Sensitivity Study of Fuel Pin for Long-cycle Metallic-Fueled SFRs

Jiwon Choe *, YuGwon Jo, Jong-Hyuck Won, Min Jae Lee, Jaewoon Yoo
Korea Atomic Energy Research Institute, 111, Daedeok-daero 989Beon-gil, Yuseong-gu, Daejeon, 34057, Republic of Korea
**Corresponding author: jchoe@kaeri.re.kr*

Keywords : long-life sodium cooled fast reactor

1. Introduction

Sodium-cooled Fast Reactors (SFRs) utilizing metallic fuel offer distinct advantages for long-cycle operation due to their hard neutron spectrum and high heavy-metal density. Long-cycle operation—often spanning several decades without refuelling—is highly desirable for enhancing proliferation resistance, reducing fuel cycle costs, and improving plant availability. However, realizing this requires fulfilling specific neutronic prerequisites: securing adequate initial excess reactivity and maintaining a flat reactivity curve throughout the cycle via internal breeding.

This paper investigates the fundamental geometric and material requirements for long-cycle operation by analysing the sensitivity of the fuel volume fraction (related to pitch-to-diameter (P/D) ratio), U-235 enrichment, and active core height. Calculations were performed from the 2D pin-cell level and expanded to 3D pin models. The neutronic prerequisites were evaluated based on the initial eigenvalue (k-eff), initial conversion ratio, and reactivity curve behaviour.

2. Computational Models for Sensitivity Analysis

2.1 Modelling Specifications and Test Cases

To identify the core requirements for long-cycle operation, a systematic sensitivity analysis has been conducted using 2D pin-cell and 3D expanded pin models, which are depicted in Figure 1. Some basic data is referred to PGSFR [1] and SALUS [2].

A 2D pin-cell model consists of three regions: fuel region with U-10Zr at 858.15 K, cladding region with HT9M at 783.15 K, Coolant region with sodium and spiral wire at 708.15 K. Typical parametric study fixes linear power density (~ 440 W/cm). However, in this study, specific heat is set to 24.06 MWth/ton to give consistent power to different problems. The gap between fuel and cladding has not been modelled, since the fuel slug was modelled in its swollen state.

A 3D pin model is based on 2D pin-cell and extended to include fuel region, with sufficiently long upper and lower structures added to reduce axial neutron influence in the calculations. It features lower reflector, lower plug, bonding, and gas plenum.

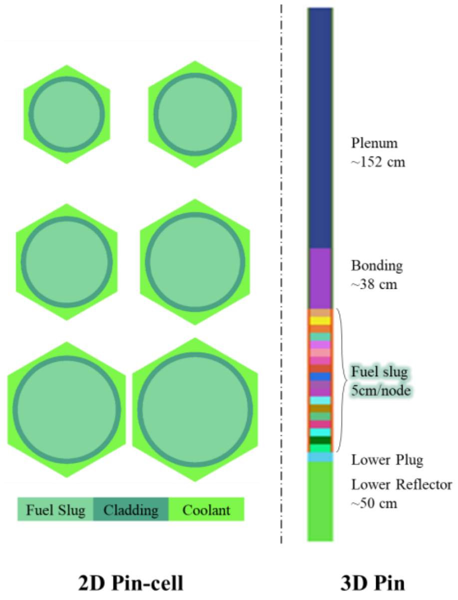

Fig. 1. Problem Image: 2D Pin-cell and 3D Pins. Plotted with McCARD.

The key parameters were varied to observe their impact on the reactivity lifespan as listed in Table I:

Geometric requirements: The fuel volume fraction (VF) was varied from 0.53 to 0.64, corresponding to varying pin outer diameters (0.74, 0.81, 0.89. 0.97, 1.05, and 1.12 cm). For 3D calculations, the active core height was varied (80, 90, 105, 120, and 140 cm) to assess axial neutron leakage effects.

Material requirements: U-235 enrichment levels were tested across a wide range (7.5, 8.7, 10.5, 12.6, 13.5, 16.5, 18.8 and 19.5%) to evaluate the trade-off between initial criticality and breeding capability.

