Assessment on Startup Ramp Rate and Threshold Power of OPR1000

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1. Introduction

A variety of experimental and analytical methods have been used to predict fuel cladding failures during power maneuvers in nuclear power plants. So a broad spectrum of startup strategies following refueling outages exists in currently operated pressurized water reactors (PWRs). An important factor of a plant's restart strategy is power ramp rate restriction. The intention of power ramp rate restriction is to prevent fuel rod damage and failure 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]. Reactor undergoing restart operation is potentially vulnerable to PCI failures. Under restart conditions, the pellet/cladding gap may be closed beyond a threshold burnup level. If the power level increases rapidly under these conditions, differential thermal expansion can result in stress concentrations in the cladding that may cause cladding failure. The susceptibility of fuel rods to PCI failures during restart has resulted in the development of power ramp rate restrictions by fuel vendors.

This paper summarizes PCI assessment according to several startup ramp rates and threshold power assessment of OPR1000. The definition of threshold power is maximum value in power range that can increase startup ramp rate rapidly. FALCON code is used for PCI assessment and it is analyzed for once-burned fuel because it is the most sensitive to PCI failure.

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 fuel assemblies (16x16) manufactured by KEPCO Nuclear Fuel (KepcoNF). OPR1000 operates under startup ramp rate restrictions similar to those that imposed by Westinghouse. Initial Startup ramp rate limitation after refueling is 10%/hr until 15, 5%/hr from 15% to 40%, 3%/hr from 40% to 100% of rated thermal power.

2.1 Modeling Approach

The FALCON fuel rod behavior code was used to perform the PCI analysis. FALCON is a fuel rod behavior analysis code developed by EPRI to analyze the steady state and transient behavior of light water reactor fuel rods throughout the lifetime of the fuel [2]. FALCON is a fully-coupled, thermo-mechanical computer code designed to provide best estimate LWR fuel rod performance analysis. FALCON is based on the finite element modeling (FEM) approach coupled with a complete set of thermal and mechanical material properties models that describe the effects of irradiation on the performance of UO2 and Zircaloy cladding. FALCON has been used to calculate the steady state performance of power reactor rods up to 70 GWd/tU and the transient behavior of test reactor rods. A special capability of FALCON is the ability to use local effects models to calculate such conditions as cladding stress concentrations during power maneuvers. The fuel rod analysis is performed using two axisymmetric two-dimensional models, one with R-Z geometry (assumes azimuthal or circumferential uniformity in thermo-mechanical behavior) and an R-θ geometry (assumes axial uniformity in thermo-mechanical behavior). The R-θ geometry model enables analysis of the cladding stress and strain distributions with more detailed pellet-cladding mechanical interaction effects than the larger full length R-Z fuel rod model.

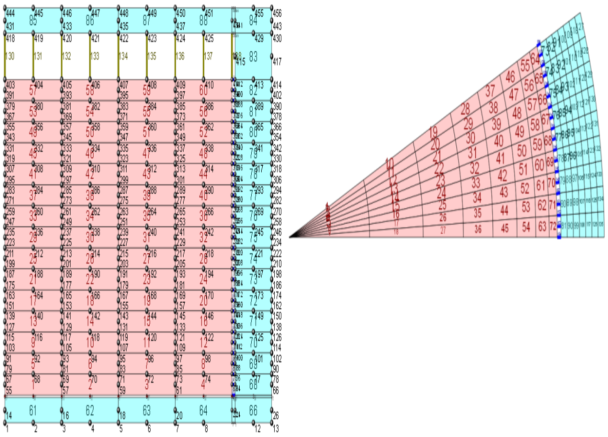

(a) R-Z(Axial) Analysis
(b) R-θ(circumferential) Analysis

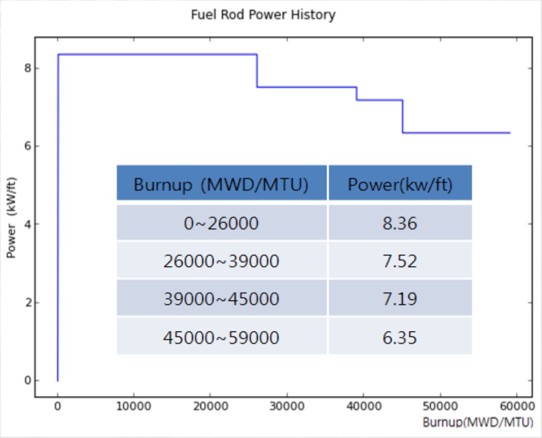
Figure 2-1. FALCON Fuel Rod Model in R-Z and R-θ Orientation

