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Comparative Analysis of Core Inventory and Decay Heat for a LEU+ Core and the SMART100 Reactor

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1. Introduction

The global effort toward carbon-neutrality has renewed interest in nuclear power, but traditional large reactors face challenges with high capital costs and long construction times [1]. Small Modular Reactors (SMRs), like the SMART100, offer a potential solution by using modular designs and passive safety features to improve economic viability and flexibility.

Alongside new reactor designs, the new nuclear fuel concepts are also being developed to enhance economic competitiveness. The LEU+ aims to extend operating cycles and improve fuel utilization by achieving higher burnup with increased enrichment. However, pushing fuel to higher burnup directly affects key safety parameters.

In reactor safety, a precise understanding of the core fission product inventory and post-shutdown decay heat is critical for safety. These values are essential inputs for severe accident analyses, defining the radioactive source term and setting performance requirements for decay heat removal and spent fuel management. This study uses the SCALE/ORIGEN code [2] to compare the core inventory and decay heat characteristics of the SMART100 core [3] with a high-burnup LEU+ core [4], and to quantitatively assess how the high-burnup strategy of the LEU+ design impacts these fundamental safety metrics.

2. Analysis Methods

2.1 Core design and case definitions

This study contrasts two distinct core designs: the SMART100, representing a reference Small Modular Reactor, and the LEU+, which embodies a high-burnup, long-cycle operational strategy aimed at enhancing economic efficiency. The SMART100 core is characterized by a 2-batch fuel management scheme and an enrichment below 5 wt% (up to 4.75 wt%), typical for standard SMR operation. In contrast, the LEU+ core utilizes higher uranium enrichment (up to 7.6 wt%), a longer operational cycle, and a more complex 3-batch fuel management scheme.

The 7.6 wt% design value was used to determine the initial core's uranium inventory, while the subsequent fuel depletion was simulated using a burnup library generated by the SCALE/ARP module with a 6 wt% input enrichment, reflecting the specifications of the underlying cross-section library which was pre-generated for enrichment up to 6 wt%. This is explicitly designed to achieve a significantly higher discharge burnup, thereby maximizing energy extraction per fuel assembly. The key design and operational parameters that define these cases are summarized in Table I.

Table. I. Inputs and assumptions for the SMART100 and LEU+ Core

Item	SMART100	LEU+
Cycle length (months)	24	30
Thermal Power (MWt)	365	520
Batch scheme	2-batch	3-batch
Maximum Enrichment (wt%)	4.75	7.6
Refueling outage	30 days	30 days
Equilibrium cycle	5 cycles	8 cycles
Average EFPD (days)	870	881.6
Maximum EFPD (days)	870	940
Uncertainty basis	ANSI/ANS-5.1-1979	

As detailed in the table, the SMART100 is modeled with a 24-month cycle and 2-batch operation, achieving a consistent 870 EFPD. The LEU+ core adopts a longer 30-month cycle and 3-batch operation with a maximum EFPD of 940 days. The significant differences in thermal power and maximum enrichment are also notable. These fundamental choices—cycle length, batch management, power, and enrichment—are the primary determinants of the fuel burnup, subsequent fission product buildup, and decay-heat behavior that are evaluated in the following sections.

2.2 Data Processing and Analysis

All calculations of isotopic inventory and decay are performed with SCALE/ORIGEN code package. Fission product major-group inventories are first evaluated by aggregating isotopes into the volatile groups of iodine (I), cesium (Cs), tellurium (Te), krypton (Kr), and xenon (Xe). This approach provides a high-level, integrated view of the nuclides most likely to become airborne in a severe accident, thus forming the primary component of the early radioactive source term.

Next, long-lived nuclides that are critical to safety are reported individually. This includes fission products like Cs-137 and Sr-90, which, due to their long half-lives and biological significance, dominate long-term land contamination risks. It also includes key actinides such as Am-241 and Cm-244, whose decay dictates the very long-term thermal load and radioactive hazard of spent nuclear fuel.

Decay heat is presented in two distinct forms: (i) absolute decay heat P(t) and (ii) fractional decay heat $P(t)/P_0$. P_0 denotes the operating power, it is 365 MWt for SMART100 and 520 MWt for LEU+. To clearly visualize the divergence between the two designs, percent differences are plotted relative to the SMART100. For power normalization, the SMART100 results are scaled using a normalization factor, which is 1.425, derived from the ratio of the core thermal powers, as shown in Eq. (1):

$$(1)\quad Parameter_{SMART100,scaled} = Parameter_{SMART100} \times \frac{P_{th,LEU+}}{P_{th,SMART100}} = Parameter_{SMART100} \times \frac{520MWt}{365MWt}$$

With these rigorous definitions and the case inputs from Table I, the following section presents the results and discusses their implications.

