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Study of Nuclear Thermal Propulsion for Interplanetary Missions: Case Study of Mars

Niloy Bhowmick, Md. Tanvir Ahammed Shifat*

Department of Mechanical Engineering, Chittagong University of Engineering & Technology, Chattogram-4349, Bangladesh

ABSTRACT

This paper studies the feasibility of Nuclear Thermal Propulsion (NTP) as an advanced and alternative technology for interplanetary missions, with a specific focus on a Mars mission scenario. Conventional chemical propulsion systems have limitations for deep space exploration due to their limited specific impulse and extended transfer durations, which constrain payload capacity and mission flexibility. The study combines a thorough literature review, theoretical modeling based on the Tsiolkovsky Rocket Equation, and Python-driven parametric analysis to compare NTP with chemical propulsion for a Mars mission. However, ongoing research suggests that NTP could play a significant role in enabling safer and more efficient interplanetary exploration within the coming decades.

Keywords: Nuclear Thermal Propulsion (NTP), Chemical propulsion, Exploration, Nuclear Energy.

1. Introduction

Throughout the 20th century, advancements in rocket science led to a rapid increase in the ambition to explore Mars and other planets. However, that drive for exploration is fundamentally limited by existing chemical propulsion systems. Chemical propulsion systems offer modest specific impulse and thrust, which are responsible for long interplanetary transfer times and restricted mission payload capacities. Advancements in propulsion technology are essential for overcoming these barriers and unlocking safer, faster, and more cost-effective deep space missions [1].

NTP appears as a promising solution which offers significantly higher specific impulse (approximately 841–1000 s) and thrust-to-weight ratios compared to conventional chemical engines (200-450 s) [2]. In NTP, a compact nuclear fission reactor heats propellant (generally hydrogen or LH2) to extremely high temperatures, expelling it through a nozzle to generate thrust. This approach allows for both reduced transit duration and increased delivered payload mass, which is especially crucial for Mars or more challenging outer planet missions [3, 4].

Nevertheless, successful deployment and demonstration of NTP face significant engineering and economic challenges, including the durability of reactor materials, long-term propellant storage solutions, and broad regulatory acceptance for nuclear-powered spacecraft [5]. This study explores the comprehensive feasibility of using NTP for interplanetary missions, with Mars as the primary case study.

2. Literature Review

Several studies have extensively analyzed the potential of NTP for interplanetary missions. The Los Alamos Scientific Laboratory (L.A.S.L.) launched the ROVER Program in 1955 with a focus of determining the feasibility of nuclear thermal propulsion, aimed at exploring the fundamental technologies needed to harness nuclear fission for spacecraft propulsion.

Fig. 1: Atomic reactor (Kiwi-A Prime) for studying the feasibility of nuclear rocket propulsion from Project ROVER [6].

As shown in Fig. 1, the ROVER program's progress and NASA's increasing requirements for advanced propulsion systems led to the establishment of the NERVA (Nuclear Engine for Rocket Vehicle Application) program (shown in Fig. 2) later in 1961 [7, 8].

Recent projects, such as the DARPA–NASA DRACO program (though the project was canceled due to challenges related to testing and safety protocols), have underscored growing interest in advancing NTP technology toward flight-readiness [10, 11]. The main objective of these initiatives is to ensure the performance and reliability of compact nuclear reactors, which are capable of operating at the high temperatures required for efficient NTP systems.

*Corresponding Author Email Address: niloybhowmick2904@gmail.com Published By: SciEn Publishing Group

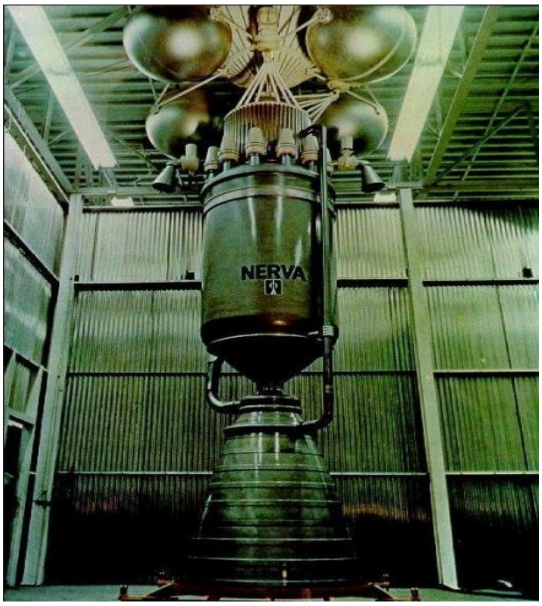

Fig. 2: NTR engine from Project NERVA [9].