Table I: Variables and Ranges for Sensitivity Study

Variables at Cold State	Range	# of cases
Pin Pitch [cm]	0.835~1.215	6
Pin Outer Diameter [cm]	0.74~1.12	
Fuel Volume Fraction [-]	0.53~0.64	
U-235 [wt.%]	7.5~19.5	8
Fuel Height [cm] in 3D case	80~140	5

2.2 Calculation Options

McCARD [3], which is a Monte Carlo code developed by the Seoul National University, has been adopted to simulate problems. ENDF/B-VII.1 [4] has been selected as a cross section library.

Boundary condition is given reflective to all 8 surfaces for 2D pin-cell problems. For 3D pin problems, the radial and axial boundary conditions are given as reflective and void, respectively.

Each problem is given 50 inactive cycles, 200 active cycles, and 3000 neutron histories per cycle, which provides a value of around 45 pcm for standard deviation of k-eff.

Matrix exponential method (MEM) and semi predictor-corrector are used in burnup calculation. The burnup interval is divided into 30 effective full power days (EFPD) up to 1 effective full power years (EFPY) and 2 EFPY up to 60 EFPY. Depletion region for fuel slug is not divided radially, but is divided axially into 5 cm. The cycle length is defined as the operation time until k-eff drops to 1.0.

3. Results and Discussion

3.1 Initial Results of Criticality and Conversion Ratio

Initial calculation results are described in Figure 2 and Figure 3. When extended from 2D pin-cell to 3D pins of 80 cm, the initial k-eff drops by about 7,500 – 16,000 pcm due to neutron leakage. Whereas when extended 3D pins of 140 cm, the drop is 3,500 – 7,500 pcm, about half of 80 cm 3D pins. In other words, the higher the fuel height, the higher the initial k-eff. On the other hand, the conversion ratio value remains largely unchanged.

The variable that has the greatest influence on the initial value is the U-235 enrichment. Fuel volume fraction also affects to both initial k-eff and initial conversion ratio. It shows that, regardless of whether neutron burning or breeding in SFRs, an enrichment of at least 10 wt.% of U-235 is required to achieve initial criticality.

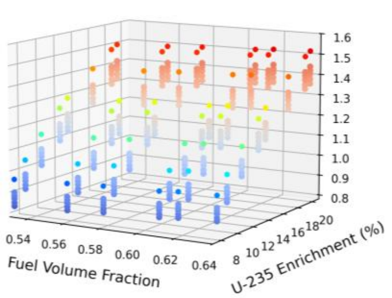

Fig. 2. Initial k-eff for all 2D pin-cells and 3D pin cases.

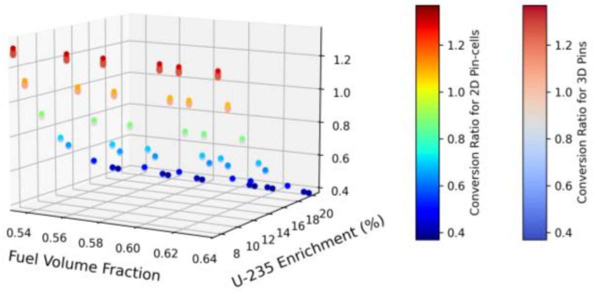

Fig. 3. Initial conversion ratio for all 2D pin-cell and 3D pin cases.

3.2 Burnup Results

Figure 4 and Figure 5 show all burnup results. It can be confirmed that although the cycle length and initial k-eff of 3D cases are shorter than that of 2D cases, the tendency of reactivity curves is similar.

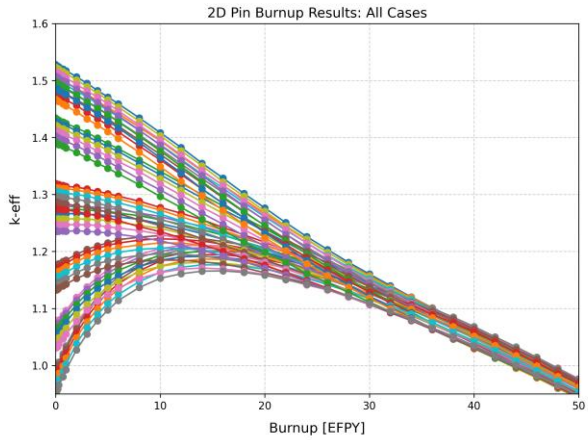

Fig. 4. Burnup results for all 2D pin-cell cases.

