

# The Future of Astronautical Propulsion

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## ABSTRACT

Space exploration will determine mankind's presence in the universe, and to progress space exploration new propulsion technologies must be developed. This paper reviews many upcoming propulsion technologies and critically evaluates all of their benefits and drawbacks. Along with explaining the future propulsion technologies, it also examines the limitations of current chemical propulsion and the necessity of advancing beyond it. Ion propulsion offers an extremely efficient method of deep space exploration while also possessing a substantial body of existing research. Nuclear thermal propulsion provides humanity with a reliable option for interplanetary missions or shorter exploration missions. Nuclear electric propulsion is a viable option for lengthy deep space exploration missions, and if used correctly it can be effective in interplanetary missions. Nuclear fusion thermal and nuclear fusion electric both extend the principles of their fission counterparts, but with higher efficiency and higher thrust. The Direct Fusion Drive is identified as the most promising technology presented, it can provide its own power and thrust vectoring. It also has an extremely high specific impulse, while maintaining a sufficient thrust. This makes it a viable option for any mission profile. The progression of these technologies will prove essential to humanity's ability to explore and inhabit the broader solar system and beyond.

## INTRODUCTION

Nearly a century has passed since the first successful rocket launch, and it opened up a lot of new possibilities for mankind. Despite these new opportunities, spacecraft propulsion is the primary limiting factor on any mission, within our solar system and beyond. The capabilities of the propulsion system determine the distance, speed and feasibility of the mission. Currently the main means of propulsion is by the combustion of a chemical fuel and an oxidizer. The power generated from this is insufficient for any large-scale exploration past the moon. A trip to Mars would take roughly 7-9 months to complete with people onboard.

Because propulsion is a primary factor in determining the feasibility of most astronautical missions, it is important to understand the limitations of current propulsion technologies, specifically chemical propulsion. Chemical propulsion has been used since the start of space exploration. While it was sufficient when the objective of missions was limited to achieving orbit around the Earth, it now significantly limits the ability to conduct deep space exploration. The most common type of chemical propulsion works by mixing a fuel and an oxidizer that react through combustion. This method of

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propulsion operates according to Newton's third law of motion, which states that for every action there is an equal and opposite reaction (NASA). The oxidizer supplies the oxygen required for combustion, most commonly liquid oxygen, and common fuels include RP-1 and liquid methane (Sia). In many liquid rocket engines, a small portion of propellant is first burned in a secondary chamber to drive turbopumps. The preburner powers the turbopumps during startup. The turbopumps force the fuel and oxidizer into the main combustion chamber at high pressure, where the propellants combust and produce rapidly expanding gases. The gases are accelerated through a narrow section known as the throat.

The throat accelerates the gases to supersonic speeds as pressure decreases. The gases then expand through the nozzle. The nozzle increases thrust by allowing further expansion, and larger nozzles enable greater expansion under low ambient pressure (Nancy Hall). In addition to liquid rocket motors, solid rocket motors are also used in spaceflight, but their inability to be throttled or restarted makes them unsuitable for most deep-space applications.

Chemical propulsion has a very low mass efficiency, with roughly 90% of a rocket's launch mass consisting of the propellant required to reach orbit (NASA). For example, a Falcon 9 rocket contains 872,369 pounds of propellant used during launch (Wikipedia). Consequently the need for massive amounts of propellant significantly increases launch costs and infrastructure requirements. In addition rockets can have negative environmental impacts. Rocket emissions contribute to localized depletion in Earth's ozone layer, and as the frequency of rocket launches increases, this problem is expected to become more relevant (Brown et al). A fundamental limiting factor stopping companies from increasing propellant mass is the Tsiolkovsky Rocket Equation. Adding more fuel makes the rocket heavier, a heavier rocket needs stronger engines, and stronger engines need more fuel. Iterating this process results in the rocket requiring exponentially more fuel for the same distance gain (Sia). This severely limits the capabilities of any chemically propelled spacecraft. This relationship is mathematically expressed by the Tsiolkovsky rocket equation:  $\Delta v = v_e \ln(m_0/m_f)$ , where  $\Delta v$  represents the change in velocity,  $v_e$  is the exhaust velocity, and  $m_0$  and  $m_f$  represent the initial and final mass of the rocket.

