Neutronic Performance and Economic Feasibility of RBSC Reflectors in LEU+ SMRs for Spent Nuclear Fuel Reduction

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***Keywords : SiC Reflector, RBSC, LEU+ Fuel, SMR**

1. Introduction

Small Modular Reactors (SMRs) are increasingly being recognized as a flexible and carbon-free energy source. However, a significant challenge facing SMR deployment is the generation of radioactive waste. Recent studies on SMR waste volumes have highlighted that SMRs can produce more spent nuclear fuel and radioactive waste per unit of energy generated compared to large-scale pressurized water reactors (PWRs) [1]. This is primarily due to the inherent neutron leakage associated with miniaturized core designs and the adoption of 2-batch fuel management schemes that limit the maximum discharge burnup.

To overcome these economic and environmental hurdles, the industry is adopting advanced fuel cycle strategies, particularly the use of LEU+ (Low Enrichment Uranium Plus) fuel with enrichment levels exceeding the conventional 5 wt% limit [2]. When combined with Soluble-Boron-Free (SBF) operations, LEU+ fuel can extend cycle lengths and minimize the volume of spent nuclear fuel.

In these compact LEU+ SBF designs, the radial reflector is essential for managing neutron leakage. Austenitic stainless steel, such as SS304, is widely recognized as an excellent and highly reliable choice for heavy reflectors due to its proven mechanical robustness and stable operational history [3]. However, from a reactor physics perspective, exploring advanced materials can yield additional neutronic advantages. Among candidate ceramic reflector materials, Silicon Carbide (SiC) has emerged as an attractive alternative that improves core performance by softening the peripheral neutron spectrum and reducing neutron absorption relative to standard metal reflectors. Graphite offers even lower thermal neutron absorption but is not adopted here, as its oxidation behavior in high-temperature water is far less benign than SiC's. Graphite oxidizes actively on water/steam contact and generates combustible gases if the canning fails, whereas SiC forms a passive, self-limiting oxide layer.

Despite these neutronic benefits, the material and machining costs of high-purity, high-density SiC are prohibitively high for commercial deployment. To address this economic barrier, this study proposes the use of Reaction Bonded Silicon Carbide (RBSC). Although RBSC has a lower density and contains manufacturing impurities, its cost is substantially lower. This paper evaluates the comprehensive neutronic performance of RBSC reflectors. The analysis focuses on cycle length extension, power peaking, and axial stability to demonstrate its viability as a cost-effective alternative.

2. Computational Model and Material Specifications

2.1. Reflector Material Properties

The primary motivation for adopting RBSC over high-purity SiC lies in its economic feasibility and its impact on the overall reactor module weight. High-purity SiC is typically manufactured using rigorous sintering processes. This results in a density of approximately 3.21 g/cm^3 but at significantly higher production costs. In contrast, RBSC is produced by infiltrating a porous carbon preform with molten silicon. This process is much more cost-effective but results in a slightly lower density of 2.95 g/cm^3. Furthermore, the infiltration process leaves residual free silicon (Si), unreacted carbon (C), and trace metal impurities such as Iron (Fe), Aluminum (Al), and Calcium (Ca).

While the presence of these trace impurities slightly alters the macroscopic cross-sections compared to high-purity SiC, the overall neutronic penalty must be weighed against the manufacturing benefits. An estimation of material costs illustrates this disparity. Standard SS304 is relatively economical at approximately 30 $/kg. High-purity SiC components can reach up to 2,000 $/kg due to the energy-intensive manufacturing and machining required for nuclear grade. RBSC provides a highly practical middle ground at an estimated cost of ~ 100 $/kg. Additionally, moving from a conventional SS304 heavy reflector (density 7.9 g/cm^3) to RBSC (2.95 g/cm^3) reduces the reflector mass by over 60%. This drastic weight reduction offers an advantage for SMRs. It significantly aids in factory-to-site module transportation and eases the lifting capacity requirements during reactor

installation. Table I compares the basic physical characteristics and estimated costs of the evaluated reflector materials.

Table I. Physical and economic characteristics of evaluated reflector materials

Material	Density (g/cm^3)	Impurities	Est. Cost ($/kg)
SS304	7.90	None (Alloy)	~ 30
High-purity SiC	3.21	None	~ 2,000
RBSC	2.95	Free Si, Free C, Trace Fe/Al/Ca	~ 100

2.2. Core Specifications and Evaluated Method

The neutronic analysis is performed using the STREAM/RAST-K two-step code system [4][5]. The target reactor analyzed is a conceptual 520 MWth SBF SMR designed for long-cycle flexible operation. The core consists of 69 fuel assemblies arranged in a 17×17 lattice structure. A uniform enrichment strategy utilizing 7.0 wt% LEU+ fuel is adopted alongside heavy utilization of gadolinia (Gd_2O_3) integral burnable absorbers. A conservative 5 mm of protective FeCrAl alloy layer is assumed for both SiC and RBSC reflectors to ensure hydrothermal oxidation resistance in the high-temperature PWR environment.

