

NEXT-GENERATION ROCKET PROPULSION: A COMPARATIVE EVALUATION OF SYSTEMS FOR ADVANCING HUMAN SPACEFLIGHT

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Abstract - While traditional chemical propulsion systems have enabled humanity to enter space and explore nearby celestial bodies, their inherent limitations — such as low fuel efficiency, high mass ratios, and inability to support long duration missions — pose significant challenges for future interplanetary travel. In contrast, advanced propulsion technologies like ion propulsion, nuclear thermal propulsion, and plasma-based engines offer promising solutions by delivering greater efficiency, longer operational lifespans, and higher specific impulse. This study adopts a comparative evaluation methodology, analyzing multiple propulsion systems using key performance metrics such as specific impulse, thrust, efficiency, feasibility, and mission suitability. The systems are compared to assess their practicality for near-term and long-term human space exploration. Moreover, this paper investigates the potential of these next-generation propulsion stems to transform the scope, safety, and feasibility of deep space missions, particularly in the context of human

exploration of Mars and beyond, highlighting the engineering advancements, physical principles, and practical challenges that must be addressed to bring these technologies from concept to mission-ready reality.

I. INTRODUCTION

Throughout the years, spaceflight has advanced, and what started out as a race to conquer space has now turned into a global effort to sustainably explore and inhabit the cosmos. While early missions focused on reaching orbit and landing on the Moon, the current focus has shifted toward long-duration missions to Mars, deep space exploration, and building permanent infrastructure beyond Earth. However, the propulsion systems that got us into space — primarily chemical rockets — are now becoming a limiting factor. These systems are powerful but inefficient for long-distance travel due to high fuel consumption, massive launch mass, and limited specific impulse. To truly expand humanity's reach beyond Earth orbit,

more advanced propulsion technologies are essential.

These next-generation propulsion systems are not just theoretical concepts — they are being actively developed and tested by major space agencies and private companies worldwide. For example, NASA’s ion propulsion systems have already powered missions like Dawn and Deep Space 1, proving their long-duration efficiency, while the upcoming DRACO project aims to demonstrate nuclear thermal propulsion in orbit within this decade. Meanwhile, concepts like VASIMR and Hall-effect thrusters are gaining traction for future cargo transport and orbital maneuvering.

My research will explore alternatives like ion propulsion, nuclear thermal propulsion, and plasma-based systems by analyzing how they function, what advantages they offer over chemical propulsion, and how close we are to seeing them in active deep space missions. Through my research, I aim to analyze the underlying physics and engineering of these propulsion methods, compare their performance metrics such as specific impulse and thrust, and evaluate their readiness for real-world missions. By identifying both their advantages and the challenges they face including energy requirements, material durability, and political or safety concerns, I hope to better understand which technologies hold the most promise for enabling efficient, safe, and scalable interplanetary spaceflight in the near future.

While chemical propulsion remains essential for launch and early mission phases, its low efficiency and high propellant mass make it unsuitable for sustained deep-space travel. As mission goals shift toward Mars and beyond, propulsion technologies must be evaluated not only on performance but also on feasibility, safety, and mission role. This paper therefore emphasizes critical comparison alongside technical description, with particular focus on near-term human exploration.

II. METHODOLOGY

This paper adopts a comparative analytical methodology to evaluate propulsion systems for human spaceflight, with a specific focus on Mars missions and deep-space exploration. The comparison is based on key performance metrics including specific impulse, thrust, propulsive efficiency, power requirements and mission feasibility. These metrics were selected because they directly influence transit time, payload capacity, crew safety, and overall mission viability.

For Mars transit analysis, simplified mission assumptions are applied, including conventional interplanetary transfer trajectories and continuous or semi-continuous thrust models where applicable. Transit time estimates are treated as approximate and are used to compare relative performance rather than predict exact mission durations. Power availability assumptions reflect current or near-term technological limits, particularly for electric and plasma propulsion systems that rely on large energy inputs.

Performance data were obtained from space agency reports and established theoretical models. Propulsion systems were evaluated comparatively rather than independently, emphasizing on thrust and efficiency. Chemical propulsion systems were assessed based on demonstrated flight performance, while nuclear thermal propulsion was evaluated using ground-test data and validated engineering models. Electric, plasma, and antimatter propulsion systems were analyzed primarily on theoretical or experimental grounds, and are explicitly identified as such.

To maintain analytical clarity, propulsion systems are categorized as either demonstrated, partially demonstrated, or

theoretical. This distinction ensures that speculative performance does not overshadow engineering feasibility. The methodology therefore prioritizes realism in assessing near-term human missions, while still recognizing the long-term potential of advanced propulsion technologies.

III. HISTORY

A. A brief history

Rocket science has been practised since ages - and has been used for a multitude of things like artillery shells, fireworks and fire-arrows. According to NASA, the Chinese fire arrow was adopted by the Mongols in northern China, who employed Chinese rocketry experts as mercenaries in the Mongol army. Thus, rockets are thought to have spread via the Mongol Invasion to other areas of Eurasia in the mid 13th century ^[1]. Moreover, the British took an active interest in the rocket technology developed by Tipu Sultan [the ruler of Mysore] and mughal artillery rockets, and developed it further during the 19th century.

But at the beginning of the 20th century, there was a boom in this ‘industry’. Scientists and researchers investigated the new field of interplanetary space travel, and its feasibility, fueled by the fictitious writers of the time like Jules Verne and H.G. Wells. In 1903, high school mathematics teacher Konstantin Tsiolkovsky (1857–1935), inspired by Verne and Cosmism, published *The Exploration of Cosmic Space by Means of Reaction Devices*, the first serious scientific work on space travel. The Tsiolkovsky rocket equation—the principle that governs rocket propulsion—is named in his honor (although it had been discovered previously, Tsiolkovsky is honored as being the first to apply it to the question of whether rockets could achieve speeds necessary for space travel, according to NASA). He also advocated

the use of liquid hydrogen and oxygen for propellant, calculating their maximum exhaust velocity. His work was essentially unknown outside the Soviet Union, but inside the country it inspired further research, experimentation and the formation of the Society for Studies of Interplanetary Travel in 1924 ^[1].

