Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 29-31, 2025

Feasibility Analysis of the Secondary Shutdown System of an i-SMR Using Binary Absorber Balls

Junwoo Lee[a], Dongju Choi[a], Yunseok Jeong[a], Yonghee Kim[a*]
Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology (KAIST)
291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea
**Corresponding author: yongheekim@kaist.ac.kr*

***Keywords :** i-SMR, SBF, Binary Sphere Packing, DEM, Ansys, Rocky ,Serpent

1. Introduction

Reactor design like the i-SMR adopts soluble-boron-free operation, which simplifies the Chemical and Volume Control System (CVCS) and enhances safety and economy by eliminating the use of soluble boron in the coolant. This approach can avoid radioactive waste from boron and mitigate corrosion. However, the absence of borated water in the safety injection system necessitates a new secondary shutdown system to meet both emergency and regulatory requirements, such as in the event of a Control Rod Drive Mechanism (CRDM) failure where it would replace the conventional boron injection system.

This study proposes a novel secondary shutdown system based on binary absorber spheres. Each sphere consists of a B_4C encapsulated by a tungsten(W) shell that increases density and accelerates gravitational settling. The B_4C absorbs neutrons, while the tungsten ensures rapid gravity-driven descent. A porous window at the control rod's bottom prevents sphere leakage during normal operation while maintaining pressure and temperature equilibrium. Under accident conditions, when coolant temperature rises, the window material melts, releasing the absorber spheres into the guide tube. Even if control rods are stuck, this passive mechanism ensures effective shutdown and achieves the effect of a control rod insertion, providing a reliable shutdown even if the rod becomes stuck. Unlike similar concepts designed only for emergencies, our system uniquely functions as a conventional control rod during normal operation as the spheres remain contained. This dual functionality is a key departure from existing designs.

The feasibility was evaluated using a two numerical approach. The Discrete Element Method (DEM) was utilized to find an optimal the packing fraction of binary spheres, and Monte Carlo simulations evaluated shutdown margin (SDM). It was confirmed that an optimal packing ratio of 3mm and 1mm spheres achieves a packing fraction of nearly 60%. It was showed that the system secures a SDM over 2900 pcm, validating its ability to replace the conventional shutdown bank.

2. Secondary Shutdown System

2.1 Binary absorber sphere (ball)

The absorber ball consists of a structure in which B_4C, with 95% of its theoretical density, is encapsulated by W(tungsten).

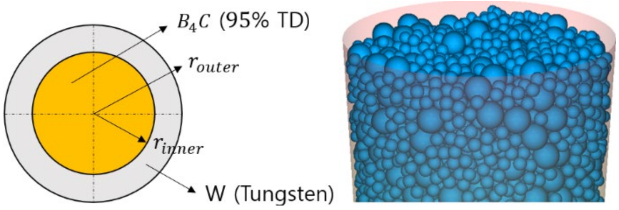


Fig. 1. Absorber ball and binary sphere packing

B_4C serves as a strong neutron absorber that reduces reactor power, while tungsten increases the overall density of the ball, thereby facilitating its rapid insertion under gravity. In the secondary shutdown system, the absorber balls replace conventional control rod materials and are contained within the control rod claddings. To ensure sufficient SDM, it is essential to maximize the number of absorber balls within the available space. In other words, increasing the packing fraction of the absorber balls is the key consideration, and to this end, the present study proposes the use of binary sphere packing as shown in Fig. 1. Specifically, we investigated the optimal diameters of two different spheres that achieve the highest packing fraction, as well as the corresponding mass ratio of each sphere within the given volume.

2.2 Porous window

As shown in Fig. 2, it contains numerous pores smaller than the ball diameter, which allow for the equalization of pressure and temperature between the inside of the guide tube and the control rod.

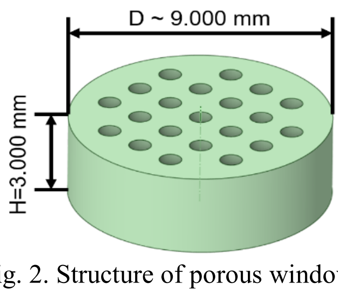


Fig. 2. Structure of porous window

The material of the porous window is selected such that it either melts or weakens in its bond with the control rod cladding at elevated temperatures. Additionally, in a primary system equipped with guide tubes, the window must maintain structural integrity under the extreme conditions– 15.5 MPa, 320 ℃, pH 7-8, and high neutron flux environment. In view of these requirements, the materials listed in the Table I can be considered as suitable window candidates.

