

DARWIN Reactor Core: Fuel and Moderator Temperature Feedback

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ABSTRACT

The DARWIN (Dispatchable Adaptive Reactor With Interchangeable compoNents) concept is proposed as a flexible reactor design. Temperature feedback effects were studied for several fuels used in light water reactors, including UO_2 , MOX, $\text{UZrH}_{1.6}$, $\text{UYH}_{1.6}$, ^{233}U , ^{235}U , ^{239}Pu , and ^{241}Pu . Fuel composition was varied by enrichment, while moderator properties were modified by boron concentration. Feedback was analysed by independently changing fuel (α_f) and moderator (α_m) temperatures using Serpent Monte Carlo simulations. For UO_2 , α_f is consistently negative across enrichments, while α_m becomes positive above approximately 2000 ppm boron at 3% enrichment. Hydride fuels exhibit a lower boron limit near 1000 ppm, with α_f remaining negative. Overall, both α_f and α_m tend to be negative under most conditions, but become less negative with higher enrichment and lower UO_2 and U fraction.

1 INTRODUCTION

Addressing climate change and adapting to extreme weather events will require highly flexible and responsive energy systems. The DARWIN (Dispatchable Adaptive Reactor With Interchangeable Components) concept proposes a modular nuclear reactor design capable of accommodating interchangeable core modules. The reactor will consist of various modules in the core (e.g., fuel elements, reactivity control, neutron reflector, isotope production), and on the secondary side (e.g., flood water pump, heat production) [1, 2]. Unlike typical light water reactors (LWRs), DARWIN's architecture allows rapid reconfiguration to support diverse applications, including electricity production, process heat production, isotope production, desalination, and emergency response, without major structural modifications. The aim is to optimise the modules for specific applications.

A central safety consideration for such a reconfigurable reactor is the temperature feedback effect—the change in reactivity in response to variations in fuel temperature (α_f) and moderator temperature (α_m). Predictable and sufficiently negative feedback reactivity coefficients are essential to prevent uncontrolled power increases, maintain stability during load changes, and ensure safe operation under both steady-state and transient conditions. In DARWIN, where fuel type, enrichment, and coolant chemistry may change depending on the mission profile, robust temperature feedback behaviour is even more essential.

The aim of this study is to:

- quantify the moderator and fuel temperature feedback coefficients for a range of fuel types, compositions, and enrichments,
- identify boron concentration limits that maintain negative moderator feedback under varying conditions, and
- compare the feedback characteristics of conventional and advanced fuels to assess their suitability for load-following and flexible operation in the DARWIN core concept.

The fuels examined include ceramic fuels (UO_2 , MOX, $\text{UZrH}_{1.6}$, $\text{UYH}_{1.6}$) and metallic isotopic fuels (^{233}U , ^{235}U , ^{239}Pu , ^{241}Pu). For each fuel, the sensitivity of reactor reactivity to changes in fuel and moderator temperature is assessed, with special attention to the effects of boron concentration in the coolant and the influence of fuel composition and enrichment on α_f and α_m . This analysis provides insight into fuel feasibility for load-following operation, inherent safety, and boron concentration limits for safe operation.

The structure of the paper is as follows: Section 2 presents the modelling approach and material parameters and Section 3 discusses the computed feedback behaviour across different fuel scenarios.

2 COMPUTATIONAL MODEL

A two-dimensional hexagonal configuration of fuel pins and assemblies was used to optimize space utilization and ensure uniform power distribution in the DARWIN reactor core. The computational model was developed using the Serpent 2.2.0 Monte Carlo code [3], with nuclear data taken from the ENDF/B-VII.1 library [4]. The goal was to perform a parametric study across a range of fuel types and configurations to evaluate their temperature feedback behaviour.

Simulations were carried out at different fuel and moderator temperatures and for varying boron concentrations in the coolant. The values used for temperature, pressure and boron concentration are typical for pressurised water reactors (PWR). The same modelling approach was applied to several fuel types and compositions.

The geometry is based on a hexagonal 2D lattice of fuel pins grouped into fuel assemblies, as shown in Figure 1. Each fuel pin consists of a central fuel pellet, a helium-filled gap, and a Zircaloy-4 cladding. Light water (H_2O) serves as both coolant and moderator. Boron is dissolved in the water.

