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Comparative Analysis of D-T and D-He³ Fusion for Mars-Bound Spacecraft

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Abstract

The feasibility of fusion propulsion for Mars-bound spacecraft depends on the selection of an optimal fuel, with Deuterium-Tritium (D-T) and Deuterium-Helium-3 (D-He³) being the primary candidates. This study presents a comparative analysis of these fuels under vacuum conditions, focusing on reaction efficiency, neutron radiation hazards, and fuel availability. The energy partitioning and neutron production rates of both reactions are examined, highlighting the shielding and structural integrity challenges posed by D-T fusion due to its relatively high neutron flux. Furthermore, specific impulse and thrust calculations are conducted to precisely assess the propulsion capabilities, considering mass flow rate constraints and fuel availability. The results indicate that while D-He³ fusion offers advantages in reduced radiation exposure and direct energy conversion potential, its fuel scarcity and ignition challenges pose significant obstacles. Conversely, D-T fusion provides higher reaction efficiency and greater thrust but requires extensive radiation shielding and thermal management. The study concludes that while neither fuel is currently viable for near-term spacecraft propulsion, advancements in fusion reactor miniaturization, cryogenic fuel storage, and thermal regulation systems could bridge existing technological gaps. Future research should focus on experimental validation of fusion propulsion systems, reactor optimization for space conditions, and improved He³ acquisition methods.

Keywords

Propulsion, Deuterium-Tritium, Deuterium-Helium-3, Direct Energy, Neutron Flux, Reaction Efficiency, Mars-Bound, Specific Impulse

1. Introduction

Chemical propulsion remains a dominant choice for spacecraft due to its well-understood mechanics and relatively simple construction [1]. It has been widely recognized as a cheap and minimally sophisticated propulsion system [2]. However, for interplanetary travel, chemical propulsion lacks sufficient thrust and specific impulse, requiring excessive amounts of propellant [3].

Alternative propulsion methods have been explored to overcome these limitations, with nuclear propulsion being a promising option. In nuclear fission, atoms split, releasing energy to heat a propellant, which expands and is expelled to generate thrust [4]. This system achieves higher specific impulse, meaning greater thrust per unit of fuel [5]. However, high development costs, radiation risks, and waste management challenges make it less practical [6].

Fusion propulsion is presented as an even more advanced alternative, offering significantly higher energy output with fewer radioactive byproducts [7]. Deuterium-tritium (D-T) and deuterium-helium-3 (D-He^3) are the two leading fusion reactions currently under consideration. Despite ongoing research, there is still no consensus on which fusion reaction, D-T or D-He^3, is more suitable for spacecraft propulsion, particularly for Mars exploration. While some studies highlight D-T fusion's higher energy output and easier ignition, others emphasize D-He^3's cleaner reaction with reduced neutron radiation. However, there remains a lack of direct comparative analysis that objectively evaluates both reactions in terms of their efficiency, safety, and economic feasibility in real-world interplanetary travel [8]. This study evaluates the feasibility of D-T and D-He^3 fusion for interplanetary propulsion, analyzing their efficiency, safety, and economic viability, with a particular focus on Mars exploration.

2. Literature Review

As mentioned earlier, chemical propulsion has long been considered a standard and very popular choice since the 1950s when it was first implemented in Sputnik Satellite [9]. It has been popularly utilized in Space Shuttle, Saturn 5 Rocket, and numerous small-scale satellites orbiting the Earth [9]. While it might be indeed a notable choice in the scope of Earth's orbit, it is highly inefficient for interplanetary travel. One of the reasons is that rockets that utilize chemical propulsion achieve specific impulses mostly in the range of 290 to 320 seconds, as indicated in **Figure 1**—specific impulse (I_{sp}) measures the efficiency of a rocket engine by identifying the thrust produced per unit of propellant consumed per second—while the optimal impulse is estimated to be approximately 2000 seconds, as given in **Table 1** [10] [11].

Table 1. I_{sp}, Thrust and propellent for electrical and chemical propulsions.

		Electrical	Chemical
1	Specific Impulse (s)	1200 - 3000	290 - 320
2	Thrust (N)	1 - 300 mN	10 - 400
3	Propellent	Xenon, NH_3	Hydrazine, N_2H_4 etc.