According to NASA's Design Reference Architecture 5.0, NTP systems can offer significant reductions in transit times compared to conventional chemical propulsion [12]. For missions targeting the outer planets, nuclear propulsion becomes even more advantageous. Solar electric propulsion (SEP) systems are efficient but face significant limitations because large distances from the Sun reduce the availability of solar power. Nuclear electric propulsion (NEP) offers better performance in the outer solar system or Deep Space missions but typically delivers low thrust, resulting in lengthy transfer times [13, 14]. Overall, scientific research consistently presents NTP as a game changing technology that will make it possible to launch more ambitious missions to Mars and beyond. However, ongoing research highlights key challenges that must be overcome for successful deployment of NTP, such as hydrogen storage and reactor material resilience.

3. Methodology

3.1 Study Design and Research Question

In this study a computational feasibility model is used to quantify how NTP changes mass and time requirements for a crew-rated Earth to Mars mission compared to a high-performance chemical LOX/LH_2 stage.

3.2 Mission Scenario and Assumptions

- Trajectory model: Patched-conic approximation with impulsive burns, using a Hohmann transfer as the baseline for comparison [15].
- The reference change in velocity, Δv to Mars is 5.8 km/s, which was used for sizing [16].
- Propulsion options (Specific Impulse):
  1. Chemical: I_{sp}= 450s [2].
  2. NTP: $I_{sp} = 900\text{s}$ [2].

- Spacecraft mass model (single in-space stage + payload):

$$m_0 = m_{payload} + m_{structure} + m_{engine} + m_{prop} \tag{1}$$

- The spacecraft's non-propellant components are allocated fixed mass fractions relative to its initial mass, m_0. The structure and tanks make up 8% of the initial mass, with a fraction of $f_s = 0.08$. For propulsion systems, the chemical propulsion configuration has an engine mass fraction of $f_{e,\,chem} = 0.04$, or 4%. For NTP, the engine, power, and reactor fraction is higher at $f_{e,\,NTP} = 0.10$, or 10%. These fractions provide a clear baseline for comparing the spacecraft's design across different propulsion systems [17].
- Reference initial mass in Low Earth Orbit:

  m_0 = 100,000 kg.

- Gravity constant:
  g_0 = 9.80665 m/s^2

3.3 Governing Equations

Rocket equation:

$$\Delta v = I_{sp} g_0 \ln \ln \left(\frac{m_0}{m_f}\right) \tag{2}$$

Mass breakdown:

$$m_f = m_{payload} + f_s m_0 + f_e m_0 \tag{3}$$

Propellant mass:

$$m_{prop} = m_0 - m_f \tag{4}$$

Payload fraction (of initial mass):

$$\phi_p = \frac{m_{payload}}{m_0} \tag{5}$$

Trip time model:

Baseline Hohmann time to Mars

$$T_H \approx 8.5 \text{ months}$$

Faster-than-Hohmann approximation: if our design provides extra Δ v margin above the 5.8 km/s baseline, we map it to time reduction via a simple linear factor

$$T \approx T_H \left(1 - \alpha \frac{\Delta v_{extra}}{\Delta v_{Mars}}\right), \quad \alpha \in [0.8, 1.2] \tag{6}$$

Use α = 1.0 for the base case.

3.4 Computational Workflow

The analysis employs a systematic approach using inputs such as specific impulse (I_{sp}), structural and engine fractions (f_s , f_e), initial mass (m_0), required change in velocity (Δ v), baseline trip time (T_H), and a reduction factor (α). Mass ratios are computed as $MR = exp\, exp \left(\Delta v / \left(I_{sp} g_0\right)\right)$, with final mass ($m_f$), and payload mass ($m_{payload}$) derived accordingly, rejecting infeasible negative payloads. Propellant mass (m_{prop}) and payload fraction ($\phi_p = m_{payload}/m_0$) are calculated, while trip time (T) is adjusted using ($T \approx T_H(1 - \alpha\Delta v_{extra}/\Delta v_{Mars})$) for higher Δv. Finally, sensitivity analyses are conducted to explore variations.

3.5. Model Validation

The model was tested and confirmed to match expected mass ratios (around 3.7 for chemical propulsion and 1.9 for NTP) and propellant shares (approximately 73% for chemical propulsion and 48% for NTP) at 5.8 km/s Δ v.