Each fuel assembly contains 127 fuel rods, and the reactor core consists of 37 fuel assemblies arranged in a hexagonal layout. Table 1 provides the fuel pin dimensions and material densities. For fuel pellets, different materials were tested, resulting to different fuel densities. Water density varies with temperature and was taken from [5]. Dimension changes due to thermal expansion were neglected, and therefore no feedback effect from neutron leakage was considered.

Table 1: Fuel pin dimensions and material properties.

	outer radius [cm]	material	density [g/cm^3]
fuel pellet	0.4096	various	variable
gap	0.4178	He	0.001591
cladding	0.4750	Zircaloy-4	6.56
coolant	/	H_2O	$\rho(T)$

The dimensions of the fuel assembly are based on the pin pitch p_p , i.e., the center-to-center distance between fuel rods. The size of the fuel assembly d_a is calculated using the equation

$$d_a = p_p(N_p - 0.5 + 1/6)\sqrt{3}, \quad (1)$$

where $N_p = 7$ is the number of fuel rods along one side of the hexagon. The overall core size, d_c , is determined from the assembly pitch p_a (which is equal to d_a) and the number of

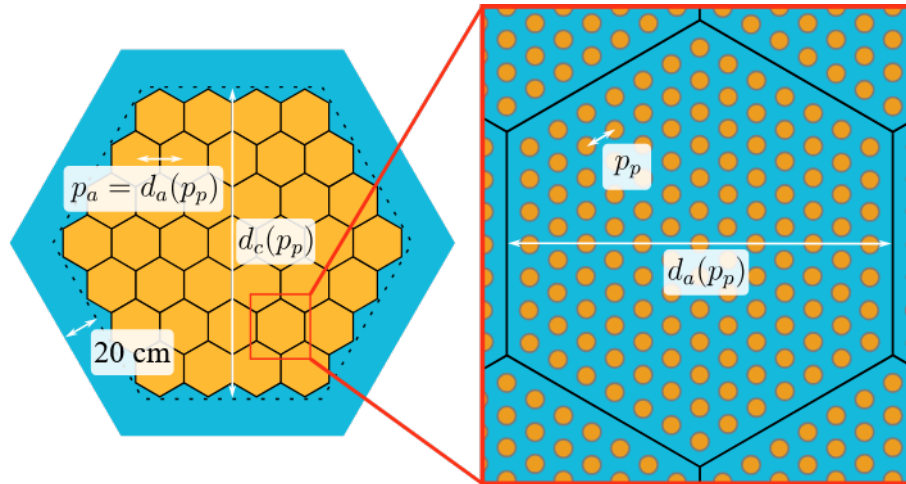


Figure 1: Schematic representation of the reactor core geometry used in the simulations. The core (right) consists of 37 hexagonal fuel assemblies, separated by an assembly pitch p_a , and is surrounded by a 20 cm thick water reflector. Each fuel assembly (left) contains 127 fuel rods arranged in a hexagonal lattice with a pin pitch p_p . The assembly size d_a , the core size d_c , and the assembly pitch p_a are derived from the pin pitch p_p . The overall core diameter d_c ranges from 73 cm (for $p_p = 1.0$ cm) to 220 cm (for $p_p = 3.0$ cm).

assemblies along one side of the hexagon $N_a = 4$, using:

$$d_c = p_a(N_a - 0.5 + 1/6)\sqrt{3}. \quad (2)$$

A 20 cm radial water reflector surrounds the core. The total core diameter varies from 73 cm (for $p_p = 1.0$ cm) to 220 cm (for $p_p = 3.0$ cm). In this study, the pin pitch was fixed at 1.4 cm, resulting in a core diameter of 103 cm. The fuel pin dimensions remain constant, and only fuel composition and boron concentration were varied.

The coolant water density was evaluated at a system pressure of 15.5 bar, across a temperature range of 560 K to 600 K in steps of 10 K. Boron concentrations in the coolant were selected as 0 ppm, 1000 ppm and 2500 ppm. All data were obtained from [5]. Fuels analysed were categorized as either pure or mixture fuels:

- pure fuels (single component): UO_2 , ^{233}U , ^{235}U , ^{239}Pu , and ^{241}Pu ,
- mixture fuels (binary compounds): MOX ($\text{UO}_2\text{-PuO}$), UZrH_X , and UYH_X .

