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Startup Ramp Rate Analysis for the OPR1000 Using FALCON Code

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1. Introduction

Most of nuclear power plant restricts the power ramp rate for preventing fuel rod damage by pellet-cladding interaction (PCI). PCI fuel failure results from a combination of mechanical and chemical interactions between the UO_2 fuel pellets and Zircaloy cladding [1]. Under restart operation conditions, the pellet-cladding gap may be closed and the differential thermal expansion can result in the stress concentrations on the cladding that may cause the fuel failure. This paper summarizes the PCI sensitivity assessment of the PLUS7 fuel during the OPR1000 startup.

2. Modeling Approach and Assumption

OPR1000 is a 2-loop PWR with rated thermal power of 2815 MWth. The reactor core is loaded with 177 PLUS7 assemblies (16x16) manufactured by KEPCO Nuclear Fuel (KepcoNF). Initial Startup ramp rate limitation of OPR1000 after refueling is 10%/hr until 15%, 5%/hr from 15% to 40% and 3%/hr from 40% to 100% of rated thermal power. This analysis is based on once-burned nuclear fuel because the gap between pellet and cladding is closed at about 10,000 MWD/MTU.

2.1 Modeling Approach

FALCON is a fuel rod behavior analysis code developed by EPRI. The FALCON fuel rod behavior code version 1.2 was used to perform the PCI analysis in this paper. Falcon Fuel Rod Performance Code, Version 1.2, is a combined steady-state and transient thermal/mechanical finite element (FE) code for analyzing light water reactor fuel behavior.

The modeling approach employed by Falcon can analyze both normal operation and accident conditions for fuel rod average burn-up levels approaching 80 gigawatt days per metric ton of uranium (GWd/tU).

Falcon is a two-dimensional FE analysis code for modeling fuel rods as an axisymmetric structure in R-Z space or as a cross-sectional slice in R-Theta coordinates space. A fully coupled thermal and mechanical solution is used to solve both steady-state and transient analyses. The robust mechanical solution allows Falcon to compute large cladding deformations such as wall thinning and ballooning as seen in loss of coolant accidents (LOCAs).

The ability to utilize R-Theta coordinate-based models also allows Falcon to perform very detailed local-effects analyses for essential cladding failure determinations. These characteristics enable the application of Falcon to a wide range of fuel performance predictive analyses that traditional approaches typically required more than one code to address.

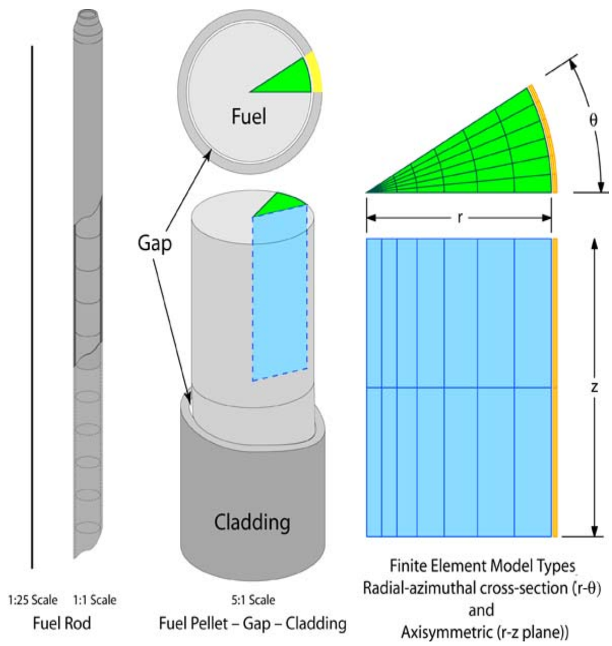

Figure 2-1. Diagram of FALCON Geometry Modeling Scope

2.2 Assumption

The geometric mechanical model for KepcoNF 16x16 PLUS7 fuel rod were constructed with detailed fuel design data like table2-1 for the PCI analysis.

