Acceleron Aerospace Journal || AAJ.11.2106-2459
Volume 3, Issue 5, pp (573-584)
Review Paper
E-ISSN- 2583-9942 || DOI: 10.61359/11.2106-2459

Comparison of Propulsion Options for Interplanetary Missions

Raviteja Bheemavarapu*

ORCID: 0009-0002-7677-8153

Department of Aerospace Engineering, Chandigarh University, Punjab, India

Abstract: This paper investigates propulsion options and trajectory designs for a manned mission from Earth to Mars, followed by a mission to Ceres. It evaluates various propulsion technologies, including traditional chemical propulsion, nuclear thermal propulsion (NTP), and electric propulsion systems such as ion thrusters and Hall effect thrusters. The analysis highlights the limitations of chemical propulsion in terms of energy efficiency and payload capacity while underscoring the potential of NTP to reduce travel time and improve crew safety due to its higher specific impulse. The study also examines the feasibility of solar and nuclear electric propulsion, focusing on their high efficiency and suitability for extended missions, and considers innovative concepts like solar sails and fusion propulsion for their theoretical advantages in thrust and velocity. Low-thrust trajectories are analyzed for their ability to minimize overall delta-V requirements, which is essential for mission success. For the Mars mission, chemical propulsion systems currently under development are evaluated alongside electric propulsion powered by nuclear reactors, which could significantly reduce travel times and propellant needs. The additional challenges of propelling a spacecraft to Ceres, a more distant destination in the asteroid belt, shift the focus to electric propulsion options, particularly advanced nuclear-electric systems, which offer the potential to enable human exploration within a reasonable timeframe. The paper concludes that the optimal propulsion system for a manned mission to Mars and Ceres requires balancing travel time, technical feasibility, and crew safety, emphasizing the necessity for further development of advanced electric propulsion technologies to facilitate ambitious human deep-space exploration.

Table of Contents

1. Introduction

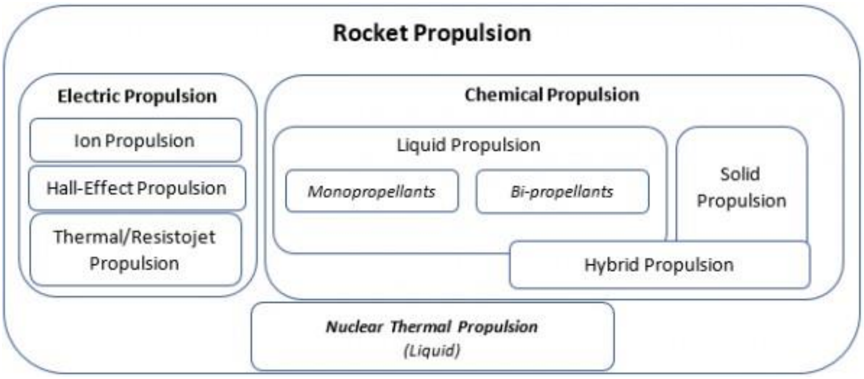
Several studies have been conducted to explore propulsion options for a manned mission from Earth to Mars and Ceres. **Galecki et al. (1987)** conducted a detailed trajectory analysis and propulsion system study for an unmanned cargo mission to Mars using nuclear-powered ion propulsion technology. **Perkins (1991)** investigated the utility of nuclear thermal rocket (NTR) upper-stage propulsion for fast Mars transfer ellipses, aiming to reduce interplanetary transit time and enhance mission economics. **Borowski et al. (2012)** highlighted the NTR as a proven growth technology for human NEO/Mars exploration missions, emphasizing its higher performance, lower launch mass, and growth potential. In terms of trajectory options, **Cassenti (2005)** examined various approaches for manned Mars missions, including opposition and conjunction class missions, direct landing on Mars with in situ propellant production, and a rapid "dash to Mars" by the crew, coupled with a hyperbolic rendezvous at Mars. **Salotti (2014)** suggested revisiting parameters impacting complexity, initial mass in low Earth orbit, risks, and development costs for the first journey to Mars, emphasizing the need to study the interdependency of mission parameters. Furthermore, **Hall et al. (1989)** discussed the design of telecommunications and navigation systems for manned Mars exploration missions, highlighting the necessity of telecommunications support and preliminary navigation functions. **Gonzales et al. (2014)** presented a feasibility study for a Mars Sample Return mission using commercial capabilities, showcasing a mission design starting in 2022, with a Falcon Heavy injecting a SpaceX

*UG Scholar, Department of Aerospace Engineering, Chandigarh University, Punjab, India. **Corresponding Author: ravitejabheemavarapu01@gmail.com.**
** Received: 12-August-2024 || Revised: 25-October-2024 || Accepted: 26-October-2024 || Published Online: 30-October-2024.

Red Dragon capsule onto a Trans Mars Injection trajectory. Overall, these studies emphasize the importance of propulsion system selection, trajectory analysis, telecommunications support, and mission design considerations for successful manned missions from Earth to Mars.