In UZrH_X and UYH_X fuels, the atomic ratio $X = 1.6$ was used. Densities for individual components were taken from various sources [6], [7], [8], as shown in Table 2.

Table 2: Fuel densities.

material	density [g/cm^3]	material	density [g/cm^3]
UO_2	10.96	Pu	19.84
PuO	14	$\text{ZrH}_{1.6}$	5.64
U	18.95	$\text{YH}_{1.6}$	4.28

The density of mixture of two components ρ_{mix} were calculated using equation

$$\rho_{\text{mix}} = \left(\frac{w_1}{\rho_1} + \frac{1 - w_1}{\rho_2} \right)^{-1}, \quad (3)$$

where w_1 is a mass fraction of the first component with density ρ_1 and ρ_2 is a density of second component. Analysis was performed for various fractions of uranium in mixture (i.e., UO_2 fraction in MOX and U in $\text{UZrH}_{1.6}$ and $\text{UYH}_{1.6}$), as well as the uranium enrichment levels from 3% to 20%.

3 TEMPERATURE FEEDBACK EFFECTS

Temperature has a significant impact on reactor reactivity. In nuclear reactors, temperature feedback arises primarily from the physical and nuclear properties of fuel and moderator materials, which change as temperature varies. For instance, increasing the fuel temperature leads to Doppler broadening of resonance absorption peaks, enhancing the probability that neutrons will be captured before causing fission—this is known as the Doppler effect. Similarly, changes in moderator temperature affect its density and, consequently, the amount of moderator, altering the neutron energy spectrum, the likelihood of sustaining fission reactions and the neutron leakage.

In this study, the temperature feedback effect is analysed by independently varying the temperatures of the fuel and moderator. The feedback response is quantified using temperature feedback coefficients, which represent the rate of reactivity change per unit temperature change for a given material. These coefficients, denoted as α_f for the fuel and α_m for the moderator, serve as key indicators of how different fuel types behave under thermal perturbations.

Temperature feedback is quantified using temperature feedback coefficients, which describe how reactivity changes with respect to a change in temperature of a specific material:

$$\alpha_j = \frac{\partial \rho}{\partial T_j}, \quad (4)$$

where α_j is the temperature feedback coefficient for material j (fuel or moderator), ρ is the reactivity, and T_j is the temperature of material j . These coefficients are not constant and can depend on the temperature itself. Therefore, they are estimated numerically using differences between two discrete temperature points:

$$\alpha_j(T_{i,j}) = \frac{\rho(T_{i+1/2,j}) - \rho(T_{i-1/2,j})}{T_{i+1/2,j} - T_{i-1/2,j}}. \quad (5)$$

Here, $T_{i\pm 1/2,j}$ are the temperature points around the evaluation point $T_{i,j}$.

A systematic parametric study was performed to assess feedback coefficients for both moderator and fuel temperature, considering different fuel types and boron concentrations.

3.1 Moderator Temperature Feedback

The moderator temperature coefficient depends more sensitively on boron concentration and core burnup. In this study the moderator temperature was varied from 560 K to 600 K in 10 K steps, while the fuel temperature remained fixed at 300 K. Fuel temperature does not affect the moderator temperature feedback, and the coefficient remains unchanged regardless of fuel temperature. These changes were implemented by adjusting:

- moderator material temperature in nuclear data,
- moderator density, and
- thermal scattering data for hydrogen.

Boron concentrations in the moderator were considered at 0 ppm, 1000 ppm, and 2500 ppm. The calculated moderator feedback coefficients α_m for various fuel types are shown in Figure 2.

