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Advancements and Future Perspectives in Space Propulsion Technologies: A Comprehensive Review

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Abstract: Space exploration beyond low-Earth orbit at a fast pace calls for propulsion systems with increased efficiency, endurance, and enhanced mission capabilities. In this internship project report, an extensive analysis of advanced space propulsion and its trends in near, medium, and far future has been done. The discussion begins with the high-power electric propulsion system in which there is analysis of propulsion strings including thrusters, cathodes, power processing units, and propellant management systems. Recent advancements in high-power Hall effect thrusters and gridded ion engines have been included, along with the problems in scaling, lifetime, power processing, and propellant availability. Next, the report analyzes mid-term propulsion options such as solar sails, electric solar wind sails, and nuclear thermal propulsion, with an emphasis on their efficiency when it comes to interplanetary travel. Finally, advanced propulsion ideas for deep-space and interstellar missions, which include nuclear electric propulsion and fusion propulsion, are analyzed according to their performance requirements and technological challenges. Literature review is utilized to compare technological readiness, propulsion efficiency, subsystem interdependency, and future development path for different space propulsion systems. The research proves that in the future space exploration will demand combined efforts of several propulsion architectures instead of relying only on one propulsion technology, such as electric, nuclear, propellant less, and fusion.

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1.Introduction

Manned flight to Mars and the establishment of deep-space infrastructure are the next big challenges facing humanity in space travel. Nonetheless, the achievement of such visionary structures is entirely dependent on the principles of physics

involved in the working of space propulsion systems (SPS). The equation that governs all vehicles that achieve their thrust (T) through mass ejection is the Tsiolkovsky Rocket Equation:

$$\Delta v = c\ ln\left(\frac{m_0}{m}\right)$$

Where Δv is the change in vehicle velocity, $m0m$ is the vehicle mass ratio, and c is the effective exhaust velocity. The effective exhaust velocity is directly proportional to the specific impulse ($Isp = \frac{c}{g_0}$) which serves as the primary metric for propellant mass efficiency.

For the last few decades, space travel has almost entirely depended on thermodynamic/chemical rockets. Although the chemical method of propulsion provides a high thrust-to-weight ratio for lifting huge payloads to the Low Earth Orbit (LEO), which are required for overcoming the gravitational pull of the Earth, it has a restriction on the molecular energy level, limiting the vacuum specific impulse to approximately 260s - 470s. For interplanetary journeys, depending only on the chemical propulsion system would require an exponential increase in propellant mass fraction.

To overcome such thermal restrictions, contemporary aerospace development is relentlessly pushing for the paradigm shift towards more sophisticated, non-chemical propulsion systems. High Power Electric Propulsion (EP) systems have reached great maturity among these systems. By utilising on-board electrical power to generate electric and magnetic fields, EP systems decouple the energy source from the propellant mass, enabling the

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acceleration of ionised plasma to exhaust velocities approaching $105 m/s$. This produces a quantum leap in propellant efficiency, yielding specific impulses ranging from 1,000s to over 7,000s.

Most importantly, the modern space propulsion needs to be studied not just in terms of individual thrusters but as propulsion "strings". The high-power EP string is made up of four strongly interrelated electromechanical subsystems:

- **The Thruster:** The main channel/grid that accelerates the plasma stream.
- **The Cathode:** The electron generator, which defines the process of ionization of the propellant and neutralization of the exhaust stream.
- **The Power Processing Unit (PPU):** The electric system that adapts the raw power from the spacecraft to the dynamic load with fault logic implementation.
- **Propellant Management System (PMS):** The fluid system that controls pressures and gassing.

While high-power electric propulsion strings like the 13kW Advanced Electric Propulsion System (AEPS) are actively nearing deployment for near-term lunar logistics, substantial technological gaps remain regarding structural scaling limits, high-current cathode degradation, and vacuum ground-facility testing effects. Looking further ahead, mid-term and far-term trends point toward revolutionary paradigms: Nuclear Thermal Propulsion (NTP), which offers the unique advantage of bridging high efficiency ($Isp \approx 700-1{,}000 s$) with a high thrust-to-weight ratio ($T/w > 1$); electrodeless plasma variants like Helicon or Rotamak systems that eliminate electrode erosion; and speculative ultra-high-efficiency fusion concepts ($Isp \approx 104-106 s$).

