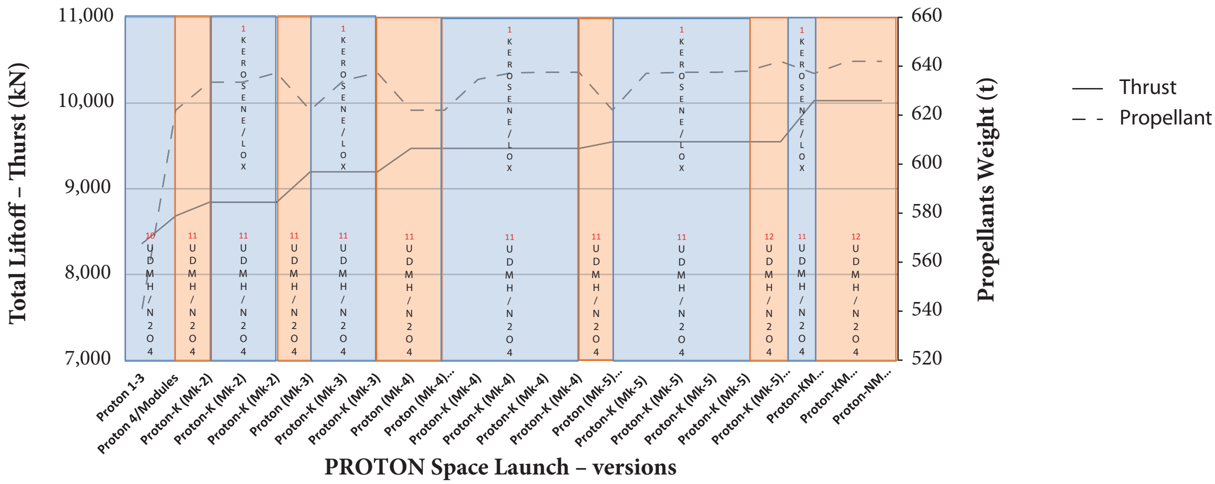

Figure 18. Thrust evolution and propellant types by engine, Space Launch Proton family.

LONG MARCH (CZ) 3 (CHINA)

The Chang Zheng 1 (CZ-1) was China's first space launch vehicle. The CZ-1 development was initiated in July 1965 in response to the demand for a rocket booster to launch the first Chinese satellite. The space launch vehicle was based on the two-stage DF-4 liquid-propellant (missile), to which is added a solid third stage rocket. The CZ-1 made only two launches, sending China's first artificial satellite Dongfanghong 1 into orbit in 1970. Figure 19 shows the evolution of the Long March and how engine type and new propellant pairs improved the successive models efficiency.

The CZ-3A launch vehicle development started in the 1980s, based on the flight proven technology of CZ-3. The main mission of this launch vehicle was to launch China's communications satellites. In February 1994, its maiden flight was successfully performed.

In April 1992, Intelsat executed a launch services contract to use a CZ-3B launcher to launch an Intelsat 708 communications satellite. This indicated that the CZ-3B development entered a new stage and the CZ-3B configuration had been acceptable by the global launch services industry. The maiden flight of CZ-3B launch failed because of altered inertial reference. After investigation and corrections, the CZ-3B launch vehicle achieved four consecutive successes in 1997 and 1998. The CZ-3B launch vehicle has been proven to be a mature powerful launch vehicle in the Long March family.

The feasibility study of CZ-4 began in 1982. Initially, the CZ-4 served as a backup launch vehicle for CZ-3 to launch China's communications satellites. After the successful launch of China first communications satellites by CZ-3, the main mission of the CZ-4 was shifted to launch sun-synchronous orbit meteorological satellites.

CZ-4 is a three-stage liquid propellant launch vehicle developed based on CZ-3, especially dedicated for launching different spacecraft for LEO, SSO and GTO missions. The launch vehicle features a newly designed third stage, which is capable of a "second ignition"; *i.e.*, shut down the engine during flight and fly under inertia for a while before the engine is reignited. This technology enabled the launch vehicle to send a heavier payload without increasing its fuel load. As of April 2006, a new satellite was successfully launched by a CZ-4B launch vehicle from Taiyuan Satellite Launch Centre (TSLC). The difference between CZ-4 types A and B is the static envelope diameter, for Type A is 2,360 mm and for Type B is 2,900 mm.

In November 2007, a three-stage CZ-4C carried a satellite from Taiyuan Satellite Launch Center. CZ-4C is an upgraded version of CZ-4B, and includes a restartable third stage, as well as a modified inter-stage design.

