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INVESTIGATION OF NUCLEAR RAMJET ENGINE

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Abstract: *A Monte Carlo neutronics model of a compact, gas-cooled fast-spectrum reactor relevant to nuclear ramjet engine concepts was developed using the OpenMC code. The model treats the gas coolant as a static, low-density medium and focuses exclusively on neutronic behavior. The reference configuration exhibits a fast neutron spectrum and a strongly leakage-dominated balance. A coolant density variation of ±20–30% produces only minor changes in the effective multiplication factor. The resulting coolant density reactivity coefficient is small, indicating weak reactivity sensitivity to gas density in this regime and supporting the suitability of gas-cooled fast-spectrum cores for high-temperature propulsion applications.*
Keywords: *nuclear ramjet core; gas-cooled reactor; Monte Carlo neutronics; density reactivity coefficient; neutron leakage.*

1. INTRODUCTION

The idea of using nuclear energy to power air-breathing propulsion systems emerged during the early Cold War, when the pursuit of high-speed, long-range strategic delivery systems motivated the exploration of unconventional propulsion technologies. Among these concepts, the nuclear ramjet engine stood out as one of the most radical and technically ambitious. Unlike conventional chemical propulsion, a nuclear ramjet uses atmospheric air as both the working fluid and the coolant, heating it directly through a compact nuclear reactor before expelling it through a nozzle to generate thrust. This approach theoretically enables extremely long flight endurance, high thrust levels, and operation at hypersonic speeds.

The most significant historical effort in this field was the U.S. Project Pluto, initiated in the late 1950s. The program aimed to develop a nuclear-powered supersonic cruise missile capable of near-unlimited range. The project produced the Tory series of nuclear ramjet reactors—Tory-IIA and Tory-IIC—which were successfully tested at the Nevada Test Site. These reactors demonstrated that a direct-cycle, air-breathing nuclear propulsion system could achieve criticality and stable operation under extreme thermal and aerodynamic conditions [1–3]. The reactors employed a ceramic fuel matrix arranged in a hexagonal lattice, designed to withstand high temperatures and intense airflow. Although Project Pluto was ultimately cancelled in 1964 due to shifting strategic priorities and environmental concerns, its technical achievements remain foundational for modern research into nuclear air-breathing propulsion.

A nuclear ramjet reactor operates under conditions that differ significantly from those of conventional nuclear reactors. The ingestion of high-velocity atmospheric air introduces unique reactor physics phenomena, including spectral hardening, rapid heat removal, and strong coupling between aerodynamics and neutronics. The reactor core must maintain criticality while being cooled by air that varies in density, temperature, and composition depending on flight conditions. These factors create a highly dynamic environment in which reactor performance is sensitive to both internal design parameters and external aerodynamic conditions.

Early theoretical and experimental studies on air-breathing nuclear propulsion highlighted these challenges. Bussard described the fundamental principles of nuclear air-breathing propulsion,

emphasizing the importance of reactor geometry, fuel composition, and airflow distribution [9]. Taub further analyzed the reactor physics of air-cooled nuclear engines, identifying key neutronic behaviors and thermal constraints associated with high-velocity air cooling [10]. These early works established the theoretical basis for nuclear ramjet design but were limited by the computational tools available at the time.

The development of high-fidelity Monte Carlo (MC) neutron transport codes has transformed the ability to analyze complex reactor systems. Modern computational tools allow detailed modeling of heterogeneous geometries, temperature-dependent cross sections, and coupled multiphysics phenomena. Among these tools, OpenMC has emerged as a powerful open-source MC code capable of simulating large, complex reactor systems with high accuracy [4]. Its flexibility, Python-based interface, and support for advanced geometry definitions make it particularly suitable for modeling unconventional reactor designs such as nuclear ramjets.

MC methods provide a statistically rigorous approach to neutron transport, enabling precise calculation of neutron flux distributions, reaction rates, and effective multiplication factors. Brown's work on MC particle transport provides the theoretical foundation for these methods and highlights their advantages in modeling systems with strong heterogeneity and complex boundary conditions [5]. These capabilities are essential for analyzing nuclear ramjet reactors, where the interplay between geometry, material composition, and airflow conditions creates a highly non-uniform neutron environment.