Furthermore, as the aerospace sector looks past interplanetary horizons toward prospective interstellar voyages, the performance requirements scale exponentially. For conceptual missions targeting nearby star systems like Alpha Centauri at relativistic speeds ($\approx 0.1c$), onboard-propellant systems face a minimum specific impulse barrier of 400,000s. This structural constraint limits the viable far-term architectural roadmap strictly to directed energy sails, antimatter annihilation, and pure thermonuclear fusion propulsion. Consequently, contemporary advancements in high-power interplanetary strings serve as the critical, incremental baseline required to pioneer the deep-space autonomy and system survivability necessary for the ultimate expansion into interstellar domains.

This report investigates the state-of-the-art across these high-priority workstreams, evaluating current technological horizons, defining critical subsystem barriers, and synthesising the future developmental trajectory of advanced space propulsion.

2. Near-Term and In-Space Propulsion Horizons (5-10 Year Domain)

The "In-Space" propulsion arena, defined conceptually as the orbital tracking space stretching from the top boundary of the LEO region up to the GEO region, is presently witnessing an impressive shift towards highly efficient all-electric systems. Although the "Escape Propulsion" propulsion systems ground-based rocket launches are bound by their need for thermodynamic propulsion to develop the enormous force necessary to counter Earth's gravitational pull continue to use chemical propulsion; it has been observed that satellites and space missions use Electric Propulsion (EP) strings for their orbital maneuvers, orbit circularising, and station keeping. Unlike chemical propulsion, which is limited to their molecules' enthalpy levels to a Isp value of around 500s, the electrostatic and electromagnetic EP strings separate their power supply from the mass of propellant, making exhaust velocities Δv in the range of 20 to 100 km/s.

2.1 Subsystem Dependencies within the EP String Architecture

As established by Jovel et al. (2022) and Kulkarni (2026), an electric propulsor cannot be evaluated as an isolated electromechanical device; it operates as an integrated "string" consisting of four critical, co-developed subsystems:

- **The Thruster:** The Elektromechanical housing where the conditioned energy and gas are used to carry out ionization, plasma confinement, and directional acceleration of particles.
- **Cathode:** This is the dual-purpose component that serves to provide ionized electrons for the discharge of plasma while at the same time providing a flow of electrons to neutralise the ion beam.
- **The Power Processing Unit (PPU):** The component that works in direct communication with the spacecraft's low- and high-voltage buses. The PPU employs isolated DC/DC converters to raise the voltage of the buses to levels necessary for thruster operation.

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- **Propellant Management System (PMS):** The liquid system that connects to high-pressure storage tanks, reducing the pressure via mechanical regulators or solenoid plenums to a consistent operational pressure (typically 37 psia) for active or passive mass flow management.

2.2 Near-Term Technology Vectors: High-Power HETs and GIEs

The near-term space market is centred around the mass production and flight qualification of mature electrostatic architectures scaling past 6kW up to tens of kilowatts.

2.2.1 High-Power Hall-Effect Thrusters (HETs)

The Hall Effect Thruster utilises an axial $E \times B$ drift of the electrons to confine them in a circumferentially oriented plasma discharge channel and to produce high thrust per power input values (T/P). Traditionally, the major limitation of the operational life of Hall thrusters was their wear and tear due to plasma ion bombardment of ceramic boron nitride channel walls, which resulted in wall erosion. The key innovative feature is Magnetic Shielding. It consists of shaping the magnetic field configuration, moving the acceleration region downstream, and orienting the magnetic field lines parallel to the channel walls. It reduces the radial component of ion kinetic energy and thus produces a protective layer of cold plasma.

