Conceptual Design and Preliminary Feasibility Study of Fluid-Driven Suspended Control Rods for Molten Salt Reactors

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Abstract

Molten salt reactors, being the only reactor type among Generation IV advanced nuclear reactors to utilize liquid fuel, offer inherent safety, high-temperature and low-pressure operation, as well as the capability for online fuel reprocessing. However, fuel salt flow results in the decay of delayed neutron precursors (DNPs) outside the core, leading to fluctuations in the effective delayed neutron fraction and consequently impacting reactor reactivity. Particularly under accident scenarios—such as combined pump shutdown and inability to rapidly scram the reactor—the reliance solely on negative temperature feedback may cause a substantial increase in core temperature, posing a threat to reactor safety. To address these issues, this paper introduces an innovative design for a passive fluid-driven Suspended Control Rod (SCR) aimed at dynamically compensating for reactivity fluctuations caused by DNPs flowing with fuel flow. The control rod operates passively by leveraging the combined effects of gravity, buoyancy, and fluid dynamic forces, thereby eliminating the need for any external drive mechanism and allowing direct integration within the core's active region. Using a 150 MWth thorium-based molten salt reactor as the reference design, a mathematical model was developed to systematically analyze the effects of key parameters—including the SCR's geometric dimensions and density—on its performance, examine its motion characteristics under different core flow conditions, and assess its feasibility for dynamic compensation of reactivity changes caused by fuel flow. The study's results demonstrate that the SCR can effectively counteract the reactivity fluctuations induced by fuel flow within molten salt reactors. Sensitivity analysis revealed that the SCR's average density exerts a profound impact on its start-up flow threshold, channel flow rate, resistance to fuel density fluctuations, and response characteristics, underscoring the critical need to optimize this parameter. Moreover, by judiciously selecting the SCR's length, number of deployed units, and placement, one can achieve the necessary reactivity control while also maintaining a favorable balance between neutron economy and heat transfer performance. Ultimately, this study provides an innovative solution for passive reactivity control in molten salt reactors, offering substantial potential for practical engineering applications.

Full Text

Preamble

Conceptual Design and Preliminary Feasibility Study of Fluid-Driven Suspended Control Rods for Molten Salt Reactors

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Molten salt reactors, being the only reactor type among Generation IV advanced nuclear reactors to utilize liquid fuel, offer inherent safety, high-temperature and low-pressure operation, as well as the capability for online fuel reprocessing. However, fuel salt flow results in the decay of delayed neutron precursors (DNPs) outside the core, leading to fluctuations in the effective delayed neutron fraction and consequently impacting reactor reactivity. Particularly under accident scenarios—such as combined pump shutdown and inability to rapidly scram the reactor—the reliance solely on negative temperature feedback may cause a substantial increase in core temperature, posing a threat to reactor safety. To address these issues, this paper introduces an innovative design for a passive fluid-driven Suspended Control Rod (SCR) aimed at dynamically compensating for reactivity fluctuations caused by DNPs flowing with fuel. The control rod operates passively by leveraging the combined effects of gravity, buoyancy, and fluid dynamic forces, thereby eliminating the need for any external drive mechanism and allowing direct integration within the core's active region. Using a 150 MWt thorium-based molten salt reactor as the reference design, a mathematical model was developed to systematically analyze the effects of key parameters—including the SCR's geometric dimensions and density—on its performance, examine its motion characteristics under different core flow conditions, and assess its feasibility for dynamic compensation of reactivity changes caused by fuel flow. The study's results demonstrate that the SCR can effectively counteract the reactivity fluctuations induced by fuel flow within molten salt reactors. Sensitivity analysis revealed that the SCR's average density exerts a profound impact on its start-up flow threshold, channel flow rate, resistance to fuel density fluctuations, and response characteristics, underscoring the critical need to optimize this parameter. Moreover, by judiciously selecting the SCR's length, number of deployed units, and placement, one can achieve the necessary reactivity control while also maintaining a favorable balance between neutron economy and heat transfer performance. Ultimately, this study provides an in-

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Keywords: Molten salt reactor, DNP flow-induced reactivity, Passive control, Suspended control rod

Introduction

Among the six Generation IV advanced reactor designs, molten salt reactors (MSRs) uniquely use liquid fuel, with molten salt serving as both fuel and coolant that circulates within a single primary loop. This design confers inherent safety, enables high-temperature and low-pressure operation, supports on-line fuel reprocessing, and is ideally suited for thorium fuel [?]. The inherent liquid fuel properties offer specific advantages for reactivity control, including the capacity for on-line refueling and reprocessing, which helps maintain a low level of backup reactivity and reduces the demands on reactivity management [?]. However, the use of liquid fuel also introduces challenges to reactivity control within MSRs. During operation, as delayed neutron precursors (DNPs) circulate with the molten salt in the primary loop, a fraction of the delayed neutrons is lost outside the core [?]. High-velocity fuel salt flow significantly diminishes the effective fraction of delayed neutrons within the core; conversely, when the primary loop flow drops sharply, delayed neutron precursors are retained within the core, resulting in a pronounced positive reactivity insertion. Should the control rod system fail to respond in a timely manner, the reactor would have to depend exclusively on its negative temperature reactivity coefficient for power modulation. However, under these circumstances, inadequate removal of decay heat leads to a marked increase in core temperature. Simulation studies have demonstrated that under design basis accident conditions—such as a complete station blackout combined with an inability to quickly scram the reactor—the outlet temperature of a large MSR may rise by 50–100°C above normal operating levels [?]. Such temperature fluctuations can impose severe thermal shock on reactor structural materials, thus posing daunting challenges for the long-term safety and maintenance of MSRs. Consequently, the development of a passive reactivity control device capable of effectively compensating for reactivity fluctuations induced by fuel flow is of significant engineering importance.

Passive safety systems have emerged as a fundamental component of modern nuclear reactor design [?, ?]. By harnessing natural physical laws such as gravity and natural convection, these systems automatically maintain reactor safety and stability during both internal and external accident scenarios, without relying on external power or human intervention [?, ?]. Depending on their driving mechanisms, passive reactivity control devices are classified into two main types. The first type is the flow-driven device, which utilizes variations in coolant flow to trigger control rod movement and adjust reactivity, effectively mitigating incidents of coolant flow or coolant loss. Representative examples include the Hydraulic Suspension Passive Shutdown Assembly (HSPSA), which has been implemented in Russia's BN series sodium-cooled fast reactors as well as in China's demonstration fast reactor CFR-600. HSPSA represents a critical technology in advanced nuclear reactor systems. Initially developed by Russia's Institute of Physics and Power Engineering (IPPE) and successfully implemented in Russia's BN series sodium-cooled fast reactors (e.g., BN-600 and BN-800), this technology has demonstrated high reliability through extensive theoretical analysis and experimental validation [?, ?]. Recognizing its potential to address China's strategic needs in fast reactor development, Chinese scholars, including Hu Wenjun, prioritized HSPSA as a key technology for domestic research [?, ?]. Building on this foundation, research groups from Xi'an Jiaotong University [?, ?], China Institute of Atomic Energy [?], Shanghai Jiaotong University [?], and Xi'an University of Technology [?] have systematically explored the hydraulic characteristics, dynamic behavior, rod drop mechanisms, and stability of liquid-suspended passive shutdown assemblies through theoretical analysis, numerical simulation, and experimental verification, thereby offering critical theoretical support and technical guidance for optimizing HSPSA design. Notably, the Chinese research teams advanced the technology by addressing key challenges in complex operating conditions. Their work not only contributed to the successful implementation of HSPSA in China's CFR-600 demonstration fast reactor but also advanced global technological progress. The second category is temperature-driven devices, which regulate reactivity based on variations in coolant temperature and are effective in mitigating both overpower accidents and loss-of-heat-removal scenarios. Representative applications include the Buoyancy Driven Shutdown Rod (BDSR) in the U.S. advanced fluoride-cooled, high-temperature pebble-bed reactor and the Floating Absorber for Safety at Transient (FAST) utilized in South Korea's advanced sodium-cooled fast reactors [?, ?]. A research team at the University of New Mexico systematically investigated the fluid dynamic properties, thermal response characteristics, and system coupling behavior of BDSR by developing theoretical models, carrying out numerical simulations, and performing experimental validations [?, ?]. Researchers at the Korea Advanced Institute of Science and Technology (KAIST), utilizing their developed transient analysis model, have extensively examined the response characteristics of FAST under various design basis accident conditions [?]. Through design optimization, they effectively mitigated power and temperature oscillations under particular scenarios, thereby markedly improving the overall safety performance of sodium-cooled fast reactors [?].