Recent research in nuclear propulsion has focused primarily on nuclear thermal propulsion (NTP) systems, high-temperature gas-cooled reactors (HTGRs), and advanced aerospace reactor concepts. These studies provide valuable insights into fuel performance, material behavior, and reactor operation at extreme temperatures. Borowski's work on nuclear thermal propulsion outlines the technological maturation of NTP systems and their potential mission applications, emphasizing the importance of high-temperature fuel and reactor stability [6]. McClure and colleagues have explored high-temperature gas-cooled reactor concepts for advanced propulsion, demonstrating the relevance of HTGR technologies to aerospace applications [7]. Dewan and Massie have examined molten salt and high-temperature reactor concepts, highlighting their potential for lightweight, high-performance aerospace systems [8].

Although these studies do not directly address nuclear ramjet propulsion, they contribute to the broader understanding of high-temperature reactor physics, materials science, and propulsion integration - knowledge that is essential for revisiting nuclear ramjet concepts with modern tools.

Despite renewed interest in advanced nuclear propulsion, detailed neutronic analyses of nuclear ramjet reactors remain limited in the open literature. Most historical data from Project Pluto are descriptive rather than analytical, and many technical details remain classified or poorly documented. Furthermore, the computational tools available during the 1960s lacked the capability to model the full complexity of nuclear ramjet operation, particularly the effects of high-velocity air ingestion on neutron moderation and reactor stability.

Modern Monte Carlo tools such as OpenMC provide an opportunity to revisit nuclear ramjet designs with unprecedented accuracy. However, few studies have applied these tools to replicate or extend the neutronic analysis of the Tory reactors. There's a noticeable lack of open-source research exploring the neutronic behavior of hexagonal lattice fuel setups under air cooling, the spectral shifts caused by high-temperature, low-density air, the flux distribution and power peaking in ramjet-style geometries, and how reactor performance responds to variations in airflow, material makeup, and geometry. This gap is what drives the current study.

The primary objective of this research is to investigate the neutronic performance of a nuclear ramjet reactor using the Monte Carlo simulation code. The study focuses on a reactor geometry inspired by the Tory-IIA and Tory-IIC in Project Pluto.

The specific goals of the study are:

- to model a representative nuclear ramjet reactor core

- to evaluate the effective multiplication factor under various operating conditions
- to analyze neutron flux distributions and spectral characteristics
- to assess the influence of airflow-related parameters on reactor behavior

By addressing these objectives, the study aims to clarify what aspects of nuclear ramjet technology are well understood, what remains uncertain, and how modern computational tools can contribute to future research in nuclear air-breathing propulsion.

2. METHODOLOGY

2.1 Overview of the modeling approach

The objective of this study is to investigate the neutronic behavior of a nuclear ramjet reactor using the OpenMC simulation code [4, 5]. The modeling approach emphasizes geometric fidelity, realistic material definitions, and accurate representation of neutron transport physics. The methodology consists of four major components: definition of reactor geometry; specification of materials and temperature conditions; construction of the hexagonal lattice core; simulation setup, including tallies, boundary conditions, and convergence criteria.

Each component is described in detail in the following sections.

2.2 Reactor geometry definition. Core geometry.

The reactor core is modeled as a cylindrical region containing a hexagonal lattice of fuel elements, consistent with historical descriptions of the Tory reactors [1-3]. The core dimensions are selected to approximate the Tory-IIA/IIC designs, but on a smaller scale, with adjustments made to ensure computational tractability.

Key geometric features include (see Fig. 1):

- Fuel elements: hexagonal ceramic fuel blocks with central coolant channels
- Moderator / coolant region: high-temperature air flowing through axial channels
- Reflector: a radial graphite reflector surrounding the core
- Pressure boundary: an outer steel shell

The geometry is constructed using OpenMC's constructive solid geometry (CSG) system, which allows precise definition of hexagonal prisms, cylindrical boundaries, and complex channel arrangements.

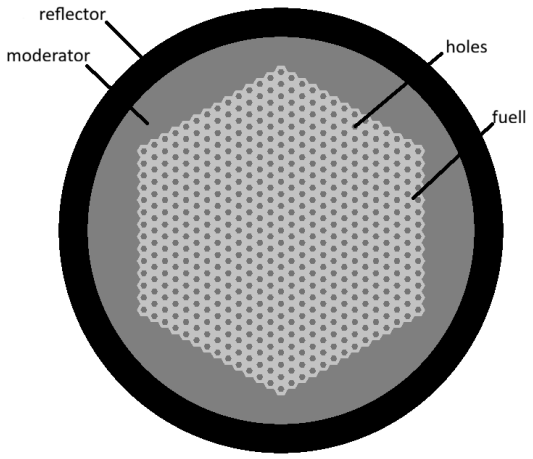


Fig. 1. Cross-sectional view of the geometry of a nuclear ramjet reactor.