This technology is benchmarked by the following active strings:

- **AEPS (Advanced Electric Propulsion System):** A 12.5 kW qualification string that uses a magnetically shielded HET (based on NASA's HERMES Technology Demonstration Unit) together with a Maxar PPU and a VACCO fluid loop, which will provide power for the Lunar Gateway.
- **BHT-6000 & SPT-140:** High-powered 6 kW and 4.5 kW commercial strings designed for Electric Orbit Raising (EOR) and Geosynchronous Station Keeping satellites.
- X3 Nested Hall Effect Thruster: A 100 kW laboratory thruster comprised of several concentric discharge channels able to produce a 5.42 N thrust, proving the absolute way towards

2.2.2 High-Power Gridded Ion Engines (GIEs)

Gridded Ion Engines achieve separation between plasma production and ion acceleration through physically biased electrostatic grids (screen grid and accelerator grid). Although GIEs are plagued with low thrust density because of the positive space charge limitations between the grids, they offer unequalled efficiency of fuel with total specific impulses reaching up to 7650 s and total efficiencies ranging from 68% to 78%.

The best current near-future example is NASA's NEXT-C (Evolutionary Xenon Thruster-Commercial). Running up to 6.9 kW power, the NEXT-C string has reached the FQ stage with full mechanical, thermal, electrical, and string integration testing completed and a throughput level set at 450 kg of Xenon.

2.3 Near-Term Subsystem Gaps and Alternative Propellants

● High Power HET Issues: HETs experience intense discharges in terms of current oscillations. In order to endure the said instabilities, high power HETs are making use of wide bandgap semiconductors, employing Silicon Carbide (SiC) MOSFETs and JFETs to provide greater voltage breakdown capacity and lower thermal conductivity losses. They are also ensuring that the efficiency of PPU conversion is maintained above 97%.

● **Xenon Availability Issue:** The growing popularity of large telecommunication satellite mega constellations has made the situation of the availability of Xenon gas rather acute. Future tendencies include the development of characterisation of thruster strings for different propellants. Krypton may be viewed as a potential propellant since its ionization energy (14.00 eV vs 12.13 eV of xenon) allows for increased efficiency. The condensable alternatives, such as Iodine, will be used for smaller satellites since they have high storage density.

3. Propellantless Space Sailing Technologies

Propellantless propulsion systems use ambient solar radiation pressure or corpuscular winds, thus eliminating the need for heavy onboard fuel reserves.

3.1.1 Solar and Photonic Sails

Solar sails use the momentum transfer of solar photons reflected or diffracted from large sheets of highly reflective, low-area-density material. This methodology has moved from historical theory to verified flight demonstration, as synthesized in Recent advances in space sailing missions and technology- review of the 6th International Symposium on Space Sailing (ISSS 2023).

• **IKAROS (JAXA, 2010):** First demonstration of interplanetary solar sail flyby ($200m^2$,$315kg$) and dynamic characterisation of solar radiation pressure (SRP) acceleration forces.

• **LightSail-2 (The Planetary Society, 2019):** Full orbit modification demonstrated in a tiny 3U CubeSat form factor, relying entirely on photonic pressure.

• **ACS3 (NASA, 2024):** A 12U CubeSat with a flexible $80m^2$ metalised thin film polymer membrane demonstrating precise orbit control, altitude change, and real-time flight trajectory modelling.

Flexible deformations and parasitic torques have been identified as two main technical barriers associated with mid-term space sails. The wrinkling of the sail film as it deploys results in unpredictable c.p. shifting, thus leading to considerable disturbances in the torque. Future trends in control will be based on shape modulation using boom winches controlled by cables (like the CABLESSail concept) as well as active mass translators and electro-optically active membranes, which change local reflectivity through voltage applications in order to perform attitude control without fuel. In terms of the future beyond that, Diffractive Solar Sailing will make use of diffractive film metamembranes (optimised with finite-difference time-domain modelling) to scatter photons.

3.1.2 Coulomb Drag Propulsion (Electric Sails)

The Electric Solar Wind Sail (E-Sail) exploits the kinetic energy of the solar wind. The system repels solar wind protons by electrostatic means using a spinning grid of tethers extended by centrifugal force and maintained at a high positive voltage by an onboard electron gun. This results in a stable Coulomb drag force that allows small spacecraft to perform propellantless interplanetary transfers throughout the heliosphere without the need for the large reflective surfaces required for photon sails.

3.2 Nuclear Thermal Propulsion (NTP) Solid Core Designs

The key technology path that can deliver high thrust and high propellant efficiency ((I_{SP}≈900−1000s) is Nuclear Thermal Propulsion. The solid core design channels cryogenic liquid hydrogen (LH_2) through a core of enriched fission reactors. The hydrogen gas is the reactor coolant. It absorbs thermal energy from the fuel elements and then expands supersonically through a converging-diverging nozzle to produce thrust.

