Decomposition of Reactor Temperature Coefficients with Spatially Heterogeneous Reflector Temperature Effects in Molten Salt Reactors

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1. Introduction

Fast-spectrum molten salt reactors (MSRs) with beryllium-based reflectors exhibit reactivity sensitivities to reflector temperature, which can introduce positive contributions to the overall reactor temperature coefficient. Variations in reflector temperature alter neutron leakage and spectral redistribution, potentially increasing reactivity under certain operating conditions. Such positive feedback complicates power maneuvering, reduces inherent stability margins during load-following operation, and poses additional challenges for transient safety analysis. Conventional analyses often treat the reflector as a spatially lumped region, obscuring localized contributions and the underlying physical mechanisms.

This study identifies reflector regions that most strongly affect reactivity, the physical pathways of these effects, and the neutron energy ranges where they are most pronounced under spatially heterogeneous temperature perturbations. A decomposition framework is developed linking boundary neutron currents, energy-dependent spectral importance, and energy-resolved leakage variations. The proposed methodology enables systematic quantification of reflector temperature effects and reveals location-dependent contributions hidden in lumped models. By clarifying the physical origin of reflector-driven feedback, this work provides a mechanistic basis for stability assessment and reflector design optimization in fast-spectrum MSRs.

2. Methods and Results

Reactivity temperature coefficients in MSRs are arise determined by a variety of factors, including temperature-dependent cross sections, density variations that affect neutron transport and moderation, and changes in boundary leakage. The reflector effectively defines a boundary condition for the core: variations in reflector temperature modify scattering properties and density, thereby affecting both neutron leakage into the reflector and neutron return to the core.

Reflector temperature effects are inherently spatial and can be strongly heterogeneous. A single bulk isothermal temperature coefficient (ITC) or a volume-averaged temperature model may therefore obscure the mechanisms that determine the sign and magnitude of the feedback.

To address this limitation, a spectral–leakage decomposition framework is proposed to characterize the physical mechanisms underlying reflector temperature feedback.

(i) the return neutron spectrum, describing the energy distribution of neutrons re-entering the core from the reflector;

(ii) the reactivity-weighted spectrum, identifying the energy ranges most influential to reactivity; and

(iii) the energy-wise leakage change, characterizing how reflector perturbations modify neutron leakage across energy.

2.1 Region-wise sensitivity analysis of the reflector temperature coefficient

Fig. 1. Cross-sectional views of the reactor geometry showing radial and axial region segmentation.

Figure 1 illustrates three representative cross-sectional views of the reactor geometry. The first panel shows the upper axial x–y cross section, while the second panel presents the lower axial x–y cross section. The third panel depicts the x–z cross section along the axial direction, highlighting the vertical segmentation of the core and reflector regions. To quantify the region-wise contributions of the reflector to the reflector temperature coefficient (RTC), the reflector was spatially segmented in both radial and axial directions, and temperature perturbations were applied independently to each region. Density variations were neglected, as the reflector is solid and its density change with temperature is negligible; the analysis therefore focuses on temperature-induced neutronic effects. All neutronics calculations were performed in continuous energy using OpenMC, and the results were subsequently processed with a 47-group structure to resolve the epithermal-to-thermal transition in the reflector.

Table I: Region-wise reflector temperature coefficient

Region-wise reflector temperature [°C]								Keff	RTC [pcm/°C]
R1	R2	R3	R4	R5	R6	R7	R8		
650	650	650	650	620	620	620	620	1.00106(8)	-
650	750	650	650	620	620	620	620	1.00131(8)	+0.25
650	650	750	650	620	620	620	620	1.00147(8)	+0.41
650	650	650	750	620	620	620	620	1.00106(9)	+0.00
650	650	650	650	720	620	620	620	1.00125(9)	+0.19
650	650	650	650	620	720	620	620	1.00130(8)	+0.24
650	650	650	650	620	620	720	620	1.00098(8)	-0.08
650	750	650	650	620	620	720	620	1.00132(8)	+0.26
650	650	750	650	620	720	620	620	1.00193(9)	+0.87
650	650	650	750	720	620	620	620	1.00132(8)	+0.26
650	750	750	750	620	620	620	620	1.00166(8)	+0.60
650	650	650	650	720	720	720	620	1.00173(8)	+0.72
650	750	750	750	720	720	720	620	1.00250(8)	+1.43
750	750	750	750	720	720	720	720	1.00448(9)	+3.40
735	735	735	735	735	735	735	735	1.00365(8)	+2.71

The first row in Table I corresponds to the reference configuration at the critical drum position (average reflector temperature 635 °C), yielding keff = 1.00106(8). Subsequent cases evaluate localized temperature increases in individual reflector segments.

When grouped by radial ring, the middle-ring segments (R3 and R6) show the strongest positive reactivity response, whereas the outer-ring segments (R4 and R5) exhibit comparatively weak sensitivity. The inner-ring segments (R2 and R7) display axial asymmetry: increasing the temperature of R2 produces a positive effect, while heating R7 results in a slight negative response.