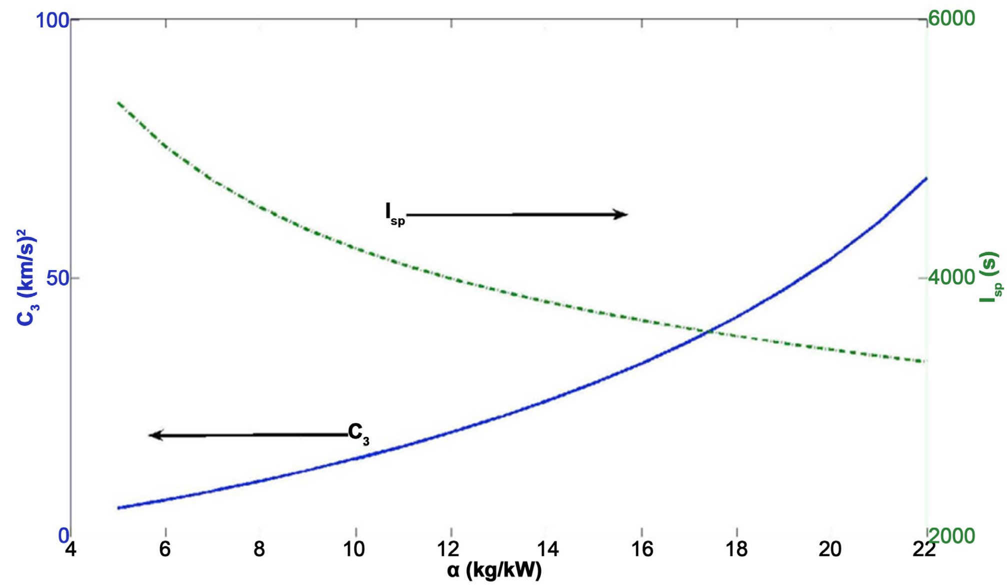

Figure 1. Correlation between C_3 and specific impulse (I_{sp}) as a function of α.

Even a stronger case against chemical propulsion would be the impracticality of its implementation in missions requiring high-velocity changes. It can be clearly illustrated by using Tsiolkovsky rocket equation:

$$\Delta v = v_e \ln\left(\frac{m_0}{m_f}\right) \tag{1}$$

Equation (1). Tsiolkovsky rocket equation

Equation (1) relates a rocket's velocity change (Δv), its exhaust velocity (v_e), and the mass ratio (m_0/m_f). For high-Δv missions, such as those to Mars, the logarithmic nature of the equation imposes a significant limitation: achieving the desired velocity necessitates an exponentially increasing amount of propellant. As more fuel is added, the rocket's total mass increases, which in turn demands even more fuel, making chemical propulsion an unlikely candidate.

Nuclear propulsion systems offer significantly higher velocity changes (Δv) than chemical propulsion due to their superior exhaust velocity (v_e) and reduced fuel requirements, enabling faster and more efficient interplanetary travel. Quantitatively, we compare the Δv values achievable by chemical propulsion and nuclear thermal propulsion (NTP). Assuming typical exhaust velocities of ~4000 m/s for chemical propulsion (liquid hydrogen/oxygen engines) and ~9000 m/s for NTP, with a mass ratio of 5—a reasonable assumption for interplanetary travel—the calculated Δv values are 7242 m/s and 14,485 m/s, respectively [12]. This increase in Δv is substantial, as it directly translates to reduced travel times. A higher Δv allows spacecraft to carry more payload instead of excessive fuel, increasing efficiency [13].

While these numerical results underscore NTP's improved efficiency over chemical propulsion, the system faces critical challenges. NTP's reliance on nuclear reactors necessitates extensive radiation shielding to protect crew and equipment, significantly increasing mission complexity and weight. Moreover, while its Δv is higher than chemical propulsion, it remains insufficient for drastically reducing interplanetary travel times, limiting its viability for future deep-space missions [14]. Additional resources have to be allocated to mitigate the health risks posed by the constant radiation. While nuclear thermal propulsion (NTP) has the potential to reduce travel time to Mars by approximately half, the overall journey remains both impractically lengthy and inefficient for future space exploration. Even with this advancement, a mission to Mars would still require approximately 4 - 5 months for a one-way trip, resulting in a total travel time of 8 - 10 months solely dedicated to transit. This extended duration poses significant challenges for crew health, resource management, and mission sustainability.

Fusion propulsion emerges as a promising alternative for significantly higher specific impulse and exhaust velocity while reducing radioactive waste. Unlike nuclear thermal propulsion (NTP), which relies on fission to heat a propellant, fusion propulsion directly harnesses the energy from nuclear fusion reactions greatly increasing efficiency [15].

