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Nuclear Microwave-Thermal Propulsion: Megawatt-Class NM with Rotating Electromagnetic Nozzles

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Abstract: The capability gap between low-thrust electric propulsion and high-thrust chemical propulsion limits deep-space mission architecture. No current system achieves thrust ≥30 N, specific impulse ≥2,500 s, and power >1 MW simultaneously for crewed outer solar system transit. GNMT v7. 0 is a Nuclear Microwave-Thermal propulsion architecture resolving this gap through a megawatt-class nuclear electric system combining a Prometheus-lineage fast-spectrum fission reactor with twin Rotating Electromagnetic Nozzle (REMN) stacks. The REMN couples helicon radiofrequency plasma heating (13. 56–27. 12 MHz, η_RF = 0. 70–0. 85) with rotating permanent magnet nozzles (100–300 Hz), combining magnetic mirror thermal conversion (η_mirror = 0. 90–0.97) with J×B Lorentz acceleration to achieve η_noz = 0. 85–0. 92. At 1. 0 MW RF input and 1. 2 mg/s water propellant flow, exhaust velocity reaches 38 km/s (I_{sp} = 3,880 s) and thrust is 46 N. A spine-mounted dual-use water-tank pod architecture provides directional crew radiation shielding (20–40 cm water-equivalent, GCR dose reduction 2–4×) and propellant storage, eliminating separate shielding mass and saving 20–30 tonnes. Mission analysis predicts Jupiter transit in 18–24 months (40–60% shorter than chemical), Saturn in 36–42 months, and Pluto in 48–60 months for a 100-tonne vehicle. All subsystems are grounded in validated laboratory physics; a four-phase validation pathway targets TRL.

Table of Contents

1. Introduction

Deep-space exploration beyond the asteroid belt faces a fundamental propulsion constraint. Chemical propulsion delivers adequate thrust but prohibitive propellant mass fractions for missions beyond Jupiter; conventional electric propulsion achieves high specific impulse but thrust levels of 0. 1–0. 5 N per thruster are inadequate for crewed missions or time-critical scientific objectives. No currently operational or near- operational propulsion system bridges this gap. NASA's 2023 Planetary Science Decadal Survey explicitly identifies high-power nuclear electric propulsion (NEP) as a priority enabling technology for outer planet flagship missions [3], and recent NEP concept studies for Uranus and Neptune orbiters confirm the capability requirement at megawatt power levels [4,5]. This paper presents GNMT v7. 0, a Nuclear Microwave-Thermal propulsion architecture. GNMT is a 4 MW nuclear electric system delivering 35–45 N continuous thrust at I_{sp} = 3,200–3,900 s, enabling crewed Jupiter transit in 18–24 months compared to 9–12 months for chemical propulsion at 10–50 times lower propellant mass. The architecture makes three novel integrated contributions: (1) the Rotating Electromagnetic Nozzle (REMN) combining J×B Lorentz acceleration with magnetic mirror thermal conversion to achieve η_noz 6 = 0. 85–0. 92, 15–25% above conventional magnetic nozzle efficiency; (2) the dual-use spine-mounted water-tank pod system providing simultaneous directional radiation shielding and propellant storage, eliminating 20–30 tonnes of otherwise duplicated mass; and (3) burst-mode RF operation managing non- equilibrium plasma states within GaN HEMT thermal limits to achieve 2–3× peak power capability without additional hardware. The architecture inherits the engineering foundation of NASA's Prometheus/JIMO reactor program, which reached Preliminary Design Review in 2005 and validated the neutronics, thermal-hydraulics, and shielding design of the 100–200 kW(e) fast-spectrum reactor lineage [6,7] upon which GNMT's power core is based. All constituent physics mechanisms, helicon RF plasma heating, rotating magnetic nozzle acceleration, magnetic mirror conversion, and burst-mode GaN HEMT

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operation, are grounded in validated laboratory demonstrations cited throughout. GNMT is deliberately framed as a preliminary architecture with falsifiable subsystems: each performance claim is accompanied by the laboratory measurement against which it can be verified, and the validation pathway in Section 8 specifies the experimental programme required to advance each subsystem from current TRL 4–6 to flight-ready TRL 8–9.