The propulsion options for a manned mission from Earth to Mars are crucial for the success of such a mission. NASA has been actively advancing propulsion technologies to facilitate human missions to Mars **[12]**. Nuclear propulsion has been identified as a potential option to expedite the journey to Mars **[16]**. In fact, NASA has been pursuing an ambitious technology development strategy to enable the use of nuclear propulsion for a human mission to Mars by 2039. In addition to nuclear propulsion, other systems such as solar electric and chemical propulsion have also been considered for crewed missions to Mars **[17]**. These systems play a vital role in performing departure and capture burns around Earth and Mars, ensuring the safe transit of crew and cargo between the two planets **[17]**. Studies have highlighted the importance of in-space propulsion systems for human Mars exploration architectures **[15]**. These systems are essential for transferring crew and cargo between Earth orbit and Mars, making them a critical component of any mission to the Red Planet [15]. Additionally, electric propulsion has been recommended as a low-risk and cost-effective approach for robotic Mars sample return missions **[20]**. Electric propulsion systems provide a viable option for fast transits to Mars, offering a reliable and efficient means of transportation for spacecraft **[20]**. Overall, the development and optimization of propulsion systems are key factors in enabling successful manned missions from Earth to Mars. By exploring various propulsion options and advancing technology in this field, NASA and other space agencies are paving the way for future human exploration of the Red Planet **[11-12,15-17,20]**.

Figure 1 Classification of Propulsion Systems



2. Literature Review

- ***Nuclear-Powered Propulsion for Mars Missions:*** Studies by Galecki, Patterson, Braun, and Blersch explore the use of nuclear-powered ion propulsion for Mars cargo transport missions. They analyze the performance and feasibility of combining nuclear electric propulsion (NEP) with detailed trajectory analysis to determine optimal propulsion systems and mission profiles. Results indicate that NEP can provide the high specific impulse and thrust-to-weight ratios required for efficient Mars cargo transport.
- ***Telecommunications and Navigation for Manned Mars Missions:*** Hall and Hastrup's paper focuses on the design of telecommunications and navigation systems for manned Mars exploration missions. It examines the unique challenges associated with providing reliable communication and navigation support for long-duration crewed missions to Mars.
- ***Manned Mars Mission Perspectives and Options:*** Clark’s work provides an overview of various perspectives and options for manned Mars missions. It discusses key technological, operational, and programmatic considerations that must be addressed to enable successful human exploration of Mars.
- ***Propulsive Options for Manned Mars Transportation:*** Braun and Blersch evaluate different propulsive options, including chemical, nuclear thermal, and nuclear electric propulsion, for a manned Mars transportation system. They assess the performance, mission suitability, and feasibility of these propulsion technologies.
- ***Nuclear Upper Stage Propulsion for Fast Mars Transfers:*** Perkins' study investigates the use of nuclear upper-stage propulsion to enable fast, high-energy transfer trajectories to Mars. The focus is on improving efficiency and reducing trip time for manned Mars missions.

- ***Trajectory Options for Manned Mars Missions:*** Cassenti's paper explores various trajectory options and their implications for manned Mars missions. It analyzes the trade-offs between mission duration, propellant requirements, and other key factors.
- ***Nuclear Thermal Rocket Engine Designs:*** Culver, Dahl, McIlwain, Borowski, McCurdy, and Packard examine the design and performance of nuclear thermal rocket (NTR) engines for Mars exploration. They highlight the potential benefits of NTR systems, such as high specific impulse and thrust-to-weight ratios, for manned Mars missions.
- ***New Trade Trees for Manned Mars Missions:*** Salotti's paper presents a new trade tree framework for evaluating manned Mars mission architectures. This approach considers a broader range of factors, including mission duration, crew size, and surface operations, to identify the most promising mission concepts.
- ***Mars Sample Return Using Commercial Capabilities:*** Gonzales et al. explore the use of commercial launch vehicles and capabilities to enable a Mars sample return mission. The study outlines a mission architecture that leverages emerging space technologies and commercial partners.
- ***Low-Enriched Uranium Nuclear Thermal Propulsion:*** Joyner et al. investigate the use of low-enriched uranium (LEU) nuclear thermal propulsion (NTP) systems for various mission options, including crewed Mars exploration. They analyze the performance, feasibility, and potential benefits of LEU NTP compared to other propulsion technologies.
- ***Low-Thrust Trajectories for Human Missions to Ceres:*** Laipert and Longuski conducted a detailed study on low-thrust trajectories for sending humans to Ceres. They constrained the flight times to 270 days for each leg of the mission and explored the use of solar electric propulsion (SEP) and nuclear electric propulsion (NEP) systems. Results indicate that these advanced propulsion technologies can enable feasible mission profiles for human exploration of Ceres.
- ***Propulsion Options for Missions to Near-Earth Objects:*** Sforza and Remo examined propulsion options for missions to near-Earth objects (NEOs), including those en route to Mars and Ceres. They evaluated chemical, electric, and nuclear propulsion systems in terms of performance, mission suitability, and feasibility. The study highlights the potential benefits of electric and nuclear propulsion for deep-space exploration.
- ***Methane Cryogenic Propulsion for Human Mars Exploration:*** Percy et al. focused on the design and development of a methane cryogenic propulsion stage for human Mars exploration. They analyzed the performance, advantages, and challenges of using methane-based chemical propulsion as an alternative to traditional hydrogen-based systems.
- ***Integrated Propulsion Concepts for Mars Missions:*** Accettura et al. investigated the use of integrated propulsion concepts, combining chemical, electric, and nuclear propulsion for Mars missions. They explored opportunities and strategies for leveraging these hybrid propulsion systems to improve overall mission performance and feasibility.

3. Conventional Propulsion Options for Interplanetary Missions

Chemical Propulsion

- Chemical rockets, such as liquid and solid propellant engines, are well-established and widely used propulsion technologies for space missions.
- They provide high thrust levels but have relatively low specific impulse (300-450 seconds), necessitating large propellant masses for interplanetary missions.
- Chemical propulsion has extensive flight heritage and is a mature technology, making it a reliable choice for many space applications.

