Development of Rapid PCI Risk Evaluation Methodology based on Hoop Stress Assessment

Hak-Kyu Yoon, Yun-Seong Nam, Jeong-Hyeon Kim, Ok-Joo Kim, Jae-Myung Choi
KEPCO Nuclear Fuel Co. Ltd., 989beon-gil 242, Daedeok-daero, Yuseong-gu, Daejeon 305-353, Korea

1. Introduction

- There is currently significant growth in generation from renewable energy sources, because of strategies to reduce carbon emissions in order to meet government policies. There is, therefore, an increasing need to transition an existing nuclear power plant from baseload operation to flexible power operations (FPO).

- FPO involves subjecting the fuel to complex time-varying power histories that could increase the duty on the fuel rods and potentially challenge their integrity, especially by pellet cladding interaction (PCI).

- Finite element analysis is generally used to assess PCI risk due to local stress analysis methodologies related to PCI (cladding gap closure kinetics assessment).

- Due to thermal and irradiation effects and operation condition, the cladding creeps inward until contact with the pellet is reached. Once pellet to cladding contact occurs the tensile stress increases until there is equilibrium between the cladding stress relaxation due to creep and the outward expansion due to swelling.

- Linear heat rate (LHR) also has an important effect for contact and cladding stress, and Figure 1 shows the relation of burnup and stress at a higher and lower LHR. For higher LHR, the gap has closed faster than lower LHR. At zero power, the gap thickness for higher LHR is larger than lower LHR due to larger power change.

2. Pellet-cladding gap behavior and hoop stress

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3. Pellet-cladding gap closure kinetics assessment

- The hoop stress increases proportionally to power after gap closed. It is therefore possible to assess the hoop stress as power to zero stress (called, PZS). PZS is related to gap closure kinetics and gap closure depend on the cladding creep laws and fuel pellet irradiation behavior. This behavior for cladding and pellet depends on the power so PZS can be assessed using PZS curve which is generated by calculation results of fuel performance code (ROPER) at various constant depletion power. PZS is related to gap closure kinetics and gap closure depend on the cladding creep laws and fuel pellet irradiation behavior. This behavior for cladding and pellet depends on the power so PZS can be assessed using PZS curve which is generated by calculation results of fuel performance code (ROPER) at various constant depletion power.

- Figure 3 shows three PZS curve with two constant depletion power 7 kW/ft (blue solid curve) and 4.3 kW/ft (green solid curve) and combined power (open dot) which is 7 kW/ft to 16 MWd/kgU (solid dot), and then 4.3 kW/ft. The PZS of the rod until about 16 MWd/kgU can be assessed along the blue solid curve, and the PZS after about 16 MWd/kgU can be assessed along the green dash curve. PZS is related to gap closure kinetics and gap closure depend on the cladding creep laws and fuel pellet irradiation behavior. This behavior for cladding and pellet depends on the power so PZS can be assessed using PZS curve which is generated by calculation results of fuel performance code (ROPER) at various constant depletion power. PZS is related to gap closure kinetics and gap closure depend on the cladding creep laws and fuel pellet irradiation behavior. This behavior for cladding and pellet depends on the power so PZS can be assessed using PZS curve which is generated by calculation results of fuel performance code (ROPER) at various constant depletion power.

4. Fuel reconditioning kinetics assessment

- Changes in the pellet diameter due to power increase induced temperature changes strain the cladding. If the power maintains, the cladding hoop tensile stress gradually decreased due to cladding creep as shown in Figure 6.

- A hoop stress decrease means an increase of PZS. Therefore in positive stress region the PZS can be assessed by hoop stress decrease curve. For example when the hoop stress goes from 300 MPa to 190 MPa (circle dot in Figure 6), the PZS increase 1.7 kW/ft (rectangular dot in Figure 6).

5. Hoop Stress evaluation results

- The hoop stress evaluation was performed using the power histories of rods in APR1400. It was conformed that the hoop stress assessment methodology simulates the ROPER and ABAQUS 3D model results well.

6. Conclusion

- Using the calculation results of ROPER code and ABAQUS 3D model, PZS assessment methodology was developed. As a result of comparison between ROPER code and ABAQUS 3D model and this methodology, this methodology simulates calculation results well. In the future, we plan to use hoop stress assessment methodology for PCI risk evaluation in startup and normal operation transient.

Figure 1. Gap and stress evaluation vs. Burnup

Figure 2. Hoop stress vs. local power

Figure 3. PZS assessment methodology

Figure 4. Comparison of ROPER calculation and PZS assessment methodology

Figure 5. PZS penalty

Figure 6. Hoop stress and ΔPZS vs. time

Figure 7. Hoop stress comparison between ROPER and PZS assessment methodology

Figure 8. Hoop stress comparison between ABAQUS model and PZS assessment methodology