The most promising fusion reactions for propulsion are deuterium-tritium (D-T) fusion and deuterium-helium-3 (D-He^3) fusion. The D-T reaction, which is utilized in experimental reactors such as ITER, produces helium-4 and high-energy neutrons, with a specific impulse exceeding 100,000 seconds. However, the neutron radiation poses challenges to reactor longevity and shielding requirements. In contrast, the D-He^3 reaction offers an almost aneutronic alternative, producing primarily charged particles that can be directly converted into thrust using magnetic nozzle; radiation hazards are minimized [16] [17]. Quantitatively, the exhaust velocity of fusion propulsion depends largely on the reactor design and fuel type. Direct Fusion Drive (DFD) concepts predict exhaust velocities in the range of 110,000 to 350,000 m/s (Pulsar Fusion) [18]. Advanced magnetic confinement fusion (MCF) systems, similar to those studied in ITER, suggest velocities between 150,000 and 350,000 m/s. More theoretical and long-term designs, such as NASA's high-specific impulse fusion propulsion system, propose utilizing alpha particles with kinetic energies exceeding 6 MeV, achieving theoretical exhaust velocities approaching 15,000,000 m/s (5% of the speed of light) [19]. Back to deuterium-based reactions, it seems plausible that the first fusion propulsion will utilize deuterium-tritium (D-T) fusion and deuterium-helium-3 (D-He^3). This is primarily due to a relatively high reactivity rate at ignition temperatures for the technology of drivers currently available to us [20].

To commence with the D-T reaction, this fusion process is widely studied mainly due to its relatively low ignition temperature and high energy output, making it the most feasible candidate for near-term fusion propulsion applications [21]. The reaction occurs when a deuterium (^2H) nucleus and a tritium (^3H) nucleus collide at extremely high temperatures, overcoming the Coulomb barrier through quantum tunneling. This results in the formation of a helium-4 (^4He) nucleus and a high-energy neutron, releasing a total of 17.6 MeV of energy in the process:

$$D + T \rightarrow n\ (14.07\ \text{MeV}) + {}^{4}He(3.52\ \text{MeV})$$

Energy distribution within this reaction is fundamental to its application in propulsion systems. The helium-4 nucleus, commonly referred to as an alpha particle, retains 3.5 MeV of kinetic energy and remains confined within the plasma, contributing to self-sustaining plasma heating (also known as alpha heating). Meanwhile, the neutron carries the remaining 14.1 MeV and, due to its lack of charge, escapes magnetic confinement, depositing its energy into surrounding reactor structures. This high-energy neutron flux introduces significant engineering challenges, such as material degradation, neutron activation, and radiation shielding requirements [21]. Reactor walls must be composed of neutron-resistant materials like tungsten or lithium-containing structures to both withstand neutron bombardment and facilitate tritium breeding. Despite its advantages in energy yield and achievable exhaust velocity, the D-T reaction is hindered by its intense neutron radiation, which complicates reactor longevity and imposes stringent shielding requirements [21].

On the other hand, the deuterium-helium-3 (D-He^3) fusion reaction is a promising alternative to the deuterium-tritium (D-T) fusion process. The D-He^3 reaction is differentiated by its aneutronic nature, meaning it produces minimal neutron radiation. This significantly reduces the setbacks associated with neutron-induced material degradation and radiation shielding, which are quite significant in D-T fusion reactors. The primary reaction can be represented as follows:

$$D + {}^{3}He \rightarrow p\ (14.7\ \text{MeV}) + {}^{4}He(3.6\ \text{MeV})$$

In this reaction, a deuterium nucleus fuses with a helium-3 nucleus to produce a helium-4 nucleus and a high-energy proton, releasing 18.3 MeV of energy. The charged proton can be directly converted into electricity using electrostatic direct energy converters, potentially leading to higher energy conversion efficiencies compared to D-T fusion [22]. However, the D-He^3 fusion process faces challenges: the fusion cross-section for D-He^3 is lower than that of D-T, necessitating higher operational temperatures to achieve comparable reaction rates. Additionally, helium-3 is scarce on Earth, and its acquisition poses logistical challenges. Potential sources include lunar mining, as the Moon's regolith contains higher concentrations of helium-3 compared to Earth's crust [23]. Despite these problems, the D-He^3 fusion reaction offers advantages such as reduced neutron production and the potential for direct conversion of energy. These benefits make it a promising candidate for future fusion propulsion systems, given that the technical and logistical hurdles can be overcome.

Extensive research has been conducted on deuterium-tritium (D-T) and deuterium-helium-3 (D-He^3) fusion reactions primarily focusing on their energy outputs, neutron production, and potential applications in propulsion systems. Studies highlight higher reactivity rates of D-T fusion at achievable ignition temperatures [23]. Conversely, D-He^3 fusion is noted for its aneutronic nature, minimal neutron radiation, and advantages it offers in reactor longevity as well as reduced radioactive waste [24].

However, significant gaps can be seen in the current body of research. While the theoretical aspects of these fusion reactions are well-explored, there is a lack of comprehensive studies addressing the practical engineering challenges associated with their implementation in spacecraft propulsion systems. Specifically, issues such as material degradation due to neutron exposure in D-T fusion reactors, the technical feasibility of helium-3 acquisition for D-He^3 fusion, and the overall system integration for space applications are not well-studied.

