

# Comprehensive Technical Analysis of Nuclear Thermal and Nuclear Electric Propulsion Systems for Interplanetary Exploration

Aashutosh Kushwaha,  
Worked under- Tapas Kumar Nandi  
IIT Kharagpur cryogenic Engineering

**Abstract**— The advancement of human civilization into the solar system is fundamentally constrained by the energy density limitations of chemical propulsion. Nuclear propulsion, encompassing thermal, electric, and pulse architectures, offers a transformative leap in specific impulse and payload capacity by leveraging the high energy density of nuclear fission. This report provides a technically rigorous examination of the evolution, physics, and design of nuclear rocket systems. It begins with a detailed historical reconstruction of the United States' Project Rover and NERVA programs, alongside the Soviet Union's RD-0410 development, highlighting the achievement of specific impulses exceeding 840 seconds. The fundamental physics of neutron kinetics and heat transfer in extreme environments are derived, focusing on the McCarthy- Wolfi and Taylor correlations for supercritical hydrogen. A comparative analysis of propellants—liquid hydrogen, ammonia, and methane—reveals the critical trade-offs between mass efficiency and storage density. Advanced concepts, including gas-core reactors, nuclear light bulbs, and the pulse propulsion of Project Orion, are evaluated for their potential to achieve interstellar velocities. The report concludes with an analysis of the current DARPA/NASA DRACO mission and the shift toward High-Assay Low-Enriched Uranium (HALEU) fuels, outlining a path for the next generation of deep-space transportation.

**Keywords**- Nuclear Thermal Propulsion (NTP); Nuclear Electric Propulsion (NEP); Specific Impulse; Project Rover; NERVA; DARPA DRACO; HALEU Fuel; Interplanetary Mission Architecture.

## I. INTRODUCTION

The exploration of deep space, particularly crewed missions to Mars and the outer planets, necessitates a paradigm shift in aerospace propulsion. For over seven decades, chemical rockets have served as the workhorse of space exploration, yet they are intrinsically limited by the energy released through exothermic chemical reactions. The most efficient chemical systems, such as the liquid hydrogen and liquid oxygen (hydrolox) engines used in the Space Shuttle and the SLS, achieve a maximum specific impulse (ISP) of approximately 450 to 480 seconds.<sup>1</sup> While sufficient for orbital maneuvers and lunar transits, these systems require massive propellant fractions for Mars missions, leading to extended transit times that expose crews to significant radiological and physiological risks.<sup>3</sup>

Nuclear propulsion offers a solution by decoupling the energy source from the propellant. In a nuclear thermal rocket (NTR), a nuclear reactor serves as a high-temperature heat exchanger, transferring energy from fission reactions to a low-molecular-weight propellant, typically hydrogen.<sup>5</sup> This process allows for exhaust velocities and specific impulses that are double or triple those of chemical systems, effectively

halving the required propellant mass for a given mission  $\Delta V$ .<sup>2</sup> Nuclear electric propulsion (NEP) takes this efficiency even further by converting reactor heat into electrical power to drive high-exhaust-velocity ion or Hall thrusters, achieving (ISP) values between 2,000 and 5,000 seconds.<sup>8</sup>

The technical challenge lies in the containment of extreme temperatures and the management of radiation. A nuclear reactor for space propulsion must operate at temperatures nearing the melting point of its materials to maximize efficiency, all while maintaining a minimal mass and volume to fit within launch vehicle constraints.<sup>7</sup> This report explores the historical precedents, the mathematical and thermodynamic foundations, and the future prospects of these systems, providing a comprehensive reference for the aerospace propulsion community.

## II. HISTORICAL DEVELOPMENT OF NUCLEAR ROCKETS

The history of nuclear rocket development is a testament to the ambitious engineering of the mid-20th century. Research into nuclear propulsion began in earnest during the 1950s, driven by

the Cold War space race and the desire for high-performance upper stages for intercontinental ballistic missiles and interplanetary spacecraft.<sup>10</sup>

### III. PROJECT ROVER AND THE NERVA PROGRAM

The United States' primary effort, Project Rover, was initiated in 1955 at the Los Alamos Scientific Laboratory (LASL) under the Atomic Energy Commission (AEC).<sup>10</sup> The project was segmented into distinct phases, beginning with the Kiwi series of reactors. Kiwi-A, the first test reactor, was operated on July 1, 1959, at a power level of 70 MW for five minutes.<sup>10</sup> These initial tests proved that hydrogen could be successfully heated in a reactor core and that the system was controllable using rotating drums.