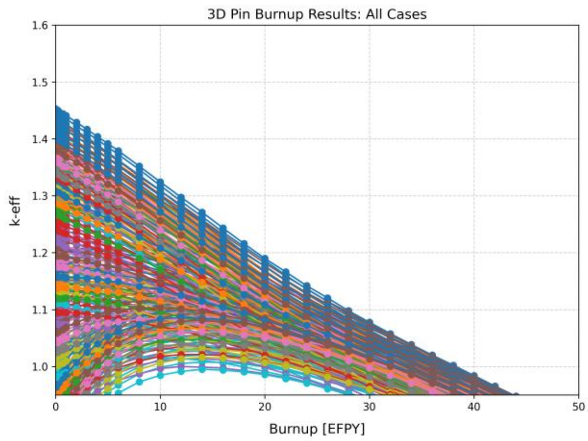

Fig. 5. Burnup results for all 3D pin cases.

The reactivity curves shows different trends depending on the conversion ratio. If the conversion ratio is less than 1.0, then the core is a burner-type reactor that produces less fissile material than it consumes. Thus, the core is burnt out linearly according to U-235 depletion. Figure 6 is reactivity curves for 3D pin cases when the initial conversion ratio is less than 0.5. The tendency is often observed when the U-235 enrichment is higher than 16% and the fuel volume fraction is around 0.58 or higher. It can guarantee long life cycle, but requires more initial fissile material.

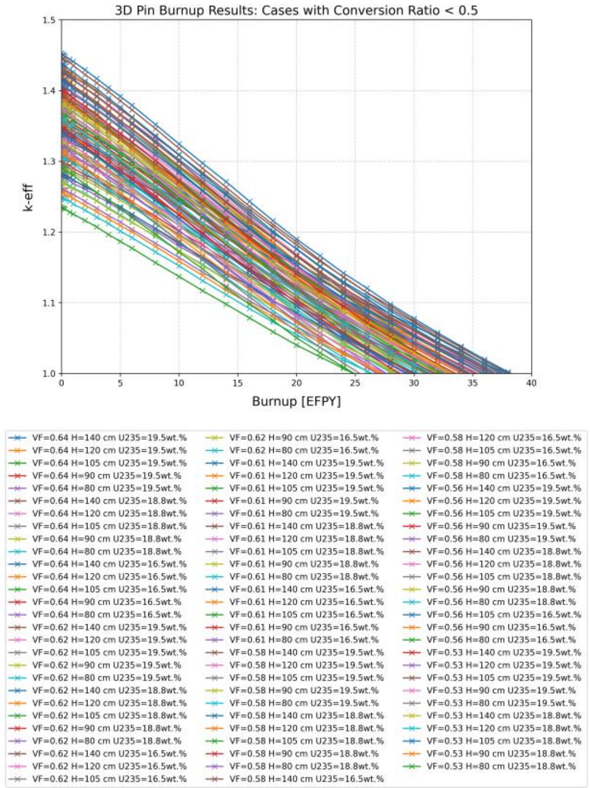

Fig. 6. Reactivity curves for 3D pin cases when the conversion ratio is less than 0.50.

On the other hand, when the conversion ratio is greater than 1.0, then the core is a breeder-type reactor that produces more fissile material than it consumes. While the initial k-eff is low, it gradually increases with burnup due to the accumulation of fissile material. Figure 7 shows the reactivity curves for the 3D pin cases when the initial breeding ratio is larger than 1.1. Most cases with 7.5 wt.% of U-235 appear in the figure.

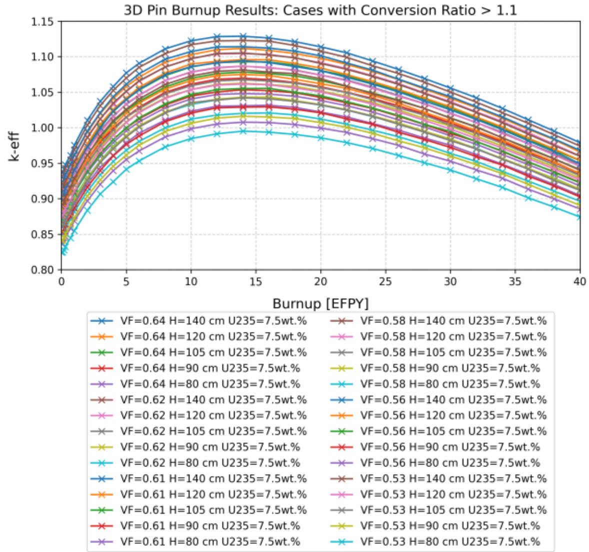

Fig. 7. Reactivity curves for 3D pin cases when the conversion ratio is larger than 1.10.