B. Early methods of Propulsion

In most of the rockets used until and in the 19th centuries, rockets were propelled based on the principle of action and reaction, with gunpowder-filled tubes providing thrust. This technology, initially developed in China, involved igniting a mixture of saltpeter, sulfur, and charcoal (black powder) to produce a rapid expansion of gases that propelled the rocket in the opposite direction. These early rockets, often attached to arrows, were used for fireworks, signaling, and warfare ^[4] – as discussed previously.

In 1912 Robert Goddard, inspired from an early age by H.G. Wells and by his personal interest in science, began a serious analysis of rockets, concluding that conventional solid-fuel rockets needed to be improved in three ways. First, fuel should be burned in a small combustion chamber, instead of building the entire propellant container to withstand the high pressures. Second, rockets could be arranged in stages. Finally, the exhaust speed (and thus the efficiency) could be greatly increased to beyond the speed of sound by using a De Laval nozzle. He patented these concepts in 1914 ^[1].

The limitations of early propulsion systems like low efficiency, poor controllability, and high mass highlight why chemical rockets alone cannot support spaceflight. These historical constraints directly motivate the search for advanced propulsion systems capable of enabling faster, safer, and more sustainable space travel.

[Provided by Wikipedia]



Fig II.B.1
R. Goddard

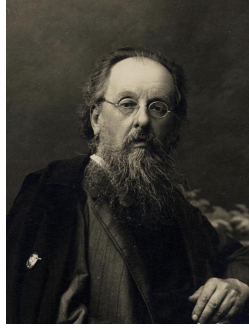


Fig III.1
K. Tsiolkovsky

IV. CHEMICAL PROPULSION

A large number of rockets in use today are chemical rockets; that is, they obtain the energy needed to generate thrust by chemical reactions to create a hot gas that is expanded to produce thrust.

The Tsiolkovsky rocket equation shows, using the law of conservation of momentum, that for a rocket engine propulsion method to change the momentum of a spacecraft, it must change the momentum of something else in the opposite direction. In other words, the rocket must exhaust mass opposite the spacecraft's acceleration direction, with such exhausted mass called propellant or reaction mass ^{[5] Sec 1.2.1 [6]}. For this to happen, both reaction mass and energy are needed. The impulse provided by launching a particle of reaction mass with mass m at velocity v is mv . But this particle has kinetic energy $\frac{mv^2}{2}$, which must come from somewhere. In a conventional solid, liquid, or hybrid rocket, fuel is burned, providing the energy, and the reaction products are allowed to flow out of the engine nozzle, providing the reaction mass ^[7].

$$\Delta v = v_e \ln \frac{m_0}{m_f} = I_{sp} g_0 \ln \frac{m_0}{m_f}$$

Above mentioned is the Rocket Equation where,

- v_e is the effective exhaust velocity;

- I_{sp} is the specific impulse in dimension of time;
- g_0 is standard gravity;
- $\ln$ is the natural logarithm function;
- m_0 is the initial total mass, including propellant, a.k.a. wet mass;
- m_f is the final total mass without propellant, a.k.a. dry mass.

When discussing the efficiency of a propulsion system, designers often focus on the effective use of the reaction mass, which must be carried along with the rocket and is irretrievably consumed when used ^[8]. Spacecraft performance can be quantified in the amount of *change in momentum per unit of propellant consumed*, also called specific impulse. This is a measure of the amount of impulse that can be obtained from a fixed amount of reaction mass. The higher the specific impulse, the better the efficiency. Ion propulsion engines have high specific impulse (~ 3000 s) and low thrust ^[9] whereas chemical rockets like monopropellant or bipropellant rocket engines have a low specific impulse (~ 300 s) but high thrust ^[10].

Most rocket engines are internal combustion heat engines (although non-combusting forms exist) ^[8]. Rocket engines generally produce a high-temperature reaction mass, as a hot gas, which is achieved by combusting a solid, liquid or gaseous fuel with an oxidiser within a combustion chamber ^[11]. The extremely hot gas is then allowed to escape through a high-expansion ratio bell-shaped nozzle, a feature that gives a rocket engine its characteristic shape ^[8]. The effect of the nozzle is to accelerate the mass, converting the thermal energy into kinetic energy, ^[8] where exhaust speeds reaching as high as 10 times the speed of sound at sea level are common.

Many different propellant combinations are used to obtain these chemical reactions, including hydrazine, liquid oxygen, liquid hydrogen, nitrous oxide, and hydrogen peroxide.

Chemically propelled rockets either have monopropellant or bipropellant engines.

[Provided by NASA]



Fig III.2

Bipropellant engines of the Lunar Module's RCS.

The dominant form of chemical propulsion for satellites has historically been hydrazine, however, this fuel is highly toxic and at risk of being banned across Europe [12]. Non-toxic 'green' alternatives are now being developed to replace hydrazine. Nitrous oxide-based alternatives are getting traction and government support, with development being led by commercial companies Dawn Aerospace, Impulse Space, and Launcher [12]. The first nitrous oxide-based system flown in space was by D-Orbit onboard their ION Satellite Carrier in 2021, using six Dawn Aerospace B20 thrusters, launched upon a SpaceX Falcon 9 rocket [12].

[Provided by Dawn Aerospace]



Fig III.3

Dawn Aerospace's B20 thruster in a static fire test.

A. Liquid Propellant

[Provided by NASA's Glenn Research Centre]

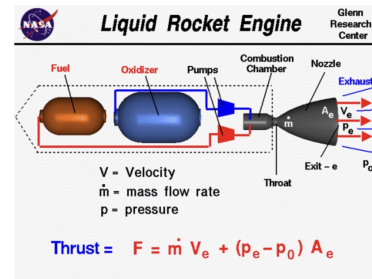


Fig III.A.1

Schematics of a liquid rocket engine.

Liquid propulsion systems are typically either a monopropellant or a bi-propellant. The propellants may be stored and fed from high-pressure fuel tanks (pressure-fed) or use turbopumps to move the propellant to the engine. Some propellants ignite on contact with one another, called hypergolic propellants [13]. These hypergolic propellants do not require any other ignition system to burn – making them much more reliable since there are no ignition systems to possibly fail. They have good in-space long-term storability but are also very toxic and corrosive to handle. The Orion vehicle European Service Module is a hypergolic propellant [13].