The subsequent Kiwi-B series introduced liquid hydrogen as a propellant but encountered significant engineering hurdles. In December 1961 and November 1962, the Kiwi-B1 and B4A reactors experienced structural failures where fuel elements were fractured and ejected from the core.<sup>10</sup> Investigations led by Harold Finger identified the cause as fluid-dynamic vibrations resulting from hydrogen flow through the interstitial spaces of the fuel elements.<sup>10</sup> These problems were resolved by modifying the core support structure, leading to the successful testing of the Kiwi-B4D and B4E models.<sup>10</sup> Following the success of the Kiwi series, the Nuclear Engine for Rocket Vehicle Application (NERVA) program aimed to develop a flight-qualified engine. The NRX (Nuclear Rocket Experimental) program achieved several milestones, including the NRX-A6, which operated for 62 minutes at 1,100 MW in December 1969.<sup>10</sup> The XE-Prime engine remains the only nuclear rocket engine to be tested in a configuration close to a flight engine, firing downward into a vacuum diffuser at the Engine Test Stand (ETS-1).<sup>10</sup> It demonstrated 28 successful starts and restarts, proving the robustness required for complex orbital maneuvers.<sup>13</sup> At its peak, the NERVA program demonstrated a specific impulse of 841 seconds and a thrust of approximately 250 kN, with a thrust-to-weight ratio suitable for upper-stage applications.<sup>10</sup>

### IV. SOVIET NUCLEAR ROCKET DEVELOPMENT

The Soviet Union developed a parallel and highly advanced nuclear thermal engine, the RD-0410 (GRAU index 11B91), from 1965 through the 1980s.<sup>15</sup> Developed by the Chemical Automatics Design Bureau in Voronezh, the RD-0410 utilized a heterogeneous core design that differed significantly from

the American graphite-based cores. The Soviet design featured uranium carbide and tungsten carbide fuel elements insulated from a zirconium hydride moderator.<sup>16</sup> This compact arrangement allowed for very high power densities and high exhaust temperatures.

Ground tests conducted at the Semipalatinsk Test Site demonstrated a specific impulse of approximately 910 seconds, which was higher than that achieved by the NERVA program.<sup>16</sup> The RD-0410 produced a thrust of 35.2 kN and was intended for use in the Kurchatov Mars mission proposal.<sup>16</sup> A unique technical solution employed by the Soviets was the addition of 1% heptane or hexane to the hydrogen propellant after it passed the moderator; this additive decomposed at high temperatures to form a protective carbon layer on the carbide fuel, significantly reducing hydrogen-induced corrosion.<sup>15</sup>

### V. FUNDAMENTALS OF NUCLEAR ROCKET PROPULSION

The physics of nuclear propulsion is governed by the principles of nuclear fission and high-temperature fluid dynamics. Unlike chemical rockets, where the propellant is also the energy source, a nuclear rocket uses a nuclear reactor as an external heat source to energize a propellant.

#### Nuclear Fission and Heat Generation

Energy generation in a nuclear rocket is based on the fission of heavy nuclei, typically Uranium-235. When a  $^{235}\text{U}$  nucleus captures a neutron, it becomes unstable and splits into two fission fragments, releasing a significant amount of kinetic energy and additional neutrons.<sup>19</sup> The average energy released per fission is approximately 200 MeV, which translates to a volumetric heat source within the fuel elements.<sup>19</sup> The power density  $PD$  of the reactor core is given by:

$$PD = \sum f \phi EF$$

where  $\sum f$  is the macroscopic fission cross-section,  $\phi$  is the average neutron flux, and  $EF$  is the energy released per fission.<sup>20</sup> In reactors like NERVA, power densities reached  $1,570 \text{ MW/m}^3$ , requiring aggressive cooling to prevent fuel melting.<sup>19</sup>

#### Neutron Kinetics and Reactor Control

Maintaining a steady-state power level requires the effective multiplication factor  $k$  to be exactly unity. The neutron

population in the core follows the four-factor formula adjusted for non-leakage:

$$k = \eta \epsilon p f L f L t$$

In this relation,  $\eta$  is the number of fission neutrons produced per absorption in the fuel,  $\epsilon$  is the fast fission factor,  $p$  is the resonance escape probability,  $f$  is the thermal utilization factor,  $L f L t$  and are the non-leakage probabilities for fast and thermal neutrons, respectively.<sup>19</sup> Control is typically achieved through the rotation of Beryllium control drums located in the reflector surrounding the core. These drums have a layer of Boron-10 (a neutron poison) on one side; rotating the poison toward the core reduces the neutron population, while rotating it away increases it.<sup>11</sup>

Parameter	Symbol	Definition/ Role
Multiplication Factor	$k$	Ratio of neutrons in one generation to the previous
Neutron Flux	$\Phi$	Density of neutrons multiplied by their average velocity
Macroscopic Cross Section	$\Sigma_f$	Probability of fission per unit path length
Regeneration Rate	$\eta$	Neutrons produced per thermal neutron absorbed in fuel

### Types of Nuclear Rockets

Nuclear propulsion concepts are categorized primarily by the state of the reactor core and the method of thrust generation. Nuclear Thermal Rockets (NTR)

Solid-core NTRs are the most technologically mature. They utilize solid fuel elements, typically made of graphite or ceramic-metallic (cermet) materials, containing enriched uranium.<sup>9</sup> Propellant is pumped through channels in these elements, absorbing heat directly. The specific impulse of a solid-core NTR is limited by the melting point of the fuel and cladding, which for materials like tungsten or graphite is around 3,000 to 3,500 K.<sup>7</sup>

