

# Management Strategy for High-Burnup and Extended-Cycle Spent Nuclear Fuel

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## 1. Introduction

Higher enrichment and higher discharge burnup are being considered to support longer operating cycles in pressurized water reactors. These changes increase decay heat, radiation source terms, and introduce additional margins to be demonstrated for criticality, thermal-hydraulic, shielding, and fuel integrity across storage, transport, and disposal. This paper organizes the key impacts of high-burnup and extended-cycle fuel and summarizes a practical set of management strategies from fresh fuel storage through deep geological disposal, based on the compiled strategy material.

## 2. High-Burnup and Extended-Cycle Fuel Characteristics

In the considered scenario, the initial enrichment increases from conventional 5 wt% U-235 toward the low-enriched uranium plus (LEU+) range up to 10 wt% U-235, while discharge burnup increases to approximately 60,000-80,000 MWd/MTU and the cycle length extends from 18 months to 24 months (PWR basis).

The management scope spans (i) fresh fuel storage, (ii) spent fuel pool regions with different rack configurations, (iii) onsite/offsite transportation, (iv) dry storage systems (metal or concrete casks/modules), and (v) final disposal in a deep geological repository.

## 3. Safety Considerations

Four cross-cutting considerations dominate the safety case for high-burnup and extended-cycle spent fuel: (1) higher decay heat requiring strengthened thermal management; (2) higher radiation fields driving shielding design and remote handling improvements; (3) potential degradation of cladding integrity under long exposure histories that must be demonstrated for storage and transport; and (4) reduced criticality margin for fresh fuel due to higher enrichment, requiring engineered neutron absorbers and/or increased lattice spacing.

### 3.1. Fuel integrity and degradation mechanisms

At higher burnup, zirconium-alloy cladding experiences oxide layer growth that reduces thermal conductivity and raises fuel rod centerline temperature, which can degrade mechanical integrity. Hydrogen uptake during oxidation can form hydrides, reducing ductility and increasing embrittlement. Increased fission gas release raises rod internal pressure, increasing hoop stress and the risk of deformation or failure. The

combined effects of pressure, embrittlement, oxide and hydrides can raise the susceptibility to creep deformation and stress corrosion cracking. Additional topics typically requiring evaluation include pellet-cladding interaction (PCI), grid fretting wear, embrittlement under LOCA-related conditions, and power ramp events. Accordingly, hot-cell testing and characterization are recommended to support integrity demonstrations for high-burnup and long-cycle fuel.

## 4. Management Strategies by Facility/Phase

### 4.1. Fresh fuel storage and spent fuel pool Region I

Existing fresh fuel storage may rely on geometric spacing without neutron absorbers. For LEU+ fresh fuel, reuse of existing racks may no longer satisfy criticality requirements. Two practical options are (i) re-racking to increase lattice spacing, and/or (ii) installing racks that incorporate neutron-absorbing materials to restore criticality margin.

### 4.2. Spent fuel pool Region II

Region II racks typically use both spacing and neutron absorbers, with additional controls such as limiting pool water level to manage shielding and using heat exchangers for thermal safety. For high-burnup and extended-cycle fuel, recommended actions include:

- Criticality: perform verification and validation (V&V) of criticality analysis methods and, if needed, increase B4C absorber content, increase spacing, and/or apply boron credit approaches. Fig. 1 shows a virtual loading curve considering spent nuclear fuel in a SFP Region II.