China is starting a new project on the next-generation Chang Zheng (CZ) rocket – medium and small launch vehicles CZ-6 and CZ-7, a new development designed to be capable of "rapid launch". The rocket will be assembled in the factory and transported to the launch site in one piece. The rocket is then fuelled in the horizontal position, before being erected on the launch pad ready for launch.

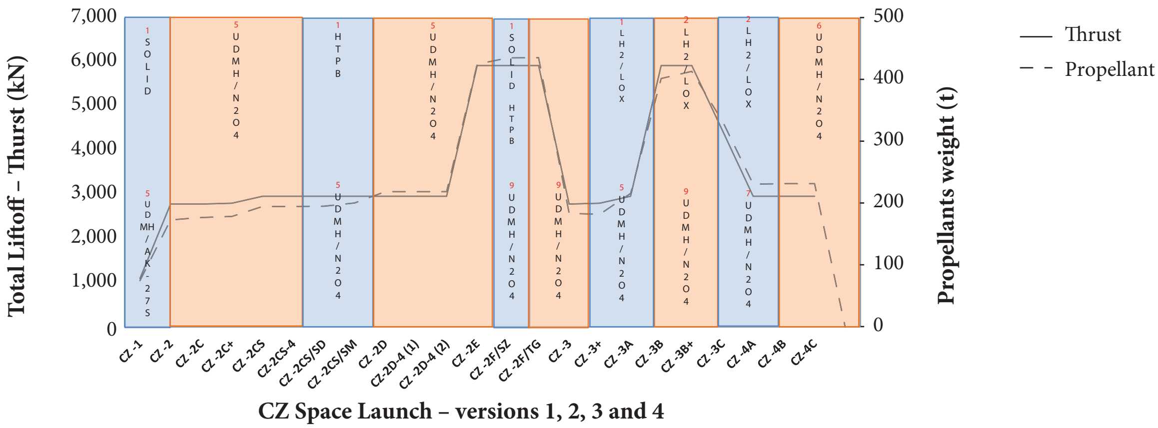

Figure 19. Thrust evolution and propellant types by engine, Space Launch CZ family.

GSLV (INDIA)

India began the development of space rockets aiming to launch Earth satellites with the foundation of the Indian Space Research Organization (ISRO) in 1969. The first SLV-3 launcher weighed 17 tons and was 22 m high and 1 m in diameter. It is a small launcher capable to carry a payload of about 40 kg into circular 500 km orbit. The ASLV was derived from SLV-3 with the addition of two boosters and its capacity reached 150 kg payload in LEO.

The PSLV (Polar Satellite Launch Vehicle) has a unique configuration of alternating solid and liquid stages. PSLV was initially designed to place 1,000 kg class Indian Remote Sensing (IRS) satellites into 900 km polar SSO. Since the first successful flight in October 1994, the capability of PSLV has been enhanced from 850 kg to the present 1,600 kg into 618 km polar SSO. The improvement in the capability through successive flights has been achieved by increased propellant loading in the stage motors.

Geosynchronous Satellite Launch Vehicle (GSLV) was declared operational after its two successful developmental test flights conducted in April 2001 and May 2003. In its first operational flight, GSLV-F01 successfully launched the 1,950 kg G-SAT 3 on September 2004. The GSLV uses a lower stage closely derived from the PSLV, with a new cryogenic third stage replacing the third and fourth stage of PSLV. In place of small solid strap-on boosters used in the PSLV, the GSLV uses four liquid boosters that are derived from the PSLV second stage. Figure 20 shows the evolution of the GSLV and how engine type and new propellant pairs improved the successive model efficiency.

