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Development of a PCI Analysis Framework Using Cumulative Damage Index (CDI) Model in Smeared-Pellet Fuel Performance Codes and Its Application to the Load-Following PWR Fuel Safety Assessment

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1. Introduction

Pellet–cladding interaction(PCI) is a primary threat to fuel integrity during load-following operation in light water reactors. Most fuel performance codes adopt a smeared-pellet structural mechanics framework. It lacks the spatial resolution to capture local stress concentrations at pellet radial cracks and pellet–pellet interfaces. Accordingly, implementing a stress concentration model into GIFT fuel performance code is essential for cladding integrity assessment under PCI condition. Futhermore, local stress concentrations, combined with fission products and cladding material properties, drive Stress Corrosion Cracking(SCC). Therefore, deterministic failure criteria based on stress are insufficient to characterize its complex behavior. To address these limitations, a probabilistic Cumulative Damage Index(CDI) model is introduced for quantitative SCC assessment. The enhanced GIFT code is coupled with a core analysis code to simulate full-core load-following scenarios, establishing a PCI–SCC fuel integrity assessment framework at the core scale.

2. Code development

Stress concentration correlation model using ANSYS, three-dimensional finite element analysis commercial program, is implemented into the GIFT fuel performance code alongside a CDI model, enhancing its PCI failure prediction capability. The upgraded GIFT code is coupled with the core analysis code SPHINCS (Simplified P3 Pin Homogenized Innovative Neutronics Core Simulator) to establish a full-core analysis framework for load-following operation[1]. This section provides an overview of each model and their integration within the core-fuel coupled code.

2.1 Stress concentration model

To evaluate local stress concentration effects, cladding geometries are constructed in ANSYS with boundary conditions derived from GIFT simulation results. The inner cladding surface is partitioned such that interfacial pressure is applied to pellet-cladding contact regions, while inner pressure is assigned to non-contact surfaces including pellet radial cracks and pellet–pellet interfaces. Stress concentration correlation based on burnup and power history is obtained from ANSYS results and implemented into GIFT, enhancing local stress evaluation under PCI conditions.

2.2 Cumulative Damage Index model

The CDI model quantifies SCC behavior and evaluates cladding integrity through probabilistic assessment. The model is based on empirical correlation derived from Zircaloy-4 experimental data, calculating failure time obtained from burnup and stress[2]. Cladding failure probability is assessed by accumulating the ratio of stress-holding time to the corresponding failure time over the stress history.

In Eq. (1), D denotes the damage fraction, Δt_i the stress-holding duration at time step i, and $t_{f,i}$ the corresponding failure time at the same time step[2].

$$D = \sum_{i=1}^{n} \Delta t_i / t_{f,i} \tag{1}$$

The failure time t_f is based on stress, burnup, and cladding temperature, defined as follows:

$$t_f = f(\sigma, \sigma_{ref}, \sigma_y, Bu, T) \tag{2}$$

where σ, σ_{ref}, σ_y, Bu, and T are applied hoop stress, burnup-dependent threshold stress, yield stress, burnup, and cladding temperature, respectively.

σ = applied hoop stress [MPa]
σ_{ref} = burnup dependent threshold stress [MPa]
σ_y = yield stress [MPa]
Bu = burnup [MWd/TU]
T = cladding temperature [K]

Since t_f is derived from out-of-pile test data, it remains a deterministic function governed by stress[2, 3]. To enable probabilistic assessment, *D = 1* is assigned as the 50% failure probability, with the failure probability range extended to 5% and 95% corresponding to *D = 0.1* and *D = 10*, respectively[2, 3].

2.3 Core-fuel integrated simulation

As burnup increases in load-following operation, the pellet-cladding gap closes. Subsequent power reduction during load-following causes the gap to reopen. Additionally, power ramping change fuel temperature and fission product density in the pellet, affecting core reactivity. Accurate load-following analysis requires feedback analysis between core and fuel behavior. While most core analysis codes calculate pellet temperature using fuel temperature tables, this approach is insufficient for capturing the feedback effects in load-following operation[1]. To address this, GIFT and SPHINCS are coupled to establish an integrated load-following analysis framework. As illustrated in Fig. 1, SPHINCS transfers pin power, burnup, neutron flux, isotopic density to GIFT for fuel performance analysis, and the resulting pellet centerline and surface temperatures are returned to SPHINCS for core neutronics calculation[1].

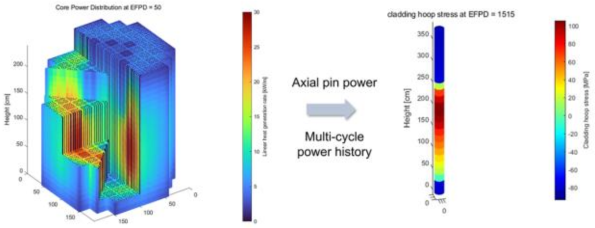

Fig. 1. Full-core simulation scheme using a coupled core(SPHINCS)-fuel(GIFT) analysis code[1].

