SPACE
{Research Note}

SPACE PROPULSION FOR SUSTAINED HUMAN EXPANSION INTO THE SOLAR SYSTEM

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Abstract: Recent advances in chemical propulsion have brought a revolution in the ability to economically access near-Earth orbit. As the world turns its eye on returning to the Moon and then on to Mars, understanding the factors to overcome from a technical perspective of space propulsion is important. First, readers are provided with motivation for why sustained missions to Mars is not as simple as sending a rocket to the planet (but still a momentous step for humanity). Next, near-term technologies and their capabilities are discussed along merits and limitations. Finally, we are in one of those exciting inflection points of human exploration and some suggestions are provided on how we must continue enabling exploration through the lens of space propulsion technology maturation.

Keywords: Space, Propulsion, Nuclear, Engineering, Technology Development

Introduction

Astronauts on a mission to Mars or other planets using current opposition class mission trajectories, would be exposed for multiple years in galactic cosmic rays (GRC). Risk of Exposure Induced Death (REID) is currently limited by NASA's radiation standards to 3% risk. For a female astronaut protected by 10-20 g/cm2 of aluminum shielding in a spacecraft (Figure 1). All current transit options to Mars pose REID greater than the safety threshold. Excessive shielding at the expense of payload is required to mitigate these issues. Other issues

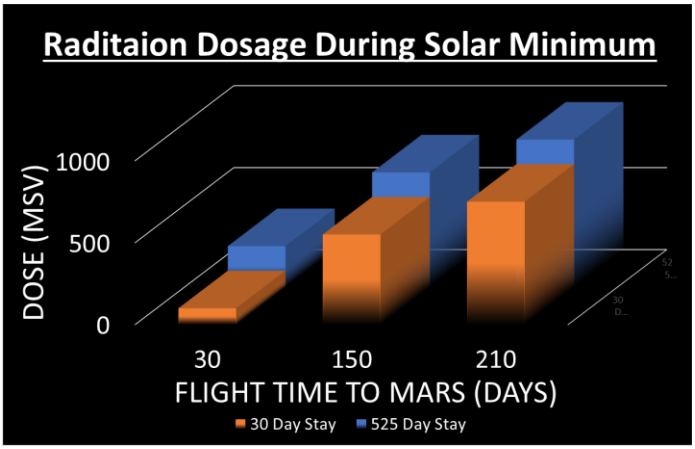

Figure 1. Radiation dosage for different travel times to Mars.

such as extended periods of weightlessness exasperate health issues. Transit vehicles will have to provide artificial gravity again at the expense of payload to provide a safe comfortable ride. This leaves two options. One, further reduce the cost of launching to orbit which our nation is making great recent progress. The other is to improve the efficiency of the space propulsion used for traveling between planets to go faster or carry more mass to aid in crew health and safety. There are many detailed reviews on the state of space propulsion technology, (Thomas, 2004) but we will focus on the propulsion research needs for fast and efficient travel for humans. Many are familiar with the Tsiolkovsky rocket equation (Ціолковскій, 1903).

$$\Delta v = I_{sp} g_o \ln\left(\frac{m_o}{m_f}\right) \tag{1}$$

where Δv is the maximum change in velocity of the spacecraft, g_o is standard gravity, m_o is the initial total mass of the spacecraft and m_f is the final total mass of the spacecraft. I_{sp} is the specific impulse which is used as the measure of efficiency of a rocket. Purely using I_{sp} for comparing different rocket technologies is a tempting but often misleading indicator of expected overall mission performance. As an example, density specific impulse when tank volume is constrained to a maximum possible size per launch is given by,

$$\Delta v \approx I_{sp} g_o \frac{\rho V}{m_f} \tag{2}$$

where ρ is the propellant density and V the volume of a fixed propellant tank. A propulsion technology with a denser propellant may give overall more Δv per launch to orbit. This is just one of the many key performance parameters that must be considered when making decisions on the development of in-space propulsion technology.

Chemical Propulsion (CP) and The Cis-lunar Economy

Chemical rockets are now starting to become a mature technology and on a trend approaching aviation cost structures where launch costs are mainly driven by propellent cost (Seedhouse 2022). The improvements in propulsive performance have now transitioned into integration and cost concerns as exemplified in the heavy lift rocket competition (Lee, 2020). Current research has focused on rotating detonation rocket engines (Cobb, 2025) but expected key performance parameters are on the order of 10% improvements in specific impulse.

