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PCI Analysis for Startup Ramp Rate of Shinkori Unit 1

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1. Introduction

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 restrictions. The intention of power ramp rate restrictions 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]. Reactors undergoing restart operations are potentially vulnerable to PCI failures. Under restart conditions, the pellet/cladding gap may be closed at relatively low linear powers for fuel rods 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.

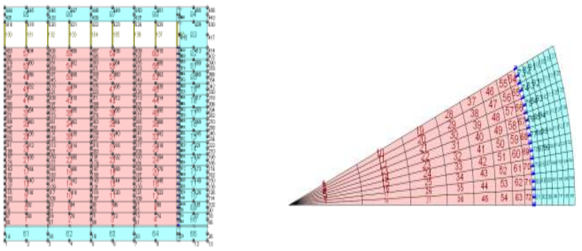
This paper summarizes FALCON's assessment of the PCI failure potential of the PLUS7 fuel during the Shinkori 1 Cycle 3 startup. Also, It is analyzed for once-burned PLUS7 fuel because it is the most sensitive to PCI failure.

2. Modeling Approach and Assumption

Shinkori 1 (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). Shinkori 1 operates under startup ramp rate restrictions similar to those imposed by Westinghouse. Initial Startup ramp rate limitation after refueling is 5%/hr until 40% and 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 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

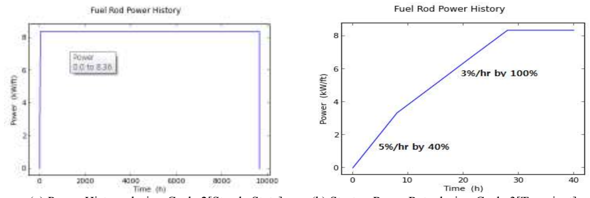
Figure 2-1. FALCON Fuel Rod Model in R-Z and R-θ Orientation

2.2 Assumption

Models for a KepcoNF 16x16 PLUS7 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 necessary 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 KepcoNF PLUS7 fuel rod parameters

Parameters	Value
Cladding Outer Diameter (cm)	0.95
Cladding Inner Diameter (cm)	0.84
Cladding Density (kg/m^3)	6.55E+3
Fuel Roughness (microns)	1.8034
Fuel Pellet Outer Diameter (cm)	0.83
Fuel Column Length (cm)	381
Fuel Enrichment (w/o U235)	4.5
Fuel Grain Size (μm)	5
Initial Fuel Density (% T.D.)	95
Gas Pressure (MPa)	2.0
Spring Constant (N/m)	4670
Coolant Inlet Temperature (°C)	295
Coolant Outlet Temperature (°C)	324.2
Coolant Pressure (psia)	2250
Coolant Mass Velocity (Mlbm/ft2/hr)	2.63016
Hydraulic Diameter (m)	0.01264



(a) Power History during Cycle 2[Steady State] (b) Startup Ramp Rate during Cycle 3[Transient]

Figure 2-2. Power History during the Shinkori 1 Cycle 2 and Cycle 3

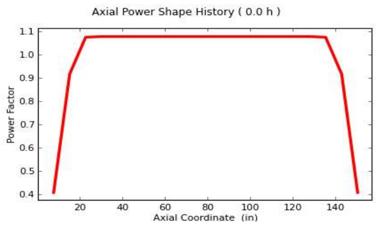


Figure 2-3. Constant Axial Power Distribution for Shinkori 1

3. Analysis Result

This section summarizes the key results of both the steady-state and PCI analyses used to assess the effect of restart ramp rate limitations on PCI fuel failures. Figure 3-1 shows the reference threshold limitation of PCI failures that published by the experimental study [3]. In this failure, PCI failure is usually occurred when maximum hoop stress is over about 350 MPa.

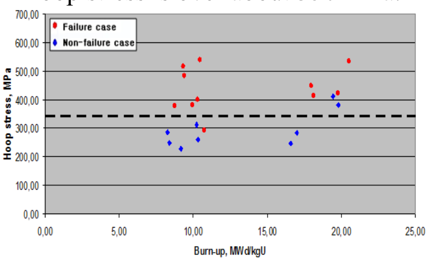


Figure 3-1. Stress-based Failure Threshold for Zr-4 and ZIRLO

3.1 Steady State Cycle Analysis

The steady-state cycle analyses, used to establish the fuel rod initial conditions at the time of reactor restart, were conducted using the FALCON code. The steady-state analyses were initiated with a time step corresponding to the first in-core burnup measurement of the cycle of interest for each reactor/fuel combination and run to the end of cycle. Once-burned fuel cases were analyzed for Shinkori 1 (PLUS7, 16x16 fuel) and figure 3-2 shows cladding axial strain result.