In summary, substantial progress has been achieved in the development of passive safety systems, with particularly notable advancements in flow-driven and temperature-driven reactivity control devices. The distinctive liquid fuel operation of molten salt reactors introduces novel technical challenges, with reactivity fluctuations induced by fuel flow being particularly significant. Considering that the reactivity fluctuations induced by fuel flow display marked flow-dependence and immediate response characteristics, whereas fuel temperature variations are relatively gradual—rendering temperature-based compensation mechanisms inherently lagged—flow-driven devices are more appropriate for compensating the reactivity fluctuations in molten salt reactors. Therefore, drawing on prior research and design experience with flow-driven devices, this study proposes an innovative passive fluid-driven suspended control rod design. The control rod is predominantly driven by gravity, buoyancy, and fluid dynamic forces. Under rated core flow conditions, fluid thrust suspends the rod at its upper limit position, minimizing neutron absorption; whereas during a sudden decrease in core flow, the rod falls under gravity, thereby introducing negative reactivity to counterbalance the positive reactivity perturbations resulting from the reduced flow. In this study, a 150 MWth thorium-based molten salt reactor is used as the reference design. A mathematical model was developed to systematically analyze the effects of key parameters—such as geometric dimensions and material density—on the performance of the suspended control rod. The model is used to compute the rod's motion characteristics under various core flow conditions and to evaluate the feasibility of compensating for reactivity fluctuations induced by fuel flow.

The present study is organized into four main sections: Part I thoroughly describes the structural features and key design parameters of the core model while providing a detailed analysis of the operating principles and structural design of the fluid-driven control rod; Part II concentrates on the computational methods, including the determination of reactivity insertion at various rod positions, the methodology for establishing rod positions under diverse core flow conditions, and the optimization strategies for the design parameters; Part III is devoted to the analysis and discussion of the results, with a focus on: (1) quantifying the relationship between flow-induced reactivity changes and core flow; (2) conducting a parameter sensitivity study of the correlation between rod position and core flow; (3) analyzing the control rod's resistance to interference from density variations; (4) identifying the key factors impacting the reactivity worth of the control rod; and (5) assessing the performance of the fluid-driven suspended control rod in compensating for flow-induced reactivity fluctuations; and Part IV concludes the study by summarizing the key findings and innovations, and by outlining potential directions for future research.

Introduction of Core Model and Fluid-Driven Control Rods

This section provides an overview of the core model configuration, design principles, and operational mechanisms of the fluid-driven control rod system. The discussion begins with a detailed description of the core architecture and critical design parameters of the reference 150 MWth thorium-fueled MSR. Subsequently, the two primary variants of fluid-driven control rods (PFCR) are examined—namely, the floating control rod (FCR) and the suspended control rod (SCR)—providing explanations of their structural configurations and operational principles. Through a comparative analysis of the characteristics of FCR and SCR, this section establishes the superior suitability of the SCR for mitigating flow-induced reactivity perturbations in MSR systems.

A. Core Model

The core model adopted in this study is a liquid thorium-based molten salt reactor (MSR) with a thermal neutron spectrum and a rated thermal power of 150 MW [**?**]. The fuel salt comprises a fluoride-lithium-beryllium eutectic containing thorium and enriched uranium, with its thermophysical parameters provided in Table 1 . Graphite serves as the moderator. The reactor comprises essential components such as the core active region, control rod assembly, graphite reflector, upper and lower plenums, downcomer annulus, internal support structures, and the primary reactor vessel (see Figure 1 [Figure 1: see original paper]).

The core configuration features a hexagonal close-packed arrangement with an equivalent diameter of 3.0 m and an active region height of 3.2 m, consisting of 241 uniformly distributed hexagonal graphite blocks, each having a side length of 18 cm. Each graphite block contains a central flow channel with a diameter of 6 cm, forming the primary path for fuel salt circulation. The graphite array is encased by a graphite reflector 20 cm thick. The core barrel encloses the reflector assembly, while the downcomer annulus is formed between the core barrel and the primary reactor vessel that houses the entire reactor structure. The core's principal design parameters are summarized in Table 1.

Six control rod guide tubes are symmetrically located at the fourth radial ring of graphite assemblies (denoted by '#' in Figure 1), ensuring physical isolation between the fuel salt and control rod assemblies while facilitating vertical movement of the control rods with complete separation from the fuel salt. The control rod system comprises six individual rods, each serving a specific function. These rods are actuated by electric drive mechanisms, which facilitate precise positioning via electrical signal control. During pump coast-down scenarios, the emergency shutdown system activates automatically when core flow rates fall below predefined safety thresholds. However, the reliance on electrical signal transmission in the control rod actuation mechanism introduces potential failure modes, including signal loss during station blackout conditions or mechanical seizure of control rods despite valid signals. Such failure mechanisms could compromise the reactor's capacity to execute an emergency shutdown following pump failure [**?**].

Building upon the preceding analysis, this investigation introduces an innovative Passive Fluid-driven Control Rod (PFCR) design concept, specifically developed to mitigate reactivity insertion risks during anticipated transient-without-scram scenarios in pump coast-down events. The PFCR system incorporates a flexible core deployment strategy based on reactivity compensation requirements. To minimize interference with the active control system, PFCR units are positioned at the midpoints of hexagonal ring segments (with active control rods located at the vertices of the hexagonal rings), as indicated by the ' *' and '&' markers in Figure 1. The deployment strategy for PFCR units is determined by specific reactivity control requirements. In scenarios with lower reactivity control demands, PFCR units are positioned radially outward from the core centerline* *with minimal population density, as exemplified by a single PFCR installation at the sixth radial ring position (indicated by one of the green '&' markers in Figure 1). Conversely, for enhanced reactivity control requirements, PFCR units are positioned closer to the core centerline with an increased population density, as demonstrated by the installation of three PFCR units at the second radial ring position (denoted by the blue* " markers in Figure 1).

B. Structure and Working Principles of Fluid-Driven Control Rods

The primary objective of the PFCR system is to compensate for positive reactivity insertion following a reduction in core flow, thereby effectively preventing temperature excursions during pump seizure events. Based on distinct operational principles, PFCR systems are categorized into two main variants: the Floating Control Rod (FCR) and the Suspended Control Rod (SCR).