3. Results and Discussion

3.1 Fission product inventory analysis

The analysis of the fission product inventory reveals a significant increase in the radioactive source term for the LEU+ core. As shown in Fig. 1, the LEU+ core generates a larger total inventory of major volatile fission product groups (I, Cs, Te, Kr, Xe) compared to the SMART100 core, an expected consequence of its higher power and longer cycle. The power-scaled SMART100 inventory aligns more closely, yet a notable gap remains, providing an initial indication that higher burnup is a influencing factor beyond thermal power.

This burnup effect is definitively quantified through the analysis of individual isotopes. Fig. 2 plots the ratio of the SMART100 inventory to the LEU+ inventory and illustrates the disproportionate impact of the high-burnup strategy. For the short-lived isotope I-131, the power-scaled ratio is close to 1.0, confirming that its inventory scales directly with power. In contrast, the ratios for long-lived fission products Cs-137 and Sr-90 drop to ~0.67 after scaling, meaning the LEU+ core contains ~50% more of these nuclides than can be explained by power alone. This phenomenon is characteristic of high-burnup fuel and has direct implications for long-term land contamination risks.

The effect is even more pronounced for actinides like Pu-238 and Cm-244, where the ratio plummets to below 0.45, indicating that the LEU+ core generates more than double the inventory of these nuclides. This directly impacts the long-term radioactive toxicity and thermal load of spent nuclear fuel.

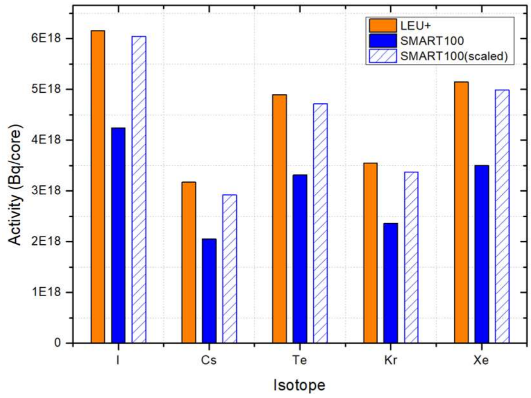

Fig. 1. Comparison of major isotopes fission product inventories

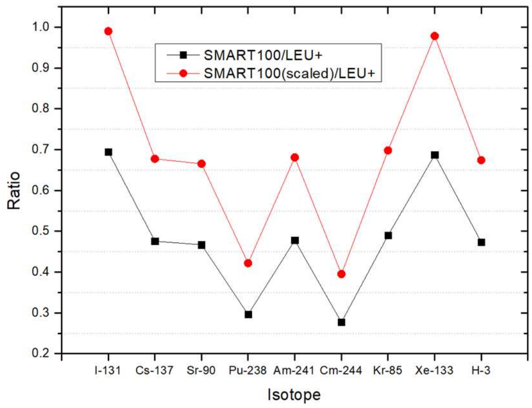

Fig. 2. Key Isotope Inventory Ratios

3.2 Decay heat characteristics and design implications

The decay-heat results follow the inventory trends. In the combined plot (Fig. 3), LEU+ shows a higher absolute decay-heat load at all times—even after power normalization—while the fractional curves diverge monotonically with cooling time. Quantitatively (Fig. 4), the LEU+–SMART100(scaled) gap in absolute decay heat grows from about 23% at 1 s to >90% by 10^9 s. Consistent with the fractional divergence—from ~20% at 1 s to ~90% by 10^9 s—this behavior reflects the larger accumulation of long-lived fission products and minor actinides in LEU+ and has direct implications for sizing residual heat removal, storage, and shielding.

