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Decay Heat and Source Term Analysis of i-SMR Spent LEU+ Fuel

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1. Introduction

Commercial nuclear vendors and operators are pursuing higher-enrichment fuel to achieve higher discharge burnup and longer operating cycles. Fuel containing 5-10wt.% U-235 can achieve higher burnup and longer fuel cycles. Studies of PWR-based SMRs using LEU+ fuel enriched to 6wt.% have reported average discharge burnups of approximately 53 GWd/MTU [1] and 57 GWd/MTU [2], indicating the potential of LEU+ fuel to achieve higher burnup and improved fuel utilization compared with conventional fuel.

In Korea, LEU+ fuel is being investigated for the Innovative Small Modular reactor (i-SMR), particularly to support soluble-boron-free operation and extend refueling intervals. However, the characteristics of i-SMR spent fuel remain less explored. Most of available spent fuel data are based on conventional fuel from large PWRs. For a given enrichment, decay heat and its contributors are influenced by irradiation history, burnup, specific power, and cooling time [3]. Therefore, characterization of i-SMR spent fuel is necessary to support the spent fuel management planning and preliminary assessments of the suitability of existing dry storage systems.

This study evaluates the decay heat and neutron and gamma source intensities of i-SMR LEU+ fuel enriched to 6wt.% U-235 over cooling times from 1 to 100 years. Two burnup cases of 54.9 and 69.9 GWd/MTU are considered. The 54.9 GWd/MTU was selected as an intermediate reference burnup based on the average discharge burnup discussed above, while 69.9 GWd/MTU was selected as the conservative extended-burnup condition for sensitivity analysis, close to the maximum pin burnup reported in Ref. [1]. The results provide a technical basis for future safety evaluations of the suitability of existing dry storage systems for i-SMR LEU+ spent fuel.

2. Materials and Methods

2.1 Computational methods

Depletion calculations were performed using the SCALE T6-DEPL sequence, which couples KENO-VI and ORIGEN. The neutron transport calculation employed the ENDF/B-VII.1 cross-section library. A modified Westinghouse 17x17 PWR assembly containing 264 fuel rods and 25 guide-tube positions was modelled using the i-SMR LEU+ fuel specifications. Burnable absorbers were omitted from this model; therefore, their impact on the isotopic inventory was not considered. The assembly model was depleted to a maximum burnup of 69.9 GWd/MTU, with isotopic inventories obtained at selected burnup points. These inventories were stored in an F71 concentration file and subsequently used as initial compositions for ORIGEN decay calculations. These calculations determined the evolution of isotopic inventory, decay heat and gamma and neutron source intensities as a function of cooling time. Neutron and gamma spectra were evaluated using 27 neutron and 19 gamma energy groups, and all results were post-processed with OPUS.

2.2 Parameters

The accurate characterization of spent fuel depends on the initial fuel enrichment , specific power, and irradiation history because these parameters determine the discharged inventory. The parameters of PWR 17x17 fuel assembly used in this study are summarized in Table I.

Table I: Fuel assembly parameters and calculation conditions

Parameter	Value
Reactor	i-SMR [4]
Fuel	UO_2, 17x17 square assembly [5]
Number of assemblies	69 [4]
Enrichment	6wt.% U-235,
Specific Power	29.5 MW/MTU
Cooling years	1-100 years
Active height	2 m
Uranium mass /fuel assembly	0.255 MTU/fuel
Reactor thermal power, MW(t)	520 MW(t) [4]

3. Results and Discussion

3.1 Decay heat analysis

The isotopic inventory of spent LEU+ fuel was evaluated to identify the major contributors to decay heat. Between 5 and 30 years of cooling, the major contributors to decay heat include Y-90, Ba-137m, Cs-

134, Cm-244, Cs-137, and Sr-90, while Am-241 dominates after 30 years of cooling. The results of total decay heat are presented in Table II.

Table II: Total decay heat (kW/MTU) for 6wt% enriched fuel at two discharge burnups

Cooling time (years)	54.9 GWd/MTU	69.9 GWd/MTU	Ratio
1	11.989	14.567	1.22
5	2.963	4.062	1.37
10	2.014	2.790	1.38
30	1.310	1.779	1.36
100	0.507	0.699	1.38

At 5 years of cooling, increasing burnup from 54.9 to 69.9 GWd/ MTU increases the decay heat from 2.963 kW/MTU to 4.062 kW/MTU, a factor of 1.37, or from 0.755 to 1.036 KW per assembly. The factor changes slightly between 5 and 100 years, suggesting the difference between two cases is mainly due to differences in the radionuclide inventory during irradiation. For instance, Cm-244 shows a stronger dependence on burnup contributing 6% of the decay heat at 54.9 GWd/MTU and 11.5% at 69.9 GWd/MTU.

3.2 Gamma and neutron intensities

Gamma and neutron intensities for both burnup cases were computed. Tables III and IV report the total intensities calculated per MTU. The neutron sources arise from spontaneous fission and (alpha, n) reactions, whereas gamma source is mainly associated with fission products and actinides.

Table III: Total Neutron Intensity (n/s/MTU) for 6wt.% enriched fuel at two discharge burnups

Cooling time	54.9 GWd/MTU	69.9 GWd/MTU	Ratio
1	9.61E+08	2.41E+09	2.51
5	7.16E+08	1.90E+09	2.65
10	5.95E+08	1.57E+09	2.64
30	2.88E+08	7.56E+08	2.63
100	3.67E+07	9.44E+07	2.57

Table IV: Total gamma intensity (γ/s/MTU) for 6wt.% enriched fuel at two discharge burnups

Cooling time	*54.9 GWd/MTU*	69.9 GWd/MTU	Factor
1	8.92E+16	1.04E+17	1.17
5	1.99E+16	2.51E+16	1.26
10	1.20E+16	1.49E+16	1.24
30	6.95E+15	8.17E+15	1.22
100	1.40E+15	1.71E+15	1.22

At 5 years of cooling, increasing the burnup from 54.9 to 69.9 GWd/MTU, corresponding to a 27% increase, increased the neutron source intensity by approximately 165%, whereas gamma intensity increased by approximately 26%. The stronger burnup dependence of neutron source intensity reflects accumulation of transuranic nuclides, especially Cm-244, whereas gamma source intensity is governed mainly by the radioactive decay of fission products.

4. Conclusions

This study evaluated the decay heat and gamma and neutron source intensities of i-SMR LEU+fuel at burnup of 54.9 and 69.9 GWd/ MTU using SCALE 6.3.2. The calculated decay heat per assembly at 5 years of cooling was 0.755 and 1.036 kW for the 54.9 and 69.9 GWd/MTU, respectively. Using the 35.5 kW thermal limit of MAGNASTOR dry storage system [5] as a reference, division of this limit by calculated decay heat per assembly gives approximately 47 and 34 assembly heat-equivalents, respectively. The lower value for higher burnup cases reflects its greater decay heat and corresponding thermal burden on the dry storage system. These values are intended only as thermal-capacity screening estimates, and do not represent the allowable loading capacity of MAGNASTOR system for i-SMR fuel. Therefore, cask-specific thermal, shielding, and criticality analyses are required to assess the suitability of existing dry storage systems for i-SMR spent fuel.

Acknowledgements

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