[**Figure 2: see original paper**] Schematic diagram of FCR (a) and SCR (b) structure

The FCR features a cylindrical configuration that comprises essential components—namely, a cladding, neutron absorber, weighting module, and gas plenum—vertically integrated into the molten salt circulation channel. The cladding serves to isolate the molten salt, while the neutron absorber captures thermal neutrons. The weighting module facilitates precise density and center-of-gravity adjustments, whereas the gas plenum performs the dual functions of density modulation and fission gas containment. Material specifications include a nickel-based alloy (density: 8900 kg/m^3) for the weighting module, Gd_2O_3 (density: 5870 kg/m^3) for the neutron absorber, and helium gas (density: 0.17 kg/m^3) in the plenum chamber. Precise density control is achieved through optimized volume ratios between the weighting module and the gas plenum, with the neutron absorber occupying 80% of the total rod length. The detailed FCR configuration is illustrated in Figure 2 (a). The FCR's mean density is engineered to be lower than that of the molten salt, resulting in partial rod protrusion above the liquid level and buoyant suspension within the fuel salt. FCR motion is governed by the equilibrium among gravitational, buoyant, and hydrodynamic forces. Increased core flow enhances hydrodynamic forces, which induce upward rod movement and reduce buoyancy until dynamic equilibrium is established, thereby stabilizing the FCR at a specific elevation. Conversely, reduced core flow results in downward movement toward a new equilibrium position.

As illustrated in Figure 2 (b), the SCR shares similar components and functions with the FCR but features a truncated conical geometry characterized by a wider upper section and a narrower base. Correspondingly, the flow channel is designed as a vertically oriented, upwardly expanding conical graphite conduit. The SCR's mean density exceeds that of the molten salt, resulting in complete submersion and suspension within the fuel salt. Similar to the FCR, SCR operation relies on the equilibrium among gravitational, buoyant, and hydrodynamic forces. Fuel salt circulation through the conical conduit establishes a pressure differential across the SCR's upper and lower surfaces, which in turn generates hydrodynamic forces. When these hydrodynamic forces exceed the resultant of gravitational and buoyant forces, upward rod movement commences. Upward SCR movement increases the annular flow area between the rod and the conical conduit, thereby reducing fuel salt velocity and consequently decreasing hydrodynamic forces until a new equilibrium position is established at a specific elevation. The SCR position exhibits a positive correlation with the core flow rate: increased core flow induces upward SCR movement, whereas decreased flow results in corresponding downward displacement.

The motion of the FCR is governed by the dynamic equilibrium between buoyancy and hydrodynamic forces. As the FCR ascends, the volume of the rod exposed above the liquid surface increases, which in turn reduces its buoyancy. This reduction in buoyancy necessitates greater hydrodynamic forces to preserve equilibrium, thereby requiring a substantial force for effective FCR actuation. Furthermore, heightened hydrodynamic forces generate larger pressure differentials across the FCR, which reduces the flow allocation within its channel. This effect may potentially lead to flow obstruction, thereby severely compromising the channel's thermal-hydraulic performance.

In contrast, the SCR remains fully submerged in the molten salt, maintaining consistent gravitational, buoyant, and hydrodynamic forces. The magnitude of the hydrodynamic force can be precisely regulated by optimizing the differential between gravitational and buoyant forces. Consequently, the SCR can be actuated with lower hydrodynamic forces, thereby minimizing its impact on the channel's flow distribution. Moreover, the displacement of the SCR is determined by the height-dependent variation in the surrounding annular flow area. This characteristic enables precise calibration of the relationship between rod position and flow rate via optimization of the SCR channel geometry, thereby facilitating effective compensation for flow-induced reactivity perturbations. The inherent design characteristics of the SCR render it particularly well suited for mitigating flow-induced reactivity oscillations, thereby demonstrating superior engineering applicability.

Under static fuel salt conditions, the SCR maintains a stable equilibrium at the base of the conical conduit due to its mean density exceeding that of the molten salt. During fuel salt circulation, increased core flow rates exacerbate DNP loss, consequently reducing core reactivity. Concurrently, elevated core flow rates induce upward movement of the SCR, releasing sufficient reactivity to compensate for the reduction in reactivity induced by DNP loss. At nominal core flow conditions, the SCR attains equilibrium at its maximum elevation, with the released reactivity exactly offsetting the reactivity deficit caused by DNP loss. During pump coast-down scenarios, when fuel salt circulation terminates, the SCR descends to the base of the conical conduit, introducing negative reactivity that precisely neutralizes the positive reactivity resulting from DNP accumulation in the core. Throughout its operational trajectory, the SCR remains within the core's active region. Under normal operating conditions, the SCR is positioned at the very top of the reactor core's active region. As shown in Figure 3 [Figure 3: see original paper], the fast neutron flux (0.05–20 MeV) at the SCR location is approximately four times lower than at the core center, so the neutron-absorbing material is expected to have a much longer irradiation lifetime. In addition, the SCR does not bear mechanical loads, irradiation does not generate gases, and there is no internal pressure, resulting in minimal overall stress. Therefore, its service life should be comparable to that of the reactor structural materials, such as the upper support plate.

[**Figure 3: see original paper**] The distribution of fast neutron flux (0.05–20 MeV)

The SCR is characterized by a straightforward structural design that does not require complex external drive mechanisms and electrical systems. Consequently, its manufacturing cost is substantially lower than that of conventional electrically driven control rod systems, which often rely on high-reliability motors, signal transmission networks, and multiple redundant components. Furthermore, the SCR employs materials that are resistant to high temperatures, irradiation, and molten salt corrosion, and adopts a fully mechanical structure with no need for precision components. This design enables reliable long-term operation under the extreme conditions of molten salt reactors, thereby significantly reducing maintenance demands and extending inspection intervals. As a fully passive system, the SCR is capable of automatically inserting the control rods under extreme accident scenarios, such as complete power failure or signal loss. This substantially enhances the inherent safety of the reactor core, mitigates the risks of unplanned shutdowns, equipment damage, and personnel hazards, and indirectly reduces long-term operational and insurance expenses.

Existing molten salt reactor control rod systems isolate the control rods from the molten salt by installing thin-walled alloy sleeves in the active core region, thereby avoiding radioactive sealing and isolation challenges for the drive mechanisms. This solution has been implemented in the US MSRE [**?**] and China's 2 MW TMSR-LF1 [**?**] reactors. However, in large-scale molten salt reactors, this approach faces the risk that alloy sleeves may experience helium embrittlement and rupture under high neutron flux irradiation, which could result in the failure of the primary circuit boundary. In contrast, the SCR is in direct contact with the molten salt and does not require any drive mechanism, thus effectively eliminating concerns related to alloy sleeve rupture and radioactive isolation of the drive system. Moreover, the SCR is fully integrated within the active core region, thereby preventing control rod ejection accidents.

In summary, the SCR system offers not only outstanding economic advantages and reduced manufacturing and maintenance costs, but also improved safety, which further supports the reduction of long-term operational and insurance expenditures.

III. Reactivity Computation and SCR Dynamic Equilibrium Modeling

This section delineates the methodological framework employed for computing reactivity and modeling the dynamic equilibrium of the SCR. The computational framework begins with an OpenMC-based evaluation of SCR reactivity variations across multiple insertion depths and diverse design configurations. Subsequently, reactivity perturbations induced by fuel flow are quantified using a point kinetics reactor model. A comprehensive dynamic equilibrium model for the SCR was developed, incorporating a detailed force analysis under a range of core flow conditions. The relationship between equilibrium position and flow rate is established through the integration of motion equations with pressure drop computations. The methodological framework culminates with an optimization algorithm that employs iterative computations to determine SCR channel flow characteristics and equilibrium positions, while simultaneously identifying the optimal parameters that satisfy reactivity control specifications.