[Provided by NASA's Glenn Research Centre]

Liquid Propulsion System	Typical Propellants	Advantages	Disadvantages
Monopropellants	Hydrazine; Green Propellants	Relatively simple	Require heavy catalyst systems to operate
Hypergolic (bi-propellant)	Hydrazine; Nitrogen Tetroxide	Long term, in-space storable Don't require an ignition source	Toxic; Corrosive Lower performing than other propellants
Cryogenic (bi-propellant)	Hydrogen; Oxygen; Methane	High performance; Relatively benign	Need to be kept very cold; can have very large tanks
Nuclear Thermal	Hydrogen	Very High Performance	Requires nuclear reactor; heavy

Fig III.A.2

Data provided by NASA's Glenn Research Centre

B. Solid Propellant

Solid propellants are typically a solid cast material that contains both fuel and oxidizer bound in suspension that can produce thrust through chemical reactions [13]. This “fuel” can be handled at room temperature until an ignition source is applied. When the propellants are

ignited, they release both the fuel and oxidizer constituents which burn and generate thrust ^[13]. The solid rocket boosters on either side of the space shuttle are examples of solid propellant rockets. These systems generate a lot of thrust, can be stored for long periods of time in a “ready-to-go” state, but generally lack the controllability of turning them off and on when thrust is no longer needed or when a series of thrust pulses is needed, with some exceptions ^[13].

[Computer Generated Image based on Real life]



Fig III.B.1

The Space Shuttle’s Solid Rocket Boosters [SRB’s] being jettisoned after running out of fuel.

C. Hybrid Propellant

Hybrid propellant systems are a combination of solid propellant systems and liquid propellant systems ^[13]. Typically, there is a solid-propellant fuel but the oxidizer needed for combustion is kept separate as a liquid or gas ^[13]. As long as the oxidizer is supplied over the solid propellant, there is combustion, and thus there is thrust. The advantages of this type of system is the high thrust of solid propellant systems combined with the controllability (on-off) of liquid propulsion systems ^[13].

D. The Problem of Chemical Propulsion

Despite their historic significance, chemical propellants now act as a major bottleneck in our ambitions for long-term, large-scale space exploration. Their low specific

impulse and poor fuel efficiency demand enormous quantities of propellant just to escape Earth’s gravity — leaving little room for payloads or extended mission capabilities. These engines rely on finite fuel and produce intense heat, increasing engineering complexity and cost. As missions become more ambitious, aiming for Mars, the outer planets, or even deep space probes — the limitations of chemical systems become more pronounced. This reinforces the urgent need to shift toward advanced propulsion technologies like ion, plasma, or nuclear thermal systems which offer greater efficiency, lower mass requirements, and longer operational lifespans enabling faster, safer, and more feasible human and robotic exploration beyond Earth orbit.

Chemical propulsion provides unmatched thrust and reliability, making it indispensable for launch and rapid orbital maneuvers. However, its low specific impulse and heavy fuel requirements severely limit payload capacity and mission duration. As a result, chemical rockets are best suited for initial mission phases rather than long-duration interplanetary travel.

V. PROPULSION TECHNOLOGIES

A. Ion Propulsion

Electric thrusters typically use much less propellant than chemical rockets because they have a higher exhaust speed (operate at a higher specific impulse) than chemical rockets ^[14]. Due to limited electric power the thrust is much weaker compared to chemical rockets, but electric propulsion can provide thrust for a longer time ^[15]. As of 2019, over 500 spacecraft operated throughout the Solar System use electric propulsion for station keeping, orbit raising, or primary propulsion ^[17]. In the future, the most advanced electric thrusters may be able to impart a delta-v of 100 km/s (62 mi/s), which

is enough to take a spacecraft to the outer planets of the Solar System (with nuclear power), but is insufficient for interstellar travel. An electric rocket with an external power source (transmissible through laser on the photovoltaic panels) has a theoretical possibility for interstellar flight ^[17]. However, electric propulsion is not suitable for launches from the Earth's surface, as it offers too little thrust.

[Provided by NASA]

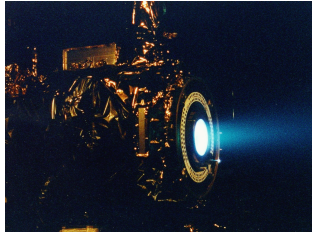


Fig IV.A.1
2.3kW ion engine of
Deep Space 1 in a static fire
test.

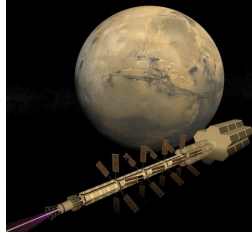


Fig IV.A.2
3D sketch of electro-
magnetic fusion
plasma thruster.

Ion propulsion rockets typically heat a plasma or charged gas inside a magnetic bottle and release it via a magnetic nozzle so that no solid matter needs to come in contact with the plasma ^[18]. It uses electric power, first to ionize atoms, and then to create a voltage gradient to accelerate the ions to high exhaust velocities ^[18]. At the highest exhaust speeds, energetic efficiency and thrust are all inversely proportional to exhaust velocity ^[14]. Their high exhaust velocity means they require huge amounts of energy and with practical power sources, they hardly use any fuel ^[14].

[Provided by Wikipedia]

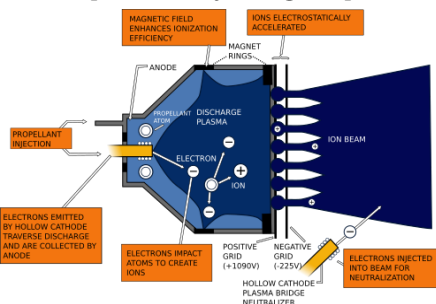


Fig IV.A.3

Diagram showing the working of an ion engine

Electric thrusters tend to produce low thrust, which results in low acceleration. Defining $1g = 9.81ms^{-1}$, the standard gravitational acceleration of Earth, and noting that $F = ma$, this can be analyzed. An NSTAR thruster (a type of spacecraft ion thruster which is a highly efficient low-thrust spacecraft thruster running on electrical power generated by solar arrays) producing a thrust force of 92 mN ^[19] will accelerate a satellite with a mass of 1 ton by -

$$\frac{0.092N}{1000kg} = 9.2 \times 10^{-5} ms^{-1}$$

However, this acceleration can be sustained for months or years at a time, in contrast to the very short burns of chemical rockets ^[20]. The force exerted is given by -

$$F = 2 \frac{\eta P}{g I_{sp}}$$

Where:

- F is the thrust force in N,
- η is the efficiency
- P is the electrical power used by the thruster in W, and
- I_{sp} is the specific impulse in seconds.