The spectral–leakage decomposition framework reveals that the middle layer serves as a critical buffer, where temperature-driven spectral shifts most effectively redistribute neutrons toward high-importance energy ranges. This mechanistic understanding, coupled with the upper-side positive RTC bias, identifies the potential of axial power tilting during MSR load-following as fuel salt temperatures peak at the outlet.

Furthermore, our findings show that a conventional lumped-parameter approach, which assumes a uniform temperature increase across the entire reflector, yields an RTC of only 2.71 pcm/°C. In contrast, the detailed region-wise evaluation conducted in this work identifies a substantially higher value of 3.40 pcm/°C. This obvious mismatch suggests that bulk analysis may underestimate the reactivity feedback by approximately 20%, leading to non-conservative safety assessments. Therefore, this work establishes a proactive design framework: optimizing the upper-middle reflector—through material grading or targeted thermal management—is not only an improvement but a requirement for ensuring robust inherent safety and structural reliability during dynamic power maneuvering.

2.2 The return neutron spectrum

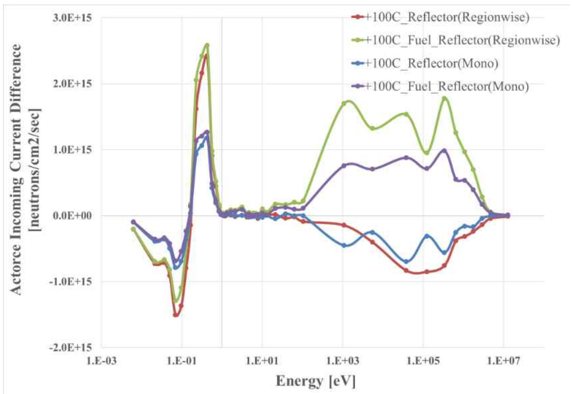

Fig. 2. Incoming neutron current at the core boundary with temperature changes: mono- and multi-region reflector comparison.

The return neutron spectrum represents the energy distribution of neutrons re-entering the core from the reflector and is quantified using the incoming current at the core boundary. The impact of reflector temperature on MSR reactivity is strongly influenced by the energy spectrum of returning neutrons rather than the magnitude of reflection itself.

As shown in Figure 2, when only the reflector temperature is increased under fixed density, the fast-energy incoming current decreases while the thermal current increases due to energy redistribution within the reflector. In contrast, when both fuel and reflector temperatures are increased, the fast-energy incoming current increases, as fuel density reduction enhances fast-neutron leakage from the core, and a significant fraction of these neutrons returns without sufficient energy degradation in the reflector. This behavior is more pronounced in the multi-region reflector model, where spatially resolved treatment strengthens the energy redistribution effect, amplifying both the reduction and enhancement of fast neutron return under each condition.

However, the reactivity effect cannot be determined solely from the incoming current. Although thermal and fast return may increase, changes in the epithermal range—where $\nu\Sigma\_f(E)$ remains significant—also affect the reactivity-weighted spectrum.

The energy-resolved leakage analysis further shows that reflector heating modifies neutron leakage in an energy-dependent manner. Consequently, the reactivity response results from the combined effects of spectral redistribution and leakage variation rather than from the magnitude of neutron return alone.

Therefore, further insight into the reactivity behavior can be obtained by examining the ν-fission-weighted flux spectrum.

2.3 Flux-weighted fission spectrum

The reactivity-weighted return spectrum was obtained by weighting the neutron return spectrum with the energy-dependent $\nu\Sigma_f$ of the fuel salt. This provides a measure of spectral importance to reactivity. While the return spectrum shows an increase in thermal neutrons, the reactivity-weighted spectrum reveals a net loss in the epithermal range, which explains the negative reactivity insertion. In this context, the return spectrum is a forward transport observable, whereas the reactivity-weighted spectrum approximates an adjoint-weighted importance function.

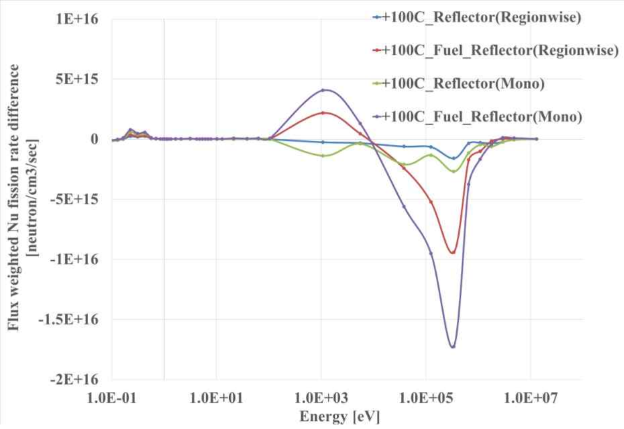

Fig. 3. Flux weighted Nu fission rate with temperature changes : mono- and multi-region reflector comparison.

