FALCON code Simulation for Verification of Fuel Preconditioning Guideline

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1. Introduction

The prevention of fuel failures due to pellet-cladding interaction (PCI) has renewed attention over the past several years in the operation of a LWR power plant. The consequences of fuel rod failure by PCI can impact plant operational efficiency by limiting flexibility in reactor operation. The most widely used approach to mitigate the occurrence of PCI failure has been to impose restrictions on the power ramp rates. The magnitude and rate of power increases are key factors in the PCI failure process. KEPCO NF (KNF) provides operational restrictions called fuel preconditioning guideline (FPG) to mitigate PCI failures. The FPG contains recommended power maneuvering restrictions that should be followed when the KNF supplied fuel is being operated in-reactor. This guideline typically includes controlled power ramp rates, threshold power levels to initiate controlled ramp rates, and restrictions on the operating conditions that impact the potential for PCI failure. The purpose of the FPG is to allow time for stress relaxation to reduce cladding stress buildup during power maneuvers. Two general approaches have been adopted in the development of FPG to mitigate PCI failure in operating commercial reactors. The first approach relies primarily on past operational experience and power ramp test. The second one uses an analytical methodology where a figure-of-merit representative of PCI vulnerability, generally cladding hoop stress, is calculated using a fuel performance code [1]. In this study, the second approach that uses the FALCON fuel rod behavior code developed by EPRI was adopted [2].

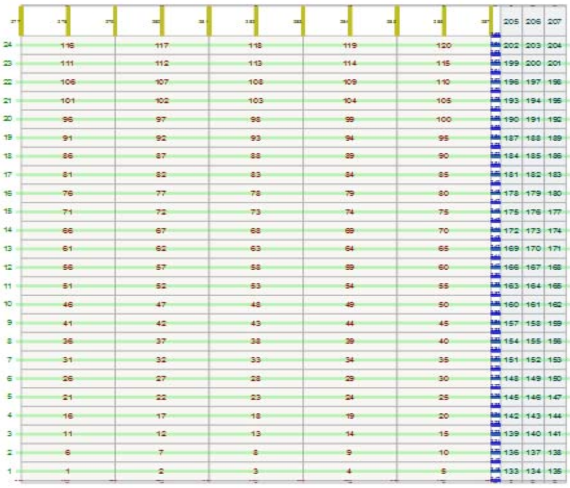
The objective of this study is to assess maneuvering restrictions on the FPG that applies to nuclear power plant. For the assessment procedures, setting the geometric modeling, bounding power history (BPH) and ramping simulations are described in detail. Finally, based on the above-mentioned assessment procedures, the summarized cladding hoop stress obtained from FALCON calculation are evaluated and then compared to the PCI failure criteria.

2. Analysis Methods and Results

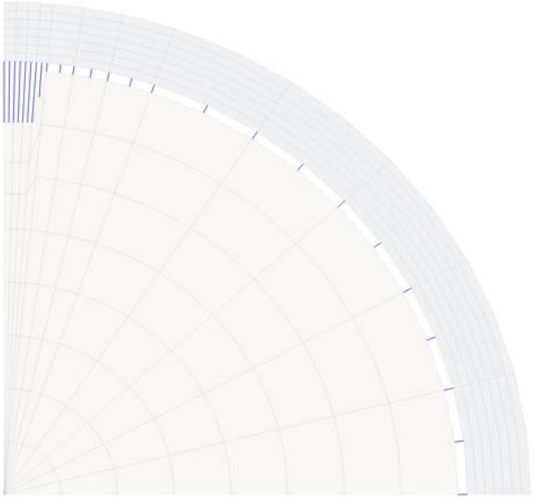
2.1 Steps in FALCON Analysis Approach

PCI analysis using FALCON consists of two primary steps. First, a steady state, full-length R-Z depletion analysis of the power maneuver is conducted. The purpose of this step is to establish the fuel rod conditions to be used at the beginning of the power maneuver analysis. Using the results from this analysis, the maximum cladding hoop stress and its location are identified. This information along with other fuel rod data such as pellet / cladding gap size is used in the next step of the analysis.

In the second step of the PCI analysis, the local cladding stress distribution is calculated using an R-θ slice model as shown in Figure 1. This model is initialized using the conditions identified in the first step of the analysis. Specifically, the conditions at the end of the depletion analysis at an axial position corresponding to the peak cladding hoop stress are used. This allows a detailed local analysis of the hoop stress distribution at the position of highest PCI vulnerability.



(a) Full Length R-Z Analysis Model



(b) R-θ Slice Analysis Model

Fig. 1. FALCON Fuel Rod Model in R-Z and R-θ Orientation with a Missing Pellet Surface

2.2 Fuel Rod Modeling

Fuel rod design information used in the analysis was taken from the Shinkori 3&4 initial core designs. Using this information, FALCON inputs were created for R-Z and R-θ model geometries. The principal fuel rod design parameters used in this study are shown in Table 1.