Because of chemical propulsion's limitations, researchers have explored alternative propulsion technologies that could enable faster and more efficient space travel. These technologies have the potential to make space exploration to distant regions of the solar system and beyond, far more feasible.

## **METHODS**

This paper is a literature review of six emerging propulsion technologies: ion propulsion, nuclear thermal propulsion, nuclear electric propulsion, nuclear fusion thermal propulsion, nuclear fusion electric propulsion and the Direct Fusion Drive. All of the sources were chosen depending on their relevance to each technology. Peer reviewed journals, research reports, and institutional publications from organizations like NASA, The National Academies of Sciences and Princeton Satellites were prioritized. Each of the technologies is evaluated based on its specific impulse, thrust capabilities, power

requirements, technological readiness and mission feasibility. The goal of this review is to assess the benefits of each method and determine the most promising candidate for future space exploration.

## **ION PROPULSION**

Ion propulsion generates thrust by ionizing a propellant gas, which is most commonly xenon. The ions are then accelerated to speeds ranging from 30–50 kilometers per second. Similar to chemical propulsion, this process operates according to Newton's third law of motion. Xenon is ionized using an electron-emitting device known as a cathode. The cathode emits electrons that collide with an electron in the xenon atoms, removing the electron and creating positively charged xenon. These ions are expelled by accelerating them using strong electric fields between charged electrostatic grids. The electrons inside the chamber are used to ionize the propellant and are confined by magnetic and electric fields. The acceleration occurs in a low-pressure environment, where electric fields control the motion of any charged matter. After the ions are expelled, a neutralizer cathode releases electrons into the exhaust to prevent the spacecraft from becoming electrically charged. The momentum of the expelled ions produces an equal and opposite force on the spacecraft.

## **ION PROPULSION RESTRICTIONS AND BENEFITS**

Although ion propulsion accelerates the ions to speeds 15 to 20 times faster than the exhaust gases in chemical propulsion, it still generates a substantially lower thrust than chemical propulsion due to the small mass of the ejected ions. However, the ion engines can operate continuously for months or even years. This allows spacecraft to reach velocities several times greater than spacecraft utilizing chemical propulsion because of the near frictionless vacuum of space (Charles). Ion engines also require significantly reduced amounts of fuel compared to chemical engines. Ion engines typically consume only a few milligrams of xenon per second, while the Space Shuttle consumed around 11,000 pounds of fuel every second (NASA). Although ion engines are incredibly efficient in terms of fuel usage, they require a substantial amount of electricity. Most spacecraft with ion propulsion rely on solar panels to provide power. However, solar panels lose effectiveness as the distance from the Sun increases. Due to the low thrust of an ion engine, ~250 millinewtons of thrust, it is incapable of launching from Earth's surface by itself. It will still require a first stage of chemical propulsion to leave the atmosphere (Charles). Although their extremely low thrust prevents their use for launch and rapid acceleration, ion engines are exceptional for deep-space missions in the near future.

## **NUCLEAR THERMAL PROPULSION**

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Unlike ion propulsion, nuclear propulsion has had extensive testing in the NERVA program, but it was never used for a real mission. One major type of nuclear propulsion is Nuclear Thermal Propulsion (NTP). This system uses liquid hydrogen as a propellant, which is then heated by a nuclear reactor. It operates by super heating the hydrogen and expelling it out of a nozzle at velocities roughly twice that of a conventional chemical rocket. Unlike chemical propulsion it does not require an oxidizer because the hydrogen is heated directly by the nuclear energy rather than combustion. This makes the rocket significantly lighter than chemical rockets, but storing the hydrogen poses its own challenge. Hydrogen in liquid form has an extremely low density (4.43lb/ft<sup>3</sup>). This makes storing it a challenge as it requires very high volume containers. Additionally, it also needs to be stored at extremely low temperatures, approximately -423°F. The nuclear reactor generates substantial heat, requiring careful thermal management to prevent unintended warming of the stored hydrogen. If the hydrogen warms up, it can create a dangerous pressure buildup inside the storage tanks. Although nuclear propulsion spacecraft will need an increased volume compared to current spacecraft, it will be substantially lighter due to its low density (National Academies). Although nuclear thermal propulsion could theoretically provide high thrust, launching nuclear reactors from Earth raises safety concerns related to potential accidents. In the event of a launch failure, radioactive materials from the reactor could be dispersed creating a radioactive debris field. For this reason, nuclear propulsion systems are typically proposed to be launched in space using conventional chemical systems and being activated after orbit is reached.