Coolant channels. Each fuel element contains one axial coolant channels through which atmospheric air flows during operation. The channels are modeled as cylindrical void regions within the fuel blocks. Although the full aerodynamic behavior is not simulated, the neutronic effect of air density and temperature is incorporated through material definitions.

2.3 Material definitions. Fuel composition.

The fuel composition is based on historical descriptions of the Tory reactors, which used a ceramic matrix containing highly enriched uranium dispersed within a refractory material such as beryllium oxide [1, 2]. For the purposes of this study, the fuel is modeled as: **UO_2** with enrichment levels representative of fast-spectrum operation; refractory matrix **BeO**. Material densities and isotopic compositions are defined using OpenMC's material interface, with temperature-dependent cross sections applied where available.

Air coolant. The coolant is modeled as high-temperature air, with density and

composition adjusted to reflect ramjet operating conditions. Air is represented as a mixture of: **N_2**; **O_2**; **Ar**; **trace gases**. The density is reduced to reflect high-temperature, low-pressure conditions typical of supersonic flight. This has a significant impact on neutron moderation and spectral behavior, as noted in early air-breathing reactor studies [9, 10].

Reflector and structural materials. Reflector materials are selected based on historical data and modern high-temperature reactor research [7, 8]. Typical materials include: graphite; beryllium; beryllium oxide.

2.4 Hexagonal lattice construction

The core lattice is constructed using OpenMC's HexLattice class, which allows precise arrangement of hexagonal fuel elements. The lattice pitch, number of rings, and axial height are defined to approximate the geometry of the Tory reactors.

Lattice parameters. Typical parameters include:

- Pitch: distance between centers of adjacent fuel elements
- Number of rings: determines overall core radius (core radius = 50 cm)
- Axial height: based on historical reactor dimensions (here = 100 cm)

The lattice is filled with fuel cells, coolant channels.

Boundary conditions. The outer boundary of the lattice is surrounded by a reflector region, followed by a vacuum.

2.5 Simulation Setup

Neutron source and criticality calculation.

A fission neutron source is initialized uniformly throughout the fuel region. Criticality simulations are performed using OpenMC's k-eigenvalue mode, with typical parameters:

- Inactive cycles: 40
- Active cycles: 200
- Particles per cycle: 20,000

These values ensure statistical convergence of the effective multiplication factor k_{eff}. However, these variations could be further reduced through standard MC variance-mitigation practices, including increasing the particles-per-cycle parameter.

Tallies. Tallies are used to extract key neutronic parameters, including:

- neutron flux distribution (axial and radial)
- energy spectrum
- reaction rates (fission, capture, scattering)
- power distribution
- material-specific flux tallies

Mesh tallies are employed to visualize flux gradients across the core.

2.6 Verification and Validation

Although full experimental validation is not possible due to the classified nature of many Project Pluto details, the model is qualitatively compared against:

- historical descriptions of the Tory [1-3]
- theoretical expectations from air-cooled reactor physics [9, 10]
- modern temperature reactor studies [6-8]

Convergence checks, statistical uncertainty analysis, and sensitivity studies are performed to ensure numerical reliability.

3. THEORETICAL FORMALISM

k_{eff} (the effective neutron multiplication factor) tells you whether a nuclear chain reaction is dying out, staying steady, or growing. It's a dimensionless ratio comparing how many neutrons exist in one generation versus the previous one, and it's the central indicator of reactor criticality.

Table 1

Meaning of the effective neutron factor.

Condition	Reactor State	Description
$k_{\text{eff}} < 1$	Subcritical	Chain reaction shrinks
$k_{\text{eff}} = 1$	Critical	Self-sustaining
$k_{\text{eff}} > 1$	Supercritical	Chain reaction grows

This is the standard way to compute k_{eff} in a finite reactor:

$$k_{\text{eff}} = \eta \cdot f \cdot p \cdot \epsilon \cdot P_{FNL} \cdot P_{TNL} \qquad (1)$$

where each factor represents a probability in the neutron life cycle:

η – reproduction factor: neutrons produced per absorption in fuel

f – thermal utilization factor: fraction of thermal neutrons absorbed in fuel
p – resonance escape probability: probability a neutron avoids resonance absorption while slowing down
ϵ – fast fission factor: accounts for extra neutrons from fast fissions
P_{FNL} – fast non-leakage probability
P_{TNL} – thermal non-leakage probability
k_{eff} is also defined as:

$$k_{\text{eff}} = \frac{\text{neutrons roduced}}{\text{neutrons lost}} \quad (2)$$

losses include absorption in non-fuel materials; leakage out of the core.