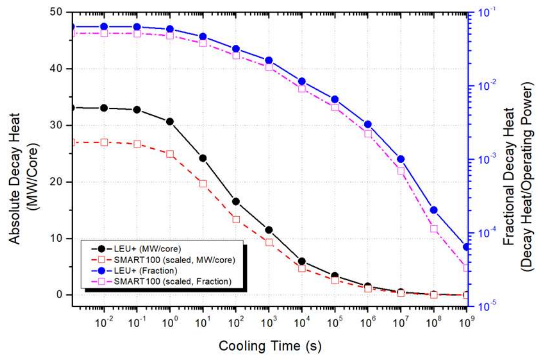

Fig. 3. Absolute decay heat (MW/core) and fractional decay heat $P(t)/P_0$

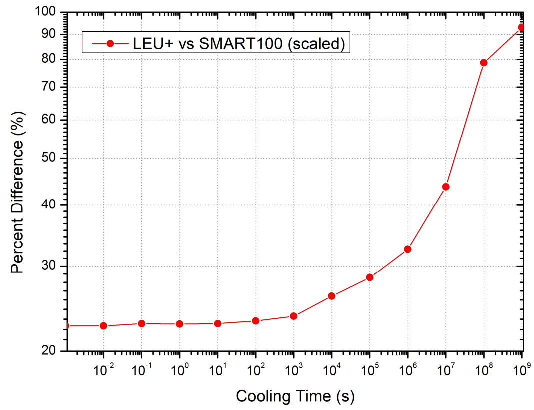

Fig. 4. Percent differences in absolute decay heat: LEU+ relative to SMART100(scaled)

As shown in Fig.5, log–log slopes are nearly identical, indicating similar cooling kinetics. SMART100 decays slightly faster around 10^7–10^8 s while LEU+ has a heavier long-time period (10^8–10^9 s), so the normalized fractions diverge and the absolute percent gap grows (~23%→~90%). In the Fig. 6, the LEU+ and SMART100(scaled) curves are separated by more than the ANSI/ANS-5.1-1979 [5] uncertainty. After 10^8 s (~3.2 years), the LEU+ lower bound lies above the SMART100 (scaled) upper bound. However, the absolute magnitudes are small, so early-time decay heat removal system sizing is largely unaffected; the difference may matter only for long-term storage/transport margins when heat-load limits are tight.

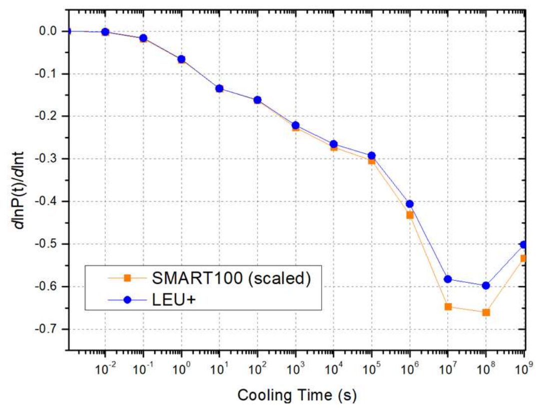

Fig. 5. Decay-heat reduction rate: SMART100(scaled) vs LEU+

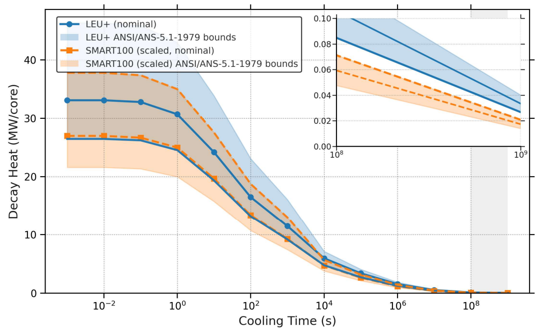

Fig. 6. Comparison of LEU+ and SMART100(scaled) decay heat with respective ANSI/ANS-5.1-1979 uncertainty bands

4. Conclusions

This study compared a high-burnup, long-cycle LEU+ core with the reference SMART100 SMR design. For consistency in comparison, the SMART100 results were scaled to the same operating power. The analysis was performed using the SCALE/ORIGEN code to evaluate fission product inventories and decay heat.

Even after power scaling, the LEU+ core showed larger fission product inventories. The main reason is the higher discharge burnup, which increases the buildup of long-lived fission products and actinides. Such behavior is expected at high burnup, but the size of the increase in this case was larger than anticipated.

Decay heat results also showed a clear separation. At the beginning of shutdown, the fractional decay heat of LEU+ was about 23% above SMART100, and after long cooling (beyond 10^7 s) the difference grew to more than 90%. This is not explained by power scaling and reflects a difference in decay heat characteristics. At later times, the LEU+ results stayed outside the ANSI/ANS-5.1-1979 uncertainty bands, which is more relevant to spent fuel storage and handling than to short-term decay heat removal.

Overall, the LEU+ core extends cycle length and improves fuel economy, but it also increases the fission product inventory and long-term decay heat, both of which contribute to the accident source term. These outcomes imply that decay heat removal, storage, and disposal strategies should be considered together with high-burnup fuel development, not as separate issues.

ACKNOWLEDGMENT

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