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

Hak-Kyu Yoon*, Yun-Seog 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
*Corresponding author: hkyoon@knfc.co.kr

1. Introduction

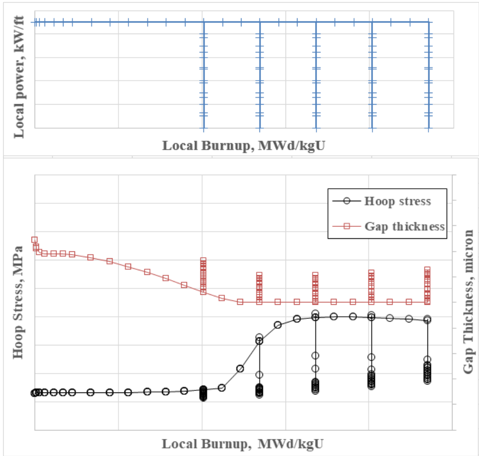
There is currently significant growth in generation from renewable energy sources, because of strategies to reduce carbon emissions in order to meet government policies. There is, therefore, an increasing need to transition an existing nuclear power plant from baseload operation to flexible power operations (FPO). However, 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)[1].

Finite element analysis is generally used to assess PCI risk due to local stress analysis and it takes long time. In addition, PCI risk is affected by time-varying power histories, it is necessary to evaluate many rod cases. Therefore, rapid PCI risk evaluation methodology is developed using results of a previous study [2].

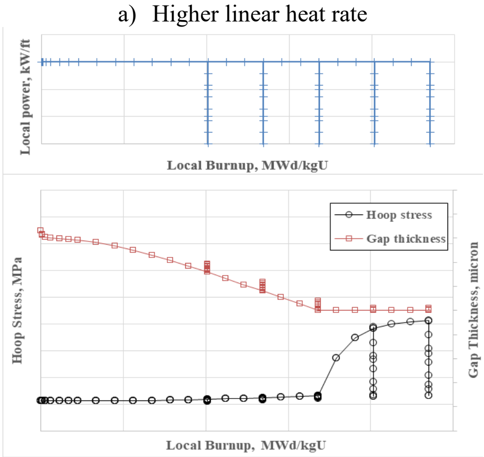
2. Pellet-cladding gap behavior and hoop stress

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.

Figure 2 shows the hoop stress change for higher and lower LHR ramping to same local power after shutdown at middle burnup. As shown in Figure1, gap thickness of lower LHR at zero power is smaller. When local power increases, the gap at lower LHR is closed faster than higher LHR. Hoop stress of lower LHR at final power is higher than higher LHR because the hoop stress increases proportionally to power after gap closed.



a) Higher linear heat rate



b) Lower linear heat rate

Figure 1. Gap and stress evaluation vs. Burnup

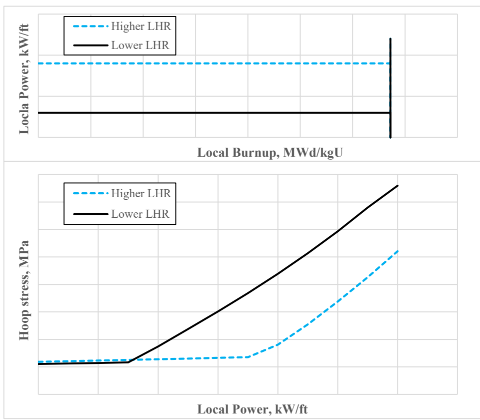


Figure 2. Hoop stress vs. local power

3. Pellet-cladding gap closure kinetics assessment

As previously mentioned, the hoop stress increases proportionally to power after gap close. 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. 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. Figure 4 shows comparison of ROPER results and results for PZS assessment methodology.

