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Effects of Fuel Relocation on LOCA Safety Analysis in APR1400

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1. Introduction

For the period of large-break loss-of-coolant accident (LBLOCA) in PWR, fuel rod can be ruptured due to the excessive plastic deformation of zirconium alloy cladding at high temperature. If such a excessive deformation happens, there is a possibility that fragmented fuel pellets can be relocated into the deformed regions by the movement of axial and radial direction inside of cladding. Fuel relocation can change the distribution of local heat source along the fuel rod [1,2]. Consequently, it will influence the rod performance such as temperature and oxidation of cladding.

Authors have studied the effect of fuel relocation to the rod performance by changing several parameters [3]. It is discovered such that packing fraction and cladding failure strain have significant impacts on fuel performance. Axial nodding and size of gap can influence the performance also. However, it has some limitations because it has been done with a fixed thermal-hydraulic (TH) boundary condition during LOCA by FRAPTRAN standalone code.

Meanwhile, as a part of safety research program, KINS has been developing a fully integrated computer code between fuel performance and system TH computer code, such as FRAPTRAN and MARS-KS [4]. This integrated code, named as FAMILY (**F**RAPTRAN **A**nd **M**ARS-KS **I**ntegrated for Safety Ana**LY**sis), can evaluate the TH behaviors and their uncertainties completely, because the TH conditions around fuel rod are calculated iteratively between two codes.

In this paper, model of packing fraction has been developed preliminarily by using the available experimental and analytical results currently. Using this model impacts of fuel relocation to rod performance such as temperature and oxidation of cladding during LOCA in APR1400 have been assessed preliminarily by utilizing the FAMILY computer code.

2. Packing Fraction Model

Since 1970s about 9 research programs have been conducted to evaluate the fuel behaviors during LOCA [1,2]. In these research programs, fuel burnup is ranging from fresh to ~90 MWd/kgU, and various types fuels are used. However, available fuel packing fraction data in deformed and bursted cladding region are limited. In this situation, PBF and Studsvik experimental data are used to establish packing fraction model. Further, FR2 and Halden data predicted by measured cladding strain and computer code are also used [5,6].

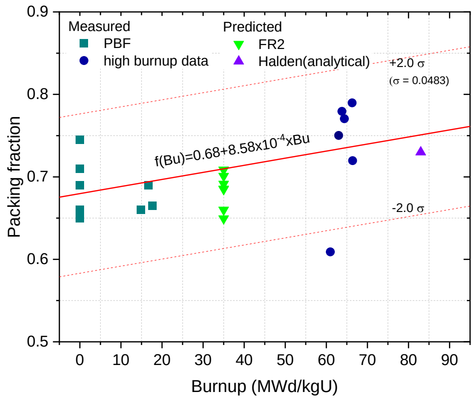

Fig. 1 Packing fraction model as a function of fuel burnup

Fig. 1 shows the data and developed packing fraction model. The simple model established as a function of fuel burnup is as follow.

$$PF(bu) = 0.68 + 8.58\times10^{-4} \times bu \qquad (1)$$

PF = packing fraction (unitless)
bu = rod average fuel burnup (MWd/kgU)
σ (standard deviation) = 0.0483
burnup = 0~90 MWd/kgU

This is a preliminary model, thereby it has to be revised more precisely if additional data are provided.

3. Analysis Details

3.1 LOCA analysis and modeling

LOCA safety analysis of APR1400 PWR plant with 16x16 ZIRLO cladding fuel is performed. Design parameters of fuel rod, operating conditions, and base irradiation power history are obtained from Ref. [7]. Initial conditions of fuel rod before accident are calculated by FRAPCON-4.0 [8]. Transient fuel behaviors for a LOCA period are analyzed by FAMILY computer code. It has a fuel relocation model developed by Quantum Technology (QT). Axial power model of

QT after relocation is modified to reflect the decay heat history along the fuel rod. Reactor core in APR1400 is divided into one hot channel and one average channel, and single fuel rod is allocated in the hot channel. In the analysis following models and conditions are used.

