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Influence of Fuel Relocation to LOCA Safety Analysis

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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. This deformation and rupture process is typically called as ballooning and burst. If ballooning and successive burst happens, there is a possibility that fragmented fuel pellets can be relocated into the ballooned regions by the movement of axial and radial direction inside of cladding. And as the fragmented (and pulverized) pellets are smaller than the size of burst opening, they can disperse into the core through the burst opening. These process possibly can induce several safety issues related to the core coolability.

Fuel relocation can change the distribution of local heat source along the fuel rod. And it will influence the rod performance such as cladding temperature and oxidation for a LOCA period. Significant amount of fuel dispersal can alter coolable geometry in the core, and it can evoke several safety concerns such as fuel-coolant interaction, re-criticality, long-term cooling, dose assessment etc [1,2].

In this paper, studies focused on the fuel relocation phenomena as a first step. Experimental results conducted since past several decades are compiled. And impacts of fuel relocation to rod performance during LOCA are assessed preliminarily.

2. Fuel Relocation and Models

Since 1970s about 9 research programs have been conducted to evaluate the fuel behaviors during LOCA [1,2]. Research program and characteristics of fuels used in each program are summarized in Table 1. Fuel burnup is ranging from fresh to ~90 MWd/kgU, and various types of zircaloy cladding materials with UO_2 fuel are used also. Through those tests, following general conclusions can be drawn.

- There is a threshold cladding hoop strain for axial fuel relocation. It is ranging 4~17%.
- Transition from coarse fuel fragment to fine fragmentation (pulverization) is strongly related to the fuel burnup. And fuel temperature exposed to steady-state irradiation and also transient during LOCA is an important parameter for the formation of pulverization.

Table 1. Fuel relocation and dispersal in LOCA test program

Program	Fuel	Burnup (MWd/kgU)	# of test
PBF	UO_2/Zr4	0-17.7	4
FR-2	“	0-36.5	39
PNL/NRU	“	0	4(bundle)
PHEBUS-LOCA	“	0	5(bundle)
FLASH	“	1.6-51.7	5
ANL	UO_2/Zr2	56	4
Halden	UO_2/Zr2,4,E110	0-92	13
Studsvik	UO_2/ZIRLO	55.2-72.6	6
MIR	UO_2/E110	0-76	3(bundle)

Considering experimental observations, relocation models are proposed by PSI, SCK•CEN and Quantum Technologies (QT) [3-5]. Among them, QT model is used in this study. QT model is composed of three parts; fragmentation of fuel pellet, axial relocation of the fragments and thermal response of relocation. And, gap size is used for the threshold of axial relocation. Packing fraction is evaluated by the binary mixture of coarse and fine fragments. In the model, the threshold strain and packing fraction of coarse and fine fragments can be controlled by user inputs. For the thermal calculation of relocated fuel, fuel thermal conductivity, density, volumetric heat source and size of gap after relocation are modified. Details can be found in Ref. 5.

3. Analysis Details

3.1 LOCA analysis

APR1400 PWR plant with 16x16 ZIRLO cladding fuel was used for LOCA safety analysis. Design parameters of fuel rod, operating conditions, and base irradiation power history were obtained from Ref. [6]. Initial conditions of fuel rod before accident were calculated by FRAPCON-4.0 [7], and transient fuel behaviors for a LOCA period were analyzed by FRAPTRAN-2.0P1. FRAPTRAN-2.0P1 is an updated version of FRAPTRAN-2.0 [8] including the fuel relocation model developed by QT.

Thermal-hydraulic boundary conditions such as heat transfer coefficient, pressure and temperature of coolant for a LOCA period were obtained from APR1400 LBLOCA safety analysis at the fuel burnup of 30MWd/kgU. Twenty evenly spaced axial nodes were allocated along the fuel rod. To obtain a larger deformation of cladding for the relocation study, fuel thermal conductivity, heat transfer coefficient of coolant and rod internal pressure were biased with the multiplication factor of 0.95, 0.80, 1.20, respectively.

3.2 Sensitivity analysis

Sensitivity study has been conducted for the identification of important uncertainty parameters in relocation model. Cladding performances must be affected by the total mass of relocated fuels. And this mass must be influenced by the packing fraction and cladding failure strain. Thermal conductivity of crumbled fuel will also change the fuel and cladding temperature. Size of gap, which is used as a threshold of axial fuel relocation in QT model, and number of axial node along the fuel rod will influence the total mass of relocated fuel. In these regards, following parameters and ranges of uncertainty are selected for sensitivity study.