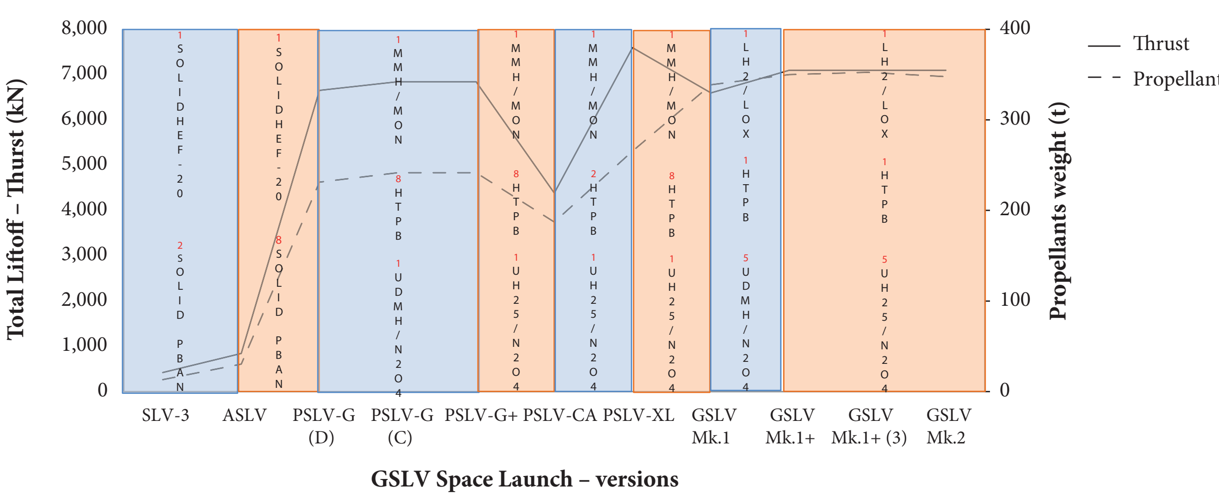

Figure 20. Thrust evolution and propellant types by engine, Space Launch GSLV family.

Table 5 shows a comparative resume about thrust, engines and propellant type in current launch vehicles of the leading space faring nations.

Table 5. Comparative in current Launch Vehicle (SPA... 2012b).

Country	Year	Launch vehicle	Thrust (kN)	N° Engines – Propellant
Europe	2003	Ariane 5ECA	14.000	2 – LH2/LOx
				2 – Solid HTPB
USA	2007	Atlas V	9.500	2 – LH2/LOx
				2 RP-1/LOx
				5 – Solid HTPB
	2005	Delta IV	8.700	3 – LH2/LOx
Russia	2002	Proton KM Breeze M	10.000	2 RP-1/LOx
				12 UDMH/N_2O_4
Japan	2009	H-IIB	10.000	2 – LH2/LOx
				4 – Solid HTPB
China	1997	CZ-3B	6.000	2 – LH2/LOx
				9 UDMH/N_2O_4
India	2004	GSLV	7.000	2 – LH2/LOx
				2 – Solid HTPB
				5 – UH25/N_2O_4

FUTURE PROPULSIONS

There are currently some projects under development looking for interesting alternatives to carry humans into the deep space. Such alternatives include some technologies already mentioned, such as solar sail, fusion, plasma, and nuclear propulsion. Table 6 presents a short resume of these alternatives, which are all still in a very low TRL (< 3).

SPACE ELEVATOR

As we have seen, space launch systems are limited until now by the physics of rocket propulsion. Most of their weight is propellant and the payload's weight represents less than 10% of the total. One important and interesting alternative solution that many studies around the world are seeking in order to provide a safer and low cost access to space is the *space elevator*.

The concept of a space elevator from Earth to orbit has been around for more than a century. The fundamental idea of the "space elevator" goes back to 1895, when the scientist Konstantin Tsiolkovsky considered building a tower from the surface of the Earth and reaching into the geostationary orbit. In 1960, Artsutanov proposed a way to build a tensile structure to the geostationary orbit. The aim was, and still is, among other objectives, to deliver payload – satellites, astronauts or other equipment – to space in an economically viable way. According to Arthur C. Clarke (in his novel *The Fountains of Paradise*, where he develops the concept of a space elevator), a radical alternative to the expensive use of rockets. After Clark, a series of other science fiction authors also used and developed the idea.

However, today we can surely assert that the idea of a space elevator no longer belongs to the science fiction scene, but is indeed blossoming as a true technological alternative that can become a reality within the next 20 years, or even less. Since 2010, there have been important contests and competitions around the world, similar to the Ansari X Prize, with the aim of rewarding the best ideas for the practical implementation of a space elevator. The main reason to think

Table 6. Project under development – propulsion system for deep space.