### Nuclear Electric Propulsion (NEP)

NEP systems decouple the reactor from the thruster entirely. The reactor generates thermal energy, which is converted to electricity using a thermodynamic cycle (such as Brayton or Rankine) or static conversion (thermionic or thermoelectric). This electricity then powers an electric thruster, such as an Ion thruster or a Hall-Effect Thruster (HET).<sup>8</sup> NEP systems achieve extremely high (2,000–5,000 s) but produce very low thrust, making them suitable for long-duration cargo missions rather than high-thrust maneuvers.<sup>8</sup>

### Nuclear Pulse Propulsion (Project Orion)

Project Orion was a radical concept that proposed propelling a spacecraft through the detonation of small nuclear shaped charges behind a massive steel pusher plate.<sup>24</sup> Unlike internal reactors, the external nature of the detonations allows the system to harness temperatures of millions of degrees, as the pusher plate only interacts with the plasma for milliseconds.<sup>24</sup> Theoretical for Orion-class vehicles ranges from 2,000 to 100,000 seconds, with thrust levels capable of launching thousands of tons into interplanetary trajectories.<sup>25</sup>

### Gas-Core and Advanced Concepts

To overcome the temperature limits of solid fuels, gas-core reactors maintain the nuclear fuel in a gaseous or plasma state (e.g., uranium hexafluoride). In the "Nuclear Light Bulb" concept, the gaseous fuel is contained within a transparent quartz tube, and heat is transferred to the hydrogen propellant via thermal radiation.<sup>22</sup> This prevents the loss of fuel while allowing propellant temperatures to reach 10,000 K or higher, yielding Isp values of up to 7,000 seconds.<sup>1</sup>

### Working Principle and Thermodynamic Cycle

The efficiency of a nuclear rocket engine depends on how effectively the heat from the reactor is converted into the kinetic energy of the propellant.

**The Thermodynamic Cycle**

Most NTR designs utilize an expander cycle, where the cryogenic propellant is first used to cool the nozzle and reactor structures, picking up heat in the process. This warmed gas then drives the turbopumps before entering the reactor core for final heating and expansion.<sup>28</sup>

The work performed by the pump  $w_p$  is given by:

$$w_p = \frac{m(P_{out} - P_{in})}{\rho}$$

where  $m$  is the mass flow rate,  $P$  is pressure, and  $\rho$  is the density.<sup>30</sup> The turbine work  $w_t$  is derived from the enthalpy change of the propellant:

$$w_t = m(h_{in} - h_{out})\eta_t$$

where  $h$  is enthalpy and  $\eta_t$  is the turbine efficiency.<sup>30</sup> In the expander cycle, the turbine and pump are on the same shaft, and the energy balance must be maintained to ensure stable operation.

**Heat Transfer in the Core**

The transfer of heat from the fuel elements to the propellant is the most critical process in the engine. Because hydrogen is often in a supercritical state at the reactor entrance, its properties vary significantly with temperature. The convective heat transfer coefficient  $\bar{h}$  is calculated using correlations such as the McCarthy-Wolfe equation:

$$Nu_u = 0.025Re^{0.8} Pr^{0.4} \left(\frac{T_w}{T_b}\right)^{-0.55}$$

where  $Nu$  is the Nusselt number,  $Re$  is the Reynolds number,  $Pr$  is the Prandtl number,  $T_w$  and is  $T_b$

the ratio of wall temperature to bulk fluid temperature.<sup>31</sup> This correlation accounts for the large temperature gradients present in the fuel channels. The local heat flux  $q''$  is then:

$$q'' = \bar{h}(T_w - T_b)$$

Properly modeling this ensures that the fuel does not exceed its structural limits while maximizing the propellant exit temperature.<sup>31</sup>

**VI. PROPELLANTS IN NUCLEAR ROCKETS**

The choice of propellant is a critical driver of both engine performance and vehicle architecture.

**Liquid Hydrogen (LH2)**

Hydrogen is the preferred propellant for NTRs due to its low molecular weight ( $M = 2.016$  g/mol). According to the relationship  $ISP = \propto \sqrt{T}$ , hydrogen provides the highest possible

$M$  specific impulse for a given reactor temperature.<sup>2</sup> However, LH2 has a very low density ( $70.8$  kg/m<sup>3</sup>), requiring extremely large tanks and advanced insulation to prevent boil-off during long-duration missions.<sup>30</sup>

**Alternative Propellants: Ammonia and Methane**

To mitigate the storage challenges of hydrogen, alternative propellants like Ammonia (NH<sub>3</sub>) and Methane (CH<sub>4</sub>) have been proposed. Ammonia is approximately ten times denser than hydrogen and has much more manageable storage temperatures.<sup>30</sup> However, its higher molecular weight ( $17.03$  g/mol) reduces the specific impulse to approximately 350–450 seconds.<sup>30</sup> Methane offers a middle ground but can lead to carbon deposition within the reactor channels, potentially clogging the flow.<sup>37</sup>

Table 1: propellant comparison table

Propellant	Molecular Weight (g/mol)	Isp (s) @ 2700 K	Density (kg/m <sup>3</sup> )	Remarks
Hydrogen (H <sub>2</sub> )	2.016	850–950	70.8	Highest performance; low density
Ammonia (NH <sub>3</sub> )	17.03	375–450	681.9	High density; easier storage

Methane (CH4)	16.04	350–500	422.6	Potential for soothing
Water (H2O)	18.01	250–300	1000	In-situ resource

### Performance Analysis

Performance is evaluated through the fundamental rocket equations, which relate mass, velocity, and energy.