3.6. Sensitivity Analysis

Variations in engine power (I_{sp} : 800–950 s for NTP) were considered to evaluate their impact on payload.

3.7. Reproducibility

Python with NumPy, Pandas and Matplotlib was used for all calculations, stored in one script/notebook with fixed inputs to ensure others can repeat the work.

4.Results & Analysis

In this section, the performance of Nuclear Thermal Propulsion (NTP) is compared against conventional chemical propulsion for interplanetary missions, focusing on the case study of a Mars transfer.

4.1. Baseline Case: Mars Transfer

The baseline trajectory assumed a Hohmann transfer, with a reference Δ v to Mars of 5.8 km/s and I_{sp} for Chemical Propulsion and NTP were 450 s and 900 s, respectively. Reference m_0 in Low Earth Orbit was 100,000 kg.

Table 1: Performance Comparison of Chemical and Nuclear Thermal Propulsion Systems (Baseline Case)

Δv (km/s)	Payload Fraction (Chemical) (%)	Payload Mass (Chemical) (kg)	Propellant Mass (Chemical) (kg)	Payload Fraction (NTP) (%)	Payload Mass (NTP) (kg)	Propellant Mass (NTP) (kg)	Trip Time (months)
5.8	14.8662	14866.2	73133.8	33.8326	33832.6	48167.4	8.50

4.2. Payload Capacity and Trip Time Improvement

Nuclear Thermal Propulsion significantly enhances the payload capacity for Mars missions. The overall average improvement in payload capacity for the NTP system compared to the chemical system is approximately 140.55%. The NTP system consistently carries a significantly larger payload across all Δv values

Table 2: Performance Comparison of Chemical and Nuclear Thermal Propulsion Systems

Δv (km/s)	Payload Fraction (Chemical) (%)	Payload Mass (Chemical) (kg)	Propellant Mass (Chemical) (kg)	Payload Fraction (NTP) (%)	Payload Mass (NTP) (kg)	Propellant Mass (NTP) (kg)	Trip Time (months)
5.5	16.7561	16756.1	71243.9	35.6247	35624.7	46375.3	8.50
5.6	16.1118	16111.8	71888.2	35.0206	35020.6	46979.4	8.50
5.7	15.4820	15482.0	72518.0	34.4232	34423.2	47576.8	8.50
5.8	14.8662	14866.2	73133.8	33.8326	33832.6	48167.4	8.50
5.9	14.2643	14264.3	73735.7	33.2487	33248.7	48751.3	8.35
6.0	13.6758	13675.8	74324.2	32.6713	32671.3	49328.7	8.21
6.1	13.1005	13100.5	74899.5	32.1004	32100.4	49899.6	8.06
6.2	12.5381	12538.1	75461.9	31.5360	31536.0	50464.0	7.91
6.3	11.9883	11988.3	76011.7	30.9779	30977.9	51022.1	7.77
6.4	11.4509	11450.9	76549.1	30.4261	30426.1	51573.9	7.62
6.5	10.9254	10925.4	77074.6	29.8805	29880.5	52119.5	7.47

As shown in Table 2, the NTP system demonstrates a substantial increase in payload capacity for Mars missions. The percentage improvement of payload capacity increases as the required Δ v increases, ranging from about 112.61% at Δ v = 5.5 km/s to over 173.49% at Δ v = 6.5 km/s. The relationship between payload fraction and Δv is further illustrated in **Fig. 3.** The table also presents a detailed breakdown of payload fraction, propellant mass, and trip time as a function of Δv. The data reveals a significant improvement in the payload fraction. A comparison of the propellant mass as a function of Δv is provided in **Fig. 4.**

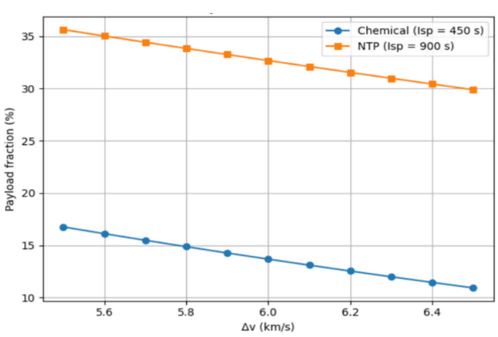

Fig. 3: Payload Fraction vs. Δv

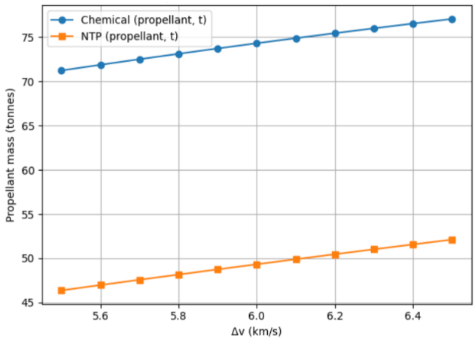

Fig. 4: Propellant Mass Comparison vs. Δv

This improved payload fraction is accompanied by a decrease in trip time (shown in **Fig. 5**), highlighting the superior performance of the NTP system compared to traditional chemical propulsion.