A. SCR Reactivity Worth Calculation

The neutronics calculations in this study were performed using the OpenMC code. Since its development by the Computational Reactor Physics Group at the Massachusetts Institute of Technology in 2011, OpenMC has benefited from continuous enhancements and significant contributions from the open-source community. OpenMC is a Monte Carlo neutron transport code that provides essential capabilities, including fixed-source calculations, effective multiplication factor determination, and subcritical system analysis. The program features an extensive Python API that facilitates functionalities such as input file generation, data post-processing, and result visualization [**?**].

Leveraging OpenMC, a comprehensive computational core model was developed to evaluate the effective multiplication factor (k_{eff}) of the SCR at various insertion depths and under different design parameters—including geometric configurations, density, and deployment strategies. Core reactivity (ρ) was computed using Equation (1), while SCR reactivity changes ($\Delta\rho$) at various positions were determined using Equation (2). Subsequently, the resulting data were processed using polynomial fitting to generate the SCR position-reactivity worth curve.

$$\rho = \frac{k_{\text{eff}} - 1}{k_{\text{eff}}} \tag{1}$$

$$\Delta\rho = \rho(h) - \rho(h_0) \tag{2}$$

Where $\rho(h)$ is the reactivity of SCR at position height h, and $\rho(h_0)$ is the reactivity of SCR at the initial position.

B. DNP Flow-Induced Reactivity

During MSR operation, fuel salt circulation induces fluctuations in the effective delayed neutron fraction, which in turn results in oscillations of core reactivity. Accurately determining these flow-induced reactivity changes would theoretically require coupling neutron transport with fluid dynamics simulations—a level of complexity that exceeds the scope of this investigation. Comprehensive methodologies addressing this issue are detailed in reference [**?**]. In this investigation, a point kinetics model that neglects spatial effects is employed to approximate fuel flow-induced reactivity changes ($\Delta\rho_{\text{fluid}}$) [**?**], with the associated estimation formulation expressed as:

$$\Delta\rho_{\text{fluid}} = \beta - \sum_i \beta_i \frac{\lambda_i + (1 - e^{-\lambda_i \tau_{\text{el}}})/\tau_c}{\lambda_i + 1/\tau_c}$$

Among these parameters, β represents the effective delayed neutron fraction in the absence of fuel salt flow in the core; β_i denotes the fraction of delayed neutrons in each group; λ_i is the decay constant for each group of DNP; τ_c indicates the residence time of the fuel salt within the core; and τ_{el} represents the residence time of the fuel salt outside the core. The parameters τ_c and τ_{el} are closely related to the core flow rate: as the core flow rate increases, τ_c decreases while τ_{el} increases. With further increases in the core flow rate, the fuel salt is recycled back into the core's active region, causing the rates of change for τ_c and τ_{el} to slow down until they eventually stabilize. The fractions and decay constants for each group of delayed neutrons are listed in Table 2 [**?**].

TABLE 2. The fraction and decay constant of each group of delayed neutrons

Group	β_i (pcm)	λ_i (s^{-1})
1	15.31	0.0127
2	108.11	0.0317
3	107.45	0.1150
4	307.51	0.3110
5	82.93	1.4000
6	41.96	3.8700

C. SCR Dynamic Equilibrium Modeling

The movement of SCR is dictated by the interplay among gravitational, buoyant, and hydrodynamic forces, with its equilibrium position under varying core flow conditions determined by their dynamic balance. Figure 4 [Figure 4: see original paper] presents a schematic illustration of the force balance analysis for the SCR.

[**Figure 4: see original paper**] Diagram of SCR's force analysis

Based on the force analysis, the corresponding motion equation for the SCR is derived as follows:

$$M_s \frac{d^{2h}}{dt^2} = F_d + F_b - G$$

In the formula, M_s represents the mass of the SCR, h is the height of the SCR's top from the bottom of the conical pipeline, and t represents time. G, F_b, and F_d denote the gravitational, buoyancy, and fluid dynamic forces acting on the SCR, respectively. These forces are calculated using the following relationships:

$$G = \rho_s V_s g \tag{3}$$

$$F_b = \rho_f V_s g \tag{4}$$

$$F_d = \Delta p_s A_s \tag{5}$$

$$V_s = \frac{\pi}{12}\left(3D_s^2 L_s + 6D_s L_s^2 \tan\theta + 4L_s^3 \tan^2\theta\right) \tag{6}$$

Here, V_s, A_s, L_s and D_s denote the SCR volume, upper base area, length, and upper base diameter, respectively; θ represents the conical taper angle; ρ_s indicates the SCR mean density; ρ_f signifies the fuel salt density; and g is the gravitational acceleration. Δp_s represents the flow-induced pressure differential across the SCR.

As the SCR is embedded in the active region of the core—with only minor differences in cross-sectional areas between its top and bottom—and under the assumption of a uniform core temperature distribution, the lift and acceleration pressure drops are neglected, accounting solely for the friction and local pressure drops. The friction pressure drop and local pressure drop are computed according to the following expressions:

$$\Delta p_\lambda = \lambda \rho_f \frac{v^2}{2} \frac{L}{D_e} \tag{7}$$

$$\Delta p_\zeta = \zeta \rho_f \frac{v^2}{2} \tag{8}$$

$$\Delta p_s = \left(\lambda \frac{L_s}{D_s} + \zeta\right) \rho_f \frac{v^2}{2} \tag{9}$$

Here, v denotes the mean flow velocity of fuel salt through the SCR conduit. The parameters λ and ζ represent the friction factor and local loss coefficient, respectively. The friction factor λ is determined by the Reynolds number ($Re = \rho v D_e/\mu$, where D_e is the equivalent diameter of the pipe, and ρ, v, and μ denote the fluid's density, velocity, and viscosity, respectively. Because Δp_λ is relatively minor, influence of fluid viscosity variations on Δp_s is also negligible. Consequently, the effect of temperature on fuel salt viscosity is disregarded in this work, and the viscosity of the fuel salt at 650°C, $\mu = 0.0072895$ Pa · s, is used throughout the analysis.). It is also influenced by the relative roughness ε ($\varepsilon = \Delta/D_e$, where Δ, defined as the absolute roughness, represents the average height of surface asperities; in this study, $\Delta = 10^{-4}$ m). The local loss coefficient ζ is primarily influenced by the conduit's geometric configuration. In practice, precise theoretical determination of λ and ζ is challenging, necessitating their estimation via experimental measurements or empirical correlations. The computational approaches for determining λ and ζ across various flow regimes are systematically summarized in Tables 3 and 4, respectively [?].

TABLE 3 . Friction loss coefficient at different Reynolds numbers in a circular pipe

Flow Regime	Empirical formula
$Re < Re_1$	$\lambda = 64/Re$
$Re_1 \leq Re \leq Re_2$	$\lambda = \frac{0.3164/Re^{0.25} - 64/Re_1}{(Re_2 - Re_1)}(Re - Re_1) + 64/Re_1$
$Re > Re_2$	$\lambda = 0.3164/Re^{0.25}$

where $Re_1 = 1160/\varepsilon^{0.11}$, $Re_2 = 2090/\varepsilon^{0.0635}$

TABLE 4 . Local loss coefficients for different pipe geometries

Pipe Geometry	Loss Coefficient
Gradually expanding pipe	$\zeta = k_{\text{grad}} \times \left(1 - \frac{A_1}{A_2}\right)^2$
Suddenly expanding pipe	$\zeta = k_{\text{sudd}} \times \left(1 - \frac{A_1}{A_2}\right)^2$
Suddenly contracting pipe	$\zeta = -0.189\left(\frac{A_1}{A_2}\right)^2 - 0.306\frac{A_1}{A_2} + 0.503$

where $k_{\text{grad}} = 7.19 \times 10^{-4}\alpha^2 + 3.33 \times 10^{-3}\alpha + 0.065$, α is the expansion angle of the diffuser, and A_1 and A_2 are the cross-sectional areas before and after, respectively.