#### The Rocket Equation

The  $\Delta v$  capability of a spacecraft is defined by the Tsiolkovsky equation:

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

where  $m_0$  is the initial mass and  $m_f$  is the final mass.<sup>7</sup> For a mission to Mars requiring a  $\Delta v$  of 8 km/s, a chemical rocket ( $I_{sp} = 400$  s) requires a mass ratio of 5.85, whereas an NTR ( $I_{sp} = 900$  s) requires only 2.48.<sup>7</sup> This reduction allows for significantly larger payloads or shorter travel times.

#### Specific Impulse vs. Temperature Trends

The relationship between chamber temperature ( $T_c$ ) and  $I_{sp}$  is the primary design trade-off. While solid-core systems are limited to  $\sim 3000$  K, advanced gaseous cores can exceed this significantly.

Table 2: comparison of chamber temperature and ISP of different propellant.

This data set illustrates the direct correlation between increasing chamber temperatures and the resulting gain in specific impulse across different propellant types.

Chamber Temp (K)	H2 Isp (s)	Methane Isp (s)	Ammonia Isp (s)
2500	825	420	380
3000	905	460	415
3500	975	500	450
4000	1045	535	485
6000	1663	640	580

### Thrust and Efficiency Relations

Thrust  $T$  is the product of the mass flow rate and the effective exhaust velocity  $v_e$ :

$$T = \dot{m} v_e + (p_e - p_a) A_e$$

The specific impulse is  $I_{sp} = \frac{v_e}{g_0}$ .<sup>34</sup> The thermal efficiency of the reactor, in the context of an NTR,

$\eta_{th}$

is nearly 100% since all the heat generated (excluding parasitic losses to shielding and radiation) is transferred to the propellant.<sup>7</sup> However, for NEP, the efficiency is limited by the Carnot efficiency of the power conversion cycle:

$$\eta_{carnot} = 1 - \frac{T_{cold}}{T_{hot}}$$

In space,  $T_{cold}$  is determined by the size and temperature of the radiators, creating a significant mass penalty for high-power NEP systems.<sup>20</sup>

Table 3: Thrust and Efficiency Comparison by Architecture

The following table synthesizes quantitative data from various nuclear and chemical systems, highlighting the inverse relationship between thrust and specific impulse.

Architecture	Specific Impulse (Isp, s)	Thrust Level (N)	Thrust-to-Weight (T/W)	System Efficiency ( $\eta$ )
Chemical (Hydrolox)	450–480	$10^5$ – $10^6$	1.0–100	$\sim 98\%$ (Combustion)
Solid-Core NTP	850–950	$10^4$ – $10^5$	0.1–1.8	$\sim 100\%$ (Thermal Transfer)
Gas-Core NTP	1550–6700	4.5 times $10^4$ – $10^5$	0.9–1.3	$\sim 100\%$ (Radiative)
Nuclear Electric	2000–10000	1–10	$10^{-4}$ – $10^{-3}$	0.54–0.67 (Thruster)
Pulse (Orion)	2000–100000	$10^6$ – $10^9$	1.0–10	N/A (External Pulse)

**Table 4: Comparative Mission Performance Analysis**

A key metric for deep-space feasibility is the "Earth Escape Mass Ratio," representing the total vehicle mass in LEO required per unit of payload mass delivered to an escape trajectory.

Metric	Chemical Rocket	Solid-Core NTR	Molten-Core NTR	Gas-Core NTR
Typical Isp (s)	450	900	2600	6700
Earth Escape Mass Ratio	~15	~3.2	~1.5	~1.2
Relative Payload Cap.	Baseline	4–6x Increase	>10x Increase	>50x Increase
Mars Trip Time	200+ Days	70–90 Days	<60 Days	<45 Days

(T/W)			
Controllability	None (Stop/Restart impossible)	Full (Throttling/Restart)	Full (Throttling/Restart)
Storage & Readiness	High stability; years	Cryogenic challenges	Cryogenic hydrogen challenges
Typical Mission Use	Launch Boosters; Missiles	Launch Stages; Orbital Man.	Interplanetary Transit; Deep Space
Maturity (TRL)	9 (Operational)	9 (Operational)	4–6 (Demo stage)

**Comparative Study (Chemical vs. Nuclear)**

A quantitative comparison highlights why nuclear propulsion is indispensable for deep-space exploration.

**Table 5: Comprehensive Comparison of Propulsion Paradigms**  
 This table summarizes the core differences between solid chemical, liquid chemical, and nuclear thermal systems in terms of performance, operation, and technological maturity.

Characteristic	Solid Chemical Rocket	Liquid Chemical Rocket	Nuclear Thermal Rocket
Primary Advantage	Simplicity & High TWR	Controllability & Efficiency	Ultra-high isp & Mass Fraction
Specific Impulse (Isp)	200–290 s	300–465 s	800–950 s
Thrust-to-Weight	50–100+	1–10	0.1–1.8

**Table 6: Comparative Study (Chemical vs. Nuclear)**

This table categorizes propulsion types by their performance metrics to define their most effective roles, from launch boosters to interstellar transport.