2.2 Assumption

Models for a KepcoNF 16x16 fuel rod were constructed with detailed fuel design data supplied by KepcoNF. The geometric mechanical model, a detailed power history which captures sufficient spatial and temporal power resolution to model both global and local conditions must be developed for a reliable PCI analysis. KepcoNF provided detailed fuel rod power and power shape data which were used to construct the power histories for the FALCON analyses. The power history and fuel rod data used in the analysis were obtained for Cycle 2 and Cycle 3 and it is assumed that startup ramp rate is increased linearly without delayed time.

Table 2-1 Fuel rod parameters

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 (μ m)
Initial Fuel Density (% T.D.)
Gas Pressure (MPa)
Spring Constant (N/m)
Coolant Inlet Temperature (°C)
Coolant Outlet Temperature (°C)
Coolant Pressure (psia)
Coolant Mass Velocity (Mlbm/ft^2/hr)
Hydraulic Diameter (m)



Burnup (MWD/MTU)	Power(kw/ft)
0~26000	8.36
26000~39000	7.52
39000~45000	7.19
45000~59000	6.35

Figure 2-2. Fuel Rod Power History

[Assumption : Max. Pin Power]

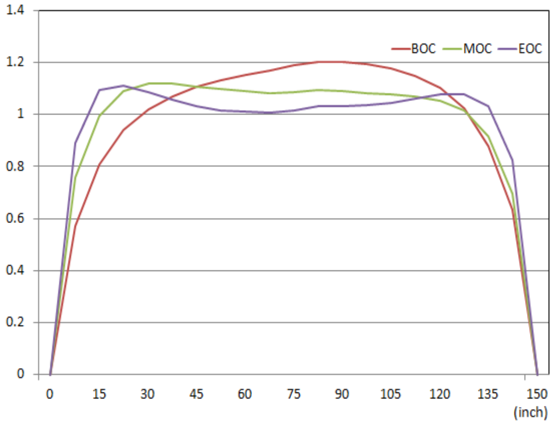
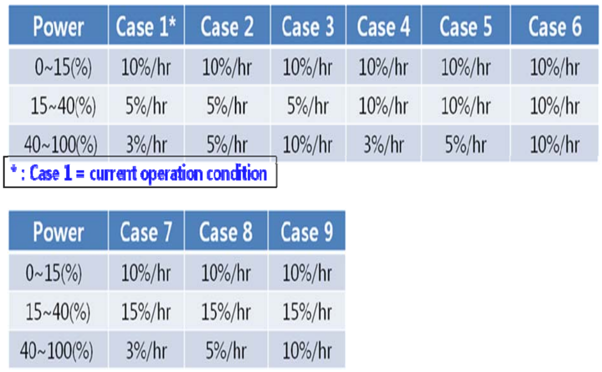


Figure 2-3. Axial Power Distribution

2.3 Cases for PCI analysis of OPR1000

PCI analysis is performed for the effect assessment according to several startup ramp rates and for threshold power assessment of OPR1000. A list of the test cases used for the evaluation of startup ramp rates is presented in Table 2.2 and a list of the test cases used for the threshold power assessment is presented in Table 2.3.

Table 2-2 Cases of startup ramp rates

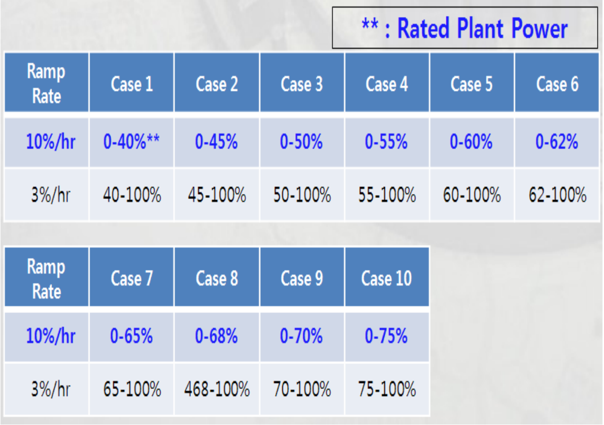


Power	Case 1*	Case 2	Case 3	Case 4	Case 5	Case 6
0~15(%)	10%/hr	10%/hr	10%/hr	10%/hr	10%/hr	10%/hr
15~40(%)	5%/hr	5%/hr	5%/hr	10%/hr	10%/hr	10%/hr
40~100(%)	3%/hr	5%/hr	10%/hr	3%/hr	5%/hr	10%/hr