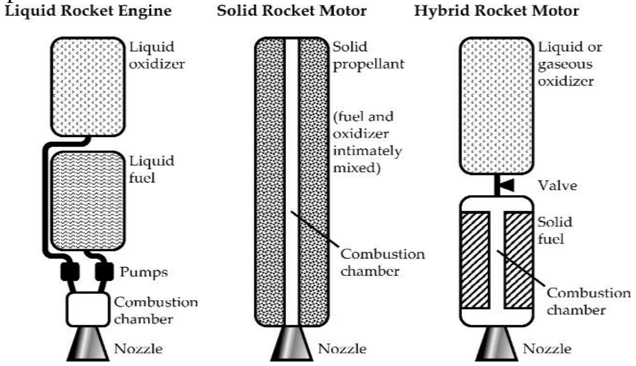


Figure-2 Classification of Chemical Propulsion Systems [Courtesy: New Space Economy]

Cryogenic Propulsion

- Cryogenic propulsion systems, which use propellants such as liquid hydrogen and liquid oxygen, offer improved performance over traditional chemical rockets.
- The study by Thomas Percy et al. explored the design and development of a methane-based cryogenic propulsion stage for human Mars exploration, highlighting its potential advantages.
- Cryogenic propulsion can provide higher specific impulse and thrust-to-weight ratios compared to conventional chemical rockets, making it suitable for deep space missions.

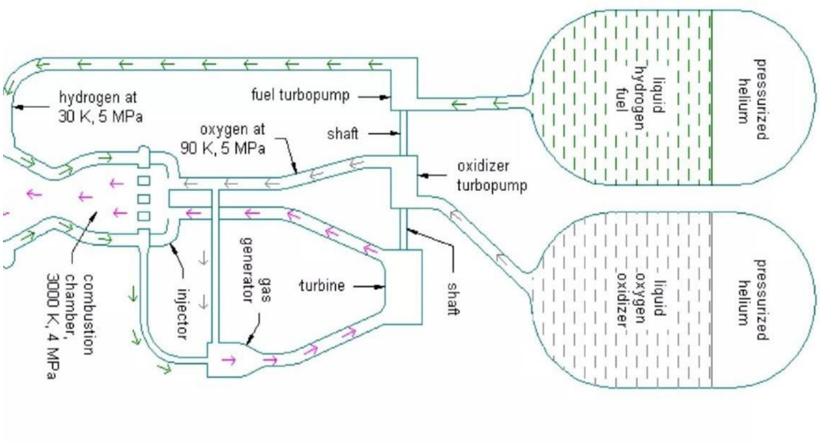


Figure-3 Illustration of Cryogenic Propulsion System Working Process [Courtesy: Rohan Sharma]

Hybrid Propulsion

- Hybrid propulsion systems combine different propulsion technologies, such as chemical with electric or nuclear, to leverage the strengths of each approach.
- Accettura et al. investigated integrated propulsion concepts that combine chemical, electric, and nuclear propulsion for Mars missions.
- Hybrid propulsion can offer improved performance, flexibility, and mission adaptability compared to relying on a single propulsion technology.

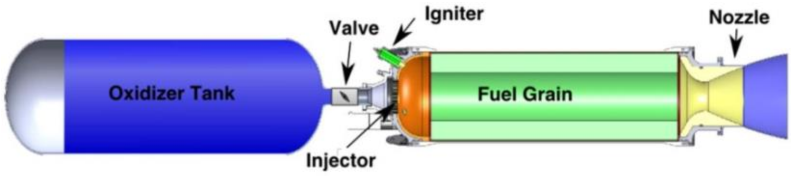


Figure-4 Hybrid Propulsion System [Courtesy: Jerome.et.al.2014]

4. Advanced Propulsion Technologies for Interplanetary Missions

Electric Propulsion

- Electric propulsion systems, such as ion engines and Hall effect thrusters, offer significantly higher specific impulse (2,000-8,000 seconds) compared to chemical rockets.
- This high specific impulse translates to much higher propellant efficiency and reduced propellant mass requirements for interplanetary missions.
- Electric propulsion can be powered by solar energy (solar electric propulsion) or nuclear energy (nuclear electric propulsion), providing greater flexibility and independence from solar radiation.
- Studies by Laipert and Longuski, Sforza and Remo, and Fearn and Martin emphasize the potential of electric propulsion for feasible mission profiles to Mars, Ceres, and other deep-space destinations.