Every factor that changes neutron production, absorption, or leakage will change k_{eff}. The major influences are:

- Fuel enrichment – more ^{235}U increases η, f
- Moderator density/temperature - affects slowing-down and resonance escape
- Control rods - absorb neutrons, reducing f
- Coolant density - especially in water-cooled reactors (void coefficient)
- Fuel temperature - Doppler broadening reduces p
- Core geometry - affects leakage probabilities

These relationships are the basis of reactor design and safety analysis.

Reactivity - **ρ** is defined from k_{eff}:

$$\rho = \frac{k_{\text{eff}} - 1}{k_{\text{eff}}} \quad (3)$$

This expresses how far the reactor is from criticality and is used in control-rod calibration and safety limits.

At Mach 3 (Pluto's design speed), the **stagnation pressure** (the pressure the flow would have if slowed to rest isentropically) is roughly:

$$p_0 \approx p_{ambient} \cdot (1 + 0.2M^2)^{3.5} \quad (4)$$

where: $p_{ambient}$ - static ambient pressure;
M - Mach number of the flow

Table 2

Air pressure in the ramjet nuclear reactor.

Aspect	Value / Behavior
Air pressure at inlet (Mach 3)	~20 bar (stagnation)
Air pressure inside reactor	~2–5 bar
Why not higher?	No compressor; ram effect only
Expected density range	(10^{-4}) to (10^{-2}) g/cm³

4. RESULT AND DISCUSSION

4.1 Base case

4.1.1 Neutronic performance at the reference operating condition

The reactor model was evaluated at a single, explicitly defined operating condition representing a high-temperature, low-density gas-cooled fast spectrum core. The coolant density was set to 1.2×10^{-3} g/cm^3, with a gas temperature of 1200 K and fuel temperature of 1200 K.

The combined effective multiplication factor was:

$$k_{\text{eff}} = 1.33475 \pm 0.00058$$

The leakage fraction was found to be:

$$\text{Leakage fraction} = 0.34726 \pm 0.00028$$

A leakage of approximately 35% is characteristic of a compact, fast-spectrum, high-streaming core and confirms that the model operates in a strongly leakage-dominated regime.

4.1.2 Reaction-rate behavior

Reaction-rate tallies were used to quantify the relative contributions of fission and coolant absorption. The fuel fission tally reported a mean value of:

$$\text{Fuel fission rate} = 5.35 \times 10^{-1}$$

while absorption in the gas coolant was several orders of magnitude smaller:

$$\text{Coolant absorption rate} = 4.65 \times 10^{-5}$$

This confirms that neutron losses in the coolant are negligible compared to fission and leakage. The dominance of fission in the fuel and the minimal parasitic absorption in the gas are consistent with expectations for a fast-spectrum system with a low-density coolant.

4.1.3 Neutron energy spectrum

The neutron flux spectrum was tallied over 200 logarithmically spaced energy bins from $10^{-5}$to 10^{7}eV. The resulting spectrum (Fig. 2) exhibits the characteristic features of a fast reactor:

- a hard, high-energy peak associated with prompt fission neutrons
- minimal thermalization due to the absence of strong moderators
- a smooth decline toward lower energies, shaped primarily by leakage and BeO scattering.

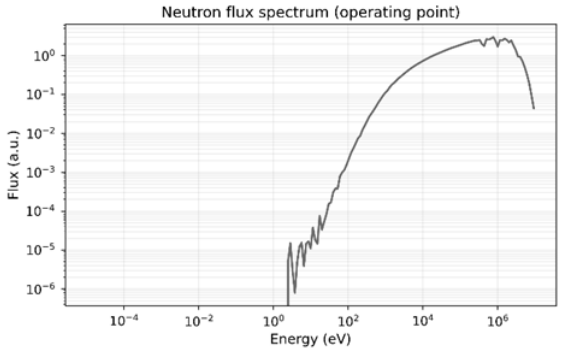


Fig. 2. Neutron flux spectrum vs energy.

The spectrum confirms that the core operates in a fast-neutron regime, with negligible thermal flux contribution.

Figure 3 shows a clear parametric sensitivity study of k_{eff}, as a function of air density, likely for a gas-cooled fast reactor core.