This historical baseline was validated by the joint AEC-NASA NERVA program (1959-1973) that achieved core exit temperatures of 2,550 K and a I_{SP} of 845 seconds with hexagonal prismatic graphite matrix composite fuel channels. And the Soviet Union achieved progress with a non-uniform modular core design inside the IRGIT test reactor. In Soviet architecture, the fuel was delivered in the form of separate fuel assembly bundles with twisted ribbon-like ternary carbide fuel elements (UC-ZrC-NbC) instead of full-scale homogeneous blocks. This distorted morphology was optimised for surface-area-to-volume ratio and allowed the prototype RD-0410 engine to survive extreme power densities of 35 MW/L and peak gas temperatures of 3,200 K.

The top modern solid core programs are the NASA-DARPA DRACO (Demonstration Rocket for Agile Cislunar Operations), with a 2027 flight milestone targeted. DRACO employs a scalable modular reactor core fueled by High-Assay Low-Enriched Uranium (HALEU) and designed to deliver active thrust configurations for over four hours at greater than 2,700 K. It does this by setting up a sophisticated digital twin modeling to simulate the transient engine startup cycling and control the cryogenic hydrogen flow of low boiling point, alleviating the classic solid core bottleneck of high temperature hydrogen chemical corrosion along the channel walls.

4.Literature survey

This section systematically evaluates the basic and state-of-the-art literature to provide a context for the development of high-power interplanetary strings, propellantless transport systems, and space nuclear cores. The research surveyed is structured into thematic streams that align directly with the technical parameters and subsystem dependencies of this report.

4.1 Historical Evolution and Taxonomy of Space Propulsion Systems

The overarching trajectory of space exploration highlights a clear division between high-thrust/low-efficiency thermodynamic launchers and low-thrust/high-efficiency in-space systems.

Flight Regimes Taxonomy Salgado et al. (2018) propose a rigorous baseline classification of flight regimes including escape propulsion (launch dynamics from surface to orbit), in-space propulsion (orbital maneuvers and station keeping in the Earth's gravity well), and deep-space propulsion (interplanetary and interstellar missions). Their analysis confirms that chemical engines on liquid oxygen/liquid hydrogen (LX_2/LH_2), hydrocarbons, or solid

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fuel forms are stuck at their thermodynamic limits, but they have a high maturity level despite being responsible for 58% of historical launch vehicle anomalies.

Performance Optimisation Metrics: The operational dichotomy is shown over 249 propulsion configurations by Rodrigues Pinto (2019), who demonstrates that an optimisation trade-off always needs to be made between the fuel efficiency of a system and the thrust-to-weight ratio. Chemical motors maximise up to 200 while non-chemical electric propulsion platforms provide specific impulses several orders of magnitude higher for the expense of reduced instant accelerations ($T/\omega \sim 10^{-6} to\ 10^{-1}$).

Advanced System Metrics: Patel et al. (2025) present a performance analysis comparison validating the reliance of near-term deep-space voyages on the maturation of nuclear thermal options and the necessity of a structural paradigm shift towards fusion cores and beamed energy propulsion configurations for far-term relativistic baselines targeting interstellar scales (0.1c).

4.2 Near-Term Architecture: High-Power Electric Propulsion Strings and Subsystem Integration

In-space tracking segments are transitioning away from analyzing isolated propulsors toward the qualification of integrated propulsion "strings".

Subsystem Coupling Gaps: The coupled performance limits of the thruster body, cathode electron emitter, Power Processing Unit (PPU), and Propellant Management System (PMS) are evaluated by Jovel et al. (2022) at scaled powers >6 kW. They highlight a critical development gap between the current flight-qualified mid-power strings (≤4.5 kW) and lab prototypes that can operate at up to 100 kW, demonstrating that the high-power regime calls for new records in current ratings and thermal management boundaries for all four string elements.