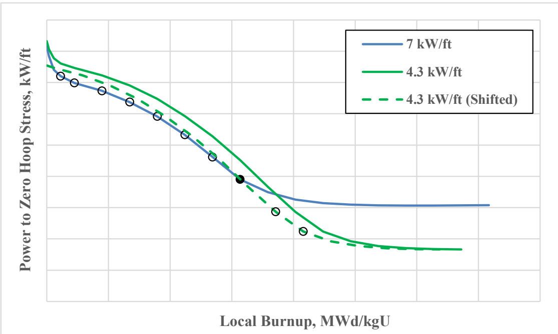


Figure 3. PZS assessment methodology

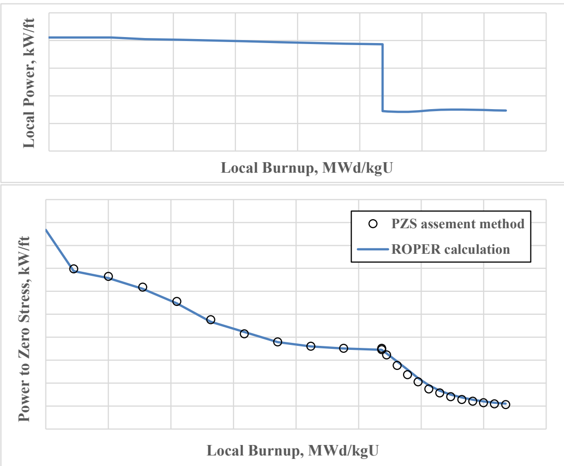


Figure 4. Comparison of ROPER calculation and PZS assessment methodology

Maximum local pellet diameter calculated by ABAQUS 3D FEM model is higher than ROPER code due to pellet hour-glassing and defect. Therefore the PZS for ABAQUS model is lower than ROPER in low burnup region and higher in high burnup. The PZS curve for ABAQUS 3D FEM can be obtained by imposing a penalty on the PZS curve for ROPER. Figure 5 shows the penalty which was determined using ABAQUS[2] and ROPER calculation results.

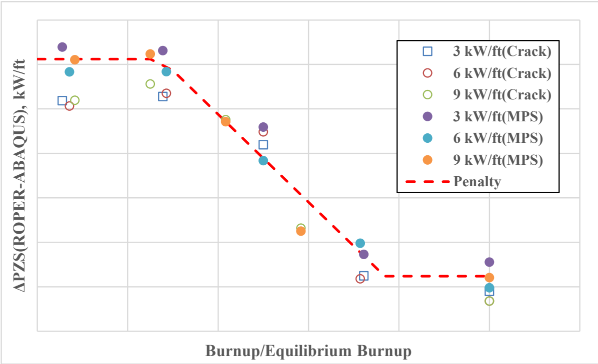


Figure 5. PZS penalty

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).

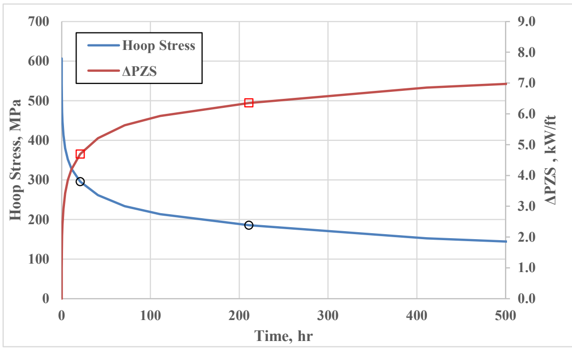


Figure 6. Hoop stress and ΔPZS vs. time

5. Hoop Stress evaluation results

The stress evaluation was performed using the power histories of rods in APR1400. Figure 7 and 8 show hoop stress comparison between ROPER or ABAQUS 3D model calculation and hoop stress assessment methodology. It was confirm that the hoop stress assessment methodology simulates the ROPER and ABAQUS 3D model results well.

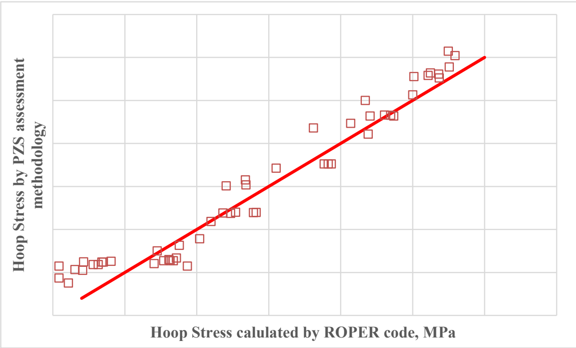


Figure 7. Hoop stress comparison between ROPER and PZS assessment methodology

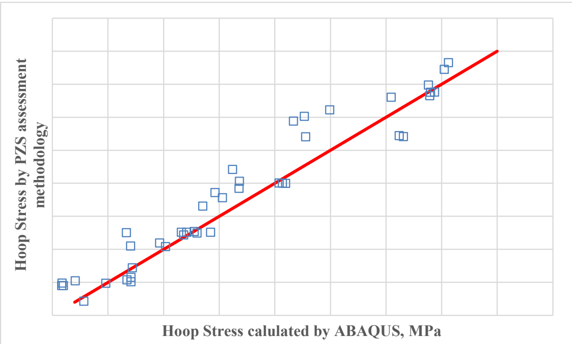


Figure 8. Hoop stress comparison between ABAQUS model and PZS assessment methodology

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.

REFERENCES

[1] S. Yagnik, An Assessment of Fuel Performance Requirements for Baseload Nuclear Power Plants Transitioning to Flexible Power Operations, 3002009087, EPRI, October 2016.

[2] Yun-seog Nam, et al., Ramp Test Rods Analysis using ROPER and ABAQUS, Transactions of the Korean Nuclear Society Spring Meeting Jeju, Korea, May 13-14, 2021.