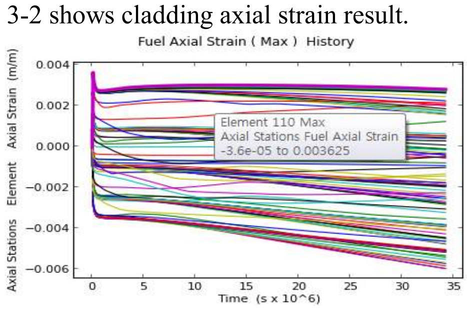
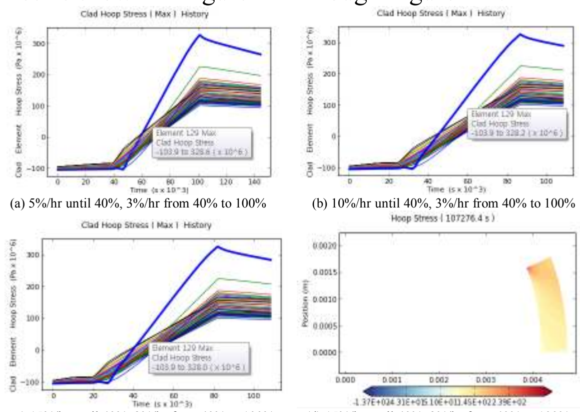


Figure 3-2. Cladding Axial Strain in Shinkori 1 Cycle 2

3.2 PCI Analysis Result

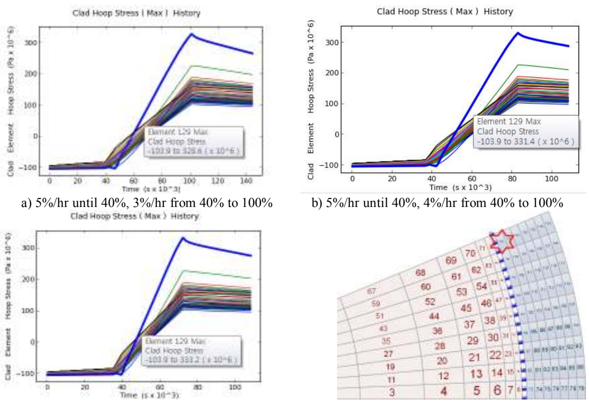
The PCI stress analysis under representative power maneuvering histories is performed using an R-θ model in FALCON code. The peak cladding hoop stress obtained from the local stress evaluation for a pellet is plotted against time (burnup) at different startup ramp rates as shown in Figure 3-3 through Figure 3-4.



(a) 5%/hr until 40%, 3%/hr from 40% to 100% (b) 10%/hr until 40%, 3%/hr from 40% to 100%

c) 15%/hr until 40%, 3%/hr from 40% to 100% (d) 15%/hr until 40%, 3%/hr from 40% to 100%

Figure 3-3. Maximum Cladding Hoop Stress at different startup ramp rates until 40% of rated thermal power



a) 5%/hr until 40%, 3%/hr from 40% to 100% b) 5%/hr until 40%, 4%/hr from 40% to 100%

c) 5%/hr until 40%, 5%/hr from 40% to 100% d) 5%/hr until 40%, 5%/hr from 40% to 100%

Figure 3-4. Maximum Cladding Hoop Stress at different startup ramp rates from 40% to 100% of rated thermal power

4. Conclusions

The objective of the PCI analysis was to assess the cladding stress state under various power ramp conditions at the peak power node location. The PCI analyses were conducted at the start of the second cycle for the once-burned fuel. The PCI analysis results are below.

- Startup ramp rate (~15%/hr) doesn't affect PCI failure until 40% of rated thermal power for Shinkori 1.
- Startup ramp rates (3%/hr, 4%/hr and 5%/hr) don't exceed the maximum hoop stress (about 350 MPa) that generates PCI failures for Shinkori 1.

REFERENCES

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

[2] Falcon Fuel Performance Code Version 1.2 Volume 1: Theoretical and Numerical Bases. EPRI, Palo Alto, CA: 2012. 1022711.

[3] FALCON User Group Meeting: GRSW-A Model of the IAEA Programme FUMEX III. EPRI, Palo Alto, 2010.