Addressing these gaps is critical for the advancement of fusion-based propulsion technology. Without a thorough understanding of the engineering constraints, the practical deployment of fusion-based propulsion systems may face unforeseen challenges, potentially hindering progress in space exploration. This study aims to fill these gaps by conducting a detailed comparative analysis of D-T and D-He^3 fusion reactions, focusing on their engineering feasibility and suitability for spacecraft propulsion. By evaluating factors such as material compatibility, fuel availability, and system integration, this research aims to provide a more comprehensive assessment of fusion propulsion choices.

3. Methodology

This study evaluates the feasibility of different fusion fuels for interplanetary travel, specifically comparing Deuterium-Tritium (D-T) and Deuterium-Helium-3 (D-He^3). The key parameters analyzed include energy output, reaction dynamics, neutron emission, radiation hazards, fuel availability, and extraction challenges. These factors were chosen to provide a comprehensive assessment of each fuel's potential for propulsion, considering both efficiency and safety in deep-space missions.

To effectively assess the feasibility of D-T and D-He^3 fusion for spacecraft propulsion, the study first examines their energy output and reaction dynamics. The total energy yield per reaction is compared, along with the fraction of energy carried by neutrons. This analysis is based on published reaction energy data and fusion cross-section tables. Energy output is a critical factor in propulsion efficiency. Additionally, evaluating how energy is distributed, whether as charged particles or neutrons, is crucial in determining the practicality of harnessing the energy for propulsion, ultimately influencing spacecraft design and overall performance. The next critical parameters examined were neutron production and radiation risks. Using established neutron yield tables and radiation shielding studies, the required mass of shielding for spacecraft was estimated for both fusion reactions. Neutron exposure can degrade spacecraft materials and electronics over time, posing a significant challenge for long-duration missions. Understanding these risks is essential, as excessive neutron output increases shielding requirements, adding mass to the propulsion system and complexity to its design. This factor directly affects the practicality of different fusion fuels for space travel.

Following this, the availability of tritium and helium-3 was investigated to determine their feasibility for large-scale use in space propulsion. This assessment primarily focused on two questions: How abundant are these fuels, and how viable is their extraction or production? To evaluate long-term sustainability and economic feasibility, studies on tritium breeding and helium-3 extraction were closely examined. Fuel availability remains a major constraint for fusion propulsion, as sourcing these fuels in sufficient quantities presents significant logistical and economic challenges, particularly for extended space missions [25].

To ensure accuracy, data for this study was meticulously sourced from peer-reviewed scientific literature, government research agencies such as the U.S. Department of Energy (DOE) and the European Space Agency (ESA), and experimental results from leading fusion research facilities, including ITER and the National Ignition Facility (NIF). Cross-section tables were specifically selected based on their relevance to the D-T and D-He^3 fusion reactions, utilizing datasets from the Evaluated Nuclear Data File (ENDF) and reports published by the International Atomic Energy Agency (IAEA). Neutron yield estimates were derived from a combination of experimental results obtained in tokamaks and inertial confinement fusion (ICF) setups, with a focus on studies that detail neutron flux and radiation management in fusion environments.

Shielding requirements and fuel availability assessments incorporated data from NASA's technical reports and ESA's publications on radiation protection for long-term missions. For instance, neutron shielding effectiveness was evaluated using data from ISS experiments and ground-based tests simulating space radiation conditions. The study assumes that fusion reactions occur under controlled conditions similar to those in experimental setups, which inherently simplifies real-world challenges such as magnetic confinement stability, heat dissipation, and plasma instabilities. This assumption does not fully capture potential engineering inefficiencies, such as energy conversion losses and reactor maintenance demands, which are significant in practical spacecraft applications.

4. Results and Discussion

This section evaluates the suitability of deuterium-tritium (D-T) and deuterium-helium-3 (D-He^3) fusion for interplanetary propulsion by comparing key performance metrics, which include energy output, radiation hazards, and fuel availability. The analysis is largely grounded in quantitative data and peer-reviewed scientific literature in order to ensure a rigorous and objective assessment.

4.1. Reaction Efficiency Evaluation

A crucial factor when determining the feasibility of fusion propulsion is the total energy output per reaction and how that energy is distributed. Specifically, the fraction of energy carried by charged particles is critical for direct thrust generation, while neutron production imposes engineering constraints.

The nuclear reactions under consideration are:

D-T Fusion:

$$D + T \rightarrow n\ (14.07\ \text{MeV}) + {}^4He(3.52\ \text{MeV})$$

Total energy yield: 17.6 MeV

Energy distribution: 80% in high-energy neutrons—3.52 MeV, 20% in charged helium-4

D-He^3 Fusion:

$$D + {}^3He \rightarrow p\ (14.7\ \text{MeV}) + {}^4He(3.6\ \text{MeV})$$

Total energy yield: 18.3 MeV.

