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Preliminary Development of a Reload Cycle BOC Hoop Stress Table for PCI Evaluation in an SMR

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1. Introduction

Small modular reactors (SMRs) are being developed for long-cycle and flexible operation, while their compact core geometry can increase neutron leakage and complicate fuel utilization [1,2]. For advanced SMR fuel designs, pellet-cladding interaction (PCI) therefore needs to be assessed not only for normal depletion but also for power changes that produce rapid pellet thermal expansion. Previous full-core LEU+ SMR analyses showed that cladding hoop stress is strongly affected by local power history and by the duration of power ramps, demonstrating the importance of realistic operating histories in PCI assessment.

This work therefore develops a reduced-order PCI screening method in which cladding hoop stress, one of the PCI risk indicators, is pre-calculated with FRAPCON[3] and organized as a burnup-dependent lookup table. The present paper focuses specifically on the beginning-of-cycle (BOC) condition of reload cycle and establishes the analysis procedure and preliminary hoop-stress values.

2. PCI Stress-Table Framework

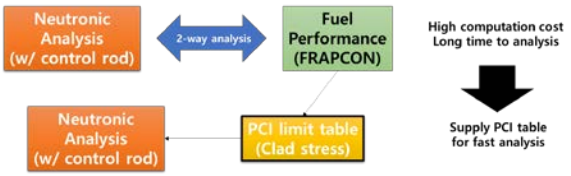


Fig. 1. Concept of a pre-calculated PCI hoop-stress table for SMR core screening.

The DeCART2D/MASTER core calculation provides pin-wise and axial power distributions over burnup [4, 5]. These distributions are screened to identify bounding fuel-power conditions, and fuel-performance calculations are then performed in advance. The resulting maximum cladding hoop stress is stored as a function of burnup and prescribed power history. During core analysis, this table can be used as a rapid PCI screening index, while detailed coupled analysis is reserved for limiting cases. Figure 1 summarizes this reduced-order concept.

3. Reload Cycle BOC Analysis Methodology

The reload cycle BOC analysis was performed in two sequential steps. First, the irradiation time corresponding to each target end of previous cycle burnup was determined. Based on the resulting end-of-cycle state, a new power history was constructed to initiate reload cycle at the prescribed burnup. The maximum cladding hoop stress during the subsequent reload cycle BOC startup was evaluated from this reconstructed history.

3.1 Step 1: Conservative Burnup-to-EFPD Mapping

The axial- and burnup-dependent powers of all fuel rods obtained from the SMR core calculation were screened, and the largest extracted linear heat generation rate (LHGR), 302.778 W/cm, was selected as the conservative 100% reference power. A bounding FRAPCON history was generated using this value with a uniform axial power factor of 1.0. The prescribed conservative power history is shown in Fig. 2, which is based on the fuel preconditioning guideline of 3% core power increase per hour. The calculation was continued from fresh fuel, and the effective full-power day (EFPD) corresponding to each target burnup from 10 to 50 GWd/MTU was extracted. These EFPD values define the end of previous cycle used in Step 2.

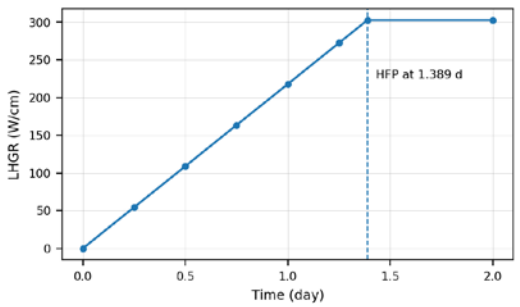


Fig. 2. Conservative power history used to establish the burnup-to-EFPD relation.