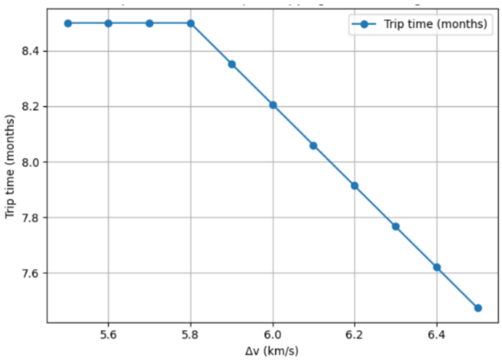

Fig. 5: Trip Time vs. Δv

4.3. Sensitivity Analysis

The results from sensitivity analysis indicate that increasing I_{sp} or thrust-to-weight ratio with Nuclear Thermal Propulsion (NTP) leads to substantial improvements in payload fraction

Table 3: Sensitivity Analysis of Payload Fraction to I_{sp} and Δv

Δv (km/s)	**Payload Fraction (Isp=800s) %**	**Payload Fraction (Isp=850s) %**	**Payload Fraction (Isp=900s) %**	**Payload Fraction (Isp=950s) %**
5.5	31.606	33.695	35.625	37.413
5.6	30.978	33.078	35.021	36.821
5.7	30.358	32.469	34.423	36.236
5.8	29.745	31.867	33.833	35.657
5.9	29.140	31.273	33.249	35.084
6.0	28.543	30.685	32.671	34.517
6.1	27.954	30.104	32.100	33.956
6.2	27.372	29.531	31.536	33.402
6.3	26.797	28.964	30.978	32.853
6.4	26.230	28.404	30.426	32.310
6.5	25.670	27.851	29.881	31.773

This table confirms that even within the NTP system, improving engine efficiency by increasing the specific impulse from 800**s** to 950**s** provides a substantial 20.98% increase in payload capacity (further illustrated in **Fig. 6**), reinforcing the benefit of this technology.

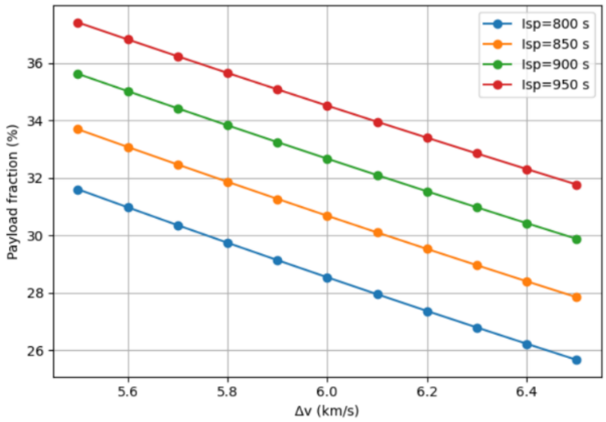

Fig. 6: Payload Fraction vs. Δv for Various I_{sp}

5. Discussion

Our analysis demonstrates that NTP offers substantial advantages for Mars missions compared to conventional chemical propulsion, notably in payload efficiency and propellant savings. The NTP system provides an overall average improvement in payload capacity of 140.55%. NTP also offers significant propellant savings (33.64%), which directly translates into higher payload delivery and improved mission efficiency. The data reveal NTP to be a promising choice for interplanetary travel, and these findings support the adoption of NTP technology for future Mars exploration.

6. Conclusion

The technical and operational viability of NTP for Mars missions is confirmed by this study. With an average increase in payload capacity of 140.55% and a 33.64% decrease in propellant consumption, the analysis shows that NTP systems provide notable benefits over traditional chemical propulsion. NTP would become a key technology for interplanetary travel as a result of these advantages, which would result in shorter trip times and increased mission flexibility. To sum up, these results support the wider development and application of NTP systems for upcoming deep-space missions, which will ultimately enhance mission performance for Mars and beyond

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