Project	Description	Country	Propulsion type
Orion	Multi-Purpose Crw Vehicle (MPCV) intended to carry astronauts into deep space (Moon, Mars anda asteroids) and then return them home to Earth. If necessary may transport cargo and crew to the space station. The design reference missions and concepts of operations require a series of challenging Guidance, Navigation and Control (GN&C) capabilities	USA - NASA and prime contractor Lockheed Martin.	Solar sail
Daedalus	To design a plausible interstellar unmanned spacecraft that could reach a nearby star within one human scientist working lifetime or about 50 years. At the time fusion research appeared to be making great strides, and in particular, inertial confinement fusion (ICF) appeared to be adaptable to a rocket engine. ICF uses small pellets of fusion fuel, typically lithium deuteride (6Li2H) with a small deuterium/tritium trigger at the center. The pellets are thrown into a reaction chamber where they are hit on all sides by lasers or another form of beamed energy. The heat generated by the beams explosively compresses the pellet, to the point where fusion takes place. The result is a hot plasma, and a small “explosion” compared to the minimum size bomb that would be required to instead create the necessary amount of fission. For Daedalus, this process was run within a large electromagnet which formed the rocket engine. After the reaction, ignited by electron beams in this case, the magnet funneled the hot gas to the rear for thrust.	England – British Interplanetary Society	Fusion
E-crew 2100	Proposes to send people to the stars by the year 2100: 100YSS (Year Starship). The very high cost of a crewed space mission comes from the need to ensure the survival and safety of the humans on-board and the need to travel at extremely high speeds to ensure it is done within a human lifetime. One way to overcome that is to do away with the wetware bodies of the crew, and send only their minds to the stars (their “software”) uploaded to advanced circuits. The basic idea of uploading is to “take a particular brain (of an astronaut, in this case), scan its structure in detail, and construct a software model of it that is so faithful to the original that, when run on appropriate hardware, it will behave in essentially the same way as the original brain”, Oxford University explains. So the size and weight of the starship will be dramatically reduced. Combined advances in neuroscience and computer science suggest that mind uploading technology could be developed in this century.	USA – DARPA And NASA and Oxford University	Light sail
Vasimr	Major goal would be for future spacecraft engine it to allow spacecraft to travel through the solar system more quickly than they can now. According to Ilin et. al. (2013), NASA’s astronaut created the VASIMR concept and has been developing it since 1977, the best option for long-range flights is nuclear power.This means that VASIMR could be integrated with the recently announced NASA Prometheus Project proposal to develop nuclear power generators for spaceflight. In order to conduct a manned trip to “Mars in just 39 days”, the VASIMR would require an electrical power level delivered only by nuclear propulsion, instead of the current estimated duration of three years, including a forced stay of 18 months on the Red Planet, while astronauts await an opening to return to Earth.	USA - NASA	Plasma

that space elevator is a possible technological achievement is the relatively recent development of carbon nanotubes, which have experienced very rapid progress in their development.

According to Swan *et al.* (2015), today’s traditional launching costs are of the order of about $25,000/kg (commercial) and $40,000/kg (government); but such launchings operate within a probability of success of 95% and their launch on time rate is close to 0%. Their projection for space elevator operations cost is about $100/kg, with a capacity around 98 tons payload per lift, for a estimated 7 days trip; but the most important feature of this kind of operation will be the very high probability of success (estimated > 99%), associated with a launch on time rate also of the order of 99% or more.

The actual concept of the space elevator system includes a vertical tether stretched from the surface of the Earth to the geostationary orbit, and electric vehicles (climbers) that drive up and down the tether, as shown in Fig. 21. The rotation of the Earth keeps the tether taut and capable of supporting the climbers.

The International Space Elevator Consortium (ISEC) is a traditional organization composed of individuals and organizations from around the world who share a vision of humanity in space. The ISEC purpose is to promote the development, construction and operation of a Space Elevator (SE) infrastructure as a revolutionary and efficient way to space for all humanity. In 2003, NASA published a report about the feasibility of a space elevator; after this study, the Lift Port Group of space companies was created in

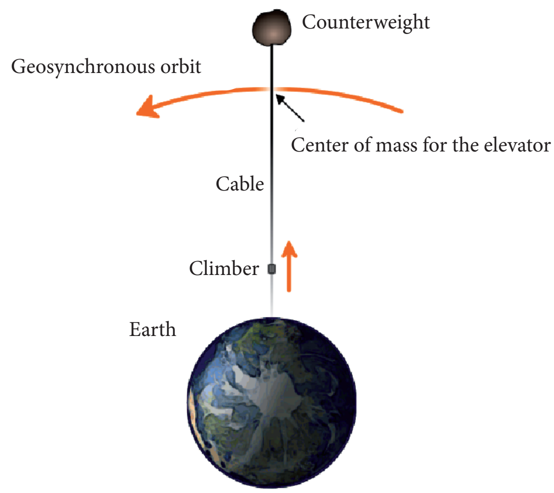

Figure 21. Space elevator concept (EUSpec: 2013).

order to build a space elevator as space transportation system. In 2015, the Canadian space company Thoth Technology awarded a patent for a space elevator that would reach about 20 kilometers above the Earth's surface.