Table I. Window material candidates

Alloy	Melting point (℃)	Composition (wt%)	Density (g/cc)
Al-Zn	382	Al 5, Zn 95	6.8-7.1
Au-Sb	360	Au 75, Sb 25	12.0-12.5
Au-Ge	356	Au 88, Ge 12	15.2
Au-Si	363	Au 97, Si 3	14.5-15.0
Mg-Zn	342	Mg 24, Zn 6	1.8-1.9
Ag_2Te	350	Ag 63.6, Te 36.4	7.5-7.8

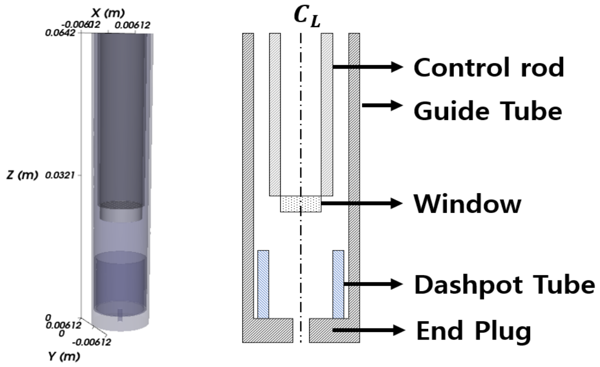


Fig. 3. Simplified Secondary shutdown system modeling in (A) 3D and (B) 2D

As illustrated in Fig. 3, the window is located at the lower end of the control rod and prevents absorber balls from spilling into the guide tube during normal operation. Consequently, under accident conditions involving a rapid increase in coolant temperature, the porous window detaches into the guide tube, enabling the absorber balls inside the control rod cladding to fall into the guide tube.

2.3 Mechanism

As discussed earlier, when reactor power increases excessively, the coolant temperature inside the guide tube rises, causing the window to detach into the guide tube. Simultaneously, as illustrated in Fig. 4, the absorber balls inside the control rod cladding fall into the guide tube, where they act as neutron absorbers, effectively producing the same effect as inserting the control rod.

This design utilizes the intrinsic melting point of the window material without relying on external mechanical or electrical devices, ensuring reliable operation even in situations where the control rod becomes stuck.

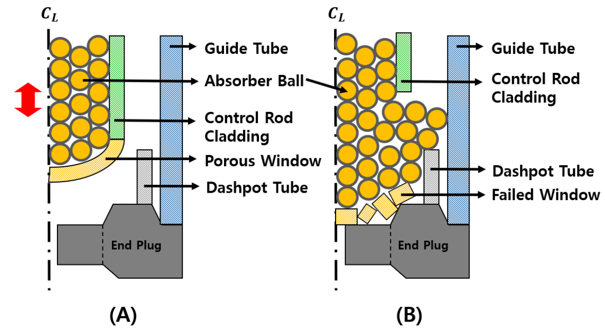


Fig. 4. (A) Normal operation, (B) Accident condition

In addition, it is essential to prevent the absorber balls from escaping outside the guide tube during their downward release following the melting of the porous window. Such a loss would not only reduce the shutdown capability of the reactor but could also obstruct the primary coolant circulation. To mitigate this risk, the bypass at lower part of the guide tube was designed with a specific flow path that establishes a flow field preventing the outward loss of balls.

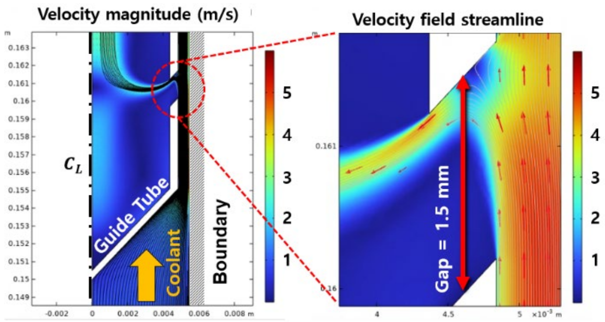


Fig. 5. Velocity and streamline of coolant in guide tube with bypass

The Fig. 5 illustrates the coolant velocity distribution under an upward flow condition of approximately 1 m/s at the bottom of the guide tube, where the coolant is directed outward only. For this CFD analysis, the COMSOL Multi-physics 6.2 was employed. The results confirm that the probability of absorber sphere loss to the exterior is negligibly small.