To explicitly isolate the direct neutronic impact of the reflector materials and exclude secondary effects arising from cumulative burnup history differences across multiple cycles, the evaluation is performed using a restart calculation method. Specifically, Cycle 8 is simulated by restarting from the exact same burnup distribution obtained at the end of the 7th cycle of the SS304 reference core. In this approach, all three evaluated reflector configurations (SS304, High-purity SiC, and RBSC) share the identical fuel composition at the beginning of the cycle (BOC).

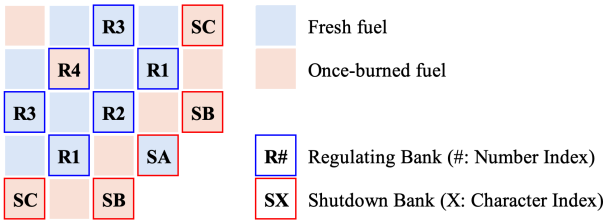


Fig. 1. Radial fuel loading strategy (2-batch) and location of control rod banks

3. Results and Discussion

3.1. Cycle Length and Reactivity Control

The enhanced neutron reflection by SiC-based materials directly translates to increased core excess reactivity. In the isolated Cycle 8 restart calculation, both the high-purity SiC and RBSC reflectors extended the cycle length compared to the SS304 baseline by approximately 2.4% and 2.1%, respectively.

The SS304 reference core achieved an Effective Full Power Days (EFPD) of 1019.4 days. The high-purity SiC reflector extended this to 1044.0 days. Notably, despite the lower density and the presence of trace impurities, the RBSC reflector achieved a cycle length of 1041.1 days. This near-identical performance supports the economic viability of substituting high-purity SiC with RBSC.

Fig. 2 and Fig. 3 illustrate the evolution of core excess reactivity and the total control rod bank insertion depth in Cycle 8. The RBSC and high-purity SiC cores start with a higher initial excess reactivity compared to the SS304 core. Consequently, the regulating control rods must be inserted deeper into the core at BOC to suppress this additional reactivity. As the fuel depletes, the excess reactivity and rod insertion curves for RBSC and high-purity SiC almost perfectly overlap. Both reach the critical depletion limit identically later than SS304. The nearly indistinguishable curves confirm that the trace impurities in RBSC do not compromise the long-term reactivity.

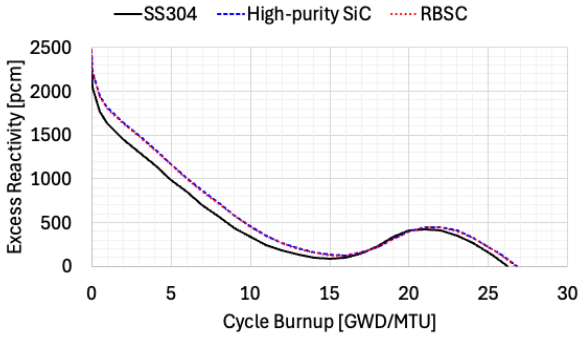


Fig. 2. Core excess reactivity during Cycle 8

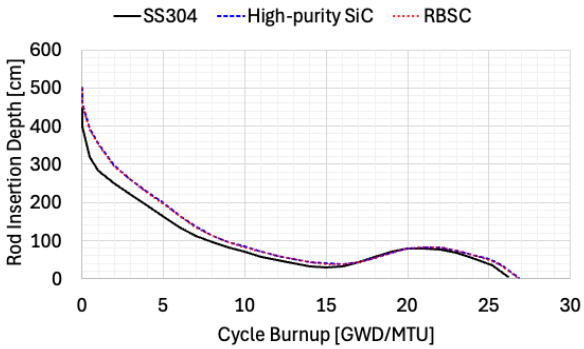


Fig. 3. Total control rod bank insertion depth during Cycle 8

3.2. Power Peaking and Axial Stability

The spectral softening effect at the core-reflector interface increases the fission rate in the peripheral

assemblies. Fig. 4 illustrates the radial power distribution of SS304 and RBSC core. This localized power boost flattens the radial power distribution. The increased peripheral power flattens the radial power distribution, effectively offsetting the peaking penalty typically caused by deeper control rod insertion.