Table 2-1 Main Parameters for Analysis

Main Parameters
Cladding Outer Diameter (cm)
Cladding Inner Diameter (cm)
Cladding Density (kg/m$^{3)}$
Fuel Roughness (microns)
Fuel Pellet Outer Diameter (cm)
Fuel Column Length (cm)
Fuel Enrichment (w/o U235)
Fuel Grain Size (μm)
Initial Fuel Density (% T.D.)
Gas Pressure (MPa)
Spring Constant (N/m)
Coolant Inlet Temperature (^{o}C)
Coolant Outlet Temperature (^{o}C)
Coolant Pressure (psia)
Coolant Mass Velocity (Mlbm/ft2/hr)
Hydraulic Diameter (m)

For the conservative analysis, a fuel rod with maximum power is chosen like figure 2-2. So This analysis assumes that the pin power of cycle 1 is 8.36 kw/ft and the pin power of cycle 2 is 7.52 kw/ft. The actual operation data is applied for the axial power distribution like figure 2-3.

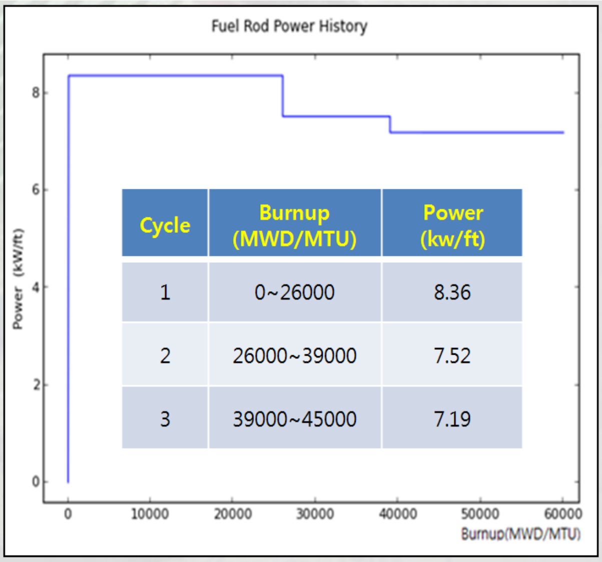

Figure 2-2. Power History[Maximum Pin Power]