Referring to Jared Diamond's book *Guns, Germs, and Steel*, (Diamond, 1999) his underlying theme is that human society is significantly influenced by the local environment. For the Moon, research culture focuses on the importance of finding water, but often overlooked is the stark absence of another element of life, carbon (Sossi, 2024). Research will be needed to understand how to bring enough carbon to develop a surrogate Earth ecosystem. How does this relate to rocket propulsion? Hydrogen and carbon are key atoms in the reactants (H2 and CH4) used for chemical propulsion. They react with oxygen, which is one of the most abundant atoms found in lunar regolith but is difficult to extract compared to water ice pockets (Burke, 2024; Lamboley, 2024). The Moon's low gravity will give it a stark long-term advantage in providing oxidizing propellant to NASA gateway (Powers, 2024). If economic ways to extract oxygen from the moon can be developed, it may be the next way to significantly reduce chemical propulsion's long term use for cis-lunar and planetary travel. Research in this area is critical. For example, developing nuclear

surface power is one of the key research areas to provide in-situ extraction (Wagh, 2025). Research on finding symbiotic relationships between sending carbon from Earth (or asteroids) for delivery to the moon and the return of excess oxygen from the lunar surface in the long term be greatly beneficial to sustained planetary exploration using chemical rockets.

Electric Propulsion (EP)

The state-of-the-art for improving rocket performance over CP is the use of electric propulsion (Esho, 2024). Here gases are ionized and accelerated through an electric or magnetic field producing a high specific impulse. Unfortunately, EP requires a power source for its energy unlike CP where the energy is stored via the chemical potential between the reactants. This significantly reduces the thrust due to it being a power limited system. Low thrust means having to patiently wait for a spaceship to slowly climb out of a planet's gravity well. This process can take days to months, negating most of the potential of moving humans quickly between planets. The requirement of a power source also adds to the issue by having to move its mass reducing the acceleration capability of the spacecraft. For a fast efficient human spacecraft, a light power source is a key enabler. Currently solar power (SEP) and nuclear fission (NEP) are considered. Solar power is limited due to diminished solar radiation as the spacecraft moves away from the sun. Nuclear fission can provide a constant source of power only limited by its radiator's ability to reject heat. Therefore, solar power works well for inner planets while nuclear is preferred for the outer planets. Due to some Mars missions using a Venus flyby to reduce Δv on the return to Earth, solar power can be a viable option. Still even assuming using theoretically light-mass power sources, electric propulsion will require on the order of 100's of megawatts to travel quickly to Mars to generate thrust to quickly escape the planets gravity wells. Research is required to significantly reduce the power to mass ratio of energy sources. Finally, at such power levels (greater than 100kW), the cost of the propellent becomes a significant factor. Traditional electric propulsion systems use noble gases such as Xenon and Argon but are rare elements on Earth. NASA studies using Xenon for transport to Mars found that a strategic reserve would be required to be stockpiled just to complete a single human mission to Mars (Herman, 2015)! Nobel gases are a critical industrial material and typically a renewable resource when released back into the Earth's atmosphere. When used for space propulsion it becomes non-renewable, and sustainability issues are paramount. As an example, Starlink satellites EP thrusters have moved to Argon away from the more efficient Xenon (Starlink, 2025). As the space economy grows, it is imperative that sustainable alternative EP propellants are developed (Tirila, 2023; Borrfors, 2023; Cassady, 2008).

Nuclear Thermal Propulsion (NTP)

In between CP and EP is nuclear thermal propulsion. For a solid core nuclear fission design, it has a specific impulse of 800-1100 sec around twice that of CP. Higher efficiency can be achieved for liquid or gaseous core reactors. Significant progress has been made by NASA and its partners for liquid core designs, but the technology is still in its early stages (Houts, 2023). Solid core designs are considered the near-term solution (NASA Glenn Research Center, 2025) and were extensively studied back in the 1950-70s (Robbins, 1991).

Compared to CP, the high specific impulse significantly reduces the propellant mass fraction. If NTP can be matured to the point of current CP, the cost of planetary exploration could be significantly reduced. The efficiency though is limited by the maximum temperature possible for a solid core. It is critical to conduct research to increase the reactor core temperature, but it will be difficult to go significantly beyond current capabilities (Burns, 2020). The trick to reaching a

high specific impulse is the use of only hydrogen as the propellant. Alternatives have been explored, but issues such as reactivity with the reactor core and large molecular mass of the propellant significantly degrade specific impulse performance (Nikitaeva, 2022). Unfortunately, storage of liquid hydrogen is difficult due to its low boiling point temperature making passive radiative cooling impractical. To date zero-boil-off active cooling still requires significant technology maturation (Duchek, 2024) and will be critical to maturing a sustainable NTP system for exploration of Mars. There are also other advanced concepts like the fission fragment rocket engine (Puri, 2024) that push beyond the NERVA derived concepts of solid fission core NTP.