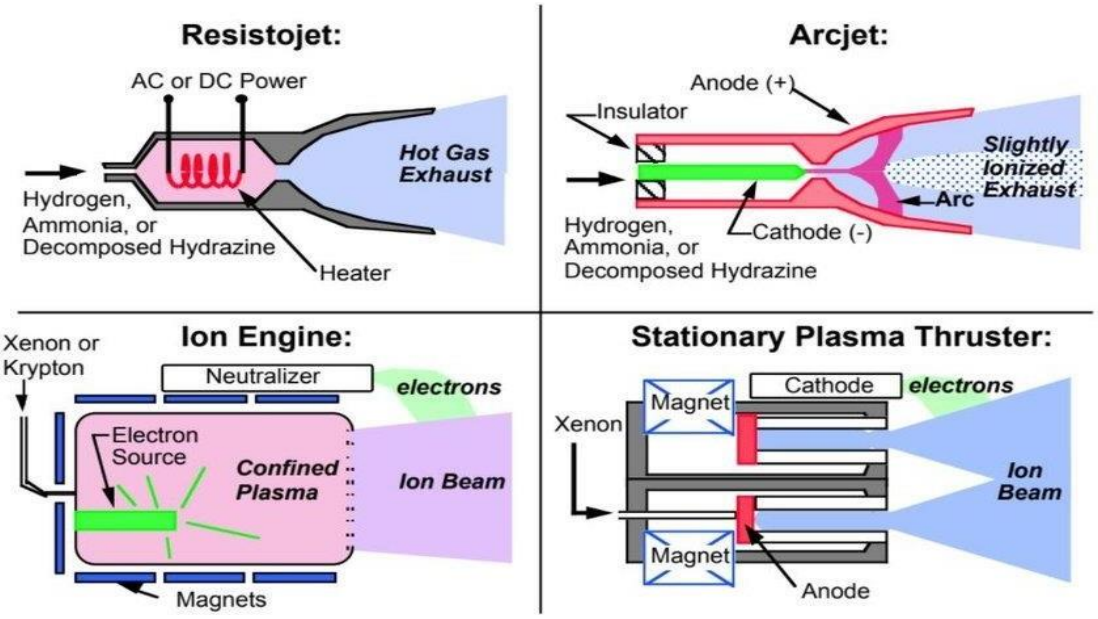


Figure-5 Classification of Different Electric Propulsion Systems [Courtesy: Ugur.et.al.2018]

Nuclear Thermal Propulsion (NTP)

- Nuclear thermal propulsion systems use a nuclear reactor to heat a propellant, typically liquid hydrogen, which is expelled through a nozzle to generate thrust.
- NTP offers very high specific impulse (800-1,000 seconds), making it more efficient for interplanetary transfers compared to chemical rockets.
- Research by Cothran et al., Loeb et al., and Borowski et al. highlights the use of NTP for human exploration of Mars and beyond, focusing on its performance benefits and technical challenges.

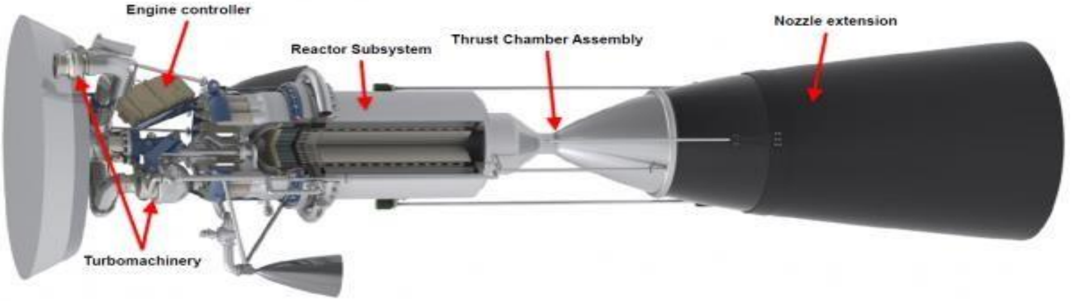


Figure-6 Conceptual Design of Nuclear Thermal Propulsion System (NTP) [Courtesy: Vladimir.et.al.2022]

Nuclear Electric Propulsion (NEP)

- NEP combines a nuclear reactor with an electric propulsion system, such as ion engines or Hall thrusters.
- It offers even higher specific impulse (3,000-8,000 seconds) than solar electric propulsion and provides independence from solar radiation.
- Studies by Galecki and Patterson, Braun and Blersch, and Loeb et al. investigate NEP's potential for cargo transport and manned missions to Mars and other deep-space destinations.

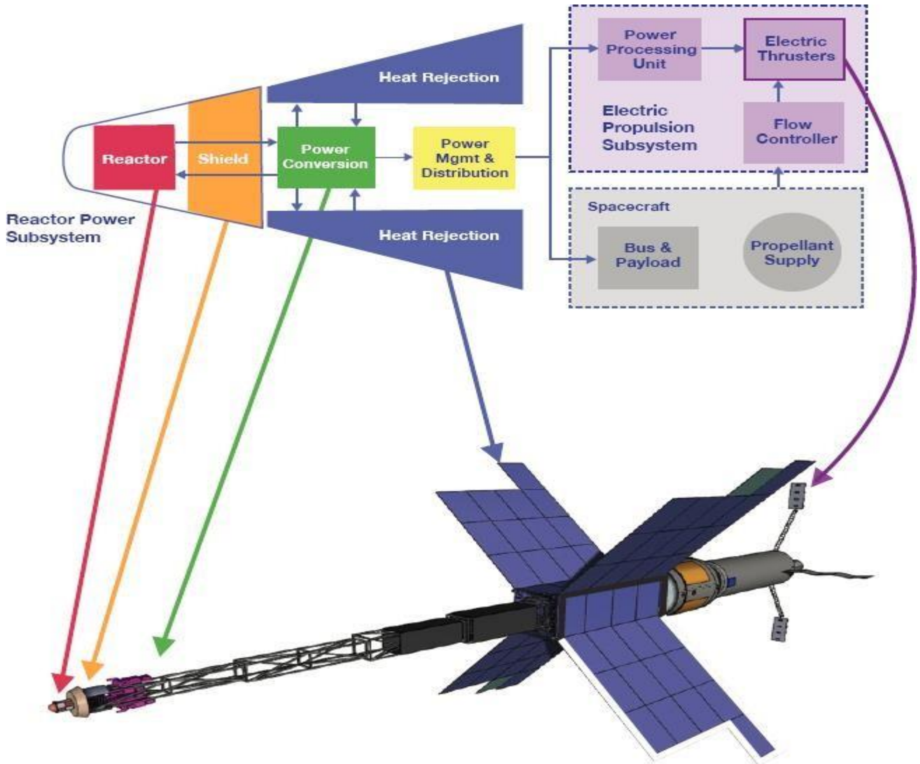


Figure-7 Nuclear Electric Propulsion Subsystems and Conceptual Design

Beamed Energy Propulsion

- Beamed energy propulsion transmits energy, such as microwaves or lasers, from a ground-based or orbital power source to a spacecraft, which then converts the energy into propulsive thrust.
- This approach, explored by Anderson et al., has the potential for enabling extremely high-speed space transportation for Mars and beyond.