As a related study, a similar conceptual design was proposed for the BANDI core, intended to achieve reactor shutdown under emergency conditions [1]. However, the design presented in this paper fundamentally differs from the BANDI concept, as it can also function as a conventional control rod during normal operation. This is possible because, as long as the porous window prevents leakage of the pellets, neutron absorbers remain inside the control rod, allowing it to perform the same role as a standard control rod under normal conditions.

3. Methods and Numerical Results

In this study, the packing fraction of binary absorber spheres was evaluated using Rocky (Ansys 2025 R2. The

k_{eff} of the i-SMR core with a new secondary shutdown system was calculated with the Monte Carlo code Serpent 2.2.1 [2], employing the ENDF/B-VII.1 nuclear data library. The input model was based on reference [3], where only the absorber material of the shutdown bank was varied.

3.1 Packing Fraction with binary absorber ball

To maximize the packing fraction of binary absorber spheres within the control rod cladding, a parametric sensitivity study was performed with respect to the sphere diameter ratio and the corresponding mass fraction occupied within the given volume. For this purpose, the Discrete Element Method (DEM) code Rocky (Ansys 2025 R2), capable of tracking particle interactions and spatial distribution, was employed as shown in Fig. 5. It should be noted that in this calculation, the coolant flow inside the guide tube was not considered, and only gravitational effects were considered. The geometrical data for the guide tube, control rod, dashpot tube, and the Control Rod Assembly (CRA) were adopted from KNF-provided specifications. The optimal packing fraction of the binary absorber spheres inside the control rod was determined as summarized in Table II.

Table II. Specifications of the binary sphere packing

Mass ratio of all 3mm balls to all 1mm balls	1:3.4
Ball density (g/cc)	10.59
Packing fraction	59.3 %

*packing fraction with only 1mm balls: 55.9 %

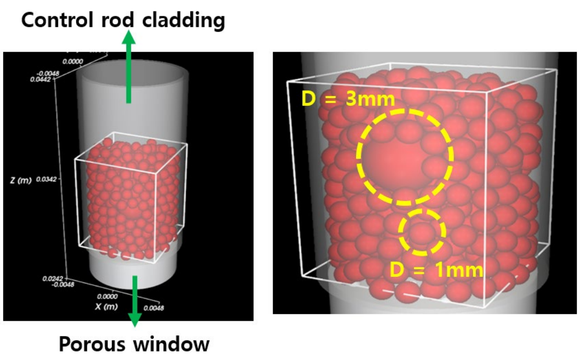


Fig. 5. Binary spheres distribution in CR cladding

In addition, the variation of packing fraction was further investigated when multiple absorber balls were assumed to accumulate at the lower part of the CRA as shown in Fig. 6. This condition corresponds to the postulated melting of the porous window, followed by the spheres falling into the guide tube. Given the complex geometrical configuration of the dashpot tube and guide tube, some change in packing fraction was anticipated.

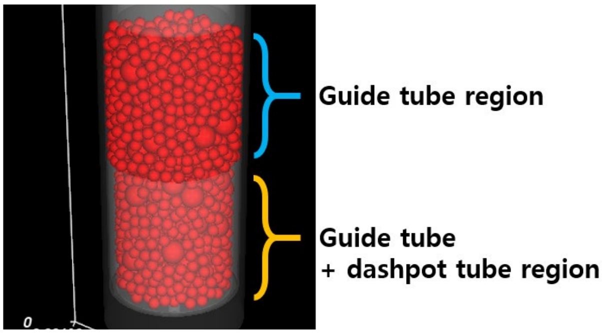


Fig. 6. Spheres distribution in lower part of CRA

However, the calculations confirmed that a nearly constant packing fraction of 59.3% was maintained under these conditions, without any significant variation.

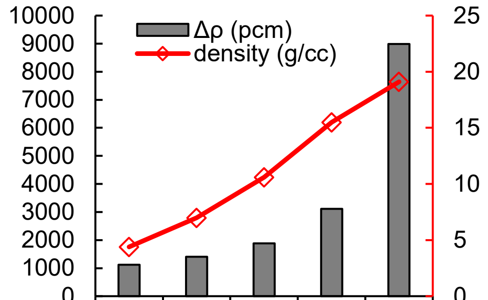
1.2 Shutdown Margin Calculation

Y/X	E	F	G	H	J
5	SB	SB	R4	SB	SB
6	SB	R2		R1	SB
7	R4		R3	SB	
8	SB	R1	SB	SB	
9	SB	SB			

Fig. 7. Control rod pattern in i-SMR [3]