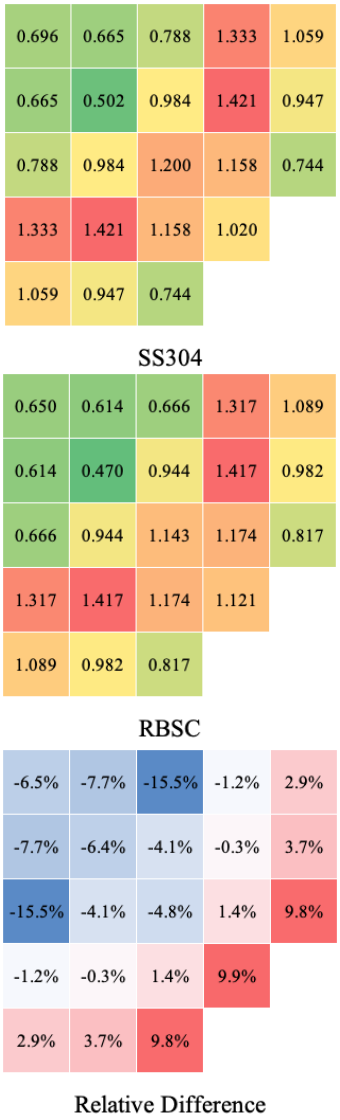


Fig. 4. Radial Power Distribution (RPD) and relative difference at BOC in Cycle 8

Fig. 5 shows the evolution of the 3-D power peaking factor (Fq) during Cycle 8. Although control rod insertion depth was increased, the power peaking was not affected. The Fq for the RBSC core is generally equal to or lower than that of the SS304 reference core throughout the cycle. The BOC Fq drops from 2.97 for SS304 to 2.86 for RBSC. This demonstrates that RBSC actively maintains and even improves thermal margins.

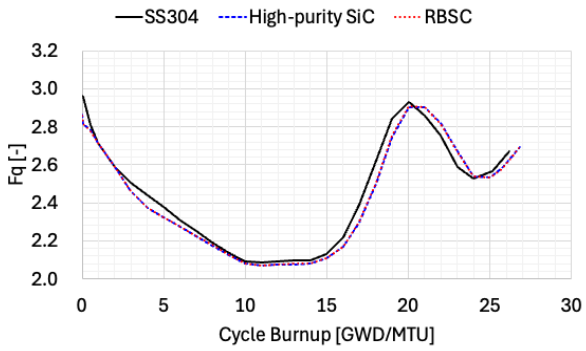


Fig. 5. Evolution of power peaking factor (Fq) during Cycle 8

Fig. 6 illustrates the Axial Shape Index (ASI) behavior across the operating cycle. ASI fluctuates as control rod banks are gradually withdrawn and overlap logic is engaged. The macroscopic ASI trend for the RBSC core closely tracks the reference core and the high-purity SiC core. The deviations observed are solely attributed to the differing critical control rod positions required to manage the higher excess reactivity. This confirms that the enhanced peripheral reflection does not induce any axial instability. Therefore, standard axial power control strategies remain fully applicable.

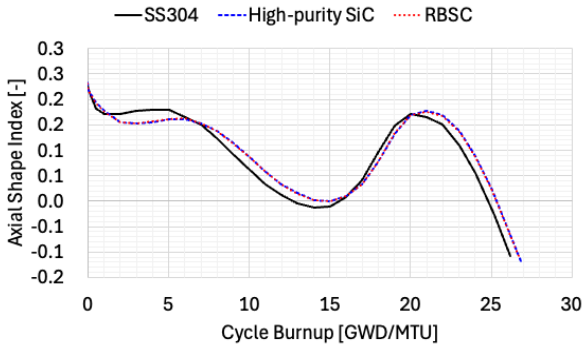


Fig. 6. Evolution of Axial Shape Index (ASI) during Cycle 8

4. Conclusion

This study demonstrated the neutronic and economic viability of RBSC reflectors in LEU+ SBF SMRs. By isolating the reflector effects through a Cycle 8 restart calculation, it was proven that substituting costly high-purity SiC with RBSC maintains nearly identical neutronic benefits. These benefits include cycle length extension and improved thermal margins at a fraction of the manufacturing cost. While SS304 remains an excellent and highly reliable standard choice for SMRs, RBSC provides a distinct neutronic performance from a reactor physics perspective. The trace impurities and slightly lower density of RBSC do not meaningfully degrade core performance. Additionally, the substantially lower density of RBSC (2.95 g/cm^3) compared to SS304 (7.90 g/cm^3) dramatically reduces

the overall mass of the reactor module. This reduction enhances SMR transportability and mitigates lifting constraints. RBSC proves to be a highly practical candidate that simultaneously addresses the economic, logistical, and spent nuclear fuel reduction challenges of next-generation advanced reactors. This evaluation is limited to core-internal neutronics, and RPV fast fluence was not assessed. SS304 additionally attenuates fast neutrons through inelastic scattering on Fe, a mechanism that is largely absent in the elastic-scattering-dominated RBSC. A quantitative comparison of RPV fast fluence and dap across the SS304, high-purity SiC, and RBSC configurations is therefore left as future work.

ACKNOWLEDGEMENT

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-2024-00422848).

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