Ion thrusters would require two days to accelerate a car to highway speed in vacuum. The technical characteristics, especially thrust, are considerably inferior to the prototypes described in literature, technical capabilities are limited by the space charge created by ions.

[Provided by NASA's Jet Propulsion Laboratory]

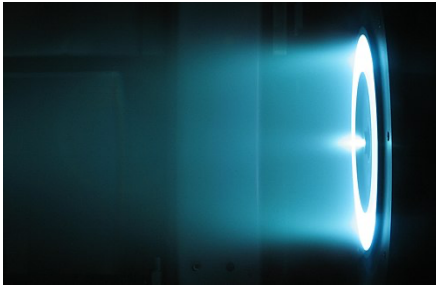


Fig IV.A.4

A 6kW Hall-effect thruster in operation

This limits the thrust density (force per cross-sectional area of the engine) ^[20]. Ion thrusters create small thrust levels (the thrust of *Deep Space 1* is approximately equal to the weight of one sheet of paper) compared to conventional chemical rockets, but achieve high specific impulse, or propellant mass efficiency, by accelerating the exhaust to high speed ^[20]. The power imparted to the exhaust increases with the square of exhaust velocity while thrust increase is linear. However, since they operate as electric (or electrostatic) motors, they convert a greater fraction of input power into kinetic exhaust power ^[20].

Despite its extremely high specific impulse and efficiency, ion propulsion produces very low thrust, resulting in slow acceleration. This makes ion engines unsuitable for crewed launches or time-critical human missions. Instead, they are best suited for uncrewed cargo transport, station-keeping, and deep-space probes where long operational lifetimes are more important than rapid transit.

B. Nuclear Propulsion

The attraction of nuclear propulsion and power in space is built on the high efficiency and theoretical capability that can be delivered with a nuclear system, namely energy efficiency of the system and endurance/capacity of the system to function over long distances.^[21] In balance, the systems needed to protect humans

in both the space-lift and operations phase are significant detriments.

A nuclear thermal rocket (NTR) is a type of thermal rocket where the heat from a nuclear reaction replaces the chemical energy of the propellants in a chemical rocket ^[22]. In an NTR, a working fluid, usually liquid hydrogen, is heated to a high temperature in a nuclear reactor and then expands through a rocket nozzle to create thrust ^[22]. The external nuclear heat source theoretically allows a higher effective exhaust velocity and is expected to double or triple payload capacity compared to chemical propellants that store energy internally ^[22]. Most liquid-fueled chemical rockets use either hydrogen or hydrocarbon combustion, and the propellant is therefore mainly water (molecular mass 18) and carbon dioxide (molecular mass 44) ^[22]. Nuclear thermal rockets using gaseous hydrogen propellant (molecular mass 2) therefore have a theoretical maximum specific impulse that is 3 to 4.5 times greater than those of chemical rockets ^[22].

[Provided by NASA's Glenn Research Centre]

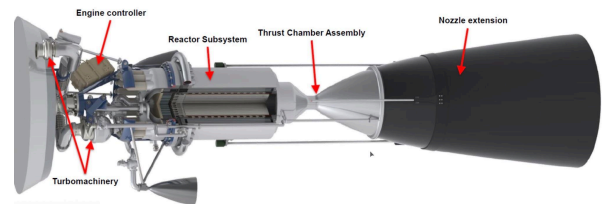


Fig IV.B.1

CAD Model of a Nuclear Thermal Propulsion (NTP)
Engine Assembly

Nuclear Thermal Propulsion (NTP) systems use a compact nuclear fission reactor to heat a working fluid, typically liquid hydrogen, which then expands and is expelled through a nozzle to generate thrust. Unlike chemical rockets, where thrust is produced via combustion, NTP systems rely on fission reactions to generate heat, offering significantly higher energy density. The hydrogen is heated inside the reactor core—where enriched uranium

undergoes fission—and then expelled at high velocity. This results in exhaust velocities v_e of approximately 8,000 to 9,500 m/s, translating to a specific impulse I_{sp} of 850–950 seconds, nearly double that of traditional chemical propulsion. The thrust produced is defined by the equation $F = m \cdot v_e$ ^[22], where m is the propellant mass flow rate. For a given power input, the exhaust velocity is also influenced by gas temperature T .

The thermal efficiency and thrust-to-weight ratio of these engines make them well-suited for deep-space missions like crewed travel to Mars, where reduced transit time minimizes radiation exposure. Solid-core reactors, such as those developed in NASA's NERVA program, are the most mature design, while more advanced liquid and gas-core reactors remain theoretical ^[23]. Current projects like DRACO (Demonstration Rocket for Agile Cislunar Operations) aim to test space-ready NTP systems using low-enriched uranium by the late 2020s. Despite technical and political challenges—including reactor safety, neutron shielding, and launch protocols—NTP remains one of the most promising near-term propulsion systems capable of bridging the gap between the Moon, Mars, and beyond ^[24].

Nuclear thermal propulsion offers a strong balance between thrust and efficiency, making it one of the most realistic candidates for human missions beyond Earth orbit. Its ability to significantly reduce transit time to Mars directly lowers crew exposure to radiation and microgravity. However, challenges related to reactor safety, shielding, and political constraints can still influence whether or not it is used.

C. Plasma Propulsion

A plasma propulsion engine is a type of electric propulsion that generates thrust from a quasi-neutral plasma. This is in contrast with ion

thruster engines, which generate thrust through extracting an ion current from the plasma source, which is then accelerated to high velocities using grids of anodes. However, in the scientific literature, the term "plasma thruster" sometimes encompasses thrusters usually designated as "ion engines" ^[25].

Plasma thrusters do not typically use high voltage grids or anodes / cathodes to accelerate the charged particles in the plasma, but rather use currents and potentials that are generated internally to accelerate the ions, resulting in a lower exhaust velocity given the lack of high accelerating voltages. This type of thruster has a number of advantages. The lack of high voltage grids of anodes removes a possible limiting element as a result of grid ion erosion. The plasma exhaust is 'quasi-neutral', which means that positive ions and electrons exist in equal numbers, which allows simple ion-electron recombination in the exhaust to neutralize the exhaust plume, removing the need for an electron gun (hollow cathode). Such a thruster often generates the source plasma using radio frequency or microwave energy, using an external antenna. This fact, combined with the absence of hollow cathodes (which are sensitive to all but noble gases), allows the possibility of using this thruster on a variety of propellants, from argon to carbon dioxide air mixtures to astronaut urine ^[26].

