Ramp Test Rods Analysis using ROPER and ABAQUS

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1. Introduction

Until now, various experiments and analyses have been carried out to prevent cladding failure that may occur during power maneuvers in commercial power plant to avoid or eliminate pellet-cladding interaction (PCI) fuel rod failures caused by stress corrosion cracking (SCC) of the cladding. As a review of literature related to PCI, the metric for assessing whether cladding failure is occurred by PCI or not includes a threshold stress, cumulative damage index (CDI), strain energy density (SED)[1,2].

In this study, using ROPER code, KEPCO NF's fuel rod performance analysis code, and ABAQUS, commercial finite element analysis program (ver. 2018), ramp test rods of various projects simulate and analyze. And we propose a threshold to limit PCI-induced fuel rod failure using stress-based method.

2. Ramp test rods and analysis methods

In this section, ramp test rods and analysis method are described.

2.1. Ramp test

The ramp test was conducted for the purpose of research on PCI mechanism by simulating the potential power transition from a nuclear power plant in a research reactor through IFPE (International Reactor Physics Experiment) and SCIP (Studsvik Cladding Integrity Program). Total 44 test rods performed on OSIRIS, over-ramp, super-ramp and trans-ramp project, and SCIP used for this analysis, 16 of which were failed during the ramp test as shown in Table I[3].

Table I: PCI ramp test rod database for failed and non-failed rods

Project	Burnup (GWd/tU)	Total/Failed/ non-Failed Rods	P_{max} (kW/m)
OSIRIS	26~27	2 / 0 / 2	39.5~45
Over-ramp	12~32	27 / 9 / 18	37~52.5
Super-ramp	35~45	6 / 0 / 6	40~49
Trans-ramp	23~30	7 / 6 / 1	42~50
SCIP	53~76	2/ 1 / 1	38~42

2.2. Analysis methods

To simulate ramp test rods, ROPER code and ABAQUS are used. First, an input file of ROPER code for each ramp test rod generates and runs. Next, by applying ROPER input and results such as fraction of fission gas, rod internal pressure to ABAQUS, a three-dimensional analysis for a segment is performed. ABAQUS user subroutines, UMATHT, UMAT and GAPCON, are used for calculating thermal and mechanical material properties for pellet and cladding and gap conductance between pellet and cladding by applying the ROPER code's model. In substitution of gap conductance loop of ROPER code, "coupled temperature-displacement" is applied. A brief analysis procedure is shown in Fig. 1.
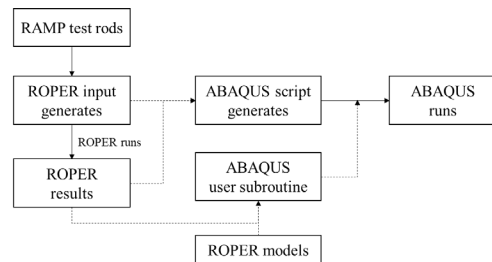

Fig. 1. Analysis procedure for ramp test rods using ROPER and ABAQUS

2.3. Finite element model and boundary conditions

When fuel rods start to burn, the thermal expansion of the pellet results in pellet cracks. To reflect it in the analysis, it is assumed that pellet has eight cracks in the radial direction from beginning-of-life and cracks in other direction are ignored. Finite element model of pellet and cladding generates a 1/16 symmetry in circumstance direction and a 1/2 symmetry in vertical direction as shown in Fig. 2. Element size at radial direction are set to be same cross-sectional area for applying radial power distribution. Element size at remaining directions are set at the same angle or length and number of elements.
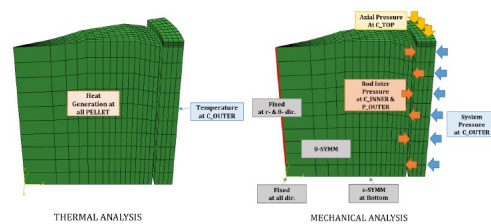

Fig. 2. Finite element model and boundary conditions

As a boundary condition for thermal analysis, heat generation rate is applied throughout pellet considering linear heat generation rate, axial power shape and radial power distribution. And cladding outer temperature, the results of ROPER, are applied to cladding outer surface. The heat generated from the pellet is transferred to the cladding via a gap conductance model between the pellet outer surface and cladding inner surface, and the rest of region not mentioned are set to insulation. In case of mechanical analysis, system pressure, provided as an input of ROPER is applied to the cladding outer surface, rod internal pressure, the results of ROPER, is applied to the cladding inner surface and pellet outer surface and axial pressure calculated from system pressure and rod internal pressure are applied to the cladding top surface. The centerline of the pellet is fixed in radial direction. The bottom surface of pellet and cladding are symmetrical in vertical direction and side surfaces of pellet and cladding except for region assumed to be cracked are symmetrical in circumstance direction. The boundary conditions for thermal and mechanical analysis are shown in Fig. 2.