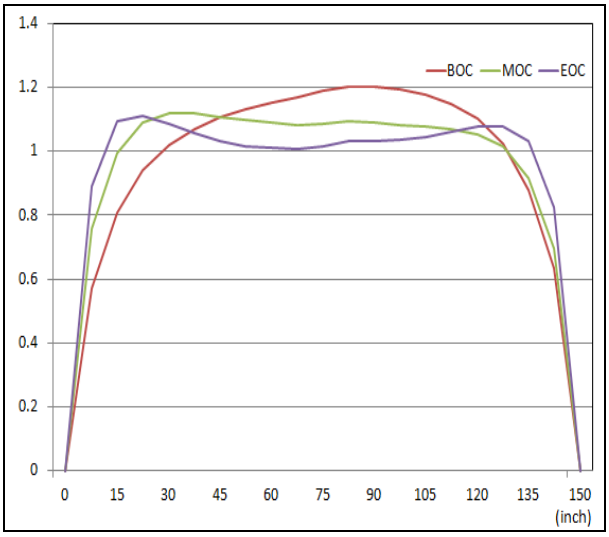

Figure 2-3. Axial Power Distribution

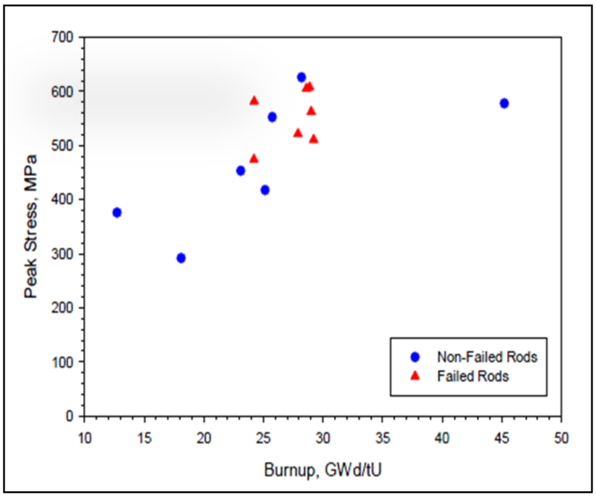

Figure 2-4. Cladding Failure Threshold by Hoop Stress

Case	Burnup (GWd/tU)	Non-Fail [Hoop Stress]	Fail [Hoop Stress]
1	24.2	417.6 MPa	474.2 MPa
2	23.4	552.2 MPa	581.3 MPa
3	29.2	375.9 MPa	510.9 MPa
4	28.9	291.8 MPa	607.7 MPa
5	29	453.2 MPa	562.5 MPa
6	28.6	577.7 MPa	605.4 MPa
7	27.9	625.8 MPa	521.6 MPa
평균		470.6 MPa	551.9 MPa
표준편차		119.9 MPa	51.0 MPa
95% 신뢰구간		381.8 MPa	514.2 MPa
		559.4 MPa	589.7 MPa

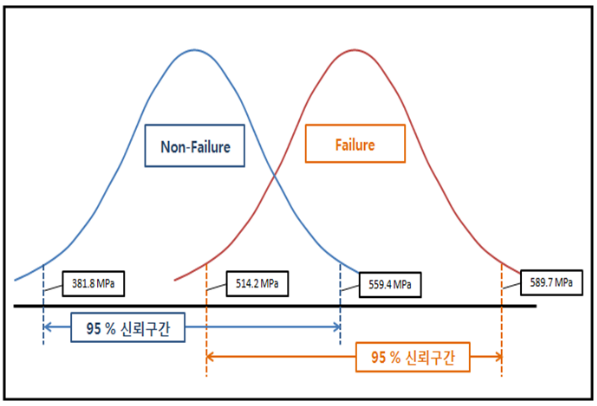

Figure 2-5. Cladding Failure Threshold by Statistics Process

Figure 2-4 shows the reference threshold limitation of PCI failures that published by the experimental study [3].

Figure 2-5 shows the reference threshold limitation of PCI failure by the statistics process. It means that PCI failure is usually occurred when maximum hoop stress is over about 514.2 MPa.

3. Analysis Result

This section summarizes the key results of both the change of pellet-cladding gap thickness according to the brun-up and the PCI sensitivity analyses according to the startup ramp rate.

3.1 Steady State Cycle Analysis

The steady-state cycle analysis was conducted using the FALCON code to establish the fuel rod initial conditions at the time of reactor restart. The steady-state analysis is initiated with a time step corresponding to the first in-core.

Figure 3-1 shows the fuel-cladding gap thickness according to the burn-up during cycle 1. As the result, the gap thickness is closed at about 10,000 MWD/MTU burnup because of pellet swelling. It means that the stress concentrations on the cladding begin.

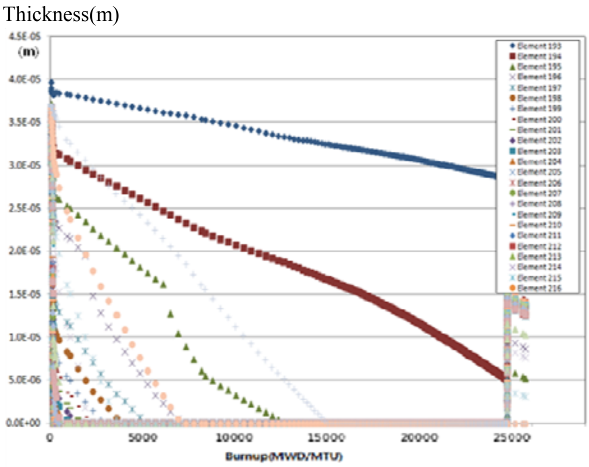

Figure 3-1. Fuel-Cladding Gap Thickness During Cycle 1

3.2 PCI Sensitivity Analysis

The PCI analysis under representative power maneuvering histories is performed using an R-θ model in FALCON code. The peak cladding hoop stress obtained from the local stress evaluation for a pellet is plotted against time (burnup).