The great challenge to make space elevator real is the development of a super-strong and flexible material that can be used to make the 100,000-km rope. The scientists assert that such a material will become real before 2030 (Swan *et al.* 2015). For a good state-of-the-art review of the available technology and still pending problems to solve (*e.g.*, the issue of space debris), see for instance Swan *et al.* (2013), Space Elevators: An Assessment of the Technological Feasibility and the Way Forward.

CONCLUSIONS

Analyzing the development of space propulsion engines technology over the last fifty years allow us to conclude about a very gradual progress that includes only incremental improvements and differential increases in thrust, specific impulse, weight reduction and fuel efficiency. In a nutshell, we have had just engineering and design gradual improvement rather than technological innovation. Our main conclusions and characteristics of the propulsion space rocket engines system are listed below:

- It can be concluded that reliable and affordable reusable engines remain a significant engineering challenge, but a challenge that can be overcome. While it took nearly a decade to reach this point and is expected to take nearly another decade to reach it, there is a good reason to believe that this incremental, determined approach will ultimately be proven successful.
- Space elevator is not a type of space propulsion, but a promissory alternative to space access to low orbits. Rockets are dangerous, complicated, relatively unreliable and incredible expensive, as Arthur C. Clarke used to say. The concept of a Space Elevator, no more a mere futuristic dream, consists of a cable – also known as a ribbon or tether – of material stretching from the Earth's surface into orbit as shown in Fig. 22. An anchor and Earth's gravity at the lower end, and a counterweight and centrifugal force at the top end keep the elevator's cable taut and stationary over the ground station. Robotic "climbers" could carry satellites up and bring minerals from the Moon, or asteroids, back. They could take tourists into orbit or convey astronauts on the first part of their journey to the stars. Estimates suggest that the cost of sending cargo into space could plummet to around \$100 per kilogram from the actual about \$20,000 per kilogram necessary for the risky rockets. "There's global interest" in this technology, "reducing the cost to access space will change the global economy", says David Horn, the Conferences Chair of the International Space Elevator Consortium (ISEC).
- The International Academy of Astronautics (IAA) showed in the "Next Steps in exploring Deep Space" (Johnson 2012) a vision for the scientific exploration of space in the first half of the 21st century. In the study, it is suggested that the future

deep space exploration requires no fundamentally new and expensive propulsion systems or launch vehicles. The tendency is to use proven technologies and a combination of astronaut and robotic capabilities for in-space assembly and fueling of reusable systems. IAA makes sure to emphasize that this study is not a strategic implementation plan for any national space program; rather, it represents a vision that can be considered by interested space agencies.

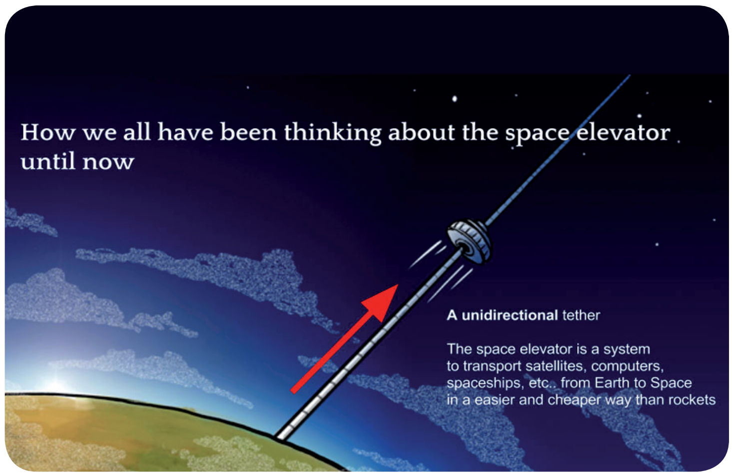

Figure 22. Space elevator by Marc Boucher, posted June 22, 2015 (SPAceref).

AUTHOR'S CONTRIBUTIONS

Conceptualization, Belderrain MCN and Devezas TC; Methodology, Belderrain MCN and Devezas TC; Investigation, Salgado MCV and Devezas TC; Writing – Original Draft, Salgado MCV; Writing – Review & Editing, Devezas TC; Funding Acquisition, Melo FCL; Resources, Salgado MCV; Supervision, Belderrain MCN and Devezas TC.

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