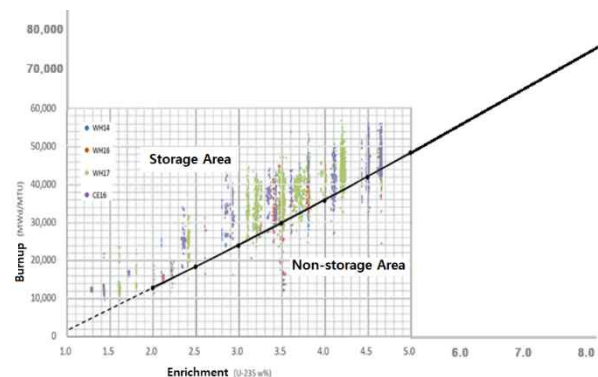


Fig. 1 Loading Curve of SFP Region II

- Shielding: re-evaluate the surface dose design target (e.g., 25  $\mu$ Sv/h) including radiological impacts under

handling and credible accident conditions (including cask drop considerations). Operationally, this can be supported by increasing pool water level and minimizing handling time during spent fuel withdrawal and loading.

- Thermal: re-assess local and bulk pool temperature margins, potentially reducing withdrawal/loading rate (e.g., from 6 assemblies/h to 4 assemblies/h) and upgrading heat exchanger capacity.

- Structural/seismic: re-perform structural and seismic evaluations to reflect increased thermal stresses. Where higher enrichment reduces total assembly mass, some drop-load bounding cases may be reduced, but this should be justified case-by-case.

#### 4.3. Transportation and dry storage systems

For transport and dry storage, systems should maintain criticality and shielding safety while meeting material-specific temperature and stress limits. An example set of cladding acceptance criteria includes cladding temperature  $\leq 400^\circ\text{C}$ , hoop stress  $\leq 90\text{ MPa}$ , and a limit on thermal cycles (e.g.,  $\leq 10$ ).

Management options for high-burnup fuel focus on extending cooling time before transfer, reducing the number of assemblies per cask, and optimizing assembly loading patterns to reduce external dose while also satisfying thermal criteria. As in pool storage, criticality method V&V and, if necessary, absorber content or configuration adjustments (including boron credit where applicable) are key. Thermal stress increases can also motivate updated structural/seismic assessments.

#### 4.4. Implications for deep geological disposal

In repository concepts, the thermal capacity of the disposal canister is often a key design driver. A comparison between a reference case (5 wt% U-235, 60 GWd/MTU) and a higher burnup case (8 wt% U-235, 80 GWd/MTU), under similar discharge power assumptions, indicates that activity and heat differences can peak around 7-11 years after discharge (approximately  $1.7 \times 10^5\text{ Ci}$  and 640 W per ton U difference), and remain non-negligible even at 100 years (about 200 W difference). Therefore, disposal package heat-load and spacing design should explicitly incorporate the high-burnup inventory, rather than relying on conventional fuel bounding assumptions. Fig. 2 shows a decay heat curves according to enrichment & burnup.

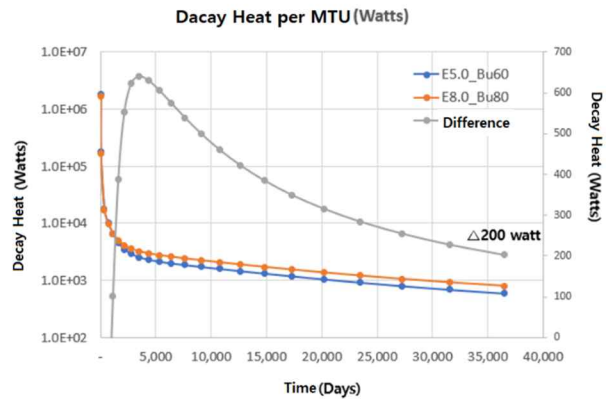


Fig. 2 Decay Heat according to Enrichment & Burnup

## 5. Conclusions

High-burnup and extended-cycle spent fuel increases source terms and can narrow margins for criticality, shielding, thermal performance, and cladding integrity across storage, transport, and disposal. A coherent management strategy combines engineered criticality controls (spacing and absorbers), updated dose and thermal evaluations with operational controls, integrity characterization supported by hot-cell testing, and design updates for dry storage and disposal heat loads. Early method V&V and staged upgrades (rack/cask loading changes, cooling time extensions, and heat removal enhancements) can provide practical pathways to safely accommodate LEU+ and higher burnup fuel.

## REFERENCES

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