Figure 3-2 shows the PCI analysis result for the current KHNP startup ramp rate. As the result, Maximum hoop stress is about 453.6(NO MPS[1] Case) and 496.7(With MPS Case)MPa that is less than fuel failure limit.

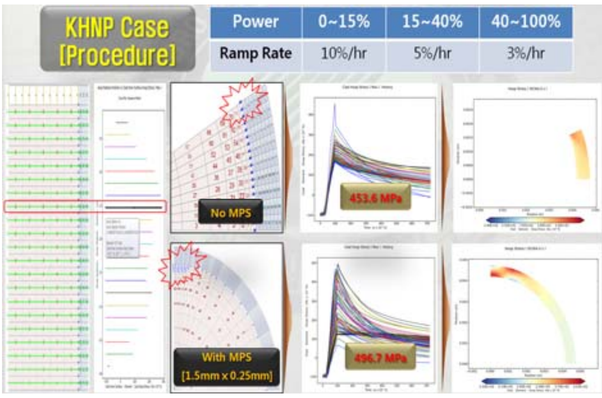

Figure 3-2. Maximum Hoop Stress from PCI Analysis (Based on KHNP Procedure criteria)

Figure 3-3 shows the PCI analysis result for the actual startup ramp rate(Kori Unit-3 Cycle 22). As the result, Maximum hoop stress is about 401.8(NO MPS Case) and 482.7(With MPS Case)MPa that is less than limit. And the result is more less than the result from figure 3-2 because the actual startup ramp rate is below those of KHNP procedure.

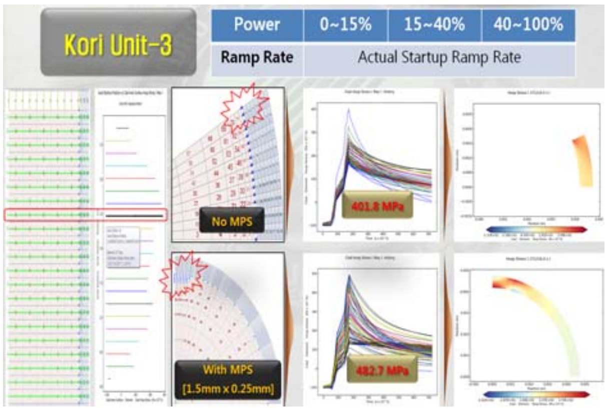

Figure 3-3. Maximum Hoop Stress from PCI Analysis (Based on Actual Startup Ramp Rate of KORI Unit-3)

Figure 3-4 shows the PCI sensitivity analysis result in low power range(0~40%). As the result, Maximum hoop stress is not sensitive about the changing of startup ramp rate in 0~40% power range.

Figure 3-4. Maximum Hoop stress about the change of startup ramp rate in 0~40% power range

Figure 3-5 shows the PCI sensitivity analysis result according to the intermittent increase(1%) of startup ramp rate. As the result, Maximum hoop stress is not sensitive about the intermittent increase(1%) of startup ramp rate in 40~100% power range.

Figure 3-5. Maximum Hoop stress about the intermittent increase(1%) of startup ramp rate in 40~90% power range

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[1] MPS : Missing Pellet Surface

4. Conclusions

The objective of the PCI analysis is to assess the cladding stress state under various power ramp conditions at the peak power node location. The PCI analysis is conducted at the start of the second cycle for the once-burned fuel because fuel-cladding gap is closed after 10,000 MWD/MTU burnup. The analysis result summarizes like below.

• Fuel-cladding gap is closed at about 10,000 MWD/MTU burnup.

• Maximum hoop stress is not sensitive about change of startup ramp rate in 0~40% power range.

• Maximum hoop stress is not sensitive about the intermittent increase(1%) of startup ramp rate in 40~100% power range.

REFERENCES

[1] Fuel Reliability Guidelines: Pellet-Cladding Interaction Failures. EPRI, Palo Alto, CA: 2008. 1015453.
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