3. PCI failure prediction

In this section, PCI failure analysis is conducted using the GIFT fuel performance code enhanced with stress concentration and CDI modules, and cladding integrity under PCI–SCC during load-following operation is evaluated through the coupled core(SPHINCS)-fuel(GIFT) analysis framework.

3.1 Stress concentration analysis

Stress concentration analysis are conducted using in-pile experimental data from the IFPE(International Fuel Performance Experiments) database, specifically the OVER-RAMP and SUPER-RAMP programs, which target PCI behavior over burnup ranges of 15–33 MWd/kgU and 33–45 MWd/kgU, respectively. In this study, a total of ten fuel rods (OVER-RAMP 7 rods, SUPER-RAMP 3 rods) are selected for stress concentration analysis using ANSYS. The average hoop stress at pellet-contact surfaces compares well with GIFT results within 50 MPa, while the maximum hoop stress at non-contact surfaces where stress concentration occurs is evaluated to be significantly higher, as shown in Fig. 2.

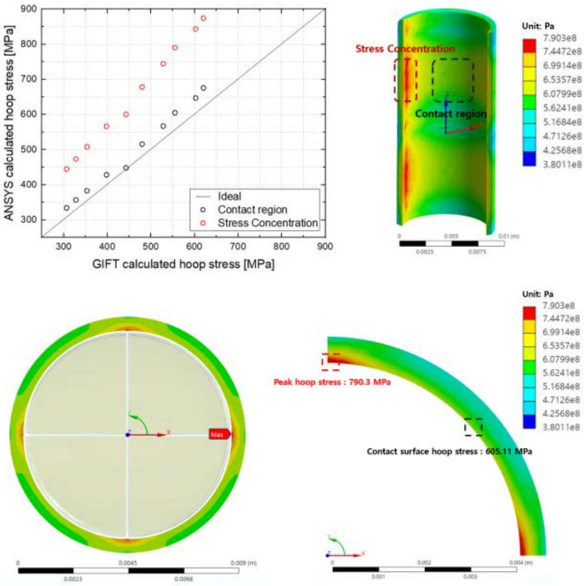

Fig. 2. Comparison between hoop stress calculated using ANSYS and GIFT from ‘OVER-RAMP.’

To incorporate stress concentration effects into GIFT while preserving its computational efficiency as a smeared-pellet fuel performance code, Stress concentration factors are defined as correlations of burnup and power history, as given in Eq. (3), enabling efficient PCI analysis within the existing framework.

$$\sigma_{\theta,peak} = f(Burnup, Power\ history)\cdot\sigma_{\theta}^{GIFT} \qquad (3)$$

Furthermore, ANSYS analysis enables evaluation of local stress concentrations in the r-θ plane, capturing the hoop stress at the inner cladding surface adjacent to pellet radial cracks. By applying the stress concentration effects to the applied hoop stress input of the CDI model, accurate cladding integrity assessment under PCI–SCC conditions is achieved.

3.2 PCI-SCC failure analysis

Deterministic failure assessment based on hoop stress cannot clearly discriminate between failed and non-failed rods, as non-failed rods are observed at stress levels exceeding those of failed rods. In contrast, CDI-based evaluation shows that no non-failed rods exist above the 95% failure boundary, as shown in Fig. 3. Since PCI–SCC failure involves the combined effects of stress, fission products, and cladding material properties, probabilistic CDI assessment should be considered alongside deterministic hoop stress criteria.

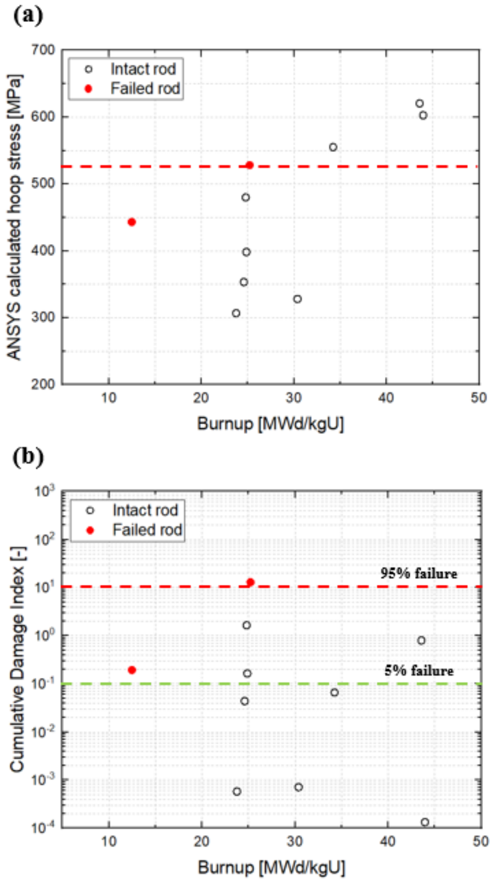

Fig. 3. PCI-SCC failure analysis (a) deterministic limit by hoop stress (b) probabilistic limit by CDI coupled with stress concentration correction