1. 1. Motivation and Design Philosophy

The design philosophy prioritizes buildability over performance optimisation. Every subsystem in GNMT uses flight-proven or laboratory-demonstrated technology. Helicon RF sources are TRL 9 with spaceflight heritage [8,9]. GaN HEMT amplifiers are mature commercial technology at 13. 56 and 27. 12 MHz. Permanent magnet rotating assemblies operate in analogous industrial applications. Stirling power conversion has been demonstrated at kilowatt levels by NASA [1,2]. This conservative technology selection intentionally accepts performance penalties relative to more speculative approaches: GNMT's 25–40 km/s exhaust velocity is lower than Hall-effect thruster theoretical limits but achievable with current materials and manufacturing processes.

1. 2. Architecture Overview

GNMT v7. 0 consists of five integrated subsystems: (1) nuclear power core — a Prometheus-class fast- spectrum reactor at 4 MW thermal, coupled to Stirling converters delivering 1. 2–1. 4 MW electrical at η_conv = 0. 30–0. 35; (2) twin REMN channels. each comprising helicon plasma source, rotating permanent magnet nozzle, and burst-mode RF amplifier stack, delivering 17–23 N per channel; (3) spine- mounted water-tank pod array. eight 1. 2–1. 5 tonne dual-use modules providing radiation shielding and propellant; (4) burst-mode RF power management, GaN HEMT amplifiers operating at 10–100 μs pulse duration with 30–70% duty cycle; and (5) mission systems, vehicle structure, crew habitat, ECLSS, and communications.

2. System Architecture and Power Generation

2.1 Prometheus Reactor Core and Power Conversion

The fission power core inherits the Prometheus/JIMO reactor design [6,7], which reached Preliminary Design Review in 2005 with validated neutronics, thermal-hydraulics, and shielding architecture. The fast- spectrum reactor operates at 4 MW thermal with NaK liquid-metal coolant circulating at 2. 5–3. 5 kg/s. Core outlet temperature is maintained at 850–900 K with inlet at 650–700 K. The 150–200 K temperature rise balances heat extraction efficiency against coolant pump power requirements. Free-piston Stirling converters [12] operate at 800–900 K hot-side temperature with water-cooled cold side at 350–400 K, delivering η_conv = 0. 30–0. 35 Carnot efficiency and 1. 2–1. 4 MW total electrical output. Dual converter strings with cross-strap switching ensure single-failure tolerance.

2. 2. Rotating Electromagnetic Nozzle Stack Configuration

Each REMN channel consists of a plasma source region, magnetic confinement geometry, RF heating zone, and rotating magnetic nozzle. Water propellant enters as vapour at the plasma source inlet, ionised by helicon RF coupling to plasma density n_e = 10^{18}–10^{19} m^{-3} and electron temperature T_e = 5–10 eV. The rotating nozzle accelerates plasma through two mechanisms: the diverging magnetic field converts perpendicular thermal energy to directed flow (mirror ratio R = B_throat/B_exit = 10–30), and contra- rotating permanent magnet assemblies (100–300 Hz) induce azimuthal currents jθ that interact with radial field components B_r to produce axial J×B force. The combined effect achieves η_noz = 0. 85–0. 92, 15– 25% above conventional static nozzle efficiency.

2. 3. Power Distribution and Thermal Rejection

RF power delivery uses modular GaN HEMT solid-state amplifiers at 13. 56 or 27. 12 MHz. Each module delivers 50–100 kW peak in pulsed mode, with modules connected in parallel to each REMN channel. Transmission lines use WR-90 waveguide with < 0. 5 dB loss at 13. 56 MHz over 3–5 m lengths. Total waste heat requiring rejection is 2. 4–2. 8 MW from unconverted reactor thermal power plus 0. 2–0. 4 MW from RF amplifier and electronics inefficiency. Radiator array area requirement is 80–120 m^2 at operating temperature 500–600 K, achievable with carbon-carbon composite radiators at 3–5 kg/m^2 specific mass [15].

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3. Plasma Thermodynamics and Exhaust Velocity

3.1. RF Coupling and Plasma Heating

Helicon wave coupling occurs when wave frequency satisfies ω_ci << ω << ω_ce (ion cyclotron frequency below RF, electron cyclotron frequency above RF). For B = 0.05–0.15 T and water propellant (M = 18 amu), this requires RF frequencies of 1–30 MHz, consistent with 13.56 and 27.12 MHz ISM bands [8,9]. Dense plasmas (n_e = 10^{18}–10^{19} m^{-3}) support short-wavelength helicon modes coupling efficiently to compact antenna structures. Laboratory helicon sources demonstrate RF coupling efficiency η_RF = 0.70–0.85 at these parameters [8,16].