String Integration Dynamics: The evolution of the electric string from the historic Space Electric Rocket Test (SERT) missions of the 1960s to modern high-power deep-space logistics is reviewed by Kulkarni (2026). Analysis shows that long duration, low thrust acceleration produces non-Keplerian, spiral-like trajectories that fundamentally change spacecraft mission profiles, data distribution, and fault logic requirements.

Hall Effect Currents and Grid Physics: In their paper, Wu et al. (2025) explain the vectors of particle acceleration in magnetic nozzles (PMN). The authors show how the internal energy of plasma ions becomes kinetic in the axial direction by way of electric field potential drops and generalised Hall effect currents. They also point out the fact that one important factor that reduces the effectiveness of electromagnetism is the detachment of charged particles from the closed magnetic lines – this results in a negative paramagnetic current causing drag.

4.3 Alternative Propellant Chemistry and Material Nanotechnology Evolution

The expansion of commercial and civil small satellite mega-constellations has introduced distinct logistical, material, and economic constraints to high-power strings.

Green and Alternative Chemistry: Dr Payal N. Bhautik and Patil (2026) investigate the development of environmentally friendly alternatives for hazardous heritage propellants such as hydrazine, with the help of energetic ionic liquids like ADN (Ammonium Dinitramide) and HAN (Hydroxylammonium Nitrate). The work is complemented by that of Boretti (2025), wherein he discusses ionisation energies and atomic masses of propellants utilised in electric propulsion systems. Although there are severe market constraints for noble gas Xenon, condensable gases such as Iodine and Bismuth provide higher storage densities along with simplified feed architectures.

Ingression of Smart Nanomaterials: Levchenko et al. (2018) have brought a revolution in thruster durability by applying adaptive nanomaterials. According to their study, channel walls having ultrananocrystalline diamond or carbon nanotube brush coatings show a wear coefficient two magnitudes lower than that of conventional ceramic under high-energy ion sputtering. Moreover, they provide a self-healing thruster design that uses plasma-assisted chemical vapour deposition technology to embed nanoparticles generated in-situ into the eroded pits on the channel walls.

Advanced Thermionic Emitters: Levchenko et al. (2020) have developed their technique for thermionic emitters. With the help of an examination of emission current densities of high-amperage hollow cathodes, they show how the replacement of conventional materials by arrays of cold field emission, formed from nanotubes or graphene flakes oriented perpendicularly to the emitter surface, makes it possible to avoid using heater units and the consumption of propellant gases via the cathode. Furthermore, they consider materials operating at elevated temperatures for the construction of electronic heat pumps.

4.4 Mid-Term Architectures: Microgravity Space Sailing and Coulomb Drag Dynamics

Propellantless propulsion frameworks harness ambient heliospheric momentum vectors to eliminate onboard chemical or electric fuel reserves.

Timelines of Flight Validation: According to Ancona and Kezerashvili (2024), there is an outline of the flight qualification record of solar sails from JAXA's interplanetary experiment with IKAROS in 2010 to NASA's recent launch of the ACS3 in 2024. This study provides an empirical starting point for sail efficiency by analyzing the sail's surface area, dry mass, and areal density from successful and unsuccessful missions.

Structural Control Shortcomings: The existing research literature recognises sail wrinkling upon unfolding and parasitic disturbance torques as two critical issues: Bhautik and Patil (2026) investigate Levchenko, Xu, et al. (2018) preventing accurate trajectory control. Current approaches to sail stabilisation utilise the CABLESSail approach, based on controlling local reflectivity by means of boom winches and shifting the center of pressure (c.p.) from the center of mass (c.m.) and allowing 3-axis control without using any chemical fuels.

Thermal Desorption and Metamembranes: In order to beat the limitations of traditional solar radiation, Ancona and Kezerashvili consider sun diving missions using sails covered with volatile substances that cause thermal desorption near the Sun and generate a mass expulsion producing an acceleration thrust that is an order of magnitude stronger than photon pressure and enabling solar system escape velocity higher than 100 km/s. Moreover, they investigate metamembranes based on diffraction with FDTD design optimisation for the beam-riding mission.

Coulomb Drag due to the Wind: Besides the photonic sail mentioned above, another kind of sail is introduced by Janhunen (2023) and Boretti (2025). The Electric Solar Wind Sail utilizes the kinetic energy of the protons present in the solar wind. Using an electron gun and keeping a high positive voltage between a spinning grid of tethers, a stable Coulomb drag is created by the E-sail.