The CDI model adopted in this study is based on empirical correlations derived from Zircaloy-4 experimental data[3]. SCC behavior is strongly dependent on cladding material properties. Therefore, direct application of this model to alternative cladding materials or coated zircaloy is limited. For such cases, recalibration of model parameters—including threshold stress and failure time constants—using corresponding experimental data is required. For coated claddings, where surface chemistry and fission product interactions may differ significantly, modification of the functional form of the failure time model may also be necessary.

3.3 Load following operation analysis using core-fuel coupled code

Load-following operation scenario adopts a monthly cycle applied to a soluble boron free SMR. In this scenario, the reactor operates at full power for three months, ramps down to 50% power over two hours, maintains reduced power for three months, and then ramps back up to 100% power. The ramp rate is set to 25%/hr based on the EPRI User Requirements Document Rev. 12.[4].

During load-following operation, hoop stress rises sharply upon power ramp-up due to gap closure and xenon effects. CDI accumulation is observed at these points, as shown in Fig. 4. The CDI values remain below 1, reflecting the short duration of elevated stress exposure. As CDI represents cumulative damage in the cladding, its value is maintained over subsequent operation in Fig. 4.

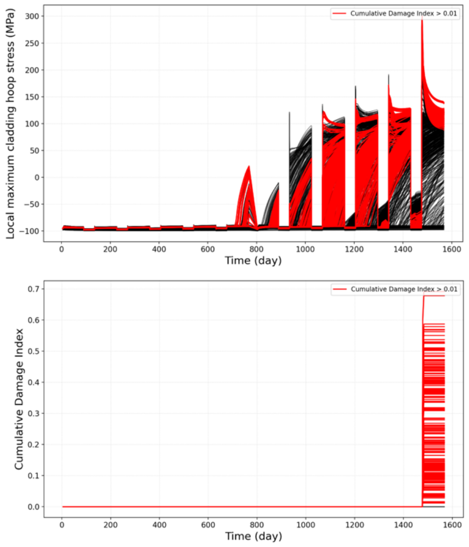

Fig. 4. Local maximum cladding hoop stress and Cumulative Damage Index(CDI) based on time in load-following operation for a soluble boron free SMR.

The integrated coupled core–fuel analysis enables full-core PCI–SCC fuel integrity evaluation under load-following operation, providing a basis for optimizing fuel rod loading patterns and predicting cladding damage. A quarter-core model is employed for computational efficiency, and the capability to assess PCI-SCC damage distribution at the core scale is shown in Fig. 5.

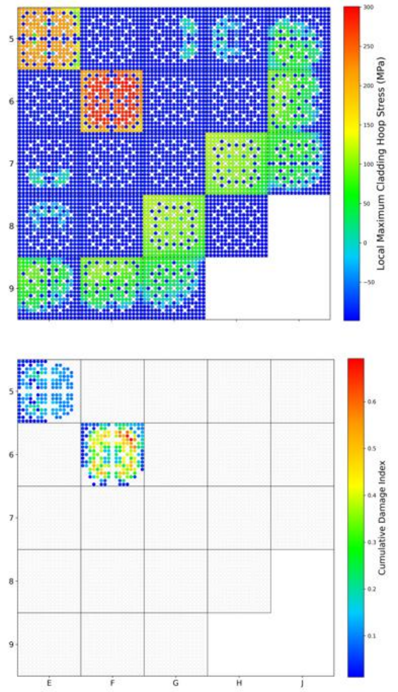

Fig. 5. Local maximum hoop stress and CDI in monthly load-following operation for soluble boron free SMR.

4. Conclusions

PCI–SCC fuel integrity assessment framework was developed by integrating stress concentration and CDI models into the GIFT fuel performance code. Stress concentration correlation derived from three-dimensional ANSYS analysis was implemented into GIFT, enabling local stress evaluation within a smeared-pellet formulation. CDI-based probabilistic assessment more clearly discriminates between failed and non-failed rods than deterministic hoop stress criteria, as validated against IFPE in-pile experimental data. The enhanced GIFT code was coupled with SPHINCS for full-core load-following analysis. CDI accumulation was confirmed to occur primarily during power ramp-up events. This framework provides a physically grounded and practical approach for PCI–SCC safety evaluation at the core scale under load-following operation.

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