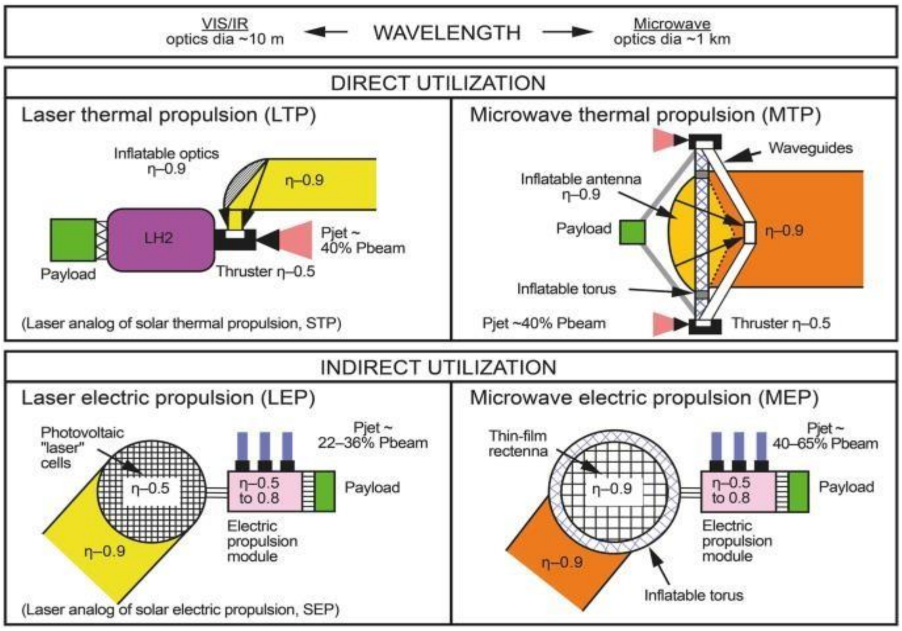


Figure-8 Classification of Beamed Energy Propulsion Systems [Courtesy: Yuri.et.al.2021]

5. Emerging and Theoretical Propulsion Technologies

Emerging and theoretical propulsion systems promise transformative capabilities for interplanetary and deep space missions. Below are some of the most innovative and forward-thinking propulsion concepts:

1. Wasim Engine (Casimir Effect Drive)

- **Concept**: This theoretical propulsion system aims to harness the Casimir effect—a tiny attractive force between closely spaced conducting plates—to produce thrust by manipulating fluctuating geometries.
- **Potential**: If feasible, the Wasim Engine could offer propellant-less propulsion, significantly reducing mission mass.
- **Challenges**: The concept remains highly theoretical, with significant scientific and engineering challenges to address before realization.

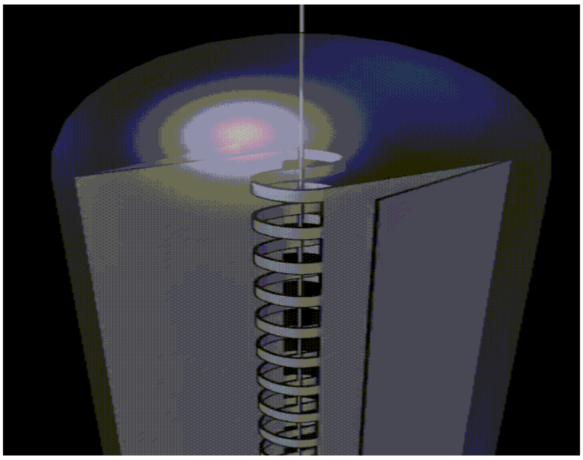


Figure-9 Conceptual Design of Wasim Engine Utilizing Casimir Force [Courtesy: Stack Exchange]

2. Fusion Rockets

- **Mechanism**: A fusion rocket would use the immense energy produced from controlled nuclear fusion reactions to heat propellant for thrust.
- **Advantages**: Fusion rockets promise high efficiency and the capability for extended deep space exploration.
- **Status**: This technology is still in research stages and requires advancements in fusion containment and energy conversion systems.

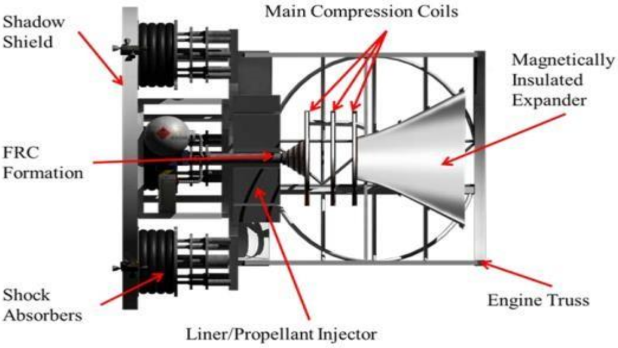


Figure-10 Schematic of a Fusion-Driven Rocket (NASA) [Courtesy: Claire.et.al.2015]

3. Bussard Ramjet

- **Design**: The Bussard Ramjet uses a magnetic field to collect and compress interstellar hydrogen as propellant, which is then fused to create thrust.
- **Potential**: Offers continuous propulsion in deep space, theoretically enabling interstellar travel.
- **Drawbacks**: The concept faces challenges, including collecting enough hydrogen and handling the energy generated from fusion.