- Packing reaction: 0.5 ~ 0.8 (0.69)
- Cladding failure strain: 15 ~ 94 %
- Thermal conductivity of crumbled fuel: +/- 20 %
- Threshold gap size: 0.1 ~ 500 μm (200 μm)
- Number of axial node: 20 ~ 200

Values of ( ) denote best-estimate in the relocation model

4. Results

4.1 Packing fraction

Fig. 1(a) shows the changes of cladding temperature with packing fraction variations. As relocation was considered with the packing fraction of 0.5, the reflood peak cladding temperature (PCT) was increased about 110 K with respect to the base case. Here, base case means that the relocation model does not activated. And the fraction was changed to 0.8, the reflood PCT was increased about 280 K.

Fig. 1(b) shows the changes of Cathcart-Powell equivalent cladding reacted (CP-ECR) with the packing fraction. As the model was activated with the fraction of 0.5, the CP-ECR was increased about 0.5% with respect to the base case. And the fraction was changed to 0.8, 2.3% of CP-ECR increase was attained.

4.2 Cladding failure strain

Fig. 2(a) shows the cladding temperature evolutions with the factorization of the relocation model as a function of failure strain. As the failure strain was given as 15 %, the increase of the reflood PCT due to relocation was about 110 K. And this difference intensified with the failure strain increase, such as the strain was given as 73 %, it was about 290 K. But 94% failure strain, the PCT increase reduced to about 180 K.

Fig. 2(b) shows the CP-ECR changes with the factorization of the relocation model as a function of failure strain. As the failure strain was given as 15 %, the increase of the CP-ECR due to relocation was 0.8 %. And as the strain was given as 73 %, it was 2.1 %. But 94 % failure strain, the ECR increase reduced to 0.6 %. This reduction of PCT and ECR at the 94% failure stain are attributed to the reduction of heat flux due to the larger deformation of cladding.

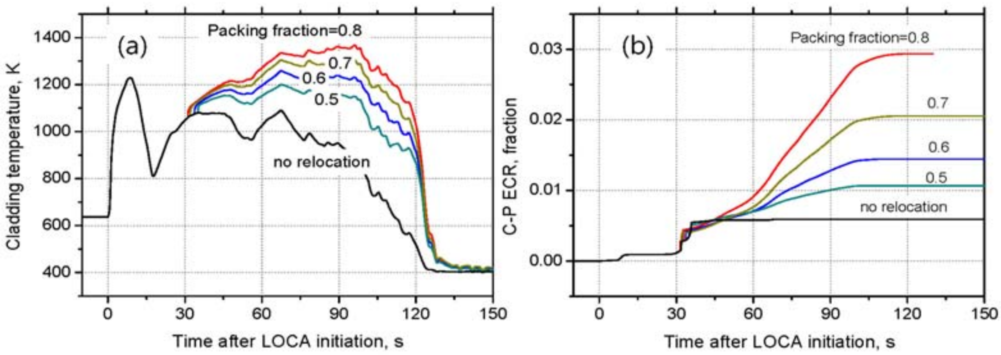

Fig.1. Changes of (a) cladding temperature and (b) CP-ECR with the variation of packing fraction from 0.5 to 0.8. Cladding failure strain is ~35%

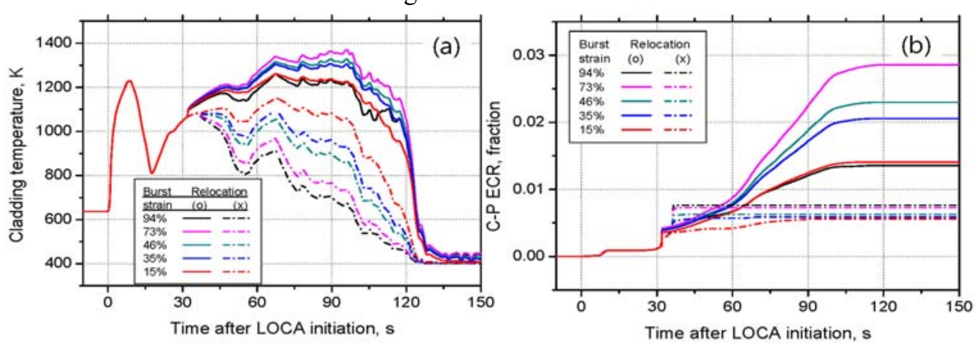

Fig.2. Changes of (a) cladding temperature and (b) CP-ECR with the failure strain and relocation consideration. Peaking factor is given as 0.69.

