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A Study on Decay Heat and Radioactivity Characteristics of LEU+ Spent Nuclear Fuel in i-SMR

Hyeonyeong Lee, Jeseok Song, Yong-deog Kim*
KEPCO International Nuclear Graduate School (KINGS),
658-91 Haemaji-ro, Seosaeng-myeon, Ulju-gun, Ulsan 45014 Republic of Korea
**Corresponding author: ydkim@kings.ac.kr*

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1. Introduction

Korea is developing innovative SMR (i-SMR) designs incorporating extended enrichment fuel (LEU+, 5.5-10 wt% U-235) to achieve longer operating cycles and improved fuel utilization [1,2]. However, while recent studies have focused on core design optimization for LEU+ fueled i-SMR [3], systematic characterization of spent fuel decay heat and radiation source terms has not been reported in the open literature. The combination of extended enrichment and unique SMR operating parameters may result in distinct decay heat and radiation source terms compared to conventional PWR fuel, requiring systematic evaluation before deployment.

This work proposes a computational methodology under development for characterizing LEU+ spent fuel from i-SMR. The framework will employ SCALE 6.3 Triton depletion and ORIGEN decay analysis to evaluate decay heat evolution and radiation source terms, supporting back-end fuel cycle system design for advanced SMR applications.

While this computational approach represents industry standard practice for conventional PWR fuel analysis, the novelty lies in its systematic application to LEU+ enriched i-SMR, establishing a comprehensive spent fuel characterization database for this emerging reactor class with its distinctive long-cycle, low-power-density operating regime.

2. Proposed Methodology

The analysis utilizes SCALE 6.3 code system [4] with Triton depletion sequence coupled with ORIGEN decay module. The computational workflow consists of sequential phases: Triton depletion calculation to generate isotopic inventories, followed by ORIGEN decay analysis to characterize radiation source terms.

The fuel assembly model represents i-SMR fuel with PWR-compatible 17×17 design incorporating LEU+ specifications. Representative enrichment cases at 5.5, 7.5, and 10 wt% U-235 are analyzed to cover the extended enrichment range, with IFBA and/or Gadolinia burnable absorbers included for long-cycle reactivity control. The Triton model employs 2D pin-by-pin geometry using 252-group ENDF/B-VII.1 cross-section library with NEWT deterministic transport solver based on method of characteristics.

The depletion analysis simulates multi-cycle irradiation representing equilibrium core conditions, tracking fresh, once-burned, and twice-burned fuel states through successive operating cycles. The calculation reflects i-SMR operating characteristics including extended cycle length enabled by LEU+ enrichment and lower specific power compared to conventional large PWRs. Cycle-specific power distributions accounting for burnup-dependent reactivity are applied, with assembly-averaged isotopic composition extracted at discharge for subsequent decay analysis.

Post-discharge ORIGEN calculations characterize spent fuel evolution over cooling periods from 1 to 1000 years, spanning wet storage, dry storage, and repository disposal timeframes. The analysis quantifies decay heat generation and its temporal evolution, total radioactivity with breakdown by nuclide category, and energy-dependent gamma and neutron source spectra for shielding applications.

3. Framework Capabilities and Applications

3.1. Isotopic Inventory Database

The framework generates comprehensive isotopic composition data for LEU+ fuel across enrichment and burnup ranges. The database includes actinides (U, Pu, Np, Am, Cm), fission products (Sr-90, Cs-137, and other dose-significant nuclides), and activation products. This inventory supports thermal design of spent fuel pool cooling systems by providing time-dependent decay heat data, enables dry storage cask heat load determination and loading curve development through accurate source term quantification, and establishes minimum cooling time requirements before transition to dry storage based on thermal and radiation criteria.

3.2. Radiation Source Characterization

Gamma and neutron source term calculations enable comprehensive shielding analysis for storage and transportation systems, providing energy-dependent source spectra required for dose rate predictions in facility design and occupational safety analysis. The source term data supports development of remote-handling equipment specifications tailored to LEU+ fuel radiation characteristics, while enabling systematic comparison with conventional PWR fuel source terms to identify any deviations attributable to extended enrichment or SMR operating conditions.

3.3. Comparative Analysis Capability

The characterized LEU+ fuel properties are systematically compared with conventional 5 wt% PWR fuel at equivalent burnup to identify differences attributable to extended enrichment effects on actinide and fission product inventories. This comparison quantifies the impact of SMR-specific operating conditions, particularly lower power density and longer cycle lengths, on spent fuel composition and decay characteristics. The analysis assesses implications for compatibility with existing storage infrastructure, determining whether LEU+ fueled i-SMR spent fuel can utilize standard PWR dry storage casks or require design modifications.

4. Validation Strategy and Applications

The methodology will be validated through comparison with published LEU+ i-SMR core analysis results [3] for isotopic inventory cross-check, and consistency checks with ANSI/ANS-5.1 decay heat standards [5] to ensure conformance with industry-accepted correlations. Benchmarking against experimental measurements will be performed where available to establish confidence intervals for key output parameters.

The spent fuel characterization database will support multiple applications across the back-end fuel cycle. Assessment of LEU+ fuel compatibility with existing PWR storage infrastructure will determine whether current facilities can accommodate i-SMR spent fuel without modification. The database will provide technical foundation for design basis development of i-SMR-specific back-end systems, enable optimization of transportation cask requirements and capacity through accurate source term specification, support repository disposal planning and waste package design with long-term isotopic evolution data, and facilitate regulatory licensing preparation by establishing quantitative technical foundation for safety analysis reports.

5. Conclusions

This work proposes a systematic computational framework for characterizing decay heat and radiation source terms from LEU+ fueled i-SMR. The SCALE 6.3-based methodology under development will provide comprehensive isotopic inventory database for extended enrichment SMR fuel, decay heat predictions across cooling periods relevant to storage system design, radiation source terms enabling shielding analysis and dose assessment, and quantitative comparison with conventional PWR fuel characteristics.

The framework development addresses critical data gaps before i-SMR deployment, enabling proactive design of back-end fuel cycle systems and supporting seamless integration with existing nuclear infrastructure. Validation calculations are currently underway using representative i-SMR operating parameters, with results to be presented at future technical meetings.

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