To determine the friction loss coefficient for a section with a non-circular cross-section, the friction loss coefficient for a circular pipe is multiplied by the corresponding shape influence factor [?]:

$$\lambda_n = k_n \lambda$$

In this formula, λ represents the friction loss coefficient for circular pipe sections under identical Reynolds numbers; λ_n denotes the friction loss coefficient for non-circular pipe sections under the same Reynolds number; and k_n is the cross-sectional shape correction coefficient.

For laminar flow, the correction factor for a circular annular tube depends on the ratio of its inner to outer diameters [?]:

$$k_n = \frac{(1-(d/D_0))^2}{1+(d/D_0)^2+\frac{1-(d/D_0)^2}{\ln(d/D_0)}}$$

Here, d and D_0 denote the inner and outer diameters, respectively.

For turbulent flow, the friction loss coefficient λ_n for a circular annular tube can be calculated using the following equation [**?**]:

$$\lambda_n = \lambda\left(0.02\frac{d}{D_0}+0.98\right)\left(1-0.27\frac{d}{D_0}\right)+0.01$$

By combining Equation (4) and Equation (5), it follows that at steady state (i.e., when $d^{2h}/dt^2 = 0$), the pressure drop acting across the SCR remains constant, namely:

$$\Delta p_{s,\text{stable}} = (\rho_s - \rho_f)V_s g/A_s$$

Furthermore, combining Equation (9) and Equation (13) yields:

$$v_{s,\text{stable}} = \sqrt{\frac{2(\rho_s-\rho_f)V_s g}{(\lambda L_s/D_s+\zeta)A_s\rho_f}}$$

Equation (14) indicates that when the SCR reaches steady equilibrium, the average flow velocity of the fuel salt through the SCR, $v_{s,\text{stable}}$, remains essentially constant independent of its position. Under these circumstances, the inlet SCR channel flow rate, $Q_{s,\text{stable}}$, is given by:

$$Q_{s,\text{stable}} = A_{\text{an}} v_{s,\text{stable}} \rho_f$$

Assuming $v_{s,\text{stable}}$ remains constant, the flow rate through the SCR channel is primarily determined by the annular area, A_{an}, which varies with the SCR position height, h (i.e., $A_{\text{an}} = f(h)$). For a conical conduit, the relationship between A_{an} and h is expressed as:

$$A_{\text{an}}(h) = \pi\left[D_f h\tan\theta + h^2\tan^2\theta + \frac{D_f^2 - D_s^2}{4}\right]$$

Consequently, under steady-state conditions, a definitive relationship exists between the SCR position height and the SCR channel flow rate:

$$Q_{s,\text{stable}}(h) = f(h)\rho_f v_{s,\text{stable}} = \pi\rho_f\left[D_f h\tan\theta + h^2\tan^2\theta + \frac{D_f^2 - D_s^2}{4}\right]v_{s,\text{stable}}$$

This demonstrates that higher instantaneous flow rates through the SCR channel correspond to larger annular areas and, consequently, higher SCR equilibrium positions, while lower flow rates result in smaller annular areas and lower SCR positions. Moreover, the instantaneous flow rate through the SCR channel is intrinsically linked to the core flow distribution characteristics. Flow distribution is evaluated using a closed parallel channel model based on two assumptions: (1) uniform flow distribution across all fuel channels, and (2) frictional pressure drop as the sole influencing factor. For a reactor with 241 channels, the average core pressure drop, ΔP_{av}, equals the pressure drop across an individual fuel channel, $\Delta P_{f,\text{fuel}}$, expressed as:

$$\Delta P_{\text{av}} = \Delta P_{f,\text{fuel}} = \lambda \rho_f \frac{v_f^2}{2} \frac{L_f}{D_f} = \lambda \rho_f \frac{Q_f^2}{2} \frac{L_f}{D_f} \left(\frac{4}{241 \rho_f \pi D_f^2} \right)^2$$

Here, L_f denotes the fuel channel length, D_f the fuel channel diameter, and Q_f the core mass flow rate.

The total pressure drop (ΔP_{CR}) across the SCR channel consists of both frictional and local pressure drop components. As shown in Figure 3, the SCR channel is composed of several successive segments, from bottom to top: a circular pipe segment, a gradual expansion segment, a sudden contraction segment, an annular segment, a sudden expansion segment, a second gradual expansion segment, a second sudden contraction segment, and a final circular pipe segment. Accordingly, the overall pressure drop can be expressed as:

$$\Delta P_{\text{CR}} = \Delta P_{\text{tube}} + \Delta P_{\text{grad,exp}} + \Delta P_s + \Delta P_{\text{sud,exp}}$$

Here, ΔP_{tube}, $\Delta P_{\text{grad,exp}}$, ΔP_s, and $\Delta P_{\text{sud,exp}}$ represent, respectively, the pressure drops across the circular pipe segment, the gradual expansion segment, the SCR segment, and the sudden expansion segment. The frictional and local pressure drop components for each segment are determined using Equation (7) and Equation (8), respectively. By adjusting the SCR channel flow rate so that its pressure drop matches the core's average pressure drop, one can determine both the channel's flow rate and the axial pressure drop distribution.

D. Optimization Methodology

For varying core flow conditions, an iterative computational approach is first employed to determine both the SCR channel flow rate and the equilibrium position height. Subsequently, an iterative optimization process is conducted to identify the parameters that satisfy the reactivity control specifications, with the iterative calculations executed using Python. The detailed iterative computational workflow is illustrated in Figure 5 [Figure 5: see original paper].

[Figure 5: see original paper] Flow Chart of Rod Position-Reactivity Calculation for SCR at Different Core Flows

The computational procedure commences with parameter initialization, followed by the evaluation of the average core pressure drop (ΔP_{av}) and the SCR channel pressure drop (ΔP_{CR}) at the current flow rate. The relative error between these pressure drops is then computed. If $(|\Delta P_{\mathrm{av}} - \Delta P_{\mathrm{CR}}|)/\Delta P_{\mathrm{av}} < \Delta E_p$, the core flow distribution is deemed converged, thereby yielding the SCR channel flow rate, Q_s. Otherwise, Q_s is adjusted and the process is iterated. After computing the flow distribution, the relative error between the SCR pressure drop (Δp_s) at the current position height and the steady-state SCR pressure drop ($\Delta p_{s,\mathrm{stable}}$) is evaluated. If the condition $(|\Delta p_s - \Delta p_{s,\mathrm{stable}}|)/\Delta p_{s,\mathrm{stable}} < \Delta E_p$ is not satisfied, the SCR position height is adjusted and the flow distribution computation is repeated. Once convergence is achieved, the core flow rate (Q_f), Q_s, and the position height (h) are output. Subsequently, the reactivity worth ($\Delta\rho_{\mathrm{rod}}$) provided by the SCR and the flow reactivity loss ($\Delta\rho_{\mathrm{fluid}}$) at the nominal core flow rate are evaluated. If $|\Delta\rho_{\mathrm{rod}} - \Delta\rho_{\mathrm{fluid}}| < 10^{-4}$, then the reactivity, $\rho_{\mathrm{rod}}(h)$, introduced by the SCR across varying core flow rates is computed and output, thereby completing the iterative process and yielding the optimal geometric parameters for the current configuration. Otherwise, the SCR's Upper base diameter, D_s, and the conical taper angle, θ, are adjusted, and the flow distribution computation is repeated.