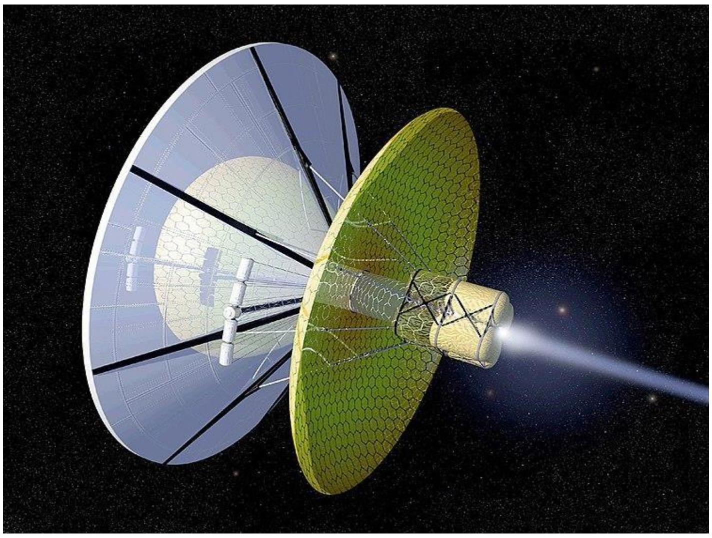


Figure-11 Illustration of a Bussard Ramjet [Source: Wikipedia]

4. Antimatter Annihilation Rockets

- **Principle**: Uses antimatter, which releases substantial energy when colliding with matter, for propulsion.
- **Benefits**: Could provide extremely high propulsion efficiency and travel speeds.
- **Limitations**: Antimatter production and storage are prohibitively expensive and complex, making this concept a distant possibility.

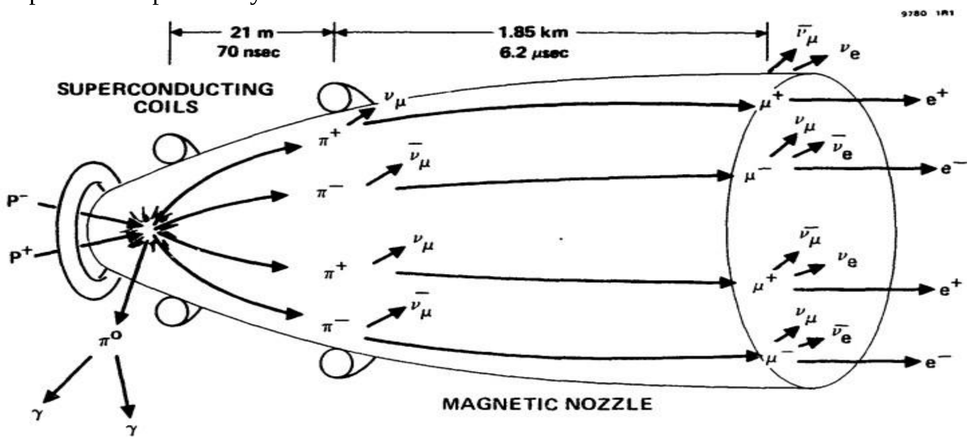


Figure-12 Schematic of First-Generation Antimatter Annihilation Rocket (Anti-proton Rockets) [Claude.et.al.2006]

5. Air-Scooping Electric Propulsion (ASEP)

- **Concept**: ASEP involves collecting sparse atmospheric molecules from the upper atmosphere as propellant, extending mission durations without onboard propellant.
- **Applications**: This approach can increase satellite lifetimes by enabling re-boosting in very low Earth orbits.
- **Advancements**: Early research indicates its potential for extending the operational life of satellites.

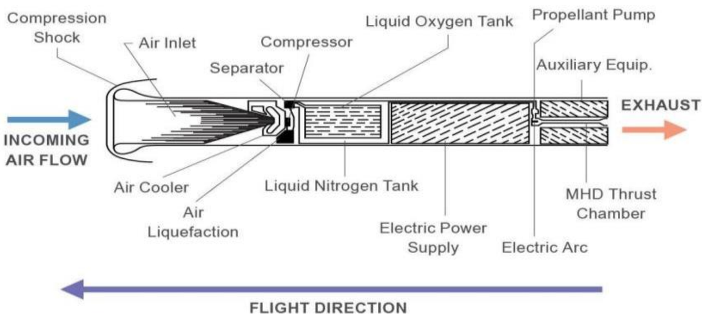


Figure-13 Schematic of Air-Scooping Electric Propulsion System

6. Solar Sailing

- **Method**: Solar sails utilize the mechanical pressure exerted by sunlight on large reflective surfaces to propel the spacecraft, allowing continuous acceleration without onboard fuel.
- **Demonstrations**: Successful missions by JAXA and The Planetary Society have validated the feasibility of solar sailing, showcasing its potential for future deep space missions.