3.2 Step 2: BOC Power-History Reconstruction

For each target burnup, the EFPD obtained in Step 1 was used to terminate the previous cycle at the desired

burnup. A new input history was then constructed with a 60-day shutdown/hold period, followed by the BOC startup from 0 to 100% power over 1.389 day (33.334 h). Thus, BOC in this study denotes the beginning of reload cycle, not the initial startup of fresh fuel. The reconstructed history is schematically shown in Fig. 3. The maximum cladding hoop stress occurring only within this BOC interval was recorded as the lookup-table value.

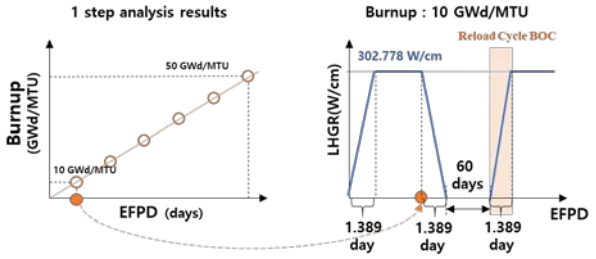


Fig. 3. Reconstructed power history for the BOC hoop-stress evaluation.

4. Results and Discussion

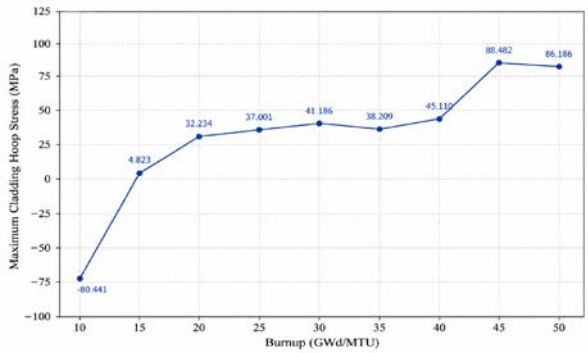


Fig. 4. Maximum cladding hoop stress during the BOC power ramp.

Figure 4 summarizes the maximum cladding hoop stress during the BOC startup as a function of burnup. At 10 GWd/MTU, pellet-cladding contact does not occur even after the BOC power increase, and the cladding remains under compressive loading, giving a maximum hoop stress of -80.441 MPa. From 15 GWd/MTU, pellet-cladding contact occurred during the BOC power increase and the maximum hoop stress became tensile. The calculated values are 4.823, 32.234, 37.001, 41.186, 38.209, 45.110, 88.482, and 86.186 MPa at 15, 20, 25, 30, 35, 40, 45, and 50 GWd/MTU, respectively. Thus, the maximum hoop stress generally increases with burnup, although small decreases are observed in some burnup intervals. In contrast, the calculated cladding hoop strain increases continuously with burnup, and the cladding temperature also shows a continuous increase as burnup increases. The non-monotonic variation in hoop stress may be associated with strain- and temperature-dependent cladding material behavior, including stress softening and relaxation. Because the cladding hoop strain and temperature both increase with burnup, these effects may partially offset the increase in mechanical loading at selected burnup intervals. Further assessment is planned to quantify the respective contributions of cladding temperature, deformation, and material softening to the local reductions in maximum hoop stress.

5. Conclusions

A burnup-dependent hoop-stress table was developed as a reduced-order PCI screening tool for SMR core analysis using the reconstructed BOC power histories. The results show a clear transition in PCI behavior with burnup. At 10 GWd/MTU, pellet-cladding contact does not occur during the BOC startup and the cladding hoop stress remains compressive (-80.441 MPa), whereas contact begins during the BOC power increase from 15 GWd/MTU and the hoop stress becomes tensile. The maximum hoop stress generally increases with burnup and reaches 88.482 MPa at 45 GWd/MTU, although modest decreases occur at selected burnup intervals. Meanwhile, both cladding hoop strain and temperature increase continuously with burnup. These results suggest that the burnup dependence of the maximum hoop stress is governed primarily by the development of pellet-cladding contact and may also be influenced by strain- and temperature-dependent cladding material behavior. Additional analyses will be performed to evaluate these effects in more detail and to support refinement of the PCI stress-table methodology.

Acknowledgment

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