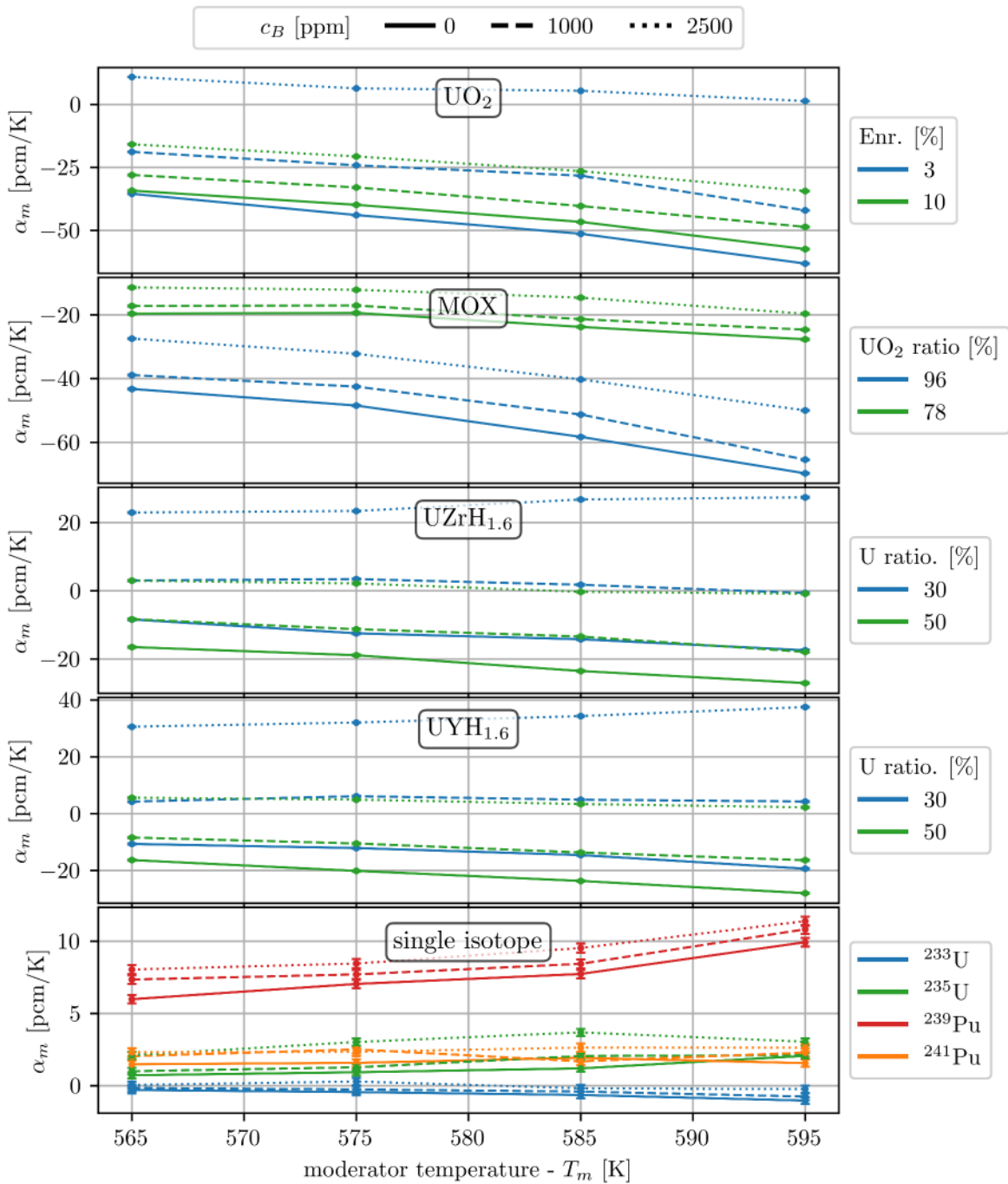


Figure 2: Moderator temperature feedback coefficient $\alpha_m(T_m)$ for a core with $p_p = 1.4$ cm, evaluated for various fuels and boron concentrations. From top to bottom: UO_2 fuel at different enrichments, MOX fuel with varying UO_2 -to-PuO ratios (U enrichment fixed at 3%), $\text{UZrH}_{1.6}$ fuel with different uranium fractions (20%), $\text{UYH}_{1.6}$ fuel with different uranium fractions (20%) and single-isotope fuels: ^{233}U , ^{235}U , ^{239}Pu , and ^{241}Pu . Calculated values are shown as points with error bars, with lines included only to guide the eye.

UO₂ Fuel

For 3 % enriched UO₂, the moderator feedback coefficient α_m becomes positive at approximately 2000 ppm boron, defining an upper operational limit for safe operation. Higher enrichments allow slightly higher boron concentrations before reaching the same limit. The impact of boron is stronger at lower enrichments — i.e., the difference in α_m with and without boron is larger at 3 % than at 10 %.