## **NUCLEAR ELECTRIC PROPULSION**

Nuclear electric propulsion utilizes a nuclear reactor to power ion thrusters. The thruster's primary limitation is the availability of electrical power. The nuclear reactor's power density is on the order of 10 kWe per 10 kg of mass (National Academies). However, when compared to the power density of solar power, approximately 200 W per 10 kg, it provides a substantial increase in available power (Caltech Magazine). The comparatively low power density of solar panels constrains the achievable thrust of ion propulsion systems. Experimental ion engines are projected to reach 5.4 newtons of thrust, consuming 102 kW, power levels that are attainable with compact space nuclear reactors (University of Michigan). The main drawback of NEP is the substantial amount of heat generated from the nuclear reactor. In the vacuum of space, heat cannot be removed through convection and must instead be dissipated via thermal radiation (Khrapach). The size of the radiator panels is directly determined by the amount of waste heat that must be rejected. As the reactor power increases, radiator mass and surface area also increase, creating a tradeoff between power and mass.

## **NUCLEAR FUSION PROPULSION**

Beyond nuclear fission propulsion, nuclear fusion propulsion represents a potential long-term option to enable dramatically faster deep-space travel. Unlike nuclear fission, which splits heavy atoms to form

smaller nuclei, nuclear fusion combines light nuclei into heavy atoms. The excess thermal energy from this process is what powers the propulsion system. There are three main uses for this thermal energy, two of which mirror fission applications. It can be used to heat up the propellant and eject it at high temperatures, significantly greater than that of nuclear fission (Gabielli et al.). The second option to utilize the heat created would be transferring it into electrical energy to power ion or hall effect engines (Wurden et al.). The final method would be a Direct Fusion Drive, an experimental technology developed by the Princeton Satellite Systems (Princeton Satellite Systems).

## **NUCLEAR FUSION THERMAL PROPULSION**

Nuclear fusion thermal propulsion uses the extreme heat created from nuclear fusion to heat up propellant and eject it through a nozzle, similar to nuclear fission thermal propulsion. The primary distinction lies in the higher plasma temperatures achievable in fusion systems, which may enable higher propellant heating compared to solid-core fission reactors (Gabielli et al.). For a thermal rocket operating at constant mass flow rate, exhaust velocity scales with the square root of propellant temperature, and thrust increases proportionally with exhaust velocity (Sutton, G. P., & Biblarz). Consequently, because exhaust velocity depends on the temperature, increasing the propellant temperature produces diminishing gains in thrust. Like nuclear thermal propulsion, fusion thermal propulsion systems do not require an oxidizer and benefit from hydrogen's low molecular mass, which contributes to its high specific impulse. Because fusion systems may achieve higher exhaust velocities, they can reduce the propellant mass required for a given mission  $\Delta v$  compared to lower-Isp systems, depending on the mission profile. In many fusion working-gas concepts, hydrogen propellant may serve both as a coolant for reactor structures and as the reaction mass expelled through the nozzle (Gabielli et al.). Liquid hydrogen has a very large liquid-to-gas expansion ratio under standard conditions, requiring careful thermal management to prevent excessive boil-off and pressure rise. Liquid hydrogen expands by several hundred times when transitioning from liquid to gas. Long term storage of liquid hydrogen requires advanced insulation and thermal management systems to minimize losses (U.S. Department of Energy). Storage solutions must also account for hydrogen embrittlement, as hydrogen diffusion into many metals can degrade strength (Hydrogen Tools). Fusion thermal propulsion concepts are projected to achieve specific impulses around 10,000 seconds. Substantially exceeding nuclear thermal propulsion systems (Forsley et al.).