[Provided by NASA's Glenn Research Centre]



Fig IV.C.1

A plasma thruster being test fired

Plasma engines have a much higher specific impulse I_{sp} than most other types of rocket technology. The VASIMR thruster can be throttled for an impulse greater than 12000 s, and Hall thrusters have attained ~2000 s. This is a significant improvement over the bipropellant fuels of conventional chemical rockets, which feature specific impulses ~450 s [27]. With high impulse, plasma thrusters are capable of reaching relatively high speeds over extended periods of acceleration. Ex-astronaut Chang-Díaz claims the VASIMR thruster could send a payload to Mars in as little as 39 days [28]. Certain plasma thrusters, such as the mini-helicon, are hailed for their simplicity and efficiency. Their theory of operation is relatively simple and can use a variety of gases, or combinations. These qualities suggest that plasma thrusters have value for many mission profiles [26].

Different types of plasma thrusters are mentioned below:

1. **Helicon plasma thrusters** use low-frequency electromagnetic waves (Helicon waves) that exist inside plasma when exposed to a static magnetic field. An RF antenna that wraps around a gas chamber creates waves and excites the gas, creating plasma. The plasma is expelled at high velocity to produce thrust via acceleration strategies that require various combinations of electric and magnetic fields of ideal topology. They belong to the category of electrodeless thrusters. These thrusters support multiple propellants, making them useful for longer missions. They can be made out of simple materials including a glass soda bottle [29].
2. **Magnetoplasmadynamic thrusters (MPD)** use the Lorentz force (a force resulting from the interaction between a

magnetic field and an electric current) to generate thrust. The electric charge flowing through the plasma in the presence of a magnetic field causes the plasma to accelerate. The Lorentz force is also crucial to the operation of most pulsed plasma thrusters [25].

3. **Pulsed inductive thrusters (PIT)** also use the Lorentz force to generate thrust, but they do not use electrodes, solving the erosion problem. Ionization and electric currents in the plasma are induced by a rapidly varying magnetic field [25].
4. **Electrodeless plasma thrusters** use the ponderomotive force which acts on any plasma or charged particle when under the influence of a strong electromagnetic energy density gradient to accelerate plasma electrons and ions in the same direction, thereby operating without a neutralizer [25].
5. **VASIMR, short for Variable Specific Impulse Magnetoplasma Rocket**, uses radio waves to ionize a propellant into a plasma. A magnetic field then accelerates the plasma out of the engine, generating thrust. A 200-megawatt VASIMR engine could reduce the time to travel from Earth to Jupiter or Saturn from six years to fourteen months, and from Earth to Mars from 6 months to 39 days [25].

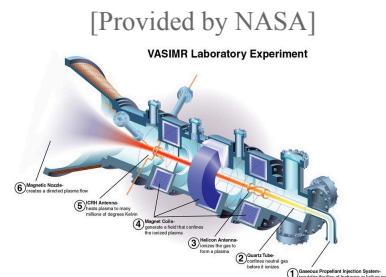


Fig IV.C.2

A schematic of the VASIMR thruster

While still in the experimental stage, plasma propulsion systems like VASIMR offer a unique combination of high efficiency, variable thrust, and potential for extremely fast interplanetary travel—making them one of the most promising candidates for future cargo missions and possibly even crewed missions once the immense power requirements can be met. Plasma propulsion systems provide exceptional efficiency and the potential for very high exhaust velocities, but they require large power sources and offer limited thrust. These constraints make them impractical for crewed launches with current technology. In the near term, plasma engines are more suitable for cargo missions and long-duration interplanetary travel once adequate power infrastructure is available.

D. Antimatter Propulsion

An antimatter rocket is a **proposed class** of rockets that use antimatter as their power source. There are several designs that attempt to accomplish this goal. The advantage to this class of rocket is that a large fraction of the rest mass of a matter/antimatter mixture may be converted to energy, allowing antimatter rockets to have a far higher energy density and specific impulse than any other proposed class of rocket ^[30].

Antimatter rockets can be divided into three types of application: those that directly use the products of antimatter annihilation for propulsion, those that heat a working fluid or an intermediate material which is then used for propulsion, and those that heat a working fluid or an intermediate material to generate electricity for some form of electric spacecraft propulsion system ^[31]. The propulsion concepts that employ these mechanisms generally fall into four categories: solid core, gaseous core, plasma core, and beamed core configurations ^[31]. The alternatives to direct antimatter annihilation

propulsion offer the possibility of feasible vehicles with, in some cases, vastly smaller amounts of antimatter but require a lot more matter propellant ^[31]. Then there are hybrid solutions using antimatter to catalyze fission/fusion reactions for propulsion.

The idea of using antimatter to power an electric space propulsion system has also been proposed. These proposed designs are typically similar to those suggested for nuclear electric rockets ^[31]. Antimatter annihilations are used to directly or indirectly heat a working fluid, as in a nuclear thermal rocket, but the fluid is used to generate electricity, which is then used to power the electric space propulsion system ^[31]. The resulting system shares many of the characteristics of other charged particle/electric propulsion proposals, typically being high specific impulse and low thrust ^[31].

[Provided by Wikipedia]

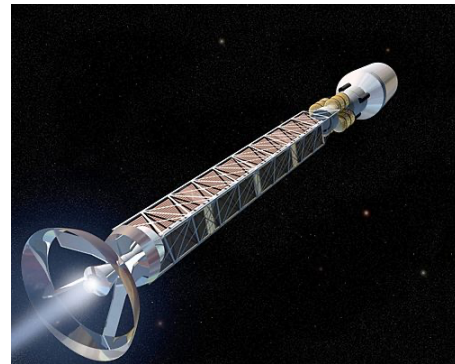


Fig IV.D.1

A proposed antimatter rocket

Below are the different types explained:

1. **Pure antimatter rocket:** Antiproton annihilation reactions produce charged and uncharged pions, in addition to neutrinos and gamma rays. The charged pions can be channelled by a magnetic nozzle, producing thrust. This type of antimatter rocket is a pion rocket. It is not perfectly efficient; energy is lost as

the rest mass of the charged (22.3%) and uncharged pions (14.38%), lost as the kinetic energy of the uncharged pions (which can't be deflected for thrust); and lost as neutrinos and gamma rays ^[31].