MOX Fuel

For MOX with 3 % enriched UO₂ and two UO₂-to-PuO mixing ratios, α_m remains negative for all boron concentrations. A stronger boron effect is observed at higher UO₂ content, although the absolute value of the coefficient is also more negative. This suggests a trade-off between reactivity control and safety margin.

Hydride Fuels (UZrH_{1.6}, UYH_{1.6})

For hydride fuels with 20 % enriched uranium, the moderator feedback becomes positive around 1000 ppm boron, depending on the U/H ratio. A lower U content increases the effect of boron, resulting in more positive feedback. This confirms the known behaviour of hydride fuels with strong moderator coupling due to hydrogen content and spectrum shift [9].

Single-Isotope Fuels

Fuels based on individual isotopes (²³⁵U, ²³⁹Pu, ²⁴¹Pu) show positive moderator feedback. For ²³³U, the feedback is slightly negative, but still small in magnitude.

3.2 Fuel Temperature Feedback

Fuel temperature was varied from 560 K to 1080 K in approximately 100 K steps, while moderator temperature was fixed at 560 K. Reactivity was recalculated using updated nuclear data for fuel temperature only. Results are presented in Figure 3.

UO₂ Fuel

Higher enrichment generally leads to less negative fuel temperature feedback (α_f). This is consistent with known behaviour: resonance broadening in ²³⁵U becomes relatively less effective as enrichment increases, due to self-shielding.

MOX Fuel

For a fixed UO₂/PuO ratio, a higher share of UO₂ results in a stronger (more negative) feedback coefficient. This indicates MOX's feedback behaviour is tunable via U/Pu ratio.

Hydride Fuels (UZrH_{1.6}, UYH_{1.6})

UZrH_{1.6} and UYH_{1.6} show slightly more negative α_f than UO₂ and MOX. The hydrogen content in the fuel matrix enhances neutron moderation, which amplifies the reactivity change with temperature. As the uranium content increases, the fuel feedback becomes less negative, suggesting reduced moderation and lower temperature sensitivity.

Single-Isotope Fuels

Fuels composed of a single isotope (e.g., ²³⁵U, ²³⁹Pu) exhibit negative α_f , though significantly smaller in magnitude than in mixed or hydride fuels. This reflects the absence of resonance broadening effects from multiple isotopes and a lack of strong coupling with the moderator.