IV. Results and Discussion

This section concentrates on the performance analysis and discussion of the SCR. Firstly, the relationship between reactivity changes caused by fuel flow is examined, elucidating the pattern by which reactivity loss varies with core flow alterations. Next, the study investigates how the SCR's average density, length, Upper base diameter, and conical taper angle affect the relationship between its rod positions and the core flow. Subsequently, the discussion addresses the effect of variations in fuel salt density on the performance of the SCR. Then, an analysis is conducted on the impact of the SCR's length, quantity, and positioning on its reactivity worth. Finally, the study investigates the reactivity compensation capabilities of SCRs with various parameters.

A. DNPs Flow-Induced Reactivity Perturbations

The reduction in the effective delayed neutron fraction caused by DNPs flow is closely related to the residence time of the DNPs both within and outside the core. At lower average fuel flow rates, a reduced proportion of DNP decays outside the core, leading to a smaller decrease in the effective delayed neutron fraction in the core and, consequently, lower reactivity loss. With increasing average fuel flow rates, the fraction of DNP decaying outside the core becomes larger, thereby causing a greater decrease in the effective delayed neutron fraction within the core and a proportional rise in reactivity loss. When the average fuel flow rate is further increased, DNP recirculates into the core's active region, resulting in a decrease and eventual saturation of the fraction of DNP decaying outside the core, at which point the reactivity loss attains its maximum value and stabilizes.

[**Figure 6: see original paper**] Relationship between DNPs flow-induced reactivity changes and core flow rate

Figure 6 illustrates the variations in flow reactivity across different core flow conditions, revealing that at lower core flow rates the flow reactivity changes considerably with flow variations, while at higher flow rates the changes are notably smaller. Consequently, based on the flow reactivity-core flow variation curve, SCR design should aim for a greater variation in rod position height or introduced reactivity at lower core flow rates and a smaller variation at higher core flow rates. At the rated core flow, the SCR is expected to release approximately 275 pcm of reactivity.

B. SCR Position-Core Flow Rate Correlation

The correlation between SCR rod position height and core flow directly impacts its reactivity insertion characteristics; thus, a detailed analysis of the key influencing factors is essential for optimizing the SCR structural design and enhancing its performance. As analyzed in Section 2.1, this correlation is chiefly determined by two key parameters: the SCR stable pressure drop ($\Delta p_{s,\mathrm{stable}}$) and the flow channel annular area ($A_{\mathrm{an}}(h)$). $\Delta p_{s,\mathrm{stable}}$ governs the response of the SCR to flow variations and influences its initial start-up flow threshold. As presented in Equation (13), $\Delta p_{s,\mathrm{stable}}$ is a function of the density difference between the SCR and fuel salt, the SCR volume, and the frontal area. In this context, the SCR volume is determined by the Upper base diameter (D_s), conical taper angle (θ), and length (L_s), whereas the frontal area depends solely on the D_s. As per Equation (16), the variation in the flow channel annular area, $A_{\mathrm{an}}(h)$, is dictated by D_s and θ.

This section uses a controlled variable approach to examine the effect of individual parameters on the SCR position-flow rate relationship. The analysis is conducted using the following initial parameters: $L_s = 30$ cm, $D_s = 7$ cm, $\theta = 2°$, $\rho_s = 2800$ kg/m^3, and $\rho_f = 2710$ kg/m^3. The calculation procedure illustrated in Figure 5 is employed to assess the influence of different parameters on the displacement of the SCR under varying core flow rates, as well as the SCR channel flow at the rated core flow rate. The results of these calculations are presented in Figures 7 and 8.

The average density (ρ_s) is the most critical parameter affecting SCR motion. As illustrated in Figure 7 [Figure 7: see original paper] (a), an increase in ρ_s leads to a significant rise in the start-up flow threshold, a rightward shift of the core flow-rod position curve, and a marked decrease in rod position height at the same core flow rate. Specifically, for every 40 kg/m^3 increase in ρ_s, the start-up flow threshold increases by approximately 10%, while the rod position at rated flow decreases by an average of 10.8 cm. Additionally, the extent of reduction in rod position height diminishes as the density increases. Simultaneously, an increase in ρ_s substantially raises the flow resistance within the SCR channel, leading to a dramatic decrease in the flow fraction allocated to the SCR. As indicated in Figure 8 [Figure 8: see original paper] (a), when ρ_s increases from 2720 kg/m^3 to 2880 kg/m^3, the flow fraction drops from approximately 85% to 53%.

An increase in SCR length (L_s) similarly raises the start-up flow threshold, shifts the core flow-rod position curve to the right, and reduces the maximum displacement. Specifically, when L_s increases from 20 cm to 40 cm, the start-up flow threshold rises by 12%, and the rod position at rated flow decreases by 2.4 cm, as illustrated in Figure 7 (b). Moreover, a longer L_s exacerbates frictional resistance within the channel, further diminishing the flow allocated to the SCR. Within the considered range, the SCR channel flow changes by about 6%, as shown in Figure 8 (b).

Increasing the upper base diameter (D_s) also results in a higher start-up flow threshold and lower rod position height at rated flow. However, its impact is minimal and can be largely neglected, as depicted in Figure 7 (c). Regarding SCR channel flow, a larger D_s leads to a reduction in flow fraction, but this reduction is limited, as shown in Figure 8 (c), indicating a relatively weak effect on the overall SCR performance.

The effect of conical taper angle (θ) on the SCR rod position-flow relationship is distinct from that of the aforementioned parameters. As θ increases, the start-up flow threshold decreases, while the maximum displacement also reduces, as illustrated in Figure 7 (d). This occurs because θ not only influences the SCR volume but also determines the annular flow area at various rod positions, which directly affects the correspondence between rod position and flow rate. An increase in θ can elevate the flow fraction in the SCR channel; for example, as θ increases from 1° to 3°, the flow fraction rises from approximately 71% to 73%, as shown in Figure 8 (d). A larger cone angle helps to expand the annular flow passage area and reduce local flow resistance, thereby enhancing channel flow. However, if θ becomes too large, it can increase the heat generation rate within the SCR channel, adversely affecting its heat transfer safety.

In summary, the average density exerts the most significant influence on the start-up flow threshold, the core flow-rod position relationship, and the channel flow, thus constituting the most critical parameter in SCR structural design. The effects of SCR length and the upper base diameter are relatively minor, rendering them secondary control parameters. In contrast, the conical taper angle has a substantial impact on the core flow-rod position relationship and may serve as an effective tuning parameter for its optimization. Consequently, optimization of SCR structural parameters should prioritize controlling the average density, appropriately selecting the SCR length and upper base diameter, and adjusting the conical taper angle to achieve the desired SCR performance for reactivity control.

C. Impact of Fuel Density Variations on SCR Performance

Variations in fuel salt temperature, online fueling, and reprocessing all result in changes in fuel salt density, which in turn affect the SCR position height at the rated core flow. Assuming a constant SCR average density, a decrease in fuel salt density causes a corresponding reduction in the SCR position height. However, if the fuel salt density exceeds the SCR average density, the SCR will remain buoyant at its highest position and will not descend, even in flow loss scenarios. Therefore, given the dynamic variations in fuel salt density, it is imperative to investigate the mechanisms by which the SCR responds to such density changes.