The maturation of a working NTP rocket engine is significantly limited by the required environmental safety mitigation requirements. For example, historical tests such as the NERVA program vented exhaust gases into the atmosphere without regard to the radiation they emitted. Modern ground testing research requires sequestering rocket exhaust gases requiring extensive ground test infrastructure (Borowski, 2013). Specifically relying on ground testing will in the author's opinion create a development cycle tempo on the order of years setting on a development path similar to hypersonic flight testing that put the United States behind other country's technology maturation progress (Tarpak, 2023).

Testing and Propulsion Research in Space

DARPA in partnership with NASA is trying to break this paradigm with the Demonstration Rocket for Agile Cislunar Operations (DRACO) program (DARPA, 2025) to minimize ground testing and focus on in-space testing. It follows the successful paradigm of commercial rocket engine development emphasizing learning through relatively rapid successive test flights. The first flight is expected to take place no later than 2027. After its flight it is imperative a sustained test program is adequately funded and does not follow the path of hypersonic scramjet development, the NASA X-43 (2001-2004) (Marshall, 2005) to the Air Force X-51 (2010-2013) (Hank, 2008) to the Hypersonic Air-breathing Weapon Concept (HAWC) (2021-present) (DARPA, 2021) flight programs, where immediate follow on funding did not follow successful flight campaigns to keep pushing technology maturation (Aviation Week Network, 2016). To this day there is still a strong argument as to whether the U.S is catching up in hypersonics to other peer nations (Magnuson, 2024; Capaccio, 2025). If technological development of advanced in-space propulsion concepts is not taken seriously, we will fall behind in another key area compared to near pear competition as they catch up (Hou, 2024).

DRACO focuses on maturing NTP technology, but there should also be a plan for technology maturation of Mega-watt EP thruster technology. Current capabilities of the largest vacuum chambers at NASA Glenn have only been able to demonstrate 100 kW class EP thrusters (a great achievement) (Jovel, 2022), but as discussed EP for fast human exploration will require MW class thruster power. Multiple small lower power thrusters could be employed but need to take into consideration plume interactions impacting the packing efficiency of the clusters. As the cost of Earth launch decreases, it will make sense to study paradigms for accelerated testing of high-power thrusters directly in space.

Fusion and Other Technology

There are other propulsion technologies further out on the horizon but should not be neglected (LaPointe, 2024). Of note for this work, fusion propulsion has similar potential and commonality as nuclear fission propulsion just discussed (Turchi, 2022). It possesses the potential for both high specific power and energy. As terrestrial power generation is experiencing a revival in fusion

research and exciting progress (Meschini, 2023), space propulsion will most likely be an early adaptor of technological breakthroughs.

I've Got the Need for Speed

Focusing on the exploration of Mars, missions for chemical propulsion rely on what is called an Opposition class trajectory. It is based on taking a Hohmann transfer orbit, an elliptical orbit used to transfer a spacecraft from one circular orbit to another resulting in the use of a minimum amount of propellant. Figure 2 shows an adapted version that uses a Venus Swing-By to further reduce propellant requirements. This is critical for CP due to the low specific impulse. The Hohmann transfer requires an alignment between Earth and Mars that occurs about every two years. As chemical rocket technology improves to a tempo of daily launches, the Hohmann transfer will be the main constraint in our exploration of the planet. If so constrained, will large armadas of rocket ships travel between the planets like migratory birds? On the other hand, how will we rapidly learn to travel to Mars at a slow cadence of one spaceship every two years?