Table 1: KNF PLUS7 Fuel rod parameters

Description	Value
Cladding outer diameter (inch)	0.374
Cladding inner diameter (inch)	ns
Cladding Material	ZIRLO
Pellet outer diameter(inch)	ns
Radial gap (mils)	ns
Enrichment (%)	4.5
Fuel density [% of T.D]	95.6
Internal gas pressure [He] (psig)	ns
Dished pellet	Yes
Fuel stack length (inch)	150

ns = not shown in report, but used in calculation

In the R-θ model geometries, pellet was modeled with KNF standard missing pellet surface (MPS). This MPS are simulated concave (material missing on the outer surface of the pellet) pellet chip that is described deep (height), width and the full length of a fuel pellet. For reasons of technical security, detailed MPS figure not shown in this report. Figure 2 is shown the MPS model in this FALCON R-θ calculation. In this calculation, coefficient of friction between fuel and cladding was used a default value of 0.5.

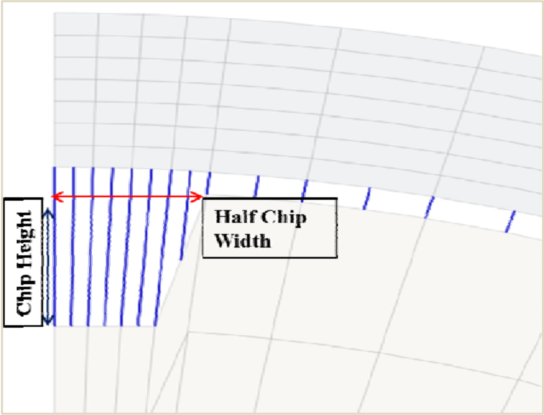


Fig. 2. Full Pellet Length MPS Models used for R-θ calculation

2.3 Searching the Bounding Power History

The case study was conducted using FALCON to evaluate the impact of power history on parameters such as the hot zero power gap (HZG) and others. Specially, HZG is a key parameter in the PCI failure process. For simulating the HZG at the end of N-1 cycle, a shutdown was simulated by reducing the power to near zero. Coolant temperatures were not changed, so the conditions were representative of hot zero power conditions. For the evaluating the effect of power histories on HZG and cladding stress, several power histories based on the Shinkori 3&4 and conservative axial power shape as shown in Figure 3 and 4, respectively, were determined. A selected bounding power history was designed to produce a small HZG at the beginning of N cycle.

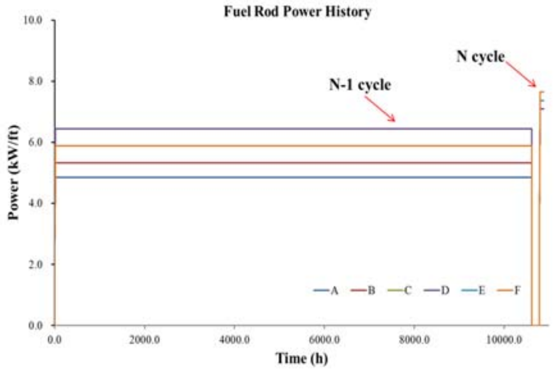


Fig. 3. Fuel Rod Power History during N-1 to N cycle

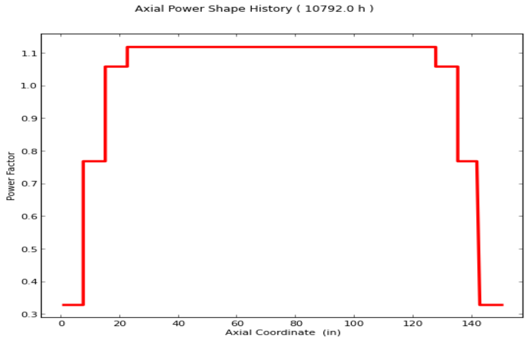


Fig. 4. Conservative Axial Power Shape History

2.4 Determination of Bounding Power History

Several power histories were analyzed using FALCON code and Table 2 shows resultant cladding hoop stress for each power history at full power of N cycle assuming HZG at the end of N-1 cycle. In the case of low power, at the end of N-1 cycle, the gap has not been yet closed, and the cladding is in a compressive stress. After shutdown of N-1 cycle, the pellet contracts and the gap opens to a larger value. At N cycle startup, the gap remains open even at full power. For example, the result of power history A is shown the largest HZG at the end of the N-1 cycle and compressive hoop stress. The gap gradually narrows down and then finally closes during N cycle operation. The gap closure eventually causes the net tensile stress in a cladding with alleviating the compressive stress. On the contrary, in case of high power during the N-1 cycle, the gap has closed at the end of the N-1 cycle. The gap re-opens at shutdown of N-1 cycle, and then closes at a slightly lower power before the full power. Note, however, that the power change above gap closure is smaller in high power case because increased pellet swelling and rod internal pressure causes the cladding to increase in diameter at the end of N-1 cycle. Under these conditions, the HZG remains larger at N cycle startup condition such as power history D. For the above reasons, power history F was selected to produce a small HZG at the start of N cycle.