As illustrated in Fig. 7, the i-SMR reactor core comprises a total of 33 Shutdown Banks (SBs), each consisting of 24 control rod waterholes. Based on these design specifications, a comparative study was conducted at BOC conditions, evaluating the effective multiplication factor (k_{eff}) of the proposed design against the reference all rods in (ARI) condition (k_{eff} = 0.90883). The analysis was performed with different tungsten coating thicknesses, while assuming a packing fraction of 59%. Due to limitations of the Serpent Monte Carlo code [2], directly modeling binary spheres at specific packing fractions is not feasible. Therefore, a conservative assumption was made that the control rod cladding is entirely filled with 1 mm B_4C balls.

If the tungsten coating is too thin, the absorber spheres may not settle quickly enough under the coolant flow field within the guide tube. Conversely, if it is too thick, sufficient shutdown margin cannot be achieved. To balance these requirements, a coating thickness of 100 μm was selected among many cases as illustrated in Fig. 8. Based on this assumption, the Shutdown Margin (SDM) was calculated as summarized in Table III.



	20	50	100	200	500
Δρ (pcm)	1125	1400	1886	3117	8986
density (g/cc)	4.39	6.98	10.59	15.51	19.1

* ARI(Ref.): 0.90883, ARO(Ref.): 1.03677
Fig. 8. Δρ(reactivity) and density of balls in terms of thickness of tungsten (W)

Table III. Shutdown margin

Reactivity Component	(pcm)
All-rod-in worth	20621
Stuck rod worth (N-1)	1685
Rod worth uncertainty (5%)	1031
Rod worth for criticality	5049
Power defect	2136
Isothermal defect	7713
Engineering error	100
Shutdown margin (SDM)	2907

The results demonstrate that an SDM almost 3000 pcm can be achieved, confirming that the proposed absorber sphere concept can provide enough reactivity control.

4. Conclusions

This study proposes a novel secondary shutdown system for the soluble-boron-free i-SMR, replacing the conventional emergency borated water injection system with the binary absorber sphere concept.

To ensure sufficient shutdown reactivity, the strategy of maximizing the packing fraction of B_4C based absorber spheres inside the control rod cladding was introduced. Using the DEM method, it was confirmed that an optimal packing fraction close to 60% can be achieved when combining 3 mm and 1 mm spheres at a mass ratio of approximately 1:3.4. Furthermore, it was demonstrated that this high packing fraction can be maintained even within the complex geometry at the lower end of the CRA.

Candidate materials capable of maintaining structural integrity in the primary system environment were investigated and organized.

A bypass structure was designed at the lower part of the guide tube to prevent the leakage of absorber spheres. CFD analysis confirmed that no streamlines from the external region entered the guide tube, indicating that the probability of absorber sphere loss is negligibly small.

Subsequently, reactivity analysis was performed with the Serpent Monte Carlo code by assuming B_4C absorber balls coated with a 100 μm tungsten layer as a replacement for the SB control rods in the i-SMR core. The results confirmed that an SDM greater than 2900 pcm can be achieved, thereby demonstrating that the proposed system can adequately substitute for the shutdown capability of the conventional SBs.

5. Future Works

Future work will focus on developing methods for joining the control rod cladding and the porous window, as well as selecting the optimal window material. In addition, the potential detachment of the window due to unintended temperature rise inside the guide tube, along with the behavior of absorber balls considering the internal flow environment, will also be analyzed.

ACKNOWLEDGEMENTS

This work was supported by the Innovative Small Modular Reactor Development Agency grant funded by the Korea Government RS-2024-00405419

REFERENCES

[1] Korea Electric Power Corporation, "Secondary shutdown system for nuclear reactors using melting seal," Korean Patent KR1020190143745A, Nov. 11, 2019.

[2] J. Leppänen, M. Pusa, T. Viitanen, V. Valtavirta, and T. Kaltiaisenaho, "The Serpent Monte Carlo code: Status, development and applications in 2013," Annals of Nuclear Energy, vol. 82, pp. 142-150, 2015, doi: 10.1016/j.anucene.2014.08.024.

[3] KNF J. S. Kim, T. S. Jung, and J. Yoon, "Reactor core design with practical gadolinia burnable absorbers for soluble boron-free operation in the innovative SMR," Nuclear Engineering and Technology, vol. 56, no. 8, pp. 3144-3154, 2024, doi: 10.1016/j.net.2024.03.015.