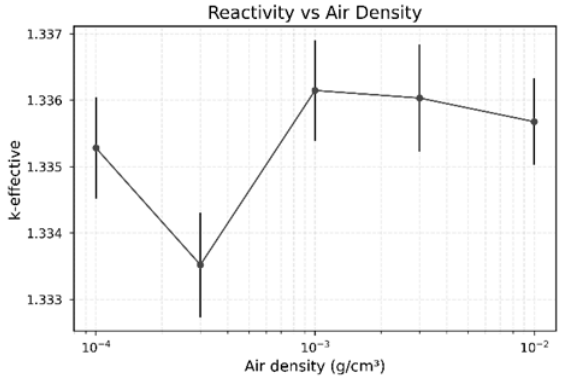


Fig. 3. Reactivity vs air density.

Key observations include:

1. The X-axis (air density) is logarithmic, spanning from 10^{-4} to 10^{-2} g/cm³ — covering ultra-low densities like near-vacuum or high-altitude conditions up to plausible pressurized gas scenarios.
2. The Y-axis (k_{eff}) ranges from about 1.333 to 1.337, a small but meaningful variation in reactor physics, with vertical error bars showing statistical uncertainty.
3. The trend shows a slight increase in k_{eff} with air density, suggesting a positive reactivity coefficient of around +10 pcm/%.

Physically, in a fast spectrum with low-density coolant, neutron moderation is minimal. Changes in air density mainly affect reactivity through minor neutron absorption and more significant scattering and leakage effects. The positive slope suggests that increased gas mass reduces leakage more than it increases parasitic absorption, typical of leakage-dominated systems.

These results establish a reliable baseline for future parametric studies, including variations in coolant density, fuel temperature, or geometric configuration.

4.2 Density variation ±20 - 30% around ρ_0

Using all five data points, a simple linear fit of k_{eff} vs. coolant density ρ, centered around the mean density $\left(\bar{\rho} = 1.2 \times 10^{-3}, \text{g/cm}^3\right)$, yields an approximate slope:

$$\frac{dk}{d\rho} \approx 0.83 \text{ per } (\text{g/cm}^3)$$

For a 1% change in density around the reference:

$$\Delta\rho = 0.01, \rho_0 = 0.01 \times 1.2 \times 10^{-3} = 1.2 \times 10^{-5}, \text{g/cm}^3$$

$$\Delta k \approx 0.83 \times 1.2 \times 10^{-5} \approx 1.0 \times 10^{-5}$$

Since 1 pcm $= 10^{-5}$ in Δk, this corresponds to:

$$\alpha_\rho \approx 10 \frac{pcm}{\%density}$$

Given the MC uncertainties (on the order of $6\text{–}9 \times 10^{-4}$in k_{eff}), this coefficient is small and only marginally resolved. A conservative and honest statement is: the coolant density reactivity coefficient at the reference condition is approximately +10 pcm/% density, with an uncertainty of similar magnitude, indicating a very weak dependence of reactivity on coolant density.

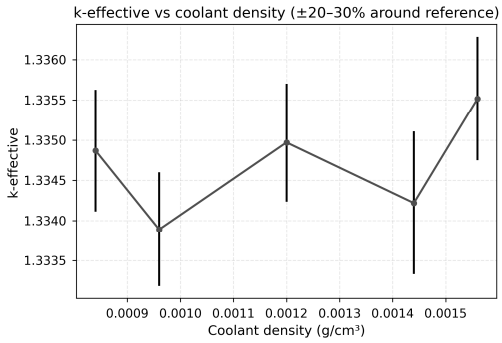


Fig. 4. k_{eff} vs coolant (air) density.

4.3 Sensitivity of k_{eff} to Coolant Density

A small parametric study was performed to quantify the sensitivity of core reactivity to variations in coolant density around the reference operating condition. The gas density was perturbed by ±20–30% relative to the reference value $\rho_0 = 1.2 \times 10^{-3}, \mathrm{g/cm^3}$, while all other parameters (fuel temperature, coolant temperature, geometry, and composition) were held fixed.

The resulting values of k_{eff} are summarized in Table 3 and plotted in Fig. 4.