- Core composed of hot fuel rod and assemblies is divided into 40 evenly spaced axial nodes.
- Two different cladding hoop strain limits due to the constraint of adjacent fuel rods are considered; 36 % and 70 %. If cladding strain reaches this limit, cladding deformation propagates axially.
- FRACAS cladding deformation model is used.
- Strain based NUREG-0630 cladding failure criterion is used.
- Analyzed fuel burnup is ranging 0~30 MWd/kgU (rod average) and maximum peak fuel power of 14.1 kW/ft is maintained within this burnup.
- Cladding inner surface oxidation is considered when cladding burst happens and also local fuel burnup exceeds 30 MWd/kgU.
- Size of gap for initiation of axial fuel relocation is set as 200 μm.

3.2 Uncertainty analysis

Regulatory LOCA audit safety analysis has been conducted with a realistic evaluation methodology, so called as a best-estimate plus uncertainty quantification (BEPU). In the analysis, we also used the BEPU methodology. Many uncertainty parameters in fuel and TH are taken into account. Considered uncertainties are composed of 36 fuel and 21 TH parameters. Details on these can be founded in previous works [9]. In this study, packing fraction is considered as an additional uncertainty parameter, and its uncertainty is set as $\pm 2\sigma$ with uniform probability density function.

Uncertainty analysis has been done at fuel burnup of 1 MWd/kgU and 30 MWd/kgU, respectively. The reason for selection these burnups is described in section 4.1. In each burnup, 124 inputs of FRAPCON and FAMIY code are produced by MOSAIQUE software [10].

4. Results

4.1 Base case analysis

Fig. 2(a) shows a typical peak cladding temperature (PCT) evolution before and after factorization of fuel relocation at 1 MWd/kgU burnup. Without fuel relocation, blowdown and reflood PCT is 1209.9 K and 1092.4 K, respectively. As fuel relocation considered, the reflood PCT increases to 1136.8 K, the blowdown PCT is not changed. Strain constraint of cladding between 36 % and 70 % do not induce any big differences in blowdown and reflood PCT. It only changes PCT evolution slightly after reaching the reflood PCT. Fig. 2(b) shows a PCT change at 30 MWd/kgU burnup. PCT at blowdown and reflood is 1176.6 K and 1054.7 K, respectively. As fuel relocation model factorized, similar to the 1 MWd/kgU case, the reflood PCT only increases to 1132.5 K. Constraint strain of cladding do not induce any differences. This implies the fuel relocation does not have any impacts on fuel behavior during blowdown period, but it may induce significant impacts on reflood period.

Fig. 3 shows the results of PCT behaviors as a function of fuel burnup, relocation and cladding constraint. The blowdown PCT is not affected by fuel relocation and cladding constraint strain, but it only influenced by fuel burnup. Maximum blowdown PCT is observed at 1 MWd/kgU, and it reduced gradually until reaching 13 MWd/kgU burnup. Then it increased gradually up to 30 MWd/kgU. These behaviors are related to the cladding deformation and fuel stored energy before accident initiation.

Meanwhile, the reflood PCT is significantly affected by the factorization of fuel relocation model, especially below ~1 MWd/kgU and above 25 MWd/kgU fuel burnup regions. In-between these burnups, the impacts are small or limited. At fresh and 30 MWd/kgU fuel, the reflood PCT has increased to ~ 80 K due to fuel relocation. Cladding constraint strain do not induce any meaningful differences again.

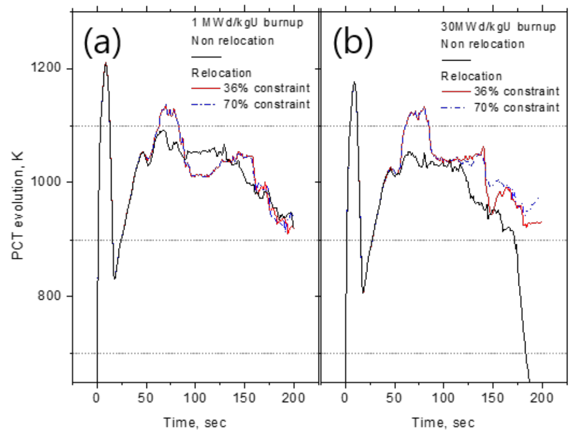

Fig. 2. PCT evolution at (a) 1 MWd/kgU and (b) 30 MWd/kgU burnup condition with and without fuel relocation.