* : Case 1 = current operation condition

Power	Case 7	Case 8	Case 9
0~15(%)	10%/hr	10%/hr	10%/hr
15~40(%)	15%/hr	15%/hr	15%/hr
40~100(%)	3%/hr	5%/hr	10%/hr

Table 2-3 Cases for threshold power assessment of OPR1000



** : Rated Plant Power

Ramp Rate	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
10%/hr	0-40%**	0-45%	0-50%	0-55%	0-60%	0-62%
3%/hr	40-100%	45-100%	50-100%	55-100%	60-100%	62-100%

Ramp Rate	Case 7	Case 8	Case 9	Case 10
10%/hr	0-65%	0-68%	0-70%	0-75%
3%/hr	65-100%	468-100%	70-100%	75-100%

Figure 2-4 shows the fuel-cladding gap thickness as the function of burn-up at steady-state. Fuel and cladding is usually contacted within 15,000 MWD/MTU. So, Start-up rates in secondary cycle are analyzed in this paper.

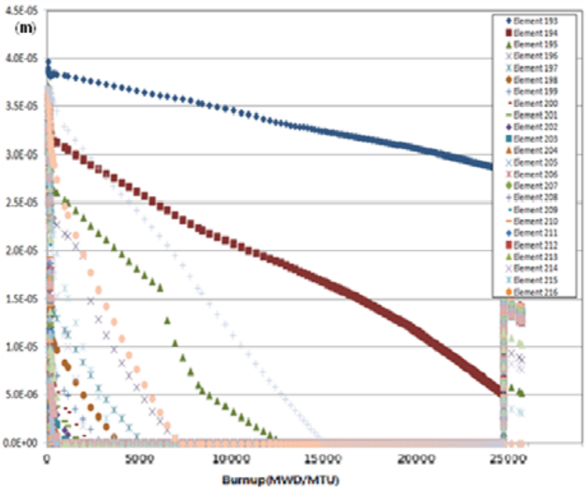


Figure 2-4. Fuel-Cladding Gap Thickness vs. Burnup

3. Analysis Result

This section summarizes the key results of both the PCI analysis according to startup ramp rates and threshold power assessment. The PCI analysis under several power maneuvering histories is performed using an R-θ model in FALCON code. The peak cladding hoop stress is obtained from the local stress evaluation for a pellet at different startup ramp rates.

3.1 PCI Analysis according to Startup Ramp Rates

PCI analysis is performed to assess the effect of restart ramp rate limitations on PCI fuel failures. Figure 3-1 shows the PCI analysis result according to startup ramp rates based on Table 2-2. Figure 3.1 illustrates that the more startup ramp rate is increased, the more hoop stress is decreased in low power range (≤ 40%). This means that PCI failure probability is decreased in low power range if the startup ramp rate is increased.

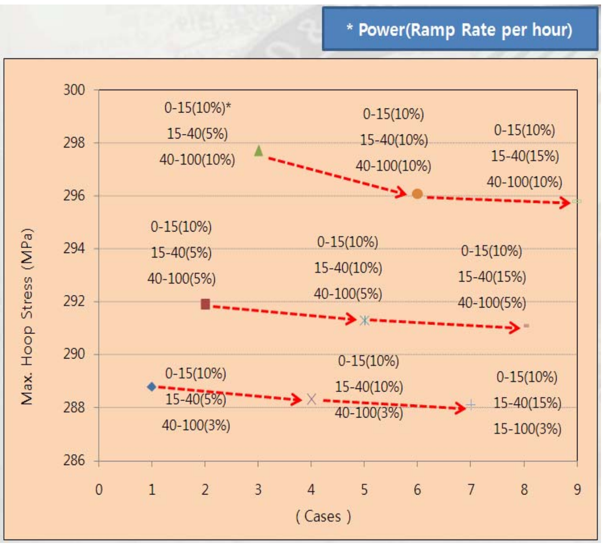


Figure 3-1. PCI analysis result of startup ramp rates

3.2 Result of Threshold Power Assessment

Recently, William et al.[3] presented the reference threshold limitation of PCI failures that published by the experimental study like Figure 3-2. Figure 3-3 illustrates PCI failure limitation with 95% reliability based on Figure 3-2. This means that PCI failure is occurred with 2.5% probability if cladding peak stress is less than 514.2 MPa. So about 510 MPa is applied in this assessment as the criteria of PCI failure.