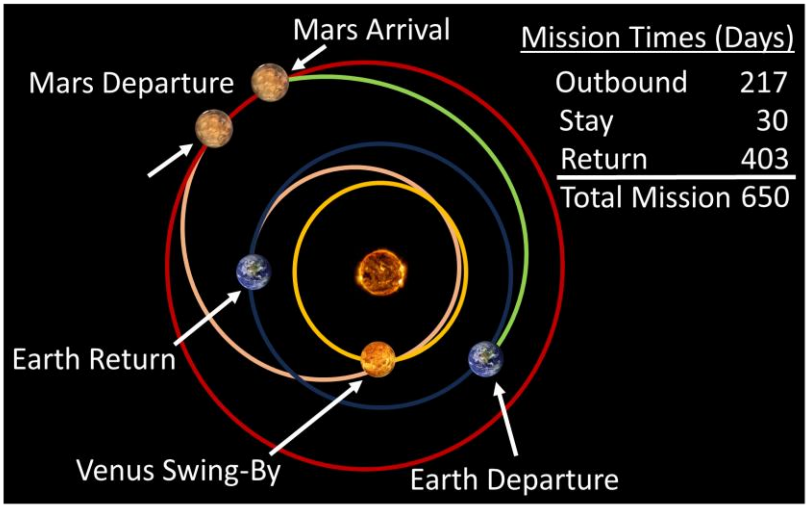

Figure 2. Example opposition class mission.

If we wish to travel faster to Mars, then a Fast-Conjunction trajectory is required. Figure 3 shows an example of the Earth to Mars leg of a mission. The maneuver requires significantly more propellant and becomes infeasible for CP. Higher efficiency nuclear propulsion will be required to significantly improve the pace of exploration. As an example, NASA Glenn conducted a study for "Fast Transit" human mission to Mars (Borowski, 2013). They looked at fast-conjunction class missions where the stay time on Mars is long (500 days or more), but the "in-space" transit

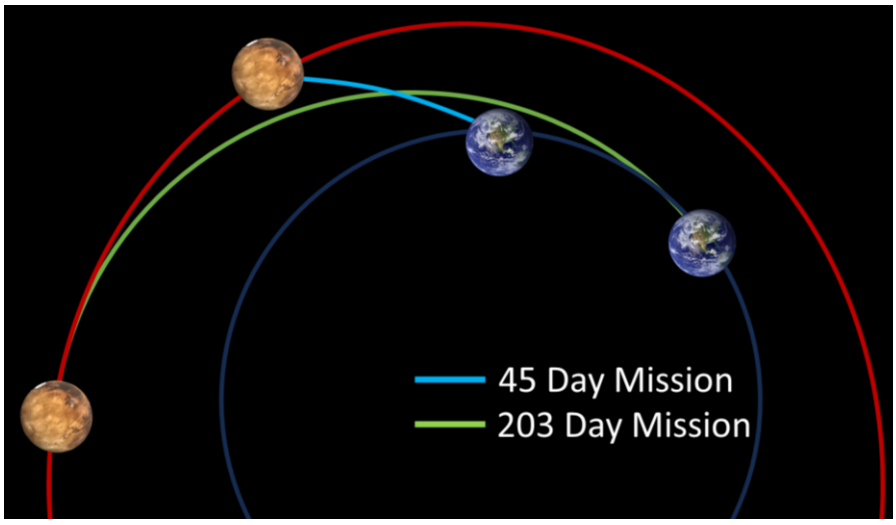

Figure 3. Fast-conjunction Earth-to-Mars leg of mission.

times were short (120 to 300 days). Figure 4 shows how the required Δv exponentially increases for an impulsive fast transfer using NTP. Their study assumed NTP technology with a specific impulse of 940 seconds. When approaching the 90-100 day "1-Way" transit times, a "Split Crewed Mission" was used with two transit vehicles. The Earth Return Vehicle would take a minimum energy trajectory and wait for it to be reused for the return trip. Research on new and novel systems that go beyond current NTP technology will be required to rapidly transport humans to Mars and should be a high priority as a long-term goal.

Bi-Modal Propulsion

Bi-Modal propulsion is the use of two propulsion technologies that consist of a high-thrust/low-efficiency unit and a low-thrust/high-efficiency unit. One unit allows for quickly escaping a planet's gravity well. The other for "accelerating" the interplanetary transit time and reducing Δv required by the low-efficiency unit during capture/escape from a planet's gravity well. Together they provide significant overall reduction in spacecraft total mass compared to just exclusively using one mode or the other. There are many different concepts, but for brevity we will focus on three examples.