Positron annihilation has also been proposed for rocketry. Annihilation of positrons produces only gamma rays. Early proposals for this type of rocket, such as those developed by Eugen Sänger, assumed the use of some material that could reflect gamma rays, used as a light sail or parabolic shield to derive thrust from the annihilation reaction, but no known form of matter (consisting of atoms or ions) interacts with gamma rays in a manner that would enable specular reflection ^[31].

2. **Thermal antimatter rocket:** This type of antimatter rocket is termed a thermal antimatter rocket as the energy or heat from the annihilation is harnessed to create an exhaust from a material or propellant. The solid core concept uses antiprotons to heat a solid, high-atomic weight, metal core. Propellant is pumped into the hot core and expanded through a nozzle to generate thrust. The performance of this concept is roughly equivalent to that of the nuclear thermal

rocket ($I_{sp} \sim 10^3$ sec) due to temperature limitations of the solid ^[31].

However, the antimatter energy conversion and heating efficiencies are typically high due to the short mean path between collisions with core atoms ($I_{sp} \sim 85\%$) ^[31]. Several methods for the liquid-propellant thermal antimatter engine using the gamma rays produced by antiproton or positron annihilation have been proposed ^[32]. These methods resemble those proposed for nuclear thermal rockets. One proposed method is to use positron annihilation gamma rays to heat a solid engine core ^[31].

Hydrogen gas is ducted through this core, heated, and expelled from a rocket nozzle. A second proposed engine type uses positron annihilation within a solid lead pellet or within compressed xenon gas to produce a cloud of hot gas, which heats a surrounding layer of gaseous hydrogen ^[31].

Although antimatter propulsion offers unmatched theoretical performance, it remains entirely speculative at present. For now, antimatter propulsion should be viewed as a long-term theoretical concept rather than a realistic option for human spaceflight.

VI. COMPARATIVE EVALUTATION

The propulsion systems were compared using a framework based on specific impulse, thrust, energy efficiency, technology, safety, and mission feasibility. Performance data were

gathered from established and cited sources, and theoretical models. Each system was evaluated relative to its suitability for crewed and uncrewed missions.

S. no	Parameter	Chemical Propulsion	Ion Propulsion	Nuclear Thermal Propulsion	Plasma Propulsion	Antimatter Propulsion [theoretical]
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1	Thrust	Very High (~35 MN)	Very Low (~92 mN)	Medium to High (~250 kN est.)	Low to Medium (~5–10 N)	Extremely High (theoretical)
2	Specific Impulse (Isp)	300–450 s	3,000–10,000 s	850–950 s	2,000–12,000 s	Up to 1,000,000 s (theoretical)
3	Fuel Efficiency	Low – high fuel mass, low Isp	Very High – low fuel use	High – good Isp/thrust balance	Extremely High	Maximum theoretical
4	Mars Transit Duration	6–9 months	1.5–2.5 years (cargo)	~3–4 months	~39 days (theoretical)	Weeks (hypothetical)
5	Cost Estimate	\$500M–\$1B per mission	\$100M–\$300 M system	\$1B–\$2B (projected)	>\$500M incl. power	>\$60T/kg (fuel cost alone)
6	Energy Source	Combustion (chemical)	Electric (solar/nuclear)	Nuclear fission	Electric + magnetic fields (nuclear ideal)	Matter–antimatter annihilation
7	Feasibility (2025)	Fully developed & flight-proven	Proven (robotic use)	Prototype stage (DRACO)	Lab-tested only	Entirely theoretical
8	Radiation / Safety	Thermal risk, manageable	Very safe – low energy	High – neutron shielding required	Magnetic containment risks	Extreme – annihilation radiation
9	Propellant Type	RP-1, LOX, LH ₂ , hydrazine	Xenon, Argon	Liquid Hydrogen	Hydrogen, Argon	Antihydrogen, antiprotons
10	Life Support Compatibility	Fully compatible	Poor (not for launch)	Feasible if well shielded	Theoretically viable	Impossible at present
11	Mission Lifespan Potential	Short–Medium (weeks–months)	Very Long (5–10+ years)	Medium–Long (2–5 years/core)	Long (5+ years)	Unlimited (fuel-limited)
12	Launch Mass	High (heavy tanks & stages)	Low (small systems)	Medium–High (reactor + fuel)	High (engine + power system)	Extremely High [containment]
13	Dry Mass / Payload Capacity	Low dry mass; staging required	High – efficient design	Medium (shielding adds mass)	Medium–High	Very poor (shielding mass dominates)
14	Engine Restart Capability	Usually no (Liquid - yes)	Yes – throttleable	Yes – restartable	Yes – variable power	Unknown
15	Thermal	High	Low	High	High	Extreme

	Management Needs	(combustion heat)		(reactor cooling)	(plasma)	(gamma radiation)
16	Infrastructure Required	A lot (pads, tanks, transport)	Solar arrays or reactors	Nuclear safety infrastructure	Power modules, radiators	Unknown
17	Environmental Impact	Moderate (CO ₂ , toxic fuels)	Minimal (noble gases)	High (radiation risk)	Low (low emissions, high energy)	Unknown, potentially extreme
18	Scalability	Low (fuel limits)	High (modular arrays)	Moderate	High	Unknown (no working model)
19	Crew Safety Risk	Moderate – heat/explosion	Low – very safe	High – reactor hazards	Moderate – power/plasma issues	Extreme – fatal without shielding

The comparative evaluation demonstrates that propulsion system selection is very important and depends on the mission type carried out. Chemical propulsion, while offering extremely high thrust, suffers from low specific impulse and high propellant mass, restricting its usefulness to launch and short-duration mission phases. In contrast, ion and plasma propulsion systems achieve very high levels of specific impulse, drastically reducing fuel requirements, but their low thrust and high power demands limit their suitability for crewed missions with current technology. Nuclear thermal propulsion is a good mix of both, combining significantly higher efficiency than chemical rockets with sufficient thrust to enable reduced Earth–Mars transit times, making it a strong candidate for

human exploration. Although antimatter propulsion dominates the table in theoretical performance, its estimated cost, extreme safety risks, and lack of feasible containment technology exclude it from realistic mission planning. Consequently, future space missions are likely to rely on hybrid propulsion systems where chemical propulsion is used for launch and initial maneuvers, while nuclear or electric systems handle sustained interplanetary travel.