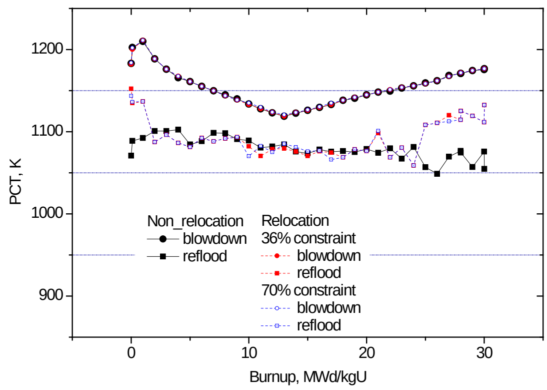

Fig. 3. Changes of blowdown and reflood PCT by changing burnup, constraint cladding strain and fuel relocation.

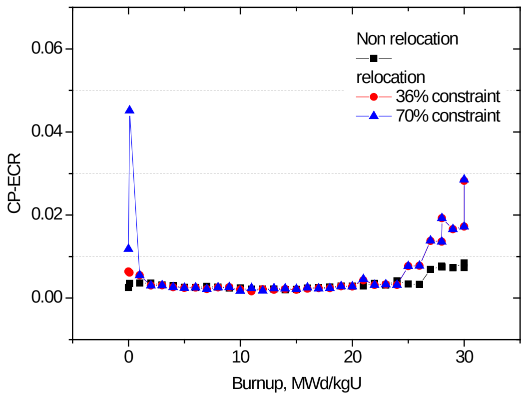

Fig. 4. LOCA induced CP-ECR as a function of burnup, constraint strain and fuel relocation.

Fig. 4 shows the LOCA induced Cathcart-Powell equivalent cladding reacted (CP-ECR). Generally, CP-ECR in non-relocation case is very low, less than ~0.01. However, after relocation model considered, it rises gradually up to ~0.03 in 36 % constraint condition. Constraint strain of cladding do not induce any big differences except for the very low burnup, less than ~1 MWd/kgU. In this condition, CP-ECR reaches ~0.045. Such a high ECR is related to the high cladding deformation. In this cases, hoop strain of cladding is attained ~60 %.

These analyses imply that fuel relocation may result in significant impacts on the performance at the fuel burnup below ~1 MWd/kgU or above ~25 MWd/kgU. Thus, uncertainty analysis has been done at fuel burnup of 1 MWd/kgU and 30 MWd/kgU condition, respectively.

4.2 Uncertainty analysis

Fig. 5 shows a typical set of 124 PCT evolutions during LOCA with and without fuel relocation at 30 MWd/kgU. If fuel relocation is not considered, as observed in Fig. 5(a), the third highest PCT at blowdown and reflood period is 1290.6 K and 1168.4 K, respectively. Meanwhile, as relocation is involved, observed at Fig. 5(b), the reflood PCTs have increased as expected. The third highest reflood PCT is 1298.2 K. This is about 130 K higher than the non-relocation cases. Similar results are observed at fuel burnup of 1 MWd/kgU condition. Without relocation model, the third highest reflood PCT in 124 runs is 1153.5 K. However, after consideration of the model, the third highest reflood PCT increases to 1234.9 K. This is about 80 K higher PCT value.

Fig. 6 shows a typical set of 124 CP-ECR evolutions during LOCA at 30 MWd/kgU burnup. As observed in Fig. 6(a), without relocation model, the first highest CP-ECR is 5.8 %. Meanwhile, if relocation is considered, it increases to 8.7 %. This is about 3 % higher CP-ECR.

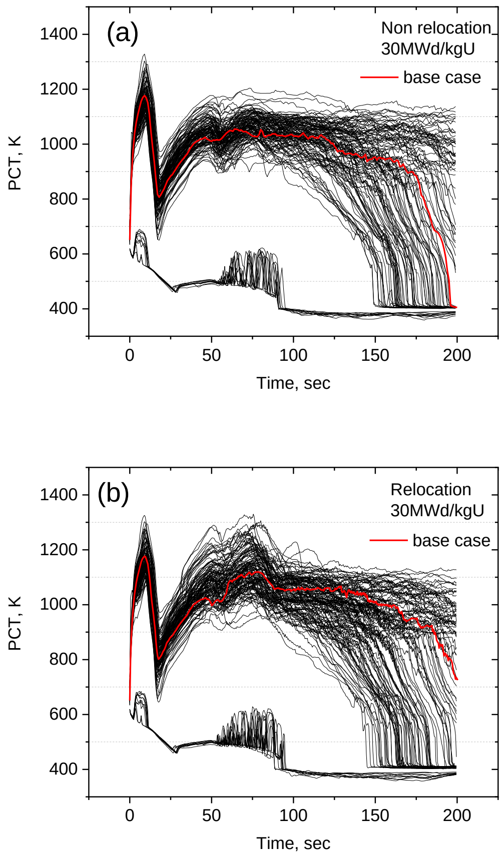

Fig. 5. 124 PCT evolutions (a) without and (b) with fuel relocation model at 30 MWd/kgU.