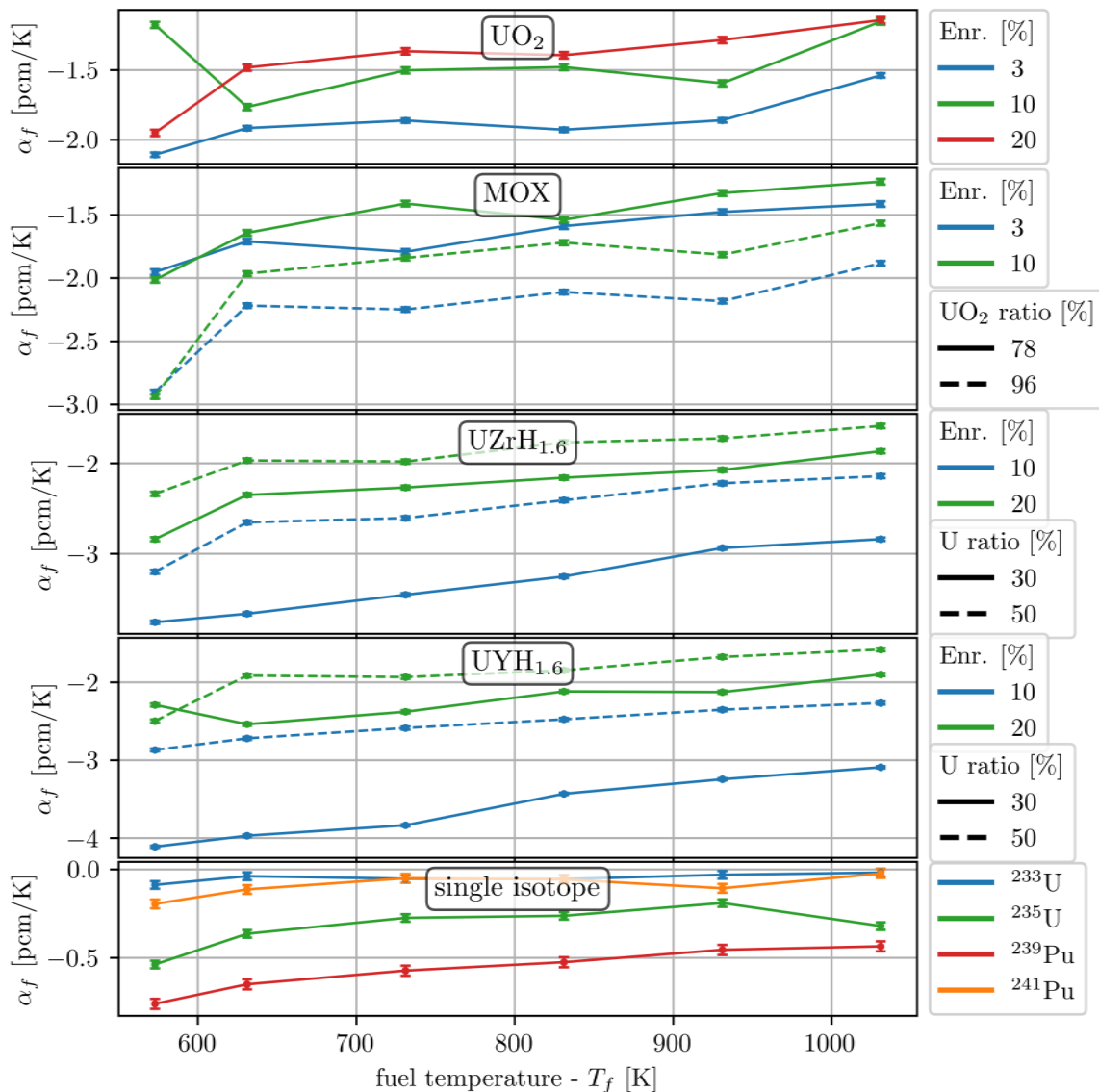


Figure 3: Fuel temperature feedback coefficient $\alpha_f(T_f)$ for a core with $p_p = 1.4$ cm for various fuel. From top to bottom: UO_2 fuel at different enrichments, MOX fuel with varying UO_2 -to-PuO ratios and U enrichments, $\text{UZrH}_{1.6}$ fuel with different uranium fractions and enrichments, $\text{UYH}_{1.6}$ fuel with different uranium fractions and enrichments, and single-isotope fuels: ^{233}U , ^{235}U , ^{239}Pu , and ^{241}Pu . Calculated values are shown as points with error bars, with lines included only to guide the eye.

4 CONCLUSIONS

Results show that boron concentration in the moderator has a significant impact on the moderator temperature feedback coefficient α_m . A conservative limit for boron concentration was identified at approximately 2000 ppm for 3% enriched UO_2 , and around 1000 ppm for hydride fuels ($\text{UZrH}_{1.6}$ and $\text{UYH}_{1.6}$), beyond which the feedback may become positive. The sensitivity to boron increases with higher uranium content in the fuel. For single-isotope fuels, moderator feedback is generally positive, except for ^{233}U , which shows a slightly negative

response.

The fuel temperature feedback coefficient, α_f , was negative in all cases. However, the magnitude of the feedback decreases (i.e., becomes less negative) with increasing enrichment. In MOX fuel, higher PuO content also reduces the magnitude of the negative feedback. For hydride fuels, the presence of hydrogen enhances the negative feedback effect, but this effect diminishes as the uranium fraction increases. For single-isotope fuels, α_f remains negative but is an order of magnitude smaller than in the mixed fuel cases.

This study provides a foundation for further investigation of advanced fuel types and configurations in the DARWIN core concept. Future work will include evaluation of power peaking, incorporating changes in both material composition and core geometry (e.g., pin pitch variation), as well as additional reactivity control mechanisms to map the limits of the design phase space. In this study, a limitation of phase space was determined, which provides a valuable reference point for guiding future research. This will support optimisation efforts using genetic algorithms or artificial intelligence.

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