This analysis is primarily based on secondary literature and theoretical performance estimates rather than experimental flight data. As a result, real-world engineering constraints, economic factors, and operational uncertainties may affect the practical performance of these propulsion systems beyond what is presented.

Sources:

- 1. Chemical Propulsion**

NASA. (n.d.). *In-space propulsion*. Retrieved August 6, 2025, from https://www.nasa.gov/smallsat-institute/sst-soa/in-space_propulsion/

- 2. Ion Propulsion**

ScienceDirect contributors. (n.d.). *Ion propulsion*. Retrieved August 6, 2025, from <https://www.sciencedirect.com/topics/physics-and-astronomy/ion-propulsion>

3. **Nuclear Thermal Propulsion (NTP)**

U.S. Department of Energy. (2025). *6 things you should know about nuclear thermal propulsion*. Retrieved August 6, 2025, from <https://www.energy.gov/ne/articles/6-things-you-should-know-about-nuclear-thermal-propulsion>

4. **Plasma Propulsion (VASIMR)**

Wikipedia contributors. (2023, October 3). *Variable Specific Impulse Magnetoplasma Rocket*. Wikipedia. Retrieved August 6, 2025, from https://en.wikipedia.org/wiki/Variable_Specific_Impulse_Magnetoplasma_Rocket

5. **Antimatter Propulsion**

NASA Technical Reports Server contributors. (2020, January 15). *Antimatter propulsion*. NASA Technical Reports Server. Retrieved August 6, 2025, from <https://ntrs.nasa.gov/api/citations/20200001904/downloads/20200001904.pdf>

6. FUTURE SCOPE

Hybrid propulsion systems, which combine the raw power of chemical engines with the efficiency of electric or plasma engines, represent one of the most promising directions for future space missions. Chemical propulsion provides the high thrust necessary for rapid launches and orbital adjustments, which helps reduce crew exposure to microgravity and space radiation during critical phases of a mission. Meanwhile, electric or plasma propulsion can take over for long-distance interplanetary travel, offering far greater fuel efficiency and extending mission range. This combination makes hybrid systems especially attractive for crewed missions to Mars, the Moon, or even asteroid mining and interplanetary cargo transport. While some experimental spacecraft have already demonstrated parts of this concept, fully integrated hybrid propulsion systems are expected to become increasingly practical over the next decade, offering a balance of mission flexibility, safety, and operational efficiency.

Another major focus for the future of space exploration is reusability and sustainability. Developing propulsion systems and spacecraft components that can be reused multiple times has the potential to drastically reduce mission costs and environmental impact.

Reusable rockets, modular propulsion units, and fuel-efficient engines would allow for more frequent crewed flights, regular cargo resupply, and reliable satellite deployment. Companies such as SpaceX and Blue Origin have already shown that reusable technology is both feasible and effective, paving the way for a more sustainable approach to space travel. Reusable systems not only lower costs but also enable the rapid launch of multiple missions, building the kind of infrastructure necessary for humans to live and work in space over extended periods.

The growing involvement of commercial space initiatives is also accelerating the development of advanced propulsion technologies. Partnerships between private companies and government agencies, including NASA, have led to the creation of crewed spacecraft, innovative propulsion systems, and reusable launch vehicles. This commercial involvement is particularly significant for human missions, as private companies focus on scalable, safe, and cost-effective designs. By encouraging competition and fostering innovation, commercial adoption is helping make human spaceflight more frequent, accessible, and technologically advanced.

Finally, the long-term presence of humans in space will depend on the development of highly reliable and efficient propulsion systems. Missions such as permanent lunar bases, Mars colonization, or deep-space exploration to the asteroid belt and beyond require engines that can combine high thrust with sustained efficiency. Nuclear thermal propulsion and hybrid systems currently appear to be the most promising for crewed missions, as they allow faster transit times and reduce the risks associated with prolonged exposure to space radiation. Achieving these objectives will also require integrated life-support systems, radiation shielding, and careful resource management. Together, these advancements could allow humanity not only to explore other worlds but also to maintain a sustainable presence in space, laying the groundwork for future interstellar missions using next-generation propulsion technologies such as antimatter or high-powered plasma drives.

7. CONCLUSION

Chemical propulsion has been the backbone of human space exploration, enabling us to reach orbit, land on the Moon, and send probes throughout the solar system. Its high thrust and reliability have made it indispensable for launch and early space missions. However, chemical engines have clear limitations in efficiency and fuel capacity, which restrict how far and how fast we can travel in deep space. As missions become longer and more ambitious, relying solely on chemical propulsion will no longer be sufficient.

Advanced propulsion systems, such as ion engines, nuclear thermal propulsion, and plasma drives, offer significant advantages for specific mission types, including long-duration interplanetary travel and deep-space exploration. These technologies provide higher efficiency, longer operational lifetimes, and specialized

capabilities that chemical propulsion alone cannot achieve. Among the advanced propulsion systems discussed, nuclear thermal propulsion appears to be the most viable option for human interplanetary missions within the next few decades. Electric and plasma propulsion systems will likely play a critical supporting role in cargo transport and deep-space operations, while antimatter propulsion remains a long-term theoretical possibility.

For humanity to truly become a spacefaring civilization, it will be necessary to adopt, refine, and combine these advanced systems, while developing the infrastructure, safety measures, and expertise needed to sustain humans beyond Earth. By doing so, we can move closer to a future where long-term human presence in space is not just possible, but sustainable.

8. REFERENCES

- [1] Valier, M., von Braun, W., & Glover, G. (n.d.). History of rockets - Wikipedia. Wikipedia, the free encyclopedia. Retrieved July 22, 2025, from https://en.m.wikipedia.org/wiki/History_of_rockets
- [2] de la Garza, A. (2016). *The Mughal Empire at War: Babur, Akbar and the Indian Military Revolution, 1500-1605*. Taylor & Francis.
- [3] Ley, W. (1932). *Grundriss einer Geschichte der Rakete*. Hachmeister & Thal.