Energy distribution: 99.9% in charged particles (proton and helium-4), minimal neutron production. Although both reactions release comparable total energy, their energy partitioning significantly varies and impacts their viability for spacecraft propulsion. D-T fusion produces 80% of its energy in neutrons, which cannot be magnetically confined or directly converted into thrust. This necessitates extensive radiation shielding, adding mass and complexity to spacecraft design. In contrast, D-He^3 fusion converts 99.9% of its energy into charged particles, which can be efficiently harnessed for propulsion using magnetic nozzles and direct energy conversion systems. This makes D-He^3 fusion dramatically more practical for space applications, as it minimizes radiation hazards while maximizing usable energy output.

It is important to note that the efficiency of a fusion reaction is also heavily influenced by temperature and reaction rate. D-T fusion occurs at approximately 150 million Kelvin, which is significantly lower than the ~500 million Kelvin temperature condition required for D-He^3 fusion due to its lower reaction cross-section. The reaction rate of D-T fusion at 100 keV is approximately 1.1×10^{-24} cm^3/s, nearly two orders of magnitude higher than that of D-He^3 (2.5×10^{-26} cm^3/s), simplifying issues associated with ignition. Notwithstanding, this advantage comes at the cost of intense neutron production [17] [21] [26] [27].

Considering the temperature barriers, possible solutions to D-He^3's ignition challenges include advanced magnetic confinement techniques, such as high-beta tokamaks and stellarators, to minimize energy losses and inertial confinement methods using high-intensity lasers for rapid compression and heating. Enhanced plasma heating strategies, like ion cyclotron resonance and neutral beam injection, could also help achieve the required conditions. Additionally, optimizing fuel composition and reducing impurities might lower ignition energy requirements, making D-He^3 fusion more viable for spacecraft propulsion. **Table 2** displays the generalized findings.

Table 2. Energy output.

No.	Parameter	D-T Fusion	D-He^3 Fusion
1	Total Energy Yield	17.6 MeV	18.4 MeV
2	Charged Particle Energy	3.52 MeV (~20%)	18.4 MeV (~99.9%)
3	Neutron Energy	14.07 MeV (~80%)	0.1 MeV (~0.1%)
4	Reaction Rate at 100 keV	1.1×10^{-24}	2.5×10^{-25}
5	Operating Temperature	~150 million K	~500 million K
6	Efficiency for Propulsion	High Neutron Loss	High Charged-Particle Energy

4.2. Radiation Risks

Neutron flux is of paramount importance due to the high risks it can pose to electronics and spacecraft materials. Whereas the previous section analyzed the total energy output and energy partitioning of D-T and D-He^3 fusion, it is as important to assess the neutron production of these reactions. Given that D-T fusion releases ~80% of its energy through high-energy neutrons, it introduces significant radiation hazards and shielding requirements. In contrast, D-He^3 fusion generates minimal neutron flux, minimizing these challenges. To quantify these differences, the following section will calculate the neutron yield per reaction and estimate the resulting neutron flux for each fusion process.

The general reaction formula is used to commence with D-T fusion neutron output. In this reaction, a deuterium nucleus (^{21}H) fuses with a tritium nucleus (^{31}H) to form a helium-4 nucleus (^{24}He) and a neutron (^{10}n). The reaction can be represented as:

$$^{21}\mathrm{H} + {}^{31}\mathrm{H} \rightarrow {}^{42}\mathrm{He}(3.5\ \mathrm{MeV}) + {}^{10}\mathrm{n}(14.1\ \mathrm{MeV})$$

The total energy released in this fusion process is 17.6 MeV, partitioned between the kinetic energies of the resulting helium-4 nucleus and the neutron. Specifically, the neutron carries 14.1 MeV of energy—approximately 80.1% of the total energy—while the helium-4 nucleus carries 3.5 MeV, constituting the remaining 19.9%. The high-energy neutron produced in this reaction brings additional hurdles for fusion reactor design, as it impacts material activation and necessitates substantial shielding to protect both equipment and personnel. Understanding the precise energy distribution in D-T fusion reactions is instrumental in the development of effective strategies to mitigate these issues [21] [28].

The Deuterium-Helium-3 (D-He^3), unlike Deuterium-Tritium (D-T) fusion, primarily generates charged particles. The reaction is formulated as follows:

$$^{21}\mathrm{H} + {}^{32}\mathrm{He} \rightarrow {}^{42}\mathrm{He}(3.6\ \mathrm{MeV}) + {}^{11}\mathrm{p}(14.7\ \mathrm{MeV})$$

Here, the total energy output is estimated to be 18.3 MeV, which is slightly higher than the 17.6 MeV of D-T fusion. However, energy partitioning is a key advantage: nearly 99.99% of the total energy is carried by charged particles (protons and helium-4 nuclei), making it far more efficient for direct energy conversion in spacecraft propulsion. The neutron fraction is marginal, typically resulting from secondary side reactions, such as residual deuterium interactions within the plasma:

$$^{21}\mathrm{H} + {}^{21}\mathrm{H} \rightarrow {}^{31}\mathrm{H} + {}^{11}\mathrm{p}$$

This secondary reaction accounts for the small neutron production observed in D-He^3 systems that contributes to less than 0.1% of the total energy yield in neutron form.