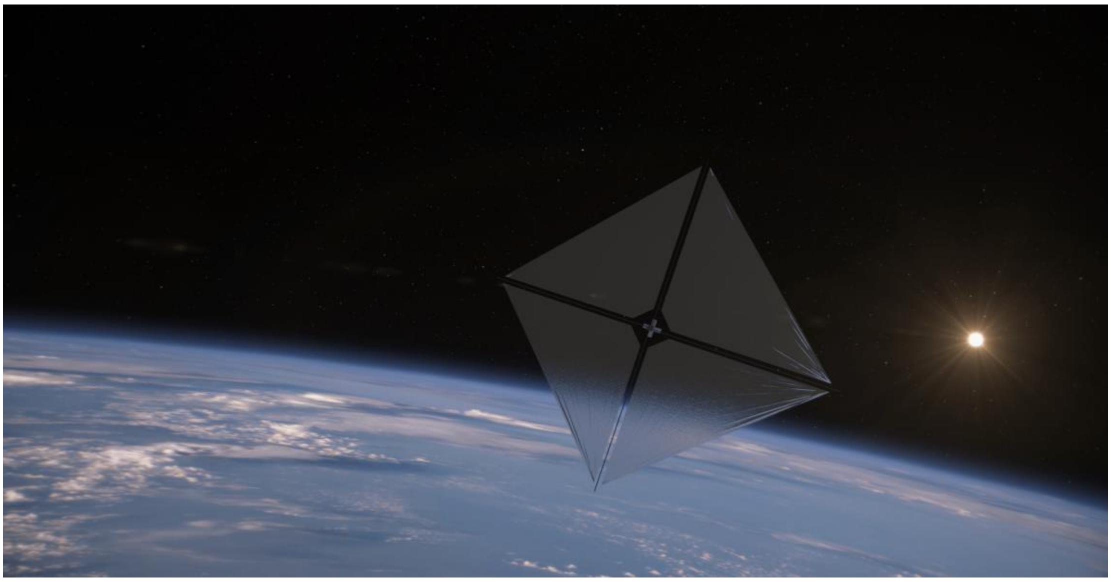


Figure-14 Concept of an Advanced Composite Solar Sail System Propelling a Spacecraft Using Solar Energy

6. Comparison of Propulsion Options

Table-1 Comparison of Propulsion Options

Propulsion Option	Performance Metrics	Mission Suitability	Cost	Feasibility
Chemical Rockets	High thrust, low specific impulse (300-450 s)	Well-established, reliable, and mature technology	Low to moderate	High
Cryogenic Propulsion	Higher specific impulse than chemical rockets	Can provide higher performance than traditional chemical rockets	Higher than chemical rockets	High
Electric Propulsion	Very high specific impulse (2,000-8,000 s)	Suitable for long-duration missions, high efficiency	Higher than chemical rockets	High
Nuclear Thermal Propulsion (NTP)	Very high specific impulse (800-1,000 s)	Can provide high performance, high efficiency	Higher than chemical rockets	High
Nuclear Electric Propulsion (NEP)	Very high specific impulse (3,000-8,000 s)	Can provide high performance, high efficiency, and independence from solar radiation	Higher than chemical rockets	High
Beamed Energy Propulsion	High thrust, high specific impulse	Can provide high performance, high efficiency	Higher than chemical rockets	High
Air-Scooping Electric Propulsion (ASEP)	High thrust, high specific impulse	Can provide high performance, high efficiency	Higher than chemical rockets	High
Solar Sailing	Continuous acceleration without onboard propellant	Can provide continuous acceleration without onboard propellant	Higher than chemical rockets	High
Hybrid Propulsion	Combines advantages	Can provide high	Higher than	High

	of different propulsion systems	performance, high efficiency	chemical rockets	
Wasim Engine	High thrust, high specific impulse	Can provide high performance, high efficiency	Higher than chemical rockets	Medium
Fusion Rocket	High thrust, high specific impulse	Can provide high performance, high efficiency	Higher than chemical rockets	Medium
Bussard Ramjet	High thrust, high specific impulse	Can provide high performance, high efficiency	Higher than chemical rockets	Medium
Antimatter Annihilation Rockets	High thrust, high specific impulse	Can provide high performance, high efficiency	Higher than chemical rockets	Medium

The table provides a comparative overview of various propulsion technologies based on key criteria relevant to space missions. *Performance Metrics* highlight the specific impulse and thrust-to-weight ratios of each option, allowing for direct comparisons of their efficiency. *Mission Suitability* examines how well each propulsion technology meets the needs of different mission types, such as long-duration or high-efficiency missions. *Cost* outlines the financial implications of each propulsion option, with advanced and theoretical systems generally incurring higher costs due to technological complexity. *Feasibility* reflects the level of current development and technical readiness, distinguishing between mature and emerging propulsion systems. Conventional options include established chemical rockets and cryogenic propulsion systems known for their reliability. Advanced systems, such as electric, nuclear thermal, and nuclear electric propulsion, offer higher efficiency but come at a higher cost. Theoretical propulsion concepts, like the Wasim Engine, Fusion Rockets, Bussard Ramjets, and Antimatter Annihilation Rockets, remain speculative, presenting immense potential but significant scientific and engineering challenges.

7. Challenges Associated with Various Propulsion System

Propulsion systems for space exploration come with unique challenges and drawbacks.

- *Conventional propulsion*, such as chemical rockets, faces limitations like low specific impulse, requiring significant propellant masses for interplanetary missions. Cryogenic propulsion introduces storage challenges due to boil-off and adds complexity and mass.
- *Advanced propulsion* options present their own hurdles. Electric propulsion, while efficient, has low thrust, resulting in longer transfer times and dependency on power generation systems, such as solar or nuclear.
- *Nuclear Thermal Propulsion* (NTP) and Nuclear Electric Propulsion (NEP) require the development of space-grade nuclear reactors and face safety and regulatory concerns, as well as the added mass and complexity of reactor systems.
- *Theoretical propulsion systems*, like the Wasim Engine, seek to combine nuclear fission and fusion but are still in early development and struggle with sustaining high-temperature plasma conditions.
- *Fusion rockets* face immense engineering hurdles in achieving controlled fusion due to the high temperatures and pressures needed.
- The *Bussard Ramjet* concept, which involves collecting interstellar hydrogen, faces difficulties in capturing and compressing enough hydrogen to create thrust.
- *Antimatter propulsion* could offer high energy output, but producing and safely storing antimatter remains a significant technological and safety challenge due to its instability and containment difficulties.