An analysis considers only the effect of temperature variation, assuming a uniform temperature distribution within the reactor core. Due to the thermal expansion effect, temperature changes will lead to changes in material density. Given the low thermal expansion coefficients and small size of the SCR's constituent materials, the thermal expansion effect for the SCR is negligible. In contrast, the fuel salt has a high thermal expansion coefficient and exhibits significant thermal expansion. Therefore, only the density change of the fuel salt resulting from temperature variation is considered, while the density change of the SCR due to temperature variation is neglected. Within a temperature range from a maximum outlet temperature of 750°C to a cold shutdown temperature of 550°C, the fuel salt density changes from about 2665 kg/m^3 to 2755 kg/m^3 [**?**]. If the SCR average density is below 2755 kg/m^3, then following a cold shutdown, the resulting drop in temperature may cause the SCR to float upward, thus posing a risk of reactor re-criticality. Thus, to avoid such scenarios, the SCR average density should be kept above 2755 kg/m^3.

When only the impacts of online fueling and reprocessing are considered, the fuel salt density is expected to rise to about 2800 kg/m^3 over the fuel's lifetime as heavy metals accumulate in the molten salt [**?**]. Thus, an SCR with a ρ_s of 2805 kg/m^3 is selected, with the other parameters identical to those in the previous section, to study the effect of changes in fuel salt density on the SCR. The calculations reveal the SCR rod position heights under varying fuel salt densities and core flow conditions, as illustrated in Figure 9 [Figure 9: see original paper].

[**Figure 9: see original paper**] SCR Position Height Correlation with Core Flow Rate and Fuel Salt Density

The results show that a decrease in fuel salt density elevates the SCR start-up flow threshold while simultaneously reducing its position height at the rated core flow. In other words, an increase in temperature—which leads to lower density—results in a lower SCR rod position height, thereby introducing negative reactivity and enhancing the reactor's negative temperature reactivity coefficient. Furthermore, increasing the fuel salt density does not change the rod position height at the rated flow since the SCR is already at its uppermost position, restrained by the top of its channel. However, higher fuel salt densities alter the SCR's response under flow loss conditions, causing it to respond more slowly. When the fuel salt density is 2800 kg/m^3, the SCR only starts to descend once the core flow decreases to about 50% of the rated value. Accordingly, to improve the SCR's resilience against disturbances due to density variations, its average density must be further increased.

Based on conservative estimates that incorporate temperature fluctuations and the effects of online fueling and reprocessing over the fuel's lifetime, it is necessary to maintain the SCR average density above 2855 kg/m^3 under cold conditions at the end of the fuel life to prevent the fuel salt density from surpassing the SCR average density. However, if the SCR average density is too high, the necessary pressure drop to drive the SCR increases, which reduces the channel flow and adversely impacts the heat transfer performance of the SCR channel. As illustrated in Figure 10 [Figure 10: see original paper], if the SCR average density exceeds 2855 kg/m^3 while the fuel salt density remains at the nominal value of 2710 kg/m^3, the channel flow drops to less than 60% of the fuel channel flow—a level that is unacceptable for heat transfer safety. However, as the fuel salt density rises, the average core pressure drop increases, leading to a greater allocation of flow to the SCR channel, which in turn improves its heat transfer capacity. Thus, as heavy metals accumulate in the molten salt and the fuel salt density rises, the heat transfer capacity within the SCR channel is enhanced.

[**Figure 10: see original paper**] SCR-to-Fuel Salt Channel Flow Rate Ratio Correlation with SCR Mean Density and Fuel Density

In summary, the influence of fuel salt density variations on the SCR fundamentally depends on the difference between the SCR average density and the fuel salt density. A greater difference enhances the SCR's resistance to density disturbances; however, it may also lead to a reduction in the channel's heat transfer performance. Therefore, it is essential to strike an optimal balance between the SCR's ability to withstand density variations and its heat transfer capability.

D. SCR Reactivity Worth

Since the fluid-driven control components and graphite components are integrated within the reactor core, their dimensions are limited by the specifications of the graphite components. Consequently, it is vital to assess whether the SCR can meet the reactivity control requirements given these dimensional limitations. Because the SCR remains entirely within the core's active region throughout its motion, its reactivity worth is predominantly determined by the neutron flux distribution within the core. Specifically, the larger the neutron flux gradient encountered within the SCR's range of motion, the more significant the change in its reactivity worth, leading to a higher amount of reactivity compensation. Considering that the variations in the SCR's Upper base diameter, conical taper angle, and average density are restricted within narrow ranges and exert minimal influence on its reactivity worth, this study primarily focuses on analyzing the effects of SCR length, the number of units, and spatial placement on reactivity, while the effects of Upper base diameter, conical taper angle, and average density are incorporated into the final iterative calculations.

The SCR is designed with a length range of 20–40 cm and a deployment quantity of 1–3 units, employing a centrally symmetric arrangement. When deploying three SCR units, a tripartite symmetric arrangement—positioned at the midpoints of the three sides (as indicated by '*' in Figure 1)—is used; for two SCR units, a bilateral symmetric arrangement at the midpoints is adopted; and for a single unit, a midpoint of one side is selected. Using the core's central axis (designated as the 0th ring) as a reference, the placement extends outward to the positions of the graphite components in the 2nd, 4th, and 6th rings, as illustrated in Figure 1. The core's axial midplane is defined as the reference plane (0 position) for the SCR's height. In calculating the SCR's reactivity worth, to ensure an adequate range of motion, the Upper base diameter is fixed at 6 cm, the conical taper angle at 2°, and the average density at 2800 kg/m^3.

Two SCR units with lengths of 20 cm, 25 cm, 30 cm, 35 cm, and 40 cm, respectively, are deployed at the graphite component positions in the 4th ring. The reactivity introduced from their lowest to highest positions is computed, with results presented in Figure 11 [Figure 11: see original paper]. As the SCR length increases, the reactivity induced by its movement exhibits an increasing trend, with the most significant reactivity introduced during the mid-range of motion and lower reactivity in the initial and final phases. Hence, to align with the DNPs flow reactivity-core flow curve depicted in Figure 6, the SCR's range of motion should be configured in the mid-to-rear section. Among all the SCR lengths evaluated, only the 20 cm variant fails to satisfy the 275 pcm reactivity control requirement. To minimize any detrimental effect on neutron economy under normal operating conditions, the SCR length should be reduced as much as possible while still meeting the reactivity control requirement.

[**Figure 11: see original paper**] Reactivity changes of SCRs with different lengths at different rod positions (two SCRs at the 4th ring component position)

SCRs with a length of 30 cm are deployed in varying quantities and at different locations within the core, and the induced reactivity changes at different heights are computed, with results presented in Figure 12 [Figure 12: see original paper]. The results indicate that a minimum of two SCR units must be deployed to meet the 275 pcm reactivity control requirement. At equal deployment quantities, the reactivity change in the 4th ring exceeds that in the 2nd ring due to the higher axial neutron flux gradient in the 4th ring, whereas in the 6th ring, with a reduced neutron flux distribution, the reactivity change for the same SCR movement is minimal.

[**Figure 12: see original paper**] Reactivity changes at different rod positions with different SCR deployment quantities and positions ($L_s = 30$ cm)

Under normal operating conditions, the SCR is positioned at the top of the core's active region, in contact with the upper support plate, with the corresponding reactivity values for different deployment quantities and positions summarized in Table 5 . The analysis reveals that, for identical deployment quantities, the placement position has a relatively minor impact on reactivity, with a difference of approximately 60 pcm between the 2nd and 6th rings. However, for an identical deployment position, the number of SCR units significantly affects reactivity, with three SCRs exhibiting approximately 100 pcm higher reactivity compared to two SCRs.