Propulsion Type	Specific Impulse (Isp)	Thrust-to-Weight (T/W)	Typical Mission Use
Chemical (Solid)	250–300 s	50–100	Launch boosters
Chemical (Liquid)	300–450 s	1–10	Upper stages; orbit insertion
Nuclear Thermal	850–1000 s	0.1–1.0	Interplanetary transit
Nuclear Electric	2000–5000 s	10 <sup>-4</sup> –10 <sup>-3</sup>	Cargo transport; deep space probes
Nuclear Pulse	2000–100,000 s	1–10	Heavy lift; interstellar

Table 7: Propulsion Performance and Mass Ratio Comparison  
 This comparison uses exhaust velocity and mass ratios to show the energy source limits of various systems during Lunar and Mars trajectories.

Propulsion System	Exhaust Velocity (Ve, km/s)	Lunar Mass Ratio (m0/mf)	Mars Mass Ratio (m0/mf)	Energy Source Limit
Saturn V (Chemical)	2.5–4.5	~15.0	~100.0	Chemical Bond Energy
NERVA (Solid NTP)	8.3–9.3	~4.0	~10.0	Reactor Temperature
Gas-Core (NTP)	15.0–18.0	~2.0	~4.0	Plasma Stability
Ion/Hall (NEP)	20.0–100.0	Variable	Variable	Power Specific Mass
Project Orion (Pulse)	19.0–31.0	~1.5	~2.5	Pusher Plate Ablation

### VII. MISSION IMPLICATIONS FOR MARS

For a crewed Mars mission, the primary benefit of NTR is the reduction in transit time. Using NTP can reduce a round trip by up to 25%, significantly lowering the crew's exposure to cosmic radiation.<sup>4</sup> Additionally, the high thrust of NTP allows for "anytime" abort capabilities and more flexible launch windows that are not as strictly dependent on planetary alignments.

### VIII. BASIC DESIGN AND SUBSYSTEMS

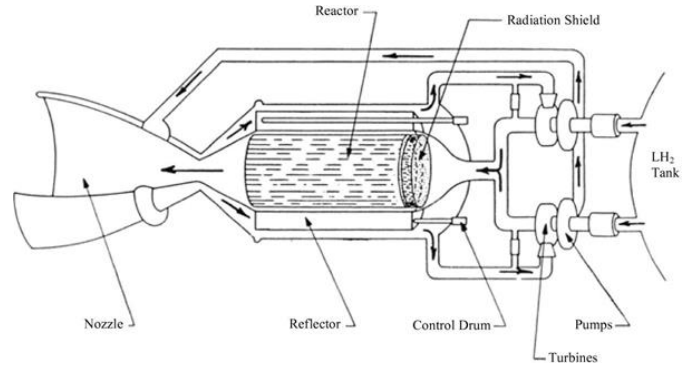


Figure 1: Nuclear Thermal Rocket Schematic

A typical NTR system consists of a large liquid hydrogen tank at the top. A turbopump assembly, driven by an expander or hot-bleed cycle, draws the LH<sub>2</sub> and passes it through regenerative cooling channels in the nozzle. The hydrogen then enters the reactor core, which consists of a Beryllium reflector containing rotating control drums and a central core of hexagonal fuel elements. After being heated to ~2,700 K, the hydrogen expands through a convergent-divergent nozzle to produce thrust.

The design of an NTP engine requires the integration of several high-performance subsystems.

#### The Reactor Core and Fuel Elements

The core typically consists of hexagonal fuel elements made of a graphite-matrix containing  $UC_2$  or  $(U, Zr)C$  particles. These elements have multiple axial coolant channels to maximize surface area for heat transfer.<sup>18</sup> In the Soviet design, the use of carbide fuels allowed for higher temperatures and a more compact core.<sup>15</sup>

#### Reactor Core with Fuel Elements

The core is visualized as a honeycomb structure of hexagonal prisms. Each prism has multiple small holes (coolant channels) running through its length. Beryllium moderator blocks are interspersed to maintain criticality, and the entire assembly is held together by a core support plate and tied tubes.<sup>13</sup>

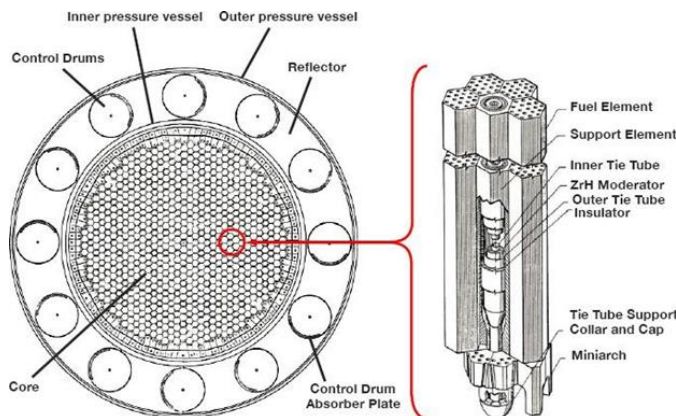


Figure 2: Reactor Core with Fuel Elements

### Turbopump and Nozzle

The turbopump must be capable of handling cryogenic hydrogen at high flow rates (e.g., 3.8 kg/s for a 33 kN engine).<sup>2</sup> The nozzle is typically a high-expansion ratio de Laval nozzle, regeneratively cooled by the incoming propellant. Advanced designs may use carbon-carbon or tungsten-rhenium materials for the throat to withstand temperatures above 3,000 K.<sup>22</sup>