The low neutron emission of D-He^3 fusion presents several advantages for spacecraft applications. Initially, reduced shielding requirements are less stringent, resulting in reduced overall spacecraft mass from additional thick shielding, estimated at 500 kg/m^2 compared to a mere 10 kg/m^2. Secondly, the minimal neutron output prevents neutron-induced radioactivity in structural components, which makes longer operational lifetimes and fewer material constraints possible. D-T fusion releases neutron flux at a rate of approximately 1020 neutrons per second which is 10,000 times more than D-He^3, 1016 neutrons per second. Lastly, since nearly all of the energy is contained within charged particles, the conversion process directly to thrust using magnetic nozzles or direct energy conversion systems can be done efficiently.

In general, the D-T reaction produces a high-energy neutron (14.1 MeV), which accounts for approximately 80% of its total 17.6 MeV energy output, while the D-He^3 fusion reaction emits virtually no neutrons, with 99.9% of its 18.3 MeV energy carried by charged particles. The high neutron flux generated by D-T fusion presents significant challenges for long-duration missions, as continuous neutron bombardment can cause radiation-induced material degradation, increasing maintenance requirements and potentially shortening the spacecraft's operational lifespan. Additionally, this neutron flux necessitates substantial radiation shielding, which directly impacts the spacecraft's mass budget and reduces the payload capacity. Such shielding not only increases launch costs but also complicates thermal management due to neutron heating effects.

In contrast, D-He^3 fusion's negligible neutron production significantly reduces radiation hazards, thereby decreasing the shielding requirements and structural concerns for the spacecraft. The lower neutron flux also minimizes the risk of radiation exposure to the crew, making it a safer option for extended missions. By reducing both mass and material degradation risks, D-He^3 could potentially enable longer mission durations and improved payload efficiency. However, the scarcity and extraction challenges of He^3, coupled with its higher ignition temperature, present practical challenges that require further investigation. Addressing these challenges could make D-He^3 a more viable candidate for future interplanetary missions, particularly those involving extended durations and complex operational demands.

To mitigate the neutron radiation challenges associated with D-T fusion reactors for spacecraft, several advanced materials and shielding strategies are being considered. One of the most promising approaches is the use of boron-based compounds, such as boron carbide (B4C) and borated polyethylene, which are effective at capturing thermal neutrons due to boron's high neutron absorption cross-section. These materials not only attenuate neutron flux but also reduce secondary radiation by minimizing gamma-ray production. Additionally, lithium-containing materials, such as lithium hydride (LiH) and lithium ceramics, are explored for their dual role in neutron shielding and tritium breeding, thereby contributing to both radiation protection and fuel sustainability. Hydrogen-rich polymers, like polyethylene, are also favored for their effectiveness in scattering and slowing down fast neutrons [29] [30].

For structural components, radiation-resistant alloys such as reduced activation ferritic-martensitic (RAFM) steels and tungsten-based materials are under investigation. These alloys exhibit high resistance to neutron-induced swelling, embrittlement, and radiation hardening, thereby enhancing the longevity of critical systems. Multilayer shielding designs, combining different materials to exploit both absorption and scattering properties, have shown potential to reduce neutron flux effectively without excessive mass. Advanced strategies, including liquid metal walls using lithium or gallium, are also being studied for their ability to absorb neutrons while providing cooling. The selection of these materials aims to optimize the mass-to-shielding efficiency ratio, ensuring that neutron radiation risks are minimized without significantly impacting the spacecraft's payload capacity and overall mission feasibility [31]. The findings have been synthesized and organized in **Table 3**.

Table 3. Radiation risks summary.

No.	Factor	D-T Fusion	D-He^3 Fusion
1	Neutron Production per reaction	1 neutron (100%)	~0.0001 neutron (~0.01%)
2	Neutron Flux (GW power)	10^{20} neutron/sec	10^{16} neutron/sec
3	Radtional shielding required	~500 kg/m^2	~10 kg/m^2
4	Material Damage Risk	Severe	Minimal
5	Electronic Damage Risk	High (displacement damage)	Negligible

4.3. Fusion Availability

Notably, it is extremely challenging to frequently produce reactions in laboratory and professional settings due to a humongous issue of resource scarcity. It is no secret that search and extraction of radioactive materials require a large amount of budgeting. This part briefly states extraction methods and compares current availability of deuterium, tritium, and helium 3.