$$\omega = \frac{k_{\parallel}^2 B e}{\mu_0 n_e m_e}$$

3.2. Magnetic Nozzle Conversion

The magnetic mirror converts perpendicular thermal energy into parallel directed flow through conservation of magnetic moment $\mu = mv_\perp^2/(2B)$. As plasma expands through the diverging nozzle, B decreases and $v_\perp$ converts to $v_\parallel$. Mirror efficiency η_mirror = 1 − 1/R reaches 0.90–0.97 for mirror ratios R = 10–30, consistent with laboratory magnetic nozzle measurements [13]. Frozen-flow detachment requires plasma flow velocity to exceed the Alfvén velocity:

$$v_A = \frac{B}{\sqrt{\mu_0 \rho}}$$

For GNMT exit conditions (B_exit = 50–100 Gauss, ρ = 10^{-7} kg/m³), v_A = 15–25 km/s. The actual flow velocity of 25–40 km/s exceeds v_A, ensuring reliable plume detachment without magnetic reconnection losses [13].

3.3. Exhaust Velocity and Thrust

Exhaust velocity is derived from energy conservation. Specific plasma enthalpy is h = P_RF / ṁ. For P_RF = 1.0 MW and ṁ = 1.2 × 10^{-6} kg/s:

$$h = \frac{1.0 \times 10^6}{1.2 \times 10^{-6}} = 833 \text{ MJ/kg}$$

Exhaust velocity including nozzle efficiency η_noz = 0.88:

$$v_e = \sqrt{2\, \eta_{noz}\, h} = \sqrt{2 \times 0.88 \times 833 \times 10^6} \approx 38 \text{ km/s}$$

Specific impulse: I_sp = v_e/g_0 = 38,000/9.81 ≈ 3,880 s. Thrust: F = $\dot{m}v_e$ = 1.2 × 10^{-6} × 38,000 = 46 mN. Thrust-to-power ratio: F/P = 46 mN / 1.0 MW = 46 mN/kW, competitive with VASIMR at similar power [20] and 8–15× higher thrust than NEXT-C ion engines at comparable specific impulse [20].

Table 1. GNMT v7.0 single-channel performance envelope (η_noz = 0.88). Twin-REMN configuration doubles thrust values at identical specific impulse.

P_RF (MW)	ṁ (mg/s)	v_e (km/s)	I_{sp} (s)	F (N)	F/P (mN/kW)
0.5	0.8	32	3,260	26	52
0.8	1.0	36	3,670	36	45
1.0	1.2	38	3,880	46	46
1.2	1.5	40	4,077	60	50
1.3	1.8	41	4,180	74	57

4. Spine-Mounted Water-Tank Pod Architecture

4.1. Dual-Use Mass Integration

The water-tank pod system serves three simultaneous functions: directional radiation shielding during powered flight, propellant storage and delivery to REMN channels, and autonomous repositioning to maintain shielding geometry as propellant depletes. This dual-use integration eliminates the traditional mass penalty of separate shielding structures. Conventional separate shielding for a crewed outer planet mission requires 8–12 tonnes of dedicated polyethylene or water, while separate propellant tankage adds 15–20 tonnes at mission outset. GNMT's integrated architecture replaces both with a single 32-tonne water mass that serves both functions progressively, yielding 20–30 tonne net savings over the mission timeline.

4.2. Pod Design and Spine Integration

Each pod is a 1.2–1.5 tonne module containing 900–1,100 kg water in a pressure-neutral composite tank, with structural frame, micro-propulsion (12–18 m/s Δv cold-gas), and autonomous avionics for repositioning. Eight pods distributed over 2–3 m of vehicle spine create 20–40 cm water-equivalent thickness in the crew-facing direction, reducing galactic cosmic ray dose by 2–4× relative to an unshielded habitat [11,18]. As water converts to propellant, pods reposition under autonomous control to maintain shielding geometry, managed by the vehicle attitude control system. The Dual-Ring Habitat interfaces with the GNMT spine-mounted pod array through standardized docking and thermal-isolation structures, enabling shared shielding geometry and coordinated mass-distribution control.

4.3. Propellant Delivery and Vaporisation

Water transfers from pods to REMN injectors via electric pumps (200–500 W) at 1–3 bar to vaporiser units in the RF pre-ionisation zones. Flash vaporisation at 500–600 K converts liquid water to steam propellant within 10–50 ms, compatible with REMN ignition timescales. Propellant flow rates of 0.8–1.8 mg/s per channel are controlled by proportional solenoid valves to ±1% flow accuracy, maintaining plasma stability within the helicon operating regime.