Each propulsion type, while promising, requires overcoming substantial scientific and engineering obstacles to become viable for space missions.

8. Conclusion

The review has highlighted the various propulsion options available for manned missions from Earth to Mars and Ceres, ranging from conventional chemical rockets to advanced electric and nuclear propulsion systems. Each technology offers unique advantages and faces distinct challenges. Chemical rockets, while mature and reliable, are limited by their relatively low specific impulse, which requires large propellant masses for interplanetary missions. Cryogenic propulsion systems can provide improved performance but face challenges in propellant storage and handling. These conventional propulsion options may be suitable for certain mission profiles, such as quick transfers to Mars, but are less efficient for longer journeys. Advanced propulsion technologies, such as electric and nuclear systems, offer significant performance advantages. Electric propulsion, including solar electric and nuclear electric variants, provides extremely high specific impulse, enabling more efficient interplanetary transfers. However, the low thrust levels of electric propulsion can result in longer transit times. Nuclear thermal propulsion, on the other hand, delivers high thrust and specific impulse, making it a promising option for missions to Mars and beyond. While these advanced propulsion systems hold great potential, they also face technical challenges. Developing reliable and safe nuclear reactors for space applications, as well as integrating them with electric or thermal propulsion, requires substantial investment and overcoming significant engineering hurdles. Based on the research and hypothesis, the propulsion option that appears best suited for a manned mission from Earth to Mars and Ceres is a hybrid approach combining chemical and nuclear electric propulsion. This hybrid system leverages the strengths of both technologies, using chemical rockets for high-thrust maneuvers near planetary bodies and nuclear electric propulsion for efficient interplanetary transfers. The increased performance and reduced propellant requirements of this hybrid approach can enable more feasible mission profiles to these distant destinations. Continued research and development in nuclear electric propulsion, along with advancements in power generation and thermal management systems, will be crucial to making this hybrid propulsion solution a reality. With the right investments and technological breakthroughs, a manned mission from Earth to Mars and Ceres could become a tangible goal in the not-too-distant future.

9. References

[1] Galecki, D., & Patterson, M. (1987). Nuclear powered Mars cargo transport mission utilizing advanced ion propulsion. https://doi.org/10.2514/6.1987-1903
[2] Hall, J., & Hastrup, R. (1989). Telecommunications and navigation systems design for manned Mars exploration missions. https://doi.org/10.1117/12.951696
[3] Clark, B. (1990). Manned Mars mission - Perspectives and options. https://doi.org/10.2514/6.1990-1
[4] Braun, R., & Blersch, D. (1989). Propulsive options for a manned Mars transportation system. *Journal of Spacecraft and Rockets, 28*(1), 85-92. https://doi.org/10.2514/3.26213
[5] Perkins, D. (1991). Nuclear upper stage propulsion for insertion to fast Mars transfer ellipses. https://doi.org/10.2514/6.1991-2054
[6] Cassenti, B. (2002). Trajectory options for manned Mars missions. *Journal of Spacecraft and Rockets, 42*(5), 890-895. https://doi.org/10.2514/1.9770
[7] Culver, D., Dahl, W., & Mcilwain, M. (2008). A unique nuclear thermal rocket engine using a particle bed reactor. *Journal Name, 246*, 714-720. https://doi.org/10.1063/1.41866
[8] Borowski, S., McCurdy, D., & Packard, T. (2012). Nuclear thermal propulsion (NTP): A proven growth technology for human NEO/Mars exploration missions. *2012 IEEE Aerospace Conference*, 1-20. https://doi.org/10.1109/AERO.2012.6187301
[9] Salotti, J. (2014). New trade tree for manned Mars missions. *Acta Astronautica*, *104*, 574-581. https://doi.org/10.1016/J.ACTAASTRO.2014.07.017
[10] Gonzales, A., Stoker, C., Lemke, L., Bowles, J., Huynh, L., Faber, N., & Race, M. (2014). Mars sample return using commercial capabilities: Mission architecture overview. *2014 IEEE Aerospace Conference*, 1-15. https://doi.org/10.1109/AERO.2014.6836421
[11] Joyner, C., Eades, M., Horton, J., Jennings, T., Kokan, T., Levack, D., Muzek, B., & Reynolds, C. (2020). LEU NTP engine system trades and mission options. *Nuclear Technology, 206*(9), 1140-1154. https://doi.org/10.1080/00295450.2019.1706982
[12] Gilland, J., Fiehler, D., & Lyons, V. (2013). Electric propulsion concepts enabled by high power systems for space exploration. https://doi.org/10.2514/6.2004-5690
[13] Laipert, F., & Longuski, J. (2012). Low-thrust trajectories for human missions to Ceres. *Acta Astronautica, 95*, 124-132. https://doi.org/10.1016/J.ACTAASTRO.2013.11.003
[14] Sforza, P., & Remo, J. (1996). Propulsion options for missions to near-Earth objects. *Acta Astronautica, 39*(7-8), 517-528. https://doi.org/10.1016/S0094-5765(97)85432-X
[15] Percy, T., Polsgrove, T., Alexander, L., & Turpin, J. (2016). Design and development of a methane cryogenic propulsion stage for human Mars exploration.

10. Conflict of Interest

The author declares no competing conflict of interest.

11. Funding

No funding was received to support this study.