## **NUCLEAR FUSION ELECTRIC PROPULSION**

Nuclear fusion electric propulsion is based on the same principle as nuclear electric propulsion. The energy generated from a fusion reactor can reach four times more than that of fission (IAEA). Because the main drawback of ion propulsion is its need for energy, a nuclear fusion reactor can substantially improve an ion engine's thrust output. The thrust of an ion engine scales linearly with the electrical input, meaning more power directly translates to more thrust (Sutton, G. P., & Biblarz). Because of the diminishing output of solar panels as they travel farther from the sun, they are not ideal for deep space or interstellar

travel. A nuclear fusion reactor can produce upwards of 100 megawatts (Wurden et al.). The strongest electric propulsion system currently is the X3 Nested Channel Hall Thruster, at full throttle it can consume 203 kW, and although never tested at full throttle it could potentially produce 10.58 newtons of thrust (University of Michigan PEPL). This is the strongest electric propulsion at present, but by the time fusion technology is refined to the level needed for astronautical travel, electric propulsion will also have been modernized. Currently electric propulsion is only viable for long distance travel due to slow acceleration, but high top speed. However, with nuclear fusion electrical propulsion electrical propulsion can reach sufficient power to make it a feasible option for shorter interplanetary missions.

## **DIRECT FUSION DRIVE**

A Direct Fusion Drive is an experimental propulsion technology developed by Princeton Satellite Systems. It works by superheating a plasma made of Helium-3 and deuterium and confining it using electromagnets (Thomas et al.). The heat creates a high pressure on the atoms and primarily produces Helium-4 and high energy protons (Thomas et al.). This causes a substantial release of energy. The energy is kinetic, rapidly moving the Helium-4. The plasma is surrounded by a coolant flow of deuterium plasma, which the Helium-4 collides with and transfers its kinetic energy (Thomas et al.). The coolant plasma is then shot out the back of the rocket through a small nozzle at 80 km/s - 120 km/s along with the Helium-4 waste (Thomas et al.). Radiation and heat emitted from the plasma is captured and used to drive a Brayton cycle, heating up a gas which is used to spin a turbine (Thomas). The turbine creates an electric current which is used to power onboard systems. The energy also powers the magnets containing the fusion plasma and the radio wave transmitter heating the helium and deuterium, creating a closed power cycle. The only inputs it needs are Helium-3 and Deuterium (Thomas). The spacecraft can weaken and strengthen the electromagnets holding the plasma to change the direction of the flow. This change in direction can steer the spacecraft in a manner identical to thrust vectoring (Takahashi et al.). The Direct Fusion Drive has a predicted specific impulse of 10,000 seconds (Thomas et al.), this is around 20 times more efficient than chemical propulsion, giving it a huge advantage in fuel consumption. The DFD operates similarly to an ion thruster, it produces up to 60 newtons of thrust, but it can sustain that thrust for many years (Thomas et al.). This means it shares the same problem as electric propulsion. It will require a separate method of propulsion to reach orbit. The key advantage of the DFD over ion or hall effect thrusters is that it generates its own power. To use ion thrusters at powers similar to a DFD, would require a large fusion reactor. This would have a consequential amount of heat waste which would require a massive array of radiators. The DFD will be significantly harder to create due to the unstable nature of the plasma and its varying densities, but it would be substantially more compact and cost effective than electric propulsion.

## **CONCLUSION**

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The advancement of astronautical propulsion is crucial to developing new technologies. One of the primary benefits of developing propulsion technologies would be advancing human transportation. Advanced propulsion can lower the radiation exposure affecting humans traveling outside of a strong magnetic field while also shortening the extended mission duration. Beyond widely recognized benefits, exploring deep space can yield substantial technological opportunities, such as the discovery of new materials and access to extraterrestrial resources. Near-Earth asteroids are estimated to hold vast quantities of metals, representing resources that could be used to advance Earth's economy along with introducing a space-based industry. Chemical propulsion restricts humanity to the inner solar system, making advancements in propulsion essential to exploring deep space.