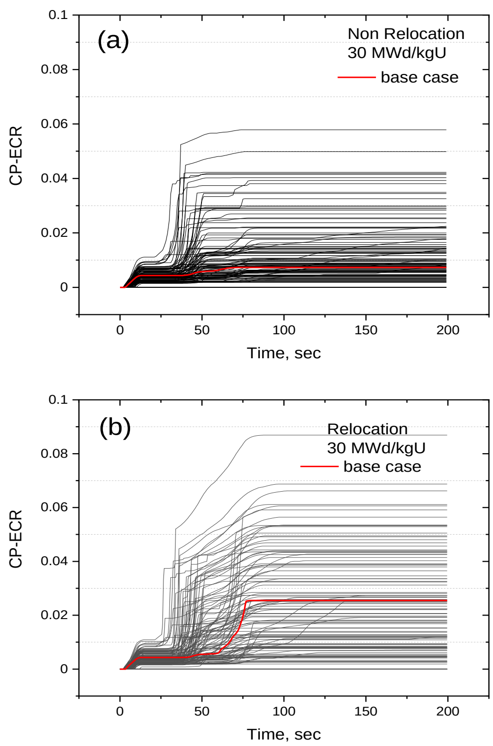

Fig. 6. 124 CP-ECR evolutions (a) without and (b) with fuel relocation model at 30 MWd/kgU.

Table 1. Summary of PCT and CP-ECR in 124 SRS

	Non-Relocation	Relocation	Δ[3]
[1]PCT$_{_Blowdown}$			
1MWd/kgU	1280.7 K	1281.3 K	0.6 K
30MWd/kgU	1290.6 K	1290.1 K	0.5 K
[1]PCT$_{_Reflood}$			
1MWd/kgU	1153.5 K	1234.9 K	81.4
30MWd/kgU	1168.4 K	1298.2 K	129.8
[2]CP-ECR			
1MWd/kgU	1.0 %	1.8 %	0.8 %
30MWd/kgU	5.8 %	8.7 %	2.9 %

[1] The third highest PCT among 124 runs
[2] The first highest ECR among 124 runs.
[3] Difference of PCT between relocation and non-relocation cases

CR-ECR increases are also founded at fuel burnup of 1 MWd/kgU. The first highest ECR is only 1.0 % if relocation is not involved. However, with relocation consideration, it increases to 1.8 %. Above described results of PCT and CP-ECR are summarized in Table 1.

4.3 Further research

Through this study fuel relocation effects on fuel behaviors, especially focused on PCT and ECR in APR1400 have been identified. But followings have to be researched further for the development of more precise and detailed modeling.

- Effects of axial nodding in core, size of fuel/clad gap for relocation initiation and cladding deformation constraint
- Effects of adjacent fuel rod conditions such as power profiles and their distortions, etc.

5. Summary

Fuel relocation model including packing fraction model and its impacts on fuel performance for a LOCA period have been evaluated in APR1400. FRAPCON4.0 and FAMILY computer codes are used in this study. Following results can be drawn preliminary.

- Packing fraction model and its uncertainty has been developed based on the available experimental data. But, researches have to be done to develop more precise model.
- Base case analysis suggests that the fuel performance during blowdown period is not affected by the fuel relocation, but it affects significantly during reflood period. Fuel burnup, especially below ~ 1 MWd/kgU and above ~25 MWd/kgU is important to the analysis of fuel relocation effects.
- Uncertainty analysis results through BEPU methodology reveal that if the relocation model is considered, the third highest reflood PCT and the first highest CP-ECR among 124 runs are increased significantly at 30MWd/kgU, such as ~130 K and ~3 %, respectively.

Above results are obtained from the given analysis conditions with the FRAPCON4.0 and FAMILY computer code. Thus it may be changed if different analysis conditions and computers are used. For example, FRAPCON4.0 has a different radial relocation model of fuel pellet compared to the previous versions, especially very low fuel burnup regions. This results in relatively high PCT/ECR values in these regions.

ACKNOWLEGEMENT

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