TABLE 5 . SCR Neutron Absorption Reactivity at its highest position

Deployment Configuration	Neutron Absorption Reactivity (10^{-5})
3R2	248
3R4	223
3R6	194
2R2	169
2R4	109
2R6	100

3R2: 3 Rods in Ring 2; 3R4: 3 Rods in Ring 4; 3R6: 3 Rods in Ring 6
2R2: 2 Rods in Ring 2; 2R4: 2 Rods in Ring 4; 2R6: 2 Rods in Ring 6

Therefore, the primary focus should be on determining the number of SCR units to deploy, after which the optimal placement can be refined. To minimize the adverse effects of SCR deployment on neutron economy, core flow distribution, and system compatibility under normal operating conditions, the number of SCR units should be kept to a minimum, and their placement should be as far from the core's central axis as possible. Thus, from a purely reactivity standpoint, deploying two SCR units in the 4th ring is the optimal solution. Under normal operating conditions, the variations in reactivity due to changes in SCR deployment position and quantity are limited, with a maximum difference of only 148 pcm. Thus, by integrating the SCR rod position-core flow relationship, an optimal deployment scheme can be determined.

E. SCR Reactivity Introduction-Core Flow Rate Correlation

Based on the preceding analysis, the SCR average density markedly affects the start-up flow threshold, channel flow, and its resistance to density disturbances, whereas the conical taper angle profoundly influences the relationship between the SCR rod position and core flow. In contrast, the SCR length and inlet diameter exert relatively minor impacts on SCR performance. Therefore, this study omits the effects of SCR length and Upper base diameter—fixed at $L_s = 30$ cm and $D_s = 7$ cm—and, following the procedure illustrated in Figure 5, calculates and screens for the conical taper angles that satisfy the reactivity compensation criteria, subsequently analyzing the reactivity compensation capabilities at different SCR average densities.

With increasing SCR average density, its displacement at rated flow diminishes; hence, a higher SCR average density necessitates a larger reactivity insertion. As illustrated in Figure 7 (a), when ρ_s is 2840 kg/m^3, 2800 kg/m^3, and 2760 kg/m^3, the corresponding displacements at rated flow are about 35 cm, 40 cm, and 50 cm, respectively. According to Figure 12, to satisfy the reactivity control requirements, the three average density conditions correspond to the following SCR deployment schemes: 3 SCR units at the 4th ring for $\rho_s = 2840$ kg/m^3, 2 SCR units at the 4th ring for $\rho_s = 2800$ kg/m^3, and 2 SCR units at the 6th ring for $\rho_s = 2760$ kg/m^3.

Figure 13 [Figure 13: see original paper] displays the reactivity variations induced by SCR motion across various core flow conditions for these scenarios.

[**Figure 13: see original paper**] The reactivity introduced by different parameter SCR under various core flow rates

The results reveal that a lower SCR average density produces a more pronounced reactivity compensation over a broader range of core flow variations, whereas a higher SCR average density enables a more rapid response to changes in flow. For instance, at $\rho_s = 2760$ kg/m^3, the flow reactivity fluctuations can be confined within 30 pcm over 55%–100% of the rated core flow, but the SCR only introduces -275 pcm of reactivity when the core flow falls below 40% of its rated value. In contrast, at $\rho_s = 2840$ kg/m^3, flow reactivity fluctuations are suppressed within 30 pcm only in the 80%–100% rated flow range, and -275 pcm reactivity is achieved only when the core flow drops below 68% of the rated value. As shown in Table 6 , from the viewpoint of neutron economy, the impact differences among these schemes are minimal, with a maximum variance of just 22 pcm. In terms of heat transfer performance, an SCR with $\rho_s = 2840$ kg/m^3 exhibits a channel flow that amounts to only 61.46% of the fuel channel flow, potentially compromising the channel's heat transfer safety.

TABLE 6 . SCR Channel Flow Rate and Neutron Absorption Reactivity at Maximum Elevation

SCR Mean Density (kg/m^3)	SCR-to-Fuel Channel Flow Rate Ratio (%)	Neutron Absorption Reactivity (10^{-5})
2840	61.46	223
2800	71.43	109
2760	78.67	100

In summary, for improved matching between flow and reactivity changes, it is advisable to select an SCR with a lower average density. In contrast, if the response speed of the SCR under loss-of-flow scenarios is of higher priority, a higher average density SCR should be chosen. However, it is important to note that increasing the average density of the SCR will decrease the flow within its channels. During the operation of a molten salt reactor, variations in the primary loop flow are generally minimal. However, under accident conditions, the response speed of the SCR becomes a crucial factor; thus, prioritizing an SCR with a higher average density is more appropriate. Therefore, taking into account both response speed and heat transfer safety, the SCR with an average density of $\rho_s = 2800$ kg/m^3 demonstrates superior performance. However, attention should be paid to the increase in fuel density toward the end of the fuel cycle and under reactor cold conditions. To prevent the fuel density from surpassing the average SCR density, timely separation of heavy metals from the fuel is required.

V. Summary

This study addresses the reactivity variations in molten salt reactors induced by fuel flow by proposing an innovative passive fluid-driven Suspended Control Rod (SCR) design and undertaking an in-depth feasibility assessment. By developing a mathematical model and conducting a sensitivity analysis, the following key conclusions were reached:

The SCR passively adjusts its position to dynamically compensate for reactivity changes caused by fuel flow. Under a defined range of core flow conditions, the SCR is capable of precise reactivity regulation and, during flow loss, introduces negative reactivity, effectively mitigating the positive reactivity excursions that arise from the retention of delayed neutron precursors.

The investigation revealed that the SCR's average density and conical taper angle are critical parameters influencing its overall performance. The SCR's average density significantly affects the start-up flow threshold, response speed, and its ability to withstand fuel density variations, whereas the conical taper angle dictates the relationship between the rod position and core flow. Optimization of these two parameters can markedly improve the SCR's responsiveness and its capacity for reactivity compensation.

Furthermore, the SCR's length, deployment quantity, and spatial positioning directly impact both its reactivity compensation effectiveness and the neutron economy. While longer SCRs and an increased number of units yield enhanced reactivity compensation, they may also impose adverse effects on the core's neutron economy. Consequently, SCR design must balance meeting the reactivity compensation requirements with minimizing its impact on neutron economy and core flow distribution.

Featuring a passive driving mechanism, the SCR efficiently compensates for reactivity fluctuations induced by fuel flow in MSRs, thereby significantly augmenting the reactor's inherent safety and operational stability. This innovative approach to passive reactivity control holds considerable potential for wide-ranging applications. Finally, this research establishes a theoretical basis for the design and optimization of SCRs, while also offering valuable insights for improving the safety of MSRs.

This study aims to demonstrate the potential of the SCR as an innovative solution for passive reactivity control in MSRs and to assess the feasibility of compensating for DNP flow reactivity effects. It should be noted that the current analytical model adopts certain simplifications. In future work, it will be necessary to construct a three-dimensional transient multiphysics model to quantitatively evaluate the dynamic response characteristics and spatial effects of the SCR under complex scenarios, such as abrupt flow transients and power oscillations, as well as to investigate the long-term service behavior of the SCR under extreme operating conditions. In addition, a hydraulic test rig will be developed in the future to validate the accuracy of the theoretical model and refine empirical coefficients. Future research will focus on a closed-loop strategy integrating multi-scale mechanistic modeling, experimental validation, and standardized design, to drive the SCR from conceptual innovation to engineering application, providing key technical support for enhancing the safety and economic competitiveness of Generation IV molten salt reactors.

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