### Radiation Shielding

A shadow shield is placed between the reactor and the rest of the spacecraft. It usually consists of a high-Z material like tungsten to attenuate gamma rays and a low-Z hydrogenous material like lithium hydride (LiH) to moderate and capture neutrons.<sup>7</sup> This shield can weigh several tons, which must be factored into the overall engine thrust-to-weight ratio.<sup>7</sup>

## IX. ADVANTAGES, CHALLENGES, AND SAFETY ISSUES

While the performance advantages are clear, nuclear propulsion presents unique challenges.

### Advantages

The primary advantage is the decoupling of energy and propellant, leading to high Isp. The use of a single propellant (monopropellant system) also eliminates the risks associated with mixing hypergolic or cryogenic oxidizers in space.<sup>6</sup>

### Technical and Operational Challenges

**1. High-Temperature Materials:** Sustaining 3,000 K while being blasted by high-pressure hydrogen leads to material loss and structural weakening.<sup>10</sup>

**2. Hydrogen Storage:** The low density and cryogenic nature of hydrogen require massive tanks and zero-boil-off (ZBO) technology.<sup>1</sup>

**3. Startup Transients:** Nuclear reactors take much longer to reach full power (up to 60 seconds) than chemical engines, requiring complex control algorithms to manage the heat during the ramp-up.<sup>29</sup>

### Safety and Public Perception

Safety is paramount, particularly concerning launch accidents. Modern mission profiles dictate that the reactor is not activated until the spacecraft is in a "Nuclear Safe Orbit" (NSO), where it would take hundreds of years to re-enter, allowing radioactive fission products to decay to safe levels.<sup>4</sup>

### Current Research and Future Prospects

Renewed interest in Mars exploration has led to the revival of nuclear propulsion programs.

### DARPA/NASA DRACO Program

The Demonstration Rocket for Agile Cislunar Operations (DRACO) is a joint program aiming to demonstrate a nuclear thermal engine in orbit by 2027.<sup>29</sup> A significant development in DRACO is the use of High-Assay Low-Enriched Uranium (HALEU) fuel, which contains between 5% and 20% <sup>235</sup>U. This is a strategic shift from the highly enriched uranium (HEU) used in the 1960s, as HALEU reduces proliferation risks and regulatory overhead.<sup>4</sup>

### Bimodal Systems and Hybrids

Future missions may utilize bimodal reactors that provide NTP for high-thrust maneuvers and then transition to a low-power NEP mode for long-duration electricity generation.<sup>3</sup> This "all-in-one" approach maximizes the utility of the nuclear core. Advanced research also continues into direct fusion drive (DFD) and microwave thermal thrusters, which could eventually provide even higher performance.<sup>5</sup>

## X. CONCLUSION

Nuclear propulsion represents the most viable technological path for the realization of deep-space human exploration. By providing specific impulses that are twice those of chemical systems, nuclear thermal rockets enable faster transit times and larger payload fractions, effectively addressing the primary barriers to Mars exploration. The historical successes of Project Rover and the NERVA program demonstrated that the core technology is sound, while the Soviet RD-0410 proved the efficiency of heterogeneous carbide cores.

However, the path forward requires solving the challenges of high-temperature material erosion and long-term cryogenic propellant storage. The current shift toward HALEU fuel in the DRACO program is a critical step in making nuclear propulsion politically and logistically feasible. Ultimately, a bimodal architecture, combining the high thrust of NTP with the high efficiency of NEP, will likely form the backbone of the transportation system that carries the first humans to Mars and beyond. The physics of the universe dictates that chemical energy is insufficient for the stars; nuclear energy is the key to our expansion into the solar system.