3.3 Selected Cases for Long-Cycle Core Design

Figure 8 shows a filtered cases where the cycle length is 30 EFPY or longer, the initial reactivity is 15,000 pcm or less, and the reactivity swing is less than 5,000 pcm.

Although the U-235 enrichment is around 10-12 %, the core height and the fuel volume fraction ranges vary widely. The key commonality is that the conversion ratio is around 0.86.

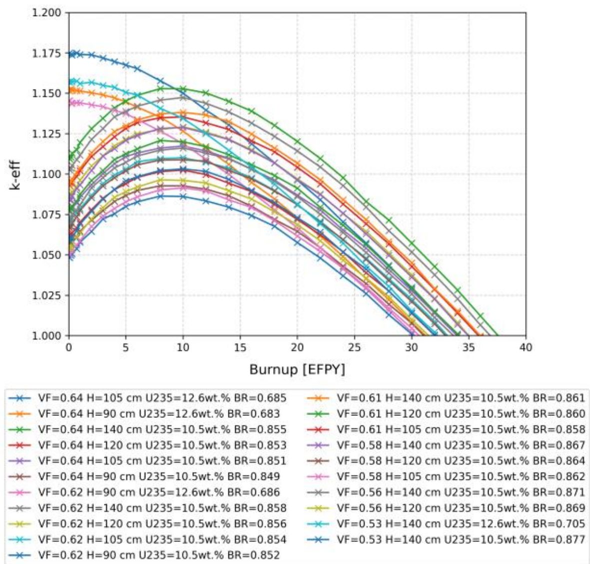

Fig. 8. Reactivity curves for 3D pin cases: when life length is longer than 30 EFPY, initial $\Delta\rho$ is less than15,000 pcm, and $\Delta\rho$ swing is less then 5000 pcm.

4. Conclusions

This sensitivity study using fuel pin model has been conducted the basic design requirements for achieving long-cycle operation in a metallic-fuelled SFR. By varying U-235 enrichment, fuel volume fraction, and active core height, the neutronic prerequisites were evaluated based on the initial k-eff, reactivity curve behaviour, cycle length, and conversion ratio.

The results demonstrate that optimized long-cycle operation primarily requires the core state with 0.86 of conversion ratio. Future long-cycle SFR designs must satisfy these basic requirements by carefully tuning the pitch-to-diameter ratio, core dimensions, and reflector assemblies to sustain criticality and internal breeding simultaneously. Consequently, incorporating optimized radial reflectors to mitigate leakage will be a critical next step in full-core design to preserve the long-cycle capabilities identified in this pin-level sensitivity study.

Key Findings:

1) At least 10 wt% of U-235 is required to achieve the initial criticality using U-Zr metallic fuel
2) A breeding ratio around 0.86 is required for long-cycle core designs with a small reactivity swing (< 5,000 pcm) and a cycle length greater than 30 years.
3) Combining reactivity curves from conversion ratio > 1.1 and conversion ratio < 0.5 would result in flattened reactivity curve with long-cycle.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(Ministry of Science and ICT)(No. RS-2025-25455699).

REFERENCES

[1] J. Yoo, J. Chang, J.Y. Lim, J.S. Cheon, T.H. Lee, S.K. Kim, K.L. Lee, H.K. Joo, “Overall System Description and Safety Characteristics of Prototype Gen IV Sodium Cooled Fast Reactor in Korea,” Nuclear Engineering and Technology, 48(5):1059-1070 (2016).

[2] J. Eoh, C.G. Park, J.Y. Lim, J.H. Kim, H. Y Ye, J. Chang, “Design and safety features of SALUS-100: A long fuel-cycled Sodium-cooled fast reactor,” Nuclear Engineering and Design, 420 (2024).

[3] H. Shim, B. Han, S.J. Jong, H. J. Park, C. Kim "MCCARD: MONTE CARLO CODE FOR ADVANCED REACTOR DESIGN AND ANALYSIS" Nuclear Engineering and Technology 44.2 pp.161-176 (2012) : 161.

[4] M. B. Chadwick, M. Herman, P. Oblozinsky, et al., "ENDF/B-VII.1 nuclear data for science and technology: Cross sections, covariances, fission product yields and decay data", Nuclear Data Sheets, 112(12):2887-2996 (2011).