Each of the propulsion systems presented provides distinct advantages that determine its feasibility for specific missions. Ion propulsion is the most mature technology presented. Its primary advantage lies in deep space exploration. The lengthy acceleration periods make it poorly suited for interplanetary missions. However, its high specific impulse and top speed make it ideal for uncrewed exploration missions. Nuclear thermal propulsion is similar to chemical propulsion, but considerably more efficient. It possesses a higher specific impulse and only requires one propellant. This lowers the proportion of the spacecraft dedicated to fuel storage while also decreasing mission durations. Nuclear electric propulsion is an upgraded power source for electric propulsion. Unlike conventional electric propulsion, which is limited by power and its proximity to a star, NEP removes this constraint entirely. This increase in electrical output directly enables increased thrust. This can potentially make it viable for interplanetary travel or crewed transportation. Nuclear fusion propulsion is the most theoretically capable option for space travel. Representing the next evolution of NTP, it benefits from a greatly increased specific impulse allowing for farther and faster travel. It can be a viable option for either crewed or uncrewed missions. Nuclear fusion electric propulsion is the next step in electric propulsion. It can be employed for any mission type, crewed, uncrewed, interplanetary or deep space. The significant increase in energy able to be provided to ion, hall effect or plasma thrusters gives it an increased thrust. With this high thrust it still displays the high specific impulse possessed by electric propulsion. Finally, the Direct Fusion Drive is the most promising technology presented, with a substantial amount of research conducted on it. However, it is still decades away from being perfected. Unlike ion and NEP systems, the DFD generates its own power internally, eliminating the need for a separate power source entirely. Although it requires two propellants, it has the highest specific impulse of the propulsion methods presented and is suitable for a wide range of mission profiles. Another benefit the DFD has over other propulsion systems is that it requires no subsystem for thrust vectoring. It should be noted that this review is based on currently available published projections and that figures for technologies still in development stages may change considerably as research continues.

<b>Technology</b>	<b>Specific</b>	<b>Thrust</b>	<b>Propellant</b>	<b>Power</b>	<b>Readiness</b>	<b>Mission</b>
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	<b>impulse</b>			<b>Source</b>		<b>Suitability</b>
<b>Chemical</b>	~450	4,000,000 - 35,000,000 N (varies by engine)	Fuel + Oxidizer	Chemical Combustion	Operational	Launch, short missions
<b>Ion Propulsion</b>	2,000 - 10,000	~250 mN – 5 N	Xenon	Solar Panels	Operational	Uncrewed deep space
<b>Nuclear Thermal</b>	800 – 1,000	~67,000 – 333,000 N	Liquid Hydrogen	Fission Reactor	Testing Phase	Crewed interplanetary
<b>Nuclear Electric</b>	2,000 – 10,000	~5 – 50 N (scalable with reactor power)	Xenon	Fission Reactor	Development	Any mission type
<b>Nuclear Fusion Thermal</b>	~10,000	~50,000 – 500,000 N (theoretical)	Liquid Hydrogen	Fusion Reactor	Theoretical	Any mission type
<b>Nuclear Fusion Electric</b>	2,000 – 10,000	Scalable, with multiple thrusters >100 N	Xenon	Fusion Reactor	Theoretical	Any mission type
<b>Direct Fusion Drive</b>	~10,000	Up to 60 N (scaleable)	Deuterium + Helium-3	Self-generating fusion	Early Development	Any mission type

Out of all the technologies presented in this paper, the Direct Fusion Drive holds the most promise. It has the capability to enable missions far beyond the reach of current technology. It is well suited for interplanetary missions, while also providing a substantial thrust over years for deep space exploration. The DFD will require at minimum several decades of continued development before it becomes operational; however, realizing these technologies will require overcoming substantial challenges. One of the main roadblocks any nuclear propulsion technology faces is the public. Despite fundamental differences between fission and fusion, public perception of nuclear technologies remains largely negative following disasters such as Chernobyl, creating a notable barrier to funding and political support. The development of these technologies will ultimately determine the extent of humanity's presence in the universe.

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