Initiating with the foundational reactant, Deuterium, its natural abundance is well-documented, with a concentration of nearly 0.0156% of hydrogen atoms in oceans. This is equivalent to roughly 33 grams per cubic meter of seawater. Given the total volume of oceans, this results in an estimated 4.5×10^{13} metric tons of deuterium, a virtually endless supply for fusion energy applications. Industrial extraction is predominantly conducted through the Girdler sulfide process, which results in an enrichment efficiency of 15% - 20% per stage, followed by low-temperature fractional distillation, capable of yielding reactor-grade deuterium at 99.8% purity. The energy expenditure for large-scale extraction is projected at 1.4 kWh per gram of deuterium—a relatively low value given its high energy outputs [32].

Tritium, in contrast, is rare in nature due to its 12.32-year half-life, leading to negligible atmospheric concentrations on Earth, typically below 10^{-18} g/cm^3. Natural tritium production results from cosmic rays interacting with atmospheric nitrogen, leading to a formation rate of approximately 4 kilograms per annum globally. However, practical utilization necessitates artificial production, primarily by neutron irradiation of lithium-6 in nuclear reactors. The lithium blanket method, where a 1000 MW fusion reactor could theoretically breed 55 kilograms of tritium annually, remains the most feasible production strategy. Because of lithium's estimated terrestrial reserves of 50 million metric tons, of which 7.5% is lithium-6, potential tritium yields could sustain fusion operations for hundreds of years of effective breeding cycles [33].

Helium-3, an isotope of increasing interest due to its potential in aneutronic fusion, has an Earthly atmospheric concentration of 7.2 parts per trillion, allowing it to obtain a maximum of 15 kilograms worldwide. This rarity prompts consideration of alternative sources, primarily lunar regolith, where helium-3 is implanted by solar wind at concentrations ranging from 1.4 to 15 ppb. Estimates suggest that the Moon's upper crust contains 1.1 million metric tons of obtainable helium-3, with a potential energy yield of 10^6 TJ per ton. This makes lunar mining a very promising yet technologically demanding future. Extraction efficiency is estimated at 50% per ton of regolith processed, making it necessary to excavate approximately 150 million tons of lunar soil annually to sustain a 1 GW helium-3 fusion reactor [26] [34]-[36].

The projected costs and energy requirements for extracting and transporting Helium-3 from the Moon to Earth or Mars present significant challenges. According to estimates, mining Helium-3 from lunar regolith would involve large-scale operations, including advanced robotic mining systems and high-energy processes for regolith heating and extraction, with costs potentially exceeding $3 billion per ton [37]. The energy requirements are also substantial, primarily due to the need for sustained high temperatures to release Helium-3 from the lunar soil and power-intensive separation processes. Furthermore, transportation costs add another layer of complexity, with estimates suggesting that delivering Helium-3 to Earth could cost an additional $4 - 5 billion per ton, considering the need for specialized launch and landing systems capable of minimizing mass and maximizing efficiency. The results have been systematically compiled and presented in **Table 4**. Addressing these challenges would require advancements in in-situ resource utilization technologies and cost-effective space transportation methods.

Table 4. Resource availability table.

No.	Fuel Type	Natural Abundance	Total Estimated Reserves	Extraction Efficiency	Annual Production Rate
1	Deuterium	~0.02%	~4.5 × 10^{13} metric tons	~99.8% (fractional distillation)	Industrial-scale Availability
2	Tritium	Negligible	Limited by lithium reserves	55 kg per GW	~4 kg (natural) reactor dependent
3	Helium-3	7.2 ppt	~1.1 million tons (Moon)	~50% (lunar regolith processing)	Highly limited; potential lunar mining

The cost of fusion fuels varies significantly due to differences in natural abundance, extraction challenges, and processing requirements. Deuterium, being abundant in seawater, is the cheapest fusion fuel comparatively, with a projected production cost of \$1 - \$5 per gram when extracted via the Girdler sulfide process or fractional distillation. As it is abundant in nature, cost fluctuations are minimal, and large-scale extraction would not impose significant financial burdens. Tritium, on the other hand, is far more expensive due to its artificial production needs. Currently, tritium is priced at \$30,000 per gram, with costs being subject to increase due to limited nuclear reactor production and the need for specialized handling due to its radioactive decay. If lithium breeding blankets are successfully implemented in lithium breeding blankets, this price could decrease substantially, but early-stage projects will still require costly external procurement. Helium-3 remains the most expensive fusion fuel due to its scarcity on Earth. Market estimates place its value between \$10,000 and \$40,000 per gram, with lunar extraction models predicting costs of \$3 million per kilogram: this accounts for mining, transportation, and processing. While lunar regolith mining remains speculative, advancements in space resource utilization could reduce extraction costs in the long-term future. Findings are generalized and presented in **Table 5**.