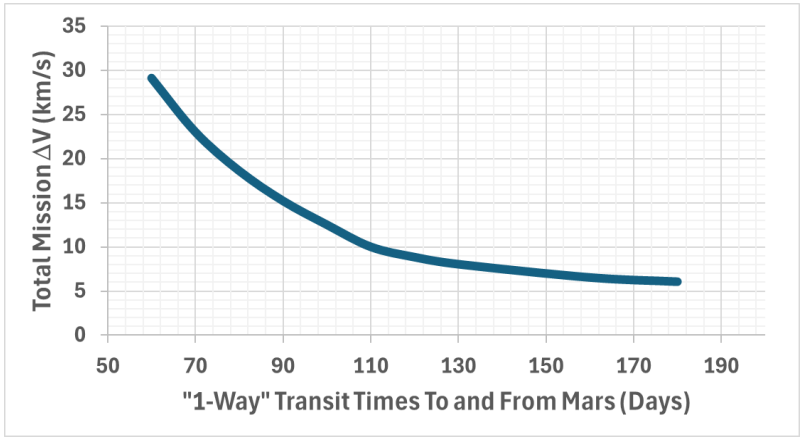

Figure 4. Total mission ΔV versus transit time.

CP-NEP

The NASA Glenn Compass team conducted analysis of a bi-modal CP-NEP spacecraft for Mars exploration (Oleson, 2021). Previous work on conjunction class with pure chemical propulsion relied on waiting on Mars 500 days for a low energy return due to Earth-Mars alignment. This resulted in a 3 year-round trip class, which results in significant health issues for the astronauts. Their study found that taking advantage of each propulsion system's positive qualities resulted in a 2 year-round trip class. The low thrust NEP system was able to significantly change the velocity over the interplanetary portion and significantly reduce the Δv required by the chemical propulsion to capture and depart from Mars' gravity well. The high thrust CP system was found to be more efficient in the gravity well due to the Oberth Effect (Oberth, 2019) (given the mission time constraints). The design was able to significantly reduce the required power for the NEP system, but 1 to 3 MWs of power was still required.

Variable Specific Impulse Magnetoplasma Rocket (VASIMR) propulsion technology (Diaz, 2000)

The VASIMR concept is an interesting EP technology where the thruster has a variable throttle. The VX-200 design had an estimated specific impulse range from 1660 to 4900 seconds (Longmier, 2012). At the level of our discussion, EP that is power limited is characterized by,

$$\frac{T_{et}}{P_e} = \frac{2\eta_{et}(I_{sp})}{I_{sp} g_o} \tag{3}$$

Where T_{et} is the thrust, P_e is the power coming from the power source and $\eta_{et}(I_{sp})$ is the efficiency of converting power to thrust and in the VASIMR case is a function of specific impulse. For use by itself, this means that the power generation unit needs 200 MW of power with a specific power of less than 0.8 kg/kW to quickly leave a planet's gravity well to allow for 150-day round trip times to Mars (Ilin, 2011). NTP has a much lower specific power and would most likely reduce EP power requirements to 10's of MW resulting in a more practical design while only sacrificing about a month or so of extra of travel time.

Wave Rotor Enhanced Nuclear (WREN) propulsion technology

Many different bi-modal concepts rely on sub-propulsion units that operate independently. During the operation of one, the other is a fully parasitic mass greatly impacting propulsion performance. Recent research has focused on the use of integrating the NEP power source into the NTP cycle (Gosse, 2024, Osborne, 2025). The energy exchange is conducted via the use of a wave rotor. The wave rotor exchange process is achieved using unsteady shock waves onboard the rotor. In this study two wave rotors were incorporated into the design. One was used to "top" a Brayton cycle allowing for the possibility of a high temperature NEP that is used over short periods of time to achieve transfer between Earth and Mars. This significantly increases the specific power (an enabling capability for other EP systems such as VASIMR). The other wave rotor uses high pressure gas to further compress propellant leaving the nuclear reactor to higher temperatures resulting in a significant increase in specific impulse (1200-1450 seconds for H2 propellant). For high Δv missions, the savings in NTP propellant mass overcomes the added dry mass of the NEP cycle. This enables "1-way" Earth to Mars transits that can start to approach 45 days without complicated Mars arrival strategies like aerobraking.

Conclusion: What does this mean for technology maturation?

Due to the favorable aspects of using a "hybrid" propulsion system similar to an automobile you may be driving today, a single technology maturation road map cannot be chosen without consideration of its impact on improving other systems. Therefor our nation and the international community should focus on a blended portfolio of research in nuclear and solar propulsion technology areas. What is clear though is the need for significant investment in these areas as the ability to launch to orbit ("halfway to anywhere") (Stine, 1996) becomes a common facet of our economy.

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