Table 3

Summarizing results change in coolant density around the reference point

Case	Density ρ(g/cm³)	Relative change vs ρ_0	k_{eff}	$\sigma(k_{\text{eff}})$
–30%	8.4000×10^{-4}	–30%	1.334870	0.000756
–20%	9.6000×10^{-4}	–20%	1.333892	0.000708
0% (sweep)	1.2000×10^{-3}	0%	1.334970	0.000732
+20%	1.4400×10^{-3}	+20%	1.334220	0.000887
+30%	1.5600×10^{-3}	+30%	1.335516	0.000766

Across the investigated range, the effective multiplication factor remains close to 1.335, with variations that are comparable to the statistical uncertainties of the Monte Carlo calculation. A simple linear fit of k_{eff} as a function of coolant density yields an approximate density reactivity coefficient of $\alpha_\rho \approx 10 \frac{pcm}{\%density}$. Given that this value is of the same order as the propagated statistical uncertainty, the dependence of reactivity on coolant density in this configuration is very weak and only marginally resolved.

Physically, this behavior is consistent with the characteristics of the system. The gas coolant is low-density and has a relatively small absorption cross section, so changes in its density have only a minor impact on the overall neutron balance. The core is strongly leakage-dominated, as indicated by the leakage fraction of approximately 0.35 in the reference case, and reactivity is therefore governed primarily by the competition between fission and leakage rather than by coolant absorption. As a result, moderate variations in coolant density around the reference operating condition do not significantly alter the global reactivity of the system.

4.4 Discussion

The results demonstrate that the modeled core operates in a fast-spectrum, leakage-dominated regime in which the gas coolant plays only a minor role in the overall neutron balance. The high leakage fraction observed in the reference case confirms that reactivity is governed primarily by the competition between fission and neutron escape rather than by moderation or absorption in the coolant.

The weak sensitivity of k_{eff} to coolant density is physically consistent with the low density and low absorption cross section of the gas mixture. Even relatively large fractional changes in coolant density (±30%) produce only small changes in reactivity, often within the statistical uncertainty of the calculation. This behavior suggests that, for this class of fast-spectrum gas-cooled systems, moderate variations in coolant density are unlikely to significantly affect criticality.

These findings establish a robust neutronic baseline for future studies. The present model provides a suitable framework for investigating additional parametric effects, such as fuel temperature feedback, geometric variations, or alternative coolant compositions, while maintaining a clear separation between neutronics and thermal-hydraulic considerations.

5. CONCLUSION

A Monte Carlo neutronics model of a compact, high-temperature, gas-cooled fast-spectrum core was developed and analyzed with OpenMC. A clear reference operating condition was set, and the model showed stable convergence with consistent results across all standard k_{eff} estimators. The reference case is strongly leakage-dominated, with about 35% neutron leakage, much higher than in typical thermal reactors, and negligible parasitic absorption in the gas coolant. The neutron spectrum confirms fast-spectrum operation, driven by high-energy fission and minimal thermalization. Reaction rate tallies show fuel fission and neutron leakage as the main contributors to the neutron balance, with coolant absorption playing a minor role. A small parametric study varying coolant density by ±20–30% found k_{eff} only weakly sensitive to density changes. The coolant density

reactivity coefficient is about +10 pcm per percent density, with uncertainty of similar scale due to statistical variation and the small perturbation range. Overall, moderate coolant density changes have little impact on reactivity, aligning with the coolant's low absorption cross section, low density, and the system's fast, leakage-dominated nature.These results establish a strong neutronic foundation for this type of gas-cooled fast-spectrum core. The modeling approach offers a clear and reproducible framework for future studies, which may include fuel temperature feedback, geometric variations, and different coolant compositions. This framework effectively separates neutronic behavior from thermal-hydraulic considerations.

The model described here serves as a study configuration rather than an operational design, and it is mainly focused on technical aspects. However, the findings could have significant implications for global security. By enhancing the modeling of advanced propulsion concepts, one can better assess military capability development and its effects on deterrence dynamics in the future.

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Investigarea motorului nuclear ramjet

Rezumat: Un model neutronic Monte Carlo al unui reactor compact cu spectru rapid, răcit cu gaz, relevant pentru conceptele de motoare nucleare statoreactoare, a fost dezvoltat folosind codul OpenMC. Modelul tratează agentul de răcire gazos ca un mediu static, cu densitate mică și se concentrează exclusiv pe comportamentul neutronic. Configurația de referință prezintă un spectru de neutroni rapizi și un echilibru puternic dominat de scurgeri. O variație a densității agentului de răcire de ±20–30% produce doar modificări minore ale factorului de multiplicare efectiv. Coeficientul de reactivitate a densității agentului de răcire rezultat este mic, indicând o sensibilitate slabă a reactivității la densitatea gazului în acest regim și susținând caracterul adecvat al miezurilor cu spectru rapid răcite cu gaz pentru aplicații de propulsie la temperaturi înalte.

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