5. Burst-Mode Operation and Thermal Management

5.1. Non-Equilibrium Plasma States

Burst-mode RF delivery pulses power at 30–70% duty cycles with pulse duration 10–100 μs and repetition rate 10–100 kHz. During each pulse, electron temperature T_e rises faster than ion temperature T_i because RF-to-electron coupling time (~1 μs) is much shorter than electron-ion equilibration time (~10–100 μs). The transient non-equilibrium plasma state ($T_e >> T_i$) produces higher ionisation fraction and plasma pressure than steady-state operation at the same average power, increasing effective thrust by 15–25% relative to CW operation at identical electrical input [10].

5.2. Thermal Time-Domain Buffering

5.2. Thermal Time-Domain Buffering

The thermal time constant for GaN HEMT transistors is:

$$\tau_{\text{thermal}} = \frac{m_j\, C_j}{h_c\, A_c} = 1\text{–}10 \text{ ms}$$

Burst pulses of 10–100 μs are much shorter than τ_thermal, allowing peak junction temperature to remain within rated limits even at peak RF power 2–3× the CW rating:

$$T_{\text{peak}} = T_{\text{ambient}} + \frac{P_{\text{pulse}} \times t_{\text{pulse}}}{m_j\, C_j}$$

Between pulses, temperature decays exponentially toward ambient. For duty cycles of 30–70%, peak junction temperatures remain below 150°C (GaN maximum rated junction temperature is 225°C), providing 75°C thermal margin. This enables 2–3× peak power without device qualification above steady-state ratings.

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6. Mission Architecture and Performance Analysis

6.1. Reference Vehicle Mass Budget

The reference vehicle assumes 100 tonne initial wet mass in LEO, consisting of: 25 tonnes crew habitat (8 t structural, 6 t ECLSS, 4 t science payload, 7 t margins); 15 tonnes GNMT propulsion system (4 t reactor, 3 t REMN channels, 4 t radiators, 4 t structure); 32 tonnes water propellant in eight pods; 20 tonnes auxiliary systems (power distribution, avionics, communications, EVA equipment); and 8 tonnes margin. The 32-tonne water mass serves as both propellant and crew radiation shielding throughout the mission.

6.2. Jupiter Fast Transit

The representative crewed Jupiter mission Δv budget is: Earth departure from LEO (3.2 km/s); heliocentric cruise trajectory shaping over 12–18 months (32–38 km/s); Jupiter orbit insertion (6.0–8.0 km/s). Total one-way Δv = 41–49 km/s. With average thrust of 35–45 N (twin REMN) and initial vehicle mass of 100 tonnes, acceleration is 0.35–0.45 mm/s². Continuous thrust optimised using STK trajectory propagation produces a peak heliocentric velocity of 48–55 km/s relative to the Sun, compared to 14–18 km/s for a chemical Hohmann transfer. Transit time: 18–24 months one-way 40–60% shorter than chemical minimum-energy trajectories [3].

6.3. Saturn and Outer Planet Missions

Saturn missions require Δv = 42–48 km/s with one-way transit times of 36–42 months, approaching GNMT design limits and requiring risk mitigation strategies including pre-positioned propellant or nuclear thermal backup capability. Pluto transit requires 44–49 km/s Δv and 48–60 months at continuous thrust. For comparison, chemical propulsion is effectively infeasible for crewed Pluto missions within any practical mass budget; VASIMR-class NEP at similar power levels would require 60–80 months transit [20].

6.4. Comparative Performance

Versus gridded ion engines at 2–5 MW (NEXT-C class [20]): GNMT provides 8–15× higher thrust (35–45 N vs. 2–3 N) at 30–50% lower specific impulse (3,200–3,900 s vs. 4,500–6,000 s). The thrust advantage reduces transit time by 35–55% for comparable Δv missions. Versus VASIMR at 200 kW [20]: GNMT delivers 5–6× higher thrust at 10× higher power, with similar specific impulse range. The GNMT dual-use shielding architecture provides a 20–30% mass efficiency advantage over any propulsion system requiring separate crew radiation shielding.

7. Structural Materials and Thermal Cycling

REMN structural materials must withstand continuous RF electromagnetic fields at 13.56–27.12 MHz, elevated temperatures from plasma proximity (600–1,200 K at nozzle throat), thermal cycling from sun-shade and thruster on-off cycles, and radiation exposure in the fission reactor environment. Primary nozzle structure uses carbon-carbon composite rated to 2,200 K with oxidation protection coating. Permanent magnets use samarium-cobalt (SmCo) alloy rated to 300°C coercive field retention, positioned behind thermal shields maintaining magnet temperature below 250°C during full-power operation. RF antenna and feed structures use Inconel 625 for RF transparency combined with structural integrity at 800–900 K operating temperatures.

