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Comparative Trade Study of Nuclear Thermal vs. Chemical Thermal Propulsion for Space Travel

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Research Engineers:

1. Introduction

- **Background**: Growing demand for high-efficiency, high-thrust propulsion for interplanetary exploration.
- **Motivation**: Assess the viability of Nuclear Thermal Propulsion compared to Chemical Thermal Propulsion for a range of missions (LEO, Mars, deep space, refueling logistics).
- **Objective**: Perform a simulation-based comparative trade study of performance, feasibility, and mission architectures.

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2. Mission Scenarios

Define clear reference missions:

1. **Low Earth Orbit (LEO) Transfer**
    - Example: Payload delivery from LEO to GEO or cislunar orbit.
2. **Mars Transit Mission**
    - Example: Human-rated Mars transfer with specified payload mass.
3. **Deep Space / Refueling Mission**
    - Example: Cargo or tanker missions beyond Mars (asteroid belt or lunar refueling depots).

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3. Propulsion Concepts

- **Chemical Thermal Propulsion (CTP)**
    - LOX/LH_2 or LOX/CH_4 baselines.
    - Isp ~ 350–450 s.

- **Nuclear Thermal Propulsion (NTP)**
  - Solid-core reactor with LH_2 propellant.
  - Isp ~ 850–950 s.
  - Reactor thermal limits and radiation shielding requirements.

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4. Performance Metrics

- Thrust-to-weight ratio (T/W).
- Specific impulse (Isp).
- Δv capability.
- Payload fraction delivered to target orbit.
- Mission duration and transit time.
- Refueling/resupply requirements.
- Mass and volume efficiency.

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5. Modeling and Simulation

- **Tools:** Python (SciPy/NumPy)
- **Equations/Models**:
  - Tsiolkovsky rocket equation.
  - Thrust equations for each propulsion type.
  - Mass breakdown (propellant, dry mass, payload).
  - Reactor power/heat transfer constraints (for NTP).
- **Simulation Outputs**:
  - Mass ratio vs. Δv.
  - Payload delivered vs. mission type.
  - Mission duration comparisons.

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6. Trade Study Framework

- **Comparison Categories**:
  - Technical performance (Isp, thrust, Δv).
  - Mass efficiency (payload delivered).
  - Mission duration.
  - Complexity (development risk, technology readiness level).
  - Safety and policy considerations (launch approval, nuclear safety).
  - Economic factors (cost per mission, infrastructure).
- **Scoring System**: Weighted trade matrix with mission scenarios.

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7. Results & Analysis

- Comparative charts and graphs for LEO, Mars, and deep space missions.
- Quantitative tradeoffs (payload mass, time-of-flight, Δv margins).
- Sensitivity analysis (e.g., effect of reactor efficiency, propellant boil-off).

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8. Discussion

- Feasibility and advantages of each propulsion type per mission.
- Role of refueling depots and long-duration missions.
- Policy and risk considerations.
- Potential hybrid architectures (e.g., NTP for transit, CTP for landing).

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9. Conclusions & Recommendations

- Which propulsion system is optimal for each mission scenario.
- Future research recommendations (e.g., bimodal NTP, nuclear electric hybrids).
- Path to implementation for human-rated missions.

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10. Deliverables

- Final technical report with trade study results.
- Simulation models (codebase, parameters).
- Presentation deck for defense/briefing.