### REFERENCES

1. A Comprehensive Review on Nuclear Thermal ... - SciSpace, accessed April 7, 2026, <https://scispace.com/pdf/a-comprehensive-review-on-nuclear-thermal-propulsion-system-13fib54uxmeqe.pdf>
2. Nuclear Thermal Rocket Simulation in NPSS - NASA Technical Reports Server, accessed April 7, 2026, <https://ntrs.nasa.gov/api/citations/20140009572/download>
3. A One-year, Short-Stay Crewed Mars Mission using Bimodal Nuclear Thermal Electric Propulsion (BNTEP) - A Preliminary Assessment, accessed April 7, 2026, <https://ntrs.nasa.gov/api/citations/20140009579/download>
4. 6 Things You Should Know About Nuclear Thermal Propulsion - Department of Energy, accessed April 7, 2026, <https://www.energy.gov/ne/articles/6-things-you-should-know-about-nuclear-thermal-propulsion>
5. Nuclear thermal rocket - Wikipedia, accessed April 7, 2026, [https://en.wikipedia.org/wiki/Nuclear\\_thermal\\_rocket](https://en.wikipedia.org/wiki/Nuclear_thermal_rocket)
6. Efficiency of Nuclear Thermal Propulsion Engine Thrust and Isp Tradeoffs and
7. Alternative Propellants on  $\Delta V$  [udggt and Architgcturg Mass for, accgssgd April 7, 2026, <https://ntrs.nasa.gov/api/citations/20240006070/download>
8. <https://ntrs.nasa.gov/api/citations/20240006070/download>
9. The Nuclear Thermal Rocket - Stanford University, accessed April 7, 2026, <http://large.stanford.edu/courses/2011/ph241/hamerly1/>
10. Comparative Analysis of Nuclear Thermal and Nuclear Electric Propulsion Systems for Enhanced Space Missions | Request PDF - ResearchGate, accessed April 7, 2026, [https://www.researchgate.net/publication/396052952\\_Comparative\\_Analysis\\_of\\_Nuclear\\_Thermal\\_and\\_Nuclear\\_Electric\\_Propulsion\\_Systems\\_for\\_Enhanced\\_Space\\_Missions](https://www.researchgate.net/publication/396052952_Comparative_Analysis_of_Nuclear_Thermal_and_Nuclear_Electric_Propulsion_Systems_for_Enhanced_Space_Missions)
11. Nuclear Thermal and Nuclear Electric Propulsion Systems for Enhanced Space Missions
12. Small Fast Spectrum Reactor Designs Suitable for Direct Nuclear Thermal Propulsion - Idaho National Laboratory, accessed April 7, 2026, <https://inldigitallibrary.inl.gov/sites/sti/sti/5517271.pdf>
13. Nuclear Thermal Propulsion Ground Test History - NASA Technical Reports Server (NTRS), accessed April 7, 2026, <https://ntrs.nasa.gov/citations/20140008771>
14. Project Rover - Wikipedia, accessed April 7, 2026, [https://en.wikipedia.org/wiki/Project\\_Rover](https://en.wikipedia.org/wiki/Project_Rover)
15. NERVA - Wikipedia, accessed April 7, 2026, <https://en.wikipedia.org/wiki/NERVA>
16. Chapter: 2 Nuclear Thermal Propulsion - National Academies of Sciences, Engineering, and Medicine, accessed April 7, 2026, <https://www.nationalacademies.org/read/25977/chapter/4>
17. NERVA Nuclear Rocket Program (1965) - Glenn Research Center, accessed April 7, 2026, <https://www1.grc.nasa.gov/wp-content/uploads/NERVA-Nuclear-Rocket-Program-1965.pdf>
18. RD-0410 | Military Wiki - Fandom, accessed April 7, 2026, <https://military-history.fandom.com/wiki/RD-0410>
19. RD-0410 - Wikipedia, accessed April 7, 2026, <https://en.wikipedia.org/wiki/RD-0410>
20. RD-0410, accessed April 7, 2026, <http://www.astronautix.com/r/rd-0410.html>
21. Russian Nuclear Rocket Engine Design for Mars Exploration - ResearchGate, accessed April 7, 2026, [https://www.researchgate.net/publication/222548572\\_Russian\\_Nuclear\\_Rocket\\_Engine\\_Design\\_for\\_Mars\\_Exploration](https://www.researchgate.net/publication/222548572_Russian_Nuclear_Rocket_Engine_Design_for_Mars_Exploration)
22. Nuclear Thermal Rocket, accessed April 7, 2026, [http://www.al.t.u-tokyo.ac.jp/lecture/Chap5\(NuclearThermal\).pdf](http://www.al.t.u-tokyo.ac.jp/lecture/Chap5(NuclearThermal).pdf)
23. NUCLEAR REACTOR CONCEPTS AND THERMODYNAMIC CYCLES - Mragheb, accessed April 7, 2026, <https://www.mragheb.com/NPRE%20402%20ME%20405%20Nuclear%20Power%20Engineering/Nuclear%20Reactors%20Concepts%20and%20Thermodynamics%20Cycles.pdf>
24. DYNAMIC NUCLEAR THERMAL ROCKET AND ENGINE MODELING JD Raderl and
25. MBR Smithl - OSTI, accessed April 7, 2026, <https://www.osti.gov/servlets/purl/1661248>
26. Design of a High-Specific Impulse Gas-Core Nuclear Thermal Rocket., accessed April 7, 2026, <https://nstopenresearch.org/articles/4-1>