- [4] (n.d.). Brief History of Rockets. NASA Glenn Research Center. Retrieved July 22, 2025, from https://www.grc.nasa.gov/www/k-12/TRC/Rockets/history_of_rockets.html
- [5] Turner, M. J. L. (2009). Rocket and Spacecraft Propulsion: Principles, Practice and New Developments. Springer.
- [6] Tsiolkovsky, K. (1954). Reactive Flying Machines (Vol. II). A. A. Blagonravov. <http://epizodsspace.airbase.ru/bibl/inostroyazyki/tsiolkovskii/tsiolkovskii-nhedy-t2-1954.pdf>
- [7] Benson, T. (2005, December 12). Beginner's Guide to Rockets. Guided Tours. Retrieved July 23, 2025, from <https://web.archive.org/web/20130814022045/http://exploration.grc.nasa.gov/education/rocket/guided.htm>
- [8] Lewis, M. J. (n.d.). Rocket Engines – Introduction to Aerospace Flight Vehicles. Eagle Pubs. Retrieved July 23, 2025, from <https://eaglepubs.erau.edu/introductiontoaerospaceflightvehicles/chapter/rocket-engines/>
- [9] (2018, April 17). Retrieved July 23, 2025, from https://web.archive.org/web/20180417143504/http://www2.l3t.com/edd/pdfs/datasheets/EP_Thrusters-XIPS_PPU%20Overview%20datasheet.pdf
- [10] (2019, March 16). Chemical Bipropellant thruster family. <https://www.space-propulsion.com/brochures/bipropellant-thrusters/bipropellant-thrusters.pdf>
- [11] (n.d.). Rocket Propulsion. Retrieved July 23, 2025, from <https://www.grc.nasa.gov/www/k-12/airplane/rocket.html>
- [12] Chips, B. A. (2021, May 6). Dawn Aerospace validates B20 thrusters in space. Bit and Chips. Retrieved July 23, 2025, from <https://bits-chips.com/article/dawn-aerospace-validates-b20-thrusters-in-space/>
- [13] (2025, April 11). Chemical Propulsion Systems | Glenn Research Center | NASA. NASA Glenn Research Center. Retrieved July 23, 2025, from <https://www1.grc.nasa.gov/research-and-engineering/chemical-propulsion-systems/>
- [14] Glushko, V., & Walker, M. (n.d.). Spacecraft electric propulsion -

- Wikipedia. Retrieved July 23, 2025, from
https://en.m.wikipedia.org/wiki/Spacecraft_electric_propulsion
- [15] (n.d.). ESA Science & Technology - Electric Spacecraft Propulsion. ESA Science & Technology. Retrieved July 23, 2025, from
<https://sci.esa.int/web/smart-1/-/34201-electric-spacecraft-propulsion?fbclid=1535>
- [16] (2011, April 16). Electric Propulsion Research. NASA Web Archives.
<https://web.archive.org/web/20110816154150/http://fluid.ippt.gov.pl/sbarral/hall.html>
- [17] Choueiri, E. Y. (2009, February 1). The Efficient Future of Deep-Space Travel--Electric Rockets. Scientific American. Retrieved July 23, 2025, from
<https://www.scientificamerican.com/article/the-efficient-future-of-deep-space/>
- [18] (2024, November 2). Ion Propulsion. NASA Science. Retrieved July 23, 2025, from
<https://science.nasa.gov/mission/dawn/technology/ion-propulsion/>
- [19] Shiga, D. (2007, September 28). Next-Generation ion engine sets new record. New Scientist. Retrieved July 27, 2025, from
<https://www.newscientist.com/article/dn12709-next-generation-ion-engine-sets-new-thrust-record/>
- [20] (n.d.). Ion thruster - Wikipedia. Wikipedia, the free encyclopedia. Retrieved July 27, 2025, from
https://en.m.wikipedia.org/wiki/Ion_propulsion
- [21] (2013, March 15). A Survey of Nuclear Propulsion Technologies for Space Applications. Retrieved July 27, 2025, from
<http://large.stanford.edu/courses/2013/ph241/micks1/>
- [22] (n.d.). Nuclear thermal rocket - Wikipedia. Wikipedia, the free encyclopedia. Retrieved July 27, 2025, from
https://en.m.wikipedia.org/wiki/Nuclear_thermal_rocket
- [23] Arrighi, R. S. (2025, July 18). Nuclear Rockets. Rocket Systems Area. Retrieved August 5, 2025, from
<https://www.nasa.gov/rocket-systems-area-nuclear-rockets/>

- [24] Ridgeway, B. (2025, May 22). Space Nuclear Propulsion. NASA. Retrieved August 5, 2025, from <https://www.nasa.gov/space-technology-mission-directorate/tdm/space-nuclear-propulsion/>
- [25] (2022, January 27). Electric propulsion for satellites and spacecraft: established technologies and novel approaches. HAL. Retrieved August 5, 2025, from <https://hal.science/hal-03545719/file/PS-ST100513%20Review%20EP%20MAZOUFFRE.pdf>
- [26] (n.d.). Plasma propulsion engine - Wikipedia. Retrieved August 5, 2025, from https://en.wikipedia.org/wiki/Plasma_propulsion_engine
- [27] Defusco, A., Craddock, C., & Faler, W. (2019, November 2). Travel Aided by Plasma Thrusters. Defence Systems Information Analysis Centre. Retrieved August 6, 2025, from <https://dsiac.dtic.mil/articles/space-travel-aided-by-plasma-thrusters-past-present-and-future/>
- [28] O'Connell, C. (2016, March 18). Antimatter to ion drives : NASA's plans for deep space exploration. COSMOS. Retrieved August 6, 2025, from <https://massless.info/images/Antimatter%20to%20ion%20drives%20NASA's%20plans%20for%20deep%20space%20Cosmos.html>
- [29] (2009, March 5). Rocket Aims For Cheaper Nudges In Space; Plasma Thruster Is Small, Runs On Inexpensive Gases. Science Daily. <https://www.sciencedaily.com/releases/2009/02/090223221524.htm>
- [30] Schmidt, G. (2011). 62nd International Astronautical Congress 2011: (IAC 2011) : Cape Town, South Africa, 3-7 October 2011. International Astronautical Federation.
- [31] (n.d.). Antimatter rocket - Wikipedia. Wikipedia, the free encyclopedia. Retrieved August 6, 2025, from https://en.wikipedia.org/wiki/Antimatter_rocket#Methods
- [32] (n.d.). <https://ui.adsabs.harvard.edu/abs/1987A...15..551V>