3. Analysis results

3.1. Comparison to PIE data

For base-irradiation and ramp test for test rods, ROPER and ABAQUS results are compared to PIE data to verify the accuracy for analysis[3]. The main focus for performing this analysis is to determine the gap between pellet and cladding prior to ramp test. This gap is an indicator the accuracy of base-irradiation modeling and is required to properly set the initial value to accurately reflect the test conditions. Tests measuring the gap among ramp tests includes the trans-ramp project and E2G rod of SCIP and their measurements are compared to ROPER and ABAQUS results as shown in Fig. 3.
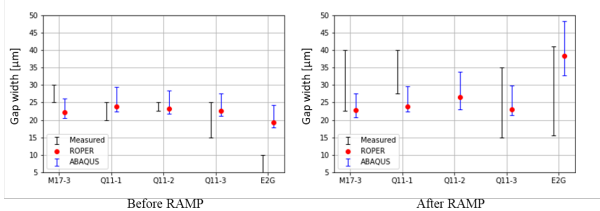

Fig. 3. Gap comparison before/after ramp for trans-ramp test rods and E2G rod

3.2. Hoop stress-based failure threshold

As results of analysis for ramp test rods, peak hoop stresses in element near to cladding inner surface via ROPER results are presented in Fig.4. FALCON results described in reference 1 are also presented. As shown in Fig. 4, failure rod and non-failure rod are not well distinguished. Therefore, the threshold value is set using peak hoop stress for failure rods. According to

the statistical method for the NRC Reg. Guide 1.126[4], the evaluation of normality for hoop stresses of failure rods are conducted, resulting in normality. Based on this, the lower one-side 95/95 tolerance limit is about 400 MPa and this value is set as threshold. This value is similar to that of references 1 and 2.
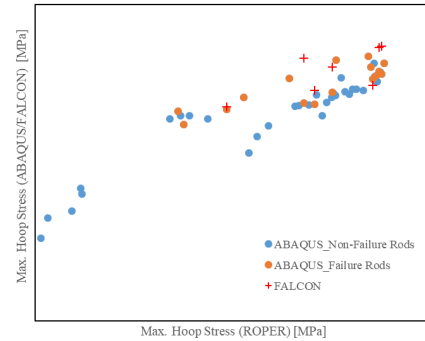

Fig. 4. Peak hoop stress comparison for ABAQUS /FALCON and ROPER

3.3. Application to start-up condition

As a preliminary analysis for PCI evaluation of fuel preconditioning guideline and flexible power operation, ABAQUS analysis for once-burnt rod, which is virtually burned to make the gap smaller after first cycle, at start-up condition is performed applying same analysis condition as ramp test rods. In addition, the inner and outer diameter of cladding is adjusted to decrease gap size. As start-up condition, power immediately increased to 50%, and then increased to 100% at 3%/hr, 5%/hr and 10%/hr. Peak hoop stress at cladding inner element did not exceed the threshold. Power history at start-up condition and peak hoop stress are presented in Fig. 5.
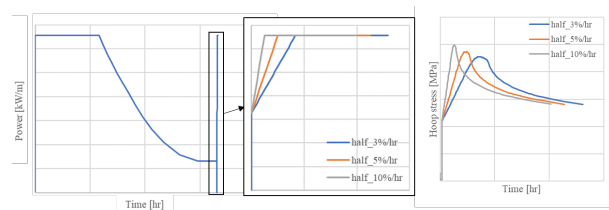

Fig. 5. Power history and peak hoop stress at start-up condition

4. Conclusion

Using ROPER code and ABAQUS, a three-dimensional analysis for ramp test rods in various projects such as over-ramp and trans-ramp are performed. As a result of those analysis, it tried to distinguish failure rods or non-failure rods by peak hoop stress of cladding inner element as a metric, but it doesn't work. Therefore, using only data of failure rods, the threshold is proposed.

In the future, we plan to propose threshold for ramp test rods through other metric such as cumulative damage index and strain energy density and to evaluate in consideration of various scenarios for fuel preconditioning and missing pellet surface effects. These results will be available as a reference for PCI evaluation in flexible power operation.

REFERENCES

[1] 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.
[2] M.W. Kennard, W. Lyon, and A. Mai, PCI Margin Analysis Methodology using the FALCON Fuel Performance Code, Top Fuel 2016, Boise, ID, U.S.A, September 11-15, 2016.
[3] International Fuel Performance Experiments (IFPE) database, Nuclear Energy Agency, assessed March 5, https://www.ocec-nea.org/jcms/pl_36358/international-fuel-performance-experiments-ifpe-database.
[4] NRC Regulatory guide 1.126 Rev.2, An Acceptable model and related statistical methods for the analysis of fuel densification, U.S. NRC, March 2010.