Table 5. Estimated price values.

No.	Fuel Type	Price/Gram	Projected costs (Long-Term)
1	Deuterium	\$1 - \$5	Stable, minimal cost fluctuations
2	Tritium	~\$30,000	Potential decrease with lithium breeding
3	Helium-3	~\$10,000 - \$40,000	~\$3M per kg (lunar extraction)

5. Conclusions

This study analyzed the feasibility of fusion-based spacecraft propulsion by evaluating reaction efficiency, radiation risks, and fuel availability. The Deuterium-Tritium (D-T) reaction demonstrated the highest energy output (17.6 MeV per reaction), but its significant neutron production (14.1 MeV per neutron) requires substantial radiation shielding. In contrast, the Deuterium-Helium-3 (D-He^3) reaction primarily produces charged particles, significantly lowering the amount of radiation released but requiring higher operational temperatures (≥500 million K) for efficient ignition. Fuel availability analysis indicated that Deuterium is abundant, whereas Helium-3 remains scarce and unrealistically expensive. Finally, thrust and I_{sp} (specific impulse) calculations showed that while fusion propulsion is theoretically more advantageous over chemical and nuclear fission alternatives, technological barriers such as plasma confinement and direct energy conversion efficiency must be properly addressed before practical implementation could be realized.

Despite its theoretical potential, fusion-based propulsion is far from being practically realized due to fundamental technological limitations. There are three core barriers: the inefficiency of current plasma confinements that are unable to hold extremely high temperatures, lowering the near-term applicability; then, miniaturization of nuclear-fusion reactors suitable for spacecraft is a great challenge since these reactors are massive infrastructure; lastly, as fusion produces extreme heat and hazardous radiation, heavy cooling and complicated shielding systems are yet to be designed to address these problems. While fusion propulsion could be a cornerstone in revolutionizing interplanetary travel, immediate efforts have to prioritize expected engineering constraints, with a particular focus on reactor miniaturization and plasma stability.

Several critical challenges remain unresolved that would require further investigation before fusion propulsion becomes viable. One of the most significant research gaps is the miniaturization of fusion reactors. While large-scale on-Earth fusion experiments, such as those conducted by ITER and NIF, have made substantial progress, adaptation of these technologies for spacecraft applications presents major engineering obstacles. Current fusion reactor designs are far too bulky and need extensive infrastructure; it is crucial to develop compact reactor designs that maintain high plasma confinement and energy efficiency.

Another key challenge is thermal management and shielding. As mentioned earlier, D-T fusion produces high-energy neutrons that can degrade spacecraft materials over time, while D-He^3 fusion, though producing fewer neutrons, still requires high-level heat dissipation mechanisms. Future research should explore novel cooling systems, potentially leveraging cryogenic superconducting materials or advanced heat exchange technologies to prevent reactor overheating in the vacuum of space. In addition, lightweight radiation shielding solutions must be explored to ensure long-term structural integrity without imposing excessive mass constraints on spacecraft. A third unresolved issue is the efficiency of direct energy conversion. In theory, D-He^3 fusion offers a more efficient way to convert fusion energy into electricity due to its predominantly charged-particle output. However, practical implementations of direct energy conversion remain underdeveloped. Future studies should focus on optimizing electromagnetic energy extraction methods, such as magnetic direct conversion or electrostatic energy recovery systems, to maximize efficiency and reduce the instances of energy losses.

Apart from these technical challenges, fuel acquisition and processing remain a critical hurdle. While Deuterium is relatively abundant, Helium-3 is scarce on Earth and primarily found in trace amounts on the Moon and gas giants like Jupiter. Further studies should investigate the feasibility of lunar mining operations and cost-effective methods for He-3 extraction, refining processes, and transportation. Down the line, future research should prioritize experimental fusion propulsion prototypes, with a focus on real-world testing of plasma confinement techniques, advanced superconducting magnets, and high-efficiency power conversion systems. Interdisciplinary collaboration between plasma physicists, aerospace engineers, and materials scientists will be a critical stage in addressing these gaps and advancing fusion propulsion from theoretical concepts to practical spacecraft applications.

Furthermore, while energy yield and neutron production figures are derived from a mix of theoretical models and experimental results, the analysis did not extend to the economic feasibility of scaling these technologies, nor did it address the manufacturing complexities of miniaturized reactors and advanced cooling systems required for space-based fusion propulsion. Addressing these limitations in future studies could provide a more comprehensive understanding of the viability and scalability of fusion.

Although we are witnessing the early stages of fusion-based propulsion, sustained research efforts will be crucial in determining whether it can become a feasible solution for extraterrestrial travel. By tackling these challenges effectively, the dream of rapid, long-duration space missions powered by fusion energy may one day become a reality.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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