4.5 Nuclear Cores and Advanced Interstellar Exploration Paradigms

As mission profiles go beyond cislunar limits toward the outer solar system and nearby interstellar space, the drop-off in solar irradiance ($1/r2$) bounds the viability of solar arrays, necessitating high-energy fission and fusion cores.

Maturity of Fission Technologies: Polzin et al. (2026) present in the NASA Technology Maturation Plan for High Power Nuclear Electric Propulsion (NEP) a thorough programmatic roadmap to attain TRL 5 maturity for megawatt-scale fission systems in space applications. In their study, Polzin et al. describe the intricate interfaces among the moderated reactor assembly (WBS 1.0), Closed Brayton cycle converters (WBS 2.0), and carbon-based heat pipe radiators (WBS 5.0). They evaluate the specific mass properties necessary for mission completion for manned opposition Mars transfer.

Metallurgy-Based Nuclear Thermal Propulsion: In relation to NTP core design, Umarani (2024) discusses solid core NTP components, with emphasis on the transition from past homogeneous graphite matrix systems (NERVA) to non-homogeneous modular cores. This is further enhanced by Du et al. (2025) by investigating the usage of twisted ribbon-like carbide fuel bundles (UC-ZrC-NbC) for the Soviet RD-0410 engine in order to achieve high surface-to-volume ratios and withstand gas.

Modelling of Interstellar Trajectories: Litchford and Sheehy (2020) provide information on interstellar mission technology assessments by NASA. They conclude that an interstellar fly-by probe mission directed towards Alpha Centauri needs a speed of ~0.1c, which is only possible through the minimum specific impulse of 400,000 seconds. Achieving such high speed for a payload similar to that of the Voyager probe (720 kg) demands an expenditure of 0.06% of the total annual energy production of the Earth, thus necessitating full autonomous FDIR avionics.

Thermonuclear Fusion Engines: Long (2022) examines the physics of Laser-Driven Inertial Confinement Fusion (ICF) for Interstellar Propulsion. The process uses focused laser pulses on a fuel capsule (DT or $D-3He$) to create ultra-high densities (~1000 × solid density) and trigger a thermonuclear fusion reaction. Long describes the interdependencies between gain factor (Q), areal density of fuel (ρR), and burn fraction (fb), showing that for future starships like Daedalus, Vista, and Icarus Resolution, a pulse frequency of 10-250 Hz is needed to produce megawatt to gigawatt jet power for pure thermonuclear fusion propulsion in space missions.

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5.Conclusion

The technology development of space propulsion through this internship report has given us an in-depth understanding about the technology development and its future possibilities. This shows that there is a huge variation of need for propulsion according to distance of travel, payload, thrust, and time period of mission. Chemical propulsion systems still continue to give high thrust for launches and major gravitational maneuvering while electric propulsion gives better specific impulse.

The examination of high-power electrical propulsion brought to attention the need for treating the propulsion system as one integral string that includes the thruster, cathode, power processing unit, and propellant management system. Despite the advances achieved by high-power Hall-effect thrusters and gridded ion engines, issues with erosion of components, power processing, thermal control, current handling, and propellant supply still remain areas for future work. Alternative propellants including krypton, iodine, and bismuth might help overcome some disadvantages of xenon.

The utilization of propellantless technologies like solar sails and electric solar wind sails is one possible means for interplanetary flights of long duration that can save on or do away with the need to carry onboard propellant. A major option that is available in this regard includes the use of nuclear thermal propulsion because of the high level of thrust and better specific impulse than traditional chemical propulsion. The future may well hold more advanced systems such as nuclear-electric and fusion propulsion.

On the whole, the results of the research suggest that the future of space propulsion will rely on further development and integration of different propulsion technologies. Enhanced performance of power sources, materials, thermal control systems, fuel use efficiency, and autonomy of spacecrafts will be necessary in order to develop these technologies from laboratory models into real-world applications. Development from high-power electric propulsion to nuclear, propellantless, and fusion propulsion is therefore the future pathway of technological evolution of propulsion technologies for deep space exploration.

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7.Conflict of Interest

The author declares no competing conflict of interest.

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