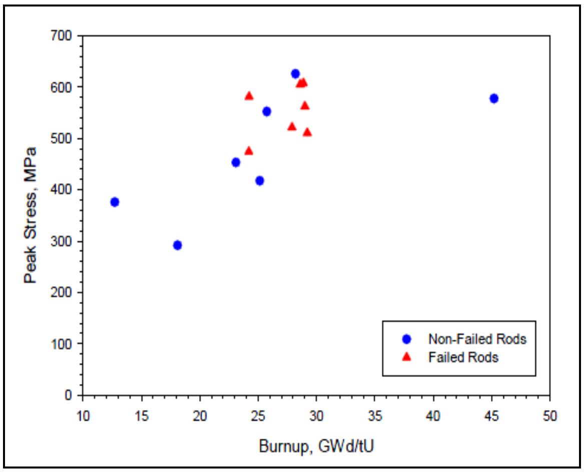


Figure 3-2. Peak Hoop Stress as a Function of Burnup [3]

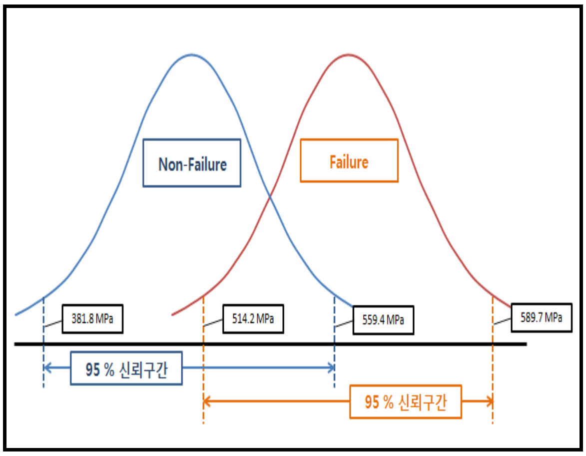
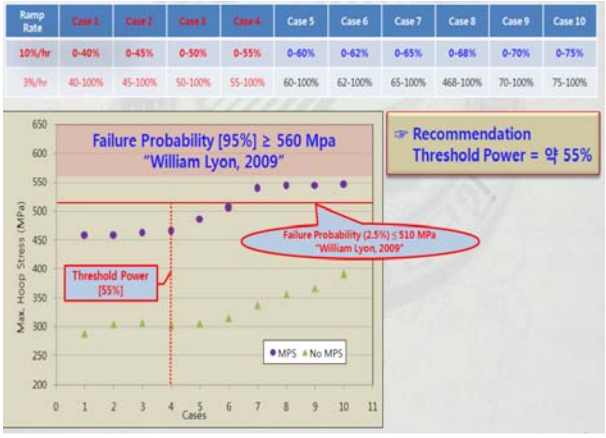


Figure 3-3. PCI Failure limitation with 95% Reliability

Figure 3-4 shows the result for threshold power assessment of OPR1000 based on Table 2-3. As the result, this paper presents that the recommended threshold power of OPR1000 is about 55% conservatively. This means that PCI failure is not occurred even though startup ramp rate is 10%/hr by plant power 55%.



Ramp Rate	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
10%/hr	0-40%	0-45%	0-50%	0-55%	0-60%	0-62%	0-65%	0-68%	0-70%	0-75%
3%/hr	40-100%	45-100%	50-100%	55-100%	60-100%	62-100%	65-100%	468-100%	70-100%	75-100%

Figure 3-4. Result of threshold power assessment of OPR100

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 analyses were conducted for the once-burned fuel from the start of the second cycle to plant power 100%. This paper presents both the PCI analysis according to startup ramp rates and threshold power assessment result like below.

- The more startup ramp rate is increased, the more PCI failure probability is decreased in low power range (≤ 40%).
- PCI failure is not occurred even though startup ramp rate is 10%/hr until the plant power reaches 55%.

REFERENCES

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