27. Analysis and Comparison of Different Propulsion Systems - JETIR.org, accessed April 7, 2026, <https://www.jetir.org/papers/JETIR2411547.pdf>
28. Nuclear Pulse Propulsion: Gateway to the Stars, accessed April 7, 2026, <https://www.ans.org/news/article-1294/nuclear-pulse-propulsion-gateway-to-the-stars/>
29. AIAA 2000-3856 - Nuclear Pulse Propulsion - Orion and Beyond - NASA Technical Reports Server, accessed April 7, 2026, <https://ntrs.nasa.gov/api/citations/20000096503/downloads/20000096503.pdf>
30. Project Orion - Stanford University, accessed April 7, 2026, <http://large.stanford.edu/courses/2021/ph241/chen1/Integrated-Steady-State-System-Package-for-Nuclear-Thermal-...>, accessed April 7, 2026, [https://indigitalibrary.inl.gov/sites/sti/sti/Sort\\_107145.pdf](https://indigitalibrary.inl.gov/sites/sti/sti/Sort_107145.pdf)
31. Demonstration Rocket for Agile Cislunar Operations - Wikipedia, accessed April 7, 2026, [https://en.wikipedia.org/wiki/Demonstration\\_Rocket\\_for\\_Agile\\_Cislunar\\_Operations](https://en.wikipedia.org/wiki/Demonstration_Rocket_for_Agile_Cislunar_Operations)
32. Engine Cycle Comparison for Alternative Propellant Nuclear Thermal Propulsion Engines, accessed April 7, 2026, <https://ntrs.nasa.gov/api/citations/20230002835/downloads/Engine%20Cycle%20Comparison%20for%20A-NTP%20Engines%20FINAL.pdf>
33. Comparison of Convective Heat Transfer Correlations and Their Application to Nuclear Thermal Propulsion Reactors, accessed April 7, 2026, [https://ntrs.nasa.gov/api/citations/20220002156/downloads/Comparison%20of%20Convective%20Heat%20Transfer%20Correlations%20and%20Their%20Application%20to%20Nuclear%20Thermal%20Propulsion%20Reactors%20\(NETS%202022\).pdf](https://ntrs.nasa.gov/api/citations/20220002156/downloads/Comparison%20of%20Convective%20Heat%20Transfer%20Correlations%20and%20Their%20Application%20to%20Nuclear%20Thermal%20Propulsion%20Reactors%20(NETS%202022).pdf)
34. Study of Heat Transfer Correlations for Supercritical Hydrogen in Regenerative Cooling Channels - SciSpace, accessed April 7, 2026, <https://scispace.com/pdf/study-of-heat-transfer-correlations-for-supercritical-1tmdbmc80.pdf>
35. Track 2: Nuclear Fission Power and Propulsion - NETS 2020, accessed April 7, 2026, <https://nets2020.ornl.gov/wp-content/uploads/2020/09/TRACK-2-Full-submission.pdf>
36. (PDF) Nuclear Thermal Propulsion - ResearchGate, accessed April 7, 2026, [https://www.researchgate.net/publication/360423825\\_Nuclear\\_Thermal\\_Propulsion\\_Propellants](https://www.researchgate.net/publication/360423825_Nuclear_Thermal_Propulsion_Propellants), accessed April 7, 2026, <http://www.astronautix.com/p/propellants.html>
37. Efficiency of Engine Thrust and Specific Impulse and Altitude Propellants on  $\Delta V$  Budget and Architecture Mass for 1st Generation Nuclear Thermal, accessed April 7, 2026, [https://ntrs.nasa.gov/api/citations/20240014769/downloads/Efficiency\\_of\\_NTP\\_Propellants\\_and\\_MEL\\_on\\_1st\\_Gen.pdf](https://ntrs.nasa.gov/api/citations/20240014769/downloads/Efficiency_of_NTP_Propellants_and_MEL_on_1st_Gen.pdf)
38. Ammonia / Hydrogen Peroxide propellant properties? - Kerbal Space Program Forums, accessed April 7, 2026, <https://forum.kerbspacespace.com/topic/179097-ammonia-hydrogen-peroxide-propellant-properties/>
39. Finite-Time Thermodynamics Perspective into Nuclear Power Plant Heat Cycle - arXiv, accessed April 7, 2026, <https://arxiv.org/html/2509.25714v1>
40. CONCEPTUAL DESIGN OF THE NGNP REACTOR SYSTEM, accessed April 7, 2026, <https://fusion.gat.com/publications/MISCONF12/A27283.pdf>
41. Solid Core Nuclear Propulsion Concept - DTIC, accessed April 7, 2026, <https://apps.dtic.mil/sti/tr/pdf/ADA202339.pdf>
42. Parametric Modeling of NTP Engine Performance for a Crewed Mars Mission, accessed April 7, 2026, [https://ntrs.nasa.gov/api/citations/20230013241/downloads/NTP\\_Parametric\\_Modeling\\_Paper\\_20231006.pdf](https://ntrs.nasa.gov/api/citations/20230013241/downloads/NTP_Parametric_Modeling_Paper_20231006.pdf)
43. Space Nuclear Propulsion - NASA, accessed April 7, 2026, <https://www.nasa.gov/wp-content/uploads/2024/05/calomino-nuclear-v4-td-tagged.pdf?emrc=67cf454f14637>
44. DRACO: Demonstration Rocket for Agile Cislunar Operations - DARPA, accessed April 7, 2026, <https://www.darpa.mil/research/programs/demonstration-rocket-for-agile-cislunar-operations>
45. (a) The RD-0410 Nuclear Thermal Engine (© Dietrich Haeseler). (b) NERVA... | Download Scientific Diagram - ResearchGate, accessed April 7, 2026, [https://www.researchgate.net/figure/a-The-RD-0410-Nuclear-Thermal-Engine-C-Dietrich-Haeseler-b-NERVA-nuclear-thermal\\_fig1\\_30762216](https://www.researchgate.net/figure/a-The-RD-0410-Nuclear-Thermal-Engine-C-Dietrich-Haeseler-b-NERVA-nuclear-thermal_fig1_30762216)