Table 2: Results of BPH calculation using FALCON code

Power History	Hot Zero Power Gap (HZG) from R-Z Model	Cladding Hoop Stress (MPa) from R-θ Model
A	0.3286	-10.5
B	0.2081	164.4
C	0.1917	205.9
D	0.2117	186.1
E	0.1917	224.3
F	**0.1917**	**240.5**

2.5 Simulation for Maneuvering Restrictions on the FPG

Maneuvering restrictions on the FPG are evaluated by FALCON simulation assuming power history which is determined above section 2.4. For additional conservatism, determined BPH is considered coast-down operation about 500MWd/MTU at the end of N-1 cycle and xenon oscillation at startup of N cycle. The startup power maneuvering for N cycle is as follows in Table 3. The objective of first simulation is to evaluate the effect of the ramp rate until threshold power. Startup ramp rate of N cycle is simulated from 5%/hr to “no limit (50%/hr)” until 50% rated thermal power (RTP) and then 3%/hr from 50% to 100% of RTP. The objective of second simulation is to evaluate the effect of the ramp rate above the threshold power. Startup ramp rate of N cycle is simulated no limit (50%/hr) until 50% RTP and then 2~4%/hr from 50% to 100% of RTP.

Table 3: Changes in Core Power for Startup Simulation

Category	Power Level(Rated Thermal Power)	Ramp Rate (%/hr)
First Simulation	0%~50%	5, 10, 15, 30, No limit(=50)
	50%~100%	3
Second Simulation	0%~50%	No limit(=50)
	50%~100%	2, 3, 4

2.6 Results of Maneuvering Restrictions Simulation

The PCI stress analysis under representative bounding power histories F with additional conservation was performed using an R-θ model with MPS in FALCON code. First ramp simulation was performed through various R-θ analyses to evaluate the effect of the ramp rate under threshold power.

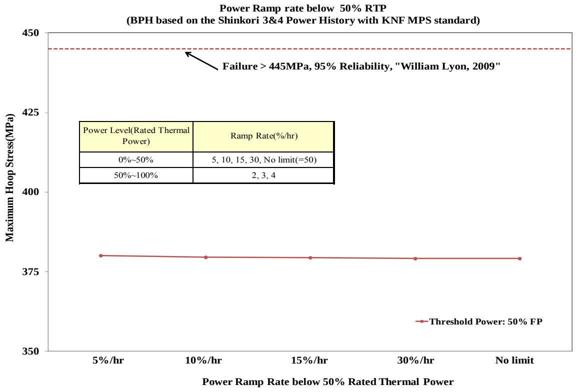


Fig. 5. Maximum Cladding Hoop Stress at different startup ramp rates from 0% to 50% of rated thermal power

Figure 5 provides a plot of the cladding hoop stress as a function of different ramp rates below the threshold power. Those results show that cladding hoop stress is almost the same level. That means ramp rate until threshold power does not affect to PCI failure, and hoop stress value have enough margin against reference PCI failure limit value. The reference PCI failures limit was published from the experimental study [3]. In this reference, PCI failure (95 percent reliability) may have chance to occur when the hoop stress exceeds about 445 MPa.

The other ramp simulation was performed to evaluate the effect of the ramp rate above the threshold power. Figure 6 provides a plot of the cladding hoop stress as a function of different ramp rates above the threshold power. And it shows that the power ramp rate of average 4%/hr case has sufficient margin to reference PCI failure limit value.

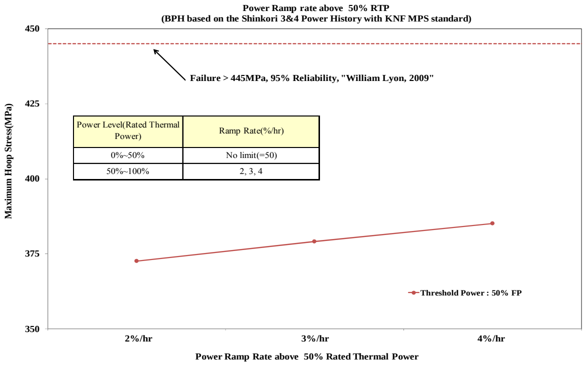


Fig. 6. Maximum Cladding Hoop Stress at different startup ramp rates from 50% to 100% of rated thermal power

3. Conclusions

FALCON simulation can be the identification of a PCI limit parameter, typically cladding hoop stress, which can be used to evaluate a power maneuvering restriction on FPG. The PCI analysis is to assess the cladding hoop stress under various power ramp conditions. Startup ramp rate doesn’t affect PCI failure until 50% of rated thermal power. Power ramp rate of average 4%/hr case doesn't exceed the PCI failure limit. Based on the FALCON simulation results, it is judged that FPG provided by KNF is appropriate to prevent fuel failure due to PCI. Further researches on the PCI analysis using the additional FEM code simulation are necessary for detailed validation of fuel preconditioning guideline.

REFERENCES

[1] Fuel Reliability Guidelines: Pellet-Cladding Interaction Failures. EPRI, Palo Alto, CA: 2008. 1015453.
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[3] W. Lyon, R. Montgomery, J. Rashid, and S. Yagnik, "PCI Analysis and Fuel Rod Failure Prediction using FALCON" , Water Reactor Fuel Performance Meeting, Paris, France, September 6–10, 2009.