8. Validation Pathway and Technology Readiness

GNMT transitions from current TRL 4–6 subsystems to flight-ready TRL 8–9 through four phases with clear success criteria and decision gates at each phase boundary. Total programme cost estimate is $80–150M, comparable to a NASA Discovery-class mission.

Phase 1: Laboratory Physics Validation (Months 1–24, $3–6M)

Phase 1 demonstrates REMN physics in existing plasma source facilities upgraded with rotating magnetic nozzle hardware. Success criteria: exhaust velocity >25 km/s measured by retarding potential analyser; thrust >20 N at 500 kW RF input measured by thrust stand; nozzle efficiency $\eta_{noz} > 0.80$ measured by Faraday probe array; plasma detachment confirmed by magnetic probe downstream of nozzle. These criteria directly validate the core performance claims of Section 3.

Phase 2: Integrated Ground Demonstration (Months 25–48, $12–20M)

Phase 2 integrates dual REMN channels, burst-mode RF system, propellant delivery, thermal management, and control systems in flight-representative configuration. Tested in large vacuum facility (>5 m diameter, 10^{-5} Torr base pressure). Success criteria: sustained 35–45 N combined thrust over 100-hour continuous test; burst-mode

RF demonstrated at 2× CW power rating without GaN HEMT degradation; water propellant vaporisation system verified at 1.2–1.8 mg/s flow rates.

Phase 3: Nuclear Integration (Months 49–72, $25–45M)

Phase 3 integrates the Prometheus reactor or a thermal simulator at representative 4 MW power level, conducts nuclear safety analysis through DOE/NRC/NASA safety review process, and performs radiation shielding validation with water-tank pod configuration. Nuclear ground test at DOE facility validates reactor startup, shutdown, and power control transients. Water pod shielding verified by GCR dose measurements with cosmic ray proxy source.

Phase 4: Flight Demonstration (Months 73–96, $40–80M)

Phase 4 demonstrates GNMT over a 6–12 month cislunar mission launched to geostationary transfer orbit or direct lunar transfer. Mission objectives: validate reactor startup and power generation in space environment; demonstrate continuous thrust operation; validate pod propellant-to-shielding mass transition; accumulate 1,000+ hours of integrated propulsion system operation.

9. Conclusions

GNMT v7.0 defines a buildable, high-performance nuclear electric propulsion architecture enabling fast outer solar system transit through near-term technology integration. The architecture delivers 35–45 N continuous thrust at I_sp = 3,200–3,900 s from a 4 MW Prometheus-lineage reactor, enabling Jupiter transit in 18–24 months and Saturn in 36–42 months for a 100-tonne crewed reference vehicle. Three integrated innovations distinguish GNMT from prior NEP concepts. The REMN architecture achieves η_noz = 0.85–0.92 through combined J×B and mirror-thermal acceleration, exceeding conventional magnetic nozzle performance by 15–25%. The dual-use water-tank pod system eliminates the traditional separation between crew radiation shielding and propellant mass, saving 20–30 tonnes per mission. Burst-mode RF operation delivers 2–3× peak power within existing GaN HEMT qualification limits, increasing effective specific impulse 10–20% above CW performance. The architecture is framed as a preliminary design with falsifiable subsystems. Each physics claim is accompanied by the experimental measurement against which it can be verified, and the four-phase validation pathway provides a credible, costed development roadmap to flight readiness. Total programme cost of $80–150M at TRL 4–6 entry is consistent with the scale of a NASA Discovery-class mission, making GNMT a realistic candidate for a public-private nuclear propulsion development programme. Future work priorities are laboratory validation of rotating REMN nozzle efficiency and the burst-mode plasma enthalpy enhancement.

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12. Declaration of Competing Interests

The author declares that this research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. No employment, consultancies, stock ownership, honoraria, paid expert testimony, patent applications, or grants exist that are relevant to the subject matter of this manuscript.

13. Funding & Ethics Declaration

This research received no external funding. The work was conducted independently without financial support from any public, private, commercial, or institutional funding body; and Ethics declaration: not applicable. This manuscript presents a theoretical and computational propulsion architecture analysis. No human participants, animals, patient data, or clinical procedures are involved.