When only the reflector temperature is altered, the fuel properties and the macroscopic fission production term remain essentially unaffected. Although thermal neutron inflow to the core increases due to enhanced moderation in the reflector, a concurrent reduction in the epithermal component limits any significant rise in the flux-weighted $\nu\Sigma_f$. The weighted production spectrum shown in Figure 3 indicates that the net change in the production term is relatively small. Therefore, the positive RTC observed in this case is primarily attributed to the reduction in neutron leakage rather than to an increase in fission production.

In contrast, the situation drastically altered when both the fuel salt and reflector temperatures are arised. All macroscopic cross-sections, including the fission production term, are reduced by the drop in fuel-salt density, and resonance absorption is further altered by Doppler broadening. As a result, the flux-weighted $\nu\Sigma_f$ exhibits a pronounced decrease in the fast-energy region, clearly visible in the production spectrum difference. Although changes in neutron return and leakage also occur, the dominant effect is the substantial reduction in fast-region fission production. This production-driven decrease outweighs any compensating effects, leading to an overall negative integral temperature coefficient (ITC).

2.4 Energy-wise leakage change

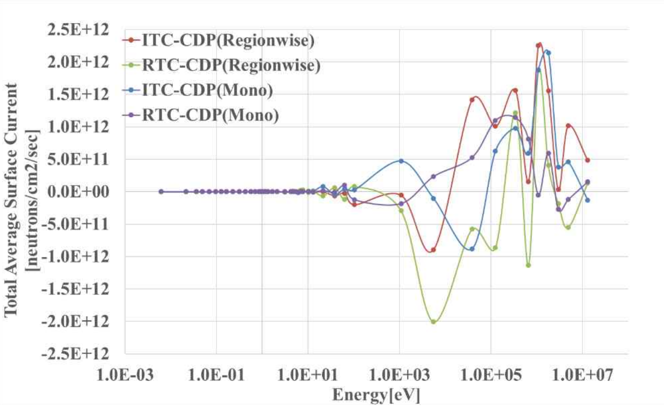

Fig. 4. Energy-resolved leakage variation with temperature changes: mono- and multi-region reflector comparison.

The mechanism of the temperature coefficient is demonstrated through energy-resolved leakage variations, where the outward surface current at the vessel boundary represents neutron leakage from the system.

When only the reflector temperature is increased, the outward current exhibits energy-dependent redistribution, with reduced leakage in the lower energy range and a compensating increase at higher energies, as depicted in Figure 4. This indicates that the positive RTC arises from energy-dependent leakage behavior rather than a uniform reduction in total leakage.

While this trend appears in both mono- and multi-region models, the mono-region treatment shows a smoothed distribution with reduced peak contrast, indicating that spatial homogenization weakens the local energy redistribution effect.

When both fuel and reflector temperatures are increased, the outward current increases in the fast-energy region due to enhanced fast-neutron leakage from fuel density reduction. The reduction in the epithermal range is attributed to spectrum hardening, which shifts neutrons toward higher energies.

Overall, these results confirm that the direction and magnitude of the temperature feedback are primarily governed by fast-energy leakage behavior.

3. Conclusions

This study clarified the physical mechanisms underlying the reflector temperature coefficient (RTC) in a fast-spectrum MSR using a spectral–leakage decomposition framework.

The region-wise perturbation analysis showed strong spatial heterogeneity. The middle-ring segments (R3 and R6) exhibited the highest positive reactivity sensitivities, while the outer-ring regions (R4 and R5) had low responses. Axial asymmetry was also noted: heating R2 resulted in a positive contribution, while heating R7 had a somewhat negative effect.

Notably, a comparative evaluation reveals that a traditional lumped model, assuming a uniform temperature increase, yields an RTC of just 2.71 pcm/°C. In contrast, our spatially resolved analysis confirms a significantly higher net RTC of +3.40 pcm/°C. This discrepancy indicates that lumped models might underestimate the positive reactivity feedback by approximately 20%, potentially leading to non-conservative safety assessments.

Spectral analysis demonstrated that the positive RTC originates from energy redistribution in the reflector, which increases the thermal neutron return to the core and enhances reactivity.

However, the reactivity-weighted $\nu\Sigma\_f$ spectrum showed only minor changes in the production term. Energy-wise leakage analysis at the vessel boundary reveals the dominant mechanism, showing a broad reduction in fast-energy neutron leakage that reflects the overall system leakage behavior. Thus, the positive RTC is mostly driven by leakage rather than production.

In contrast, when both fuel and reflector temperatures were increased (ITC case), fuel density reduction and Doppler broadening significantly decreased fast-region fission production and increased fast-neutron leakage, yielding an overall negative temperature coefficient.

These findings show that the direction and magnitude of temperature feedback in fast-spectrum MSRs are governed mainly by fast-energy leakage and production balance, and that spatially resolved analysis is essential to capture reflector-driven effects.

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