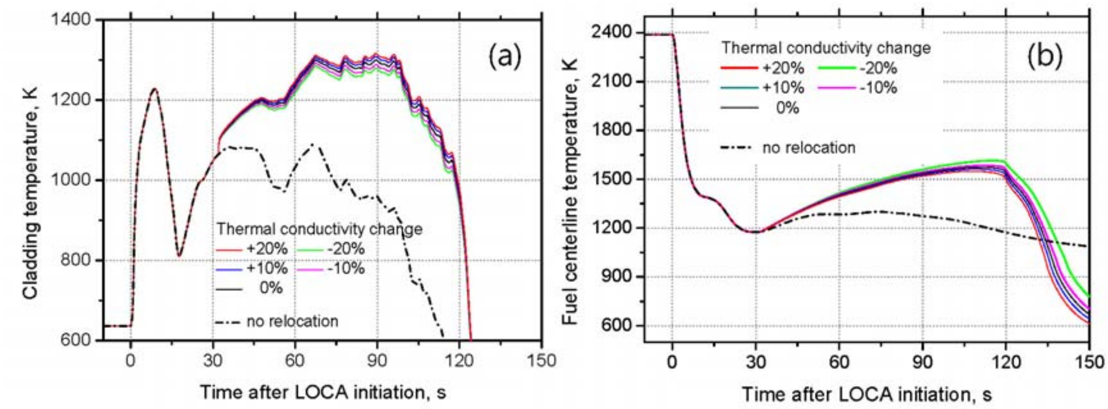

Fig.3. Changes of (a) cladding temperature and (b) fuel centerline temperature with the given effective thermal conductivity variations of crumbled fuel

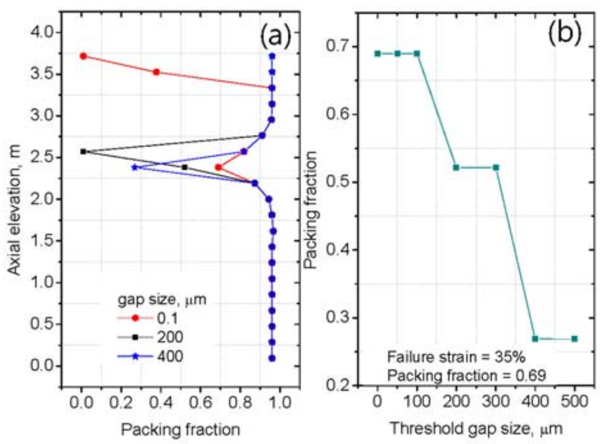

Fig. 4. Changes of packing fraction (a) along the fuel rod and (b) burst node with the threshold gap size

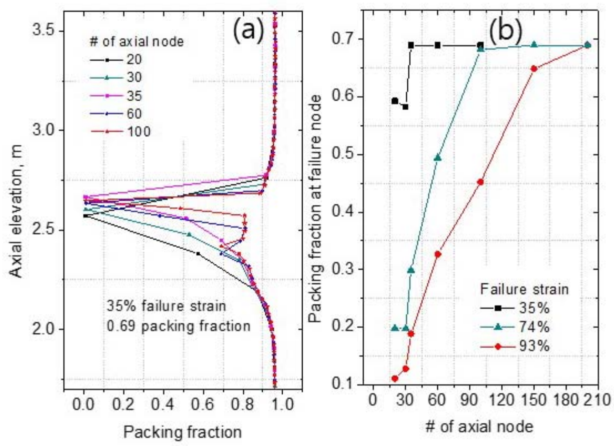

Fig. 5. Changes of packing fraction (a) along the fuel rod and (b) at burst node with the number of axial node

4.3 Effective thermal conductivity

Fig. 3(a) shows the cladding temperature changes with the changes of effective thermal conductivity of crumbled fuel. As the conductivity was varied from -20 % to +20 % with respect to the base case, the reflood PCT was changed from -20 K to +16 K, respectively. Fig. 3(b) shows the fuel centerline temperature with the conductivity change. As the conductivity was changed from -20 % to +20 %, the peak centerline temperature for a reflood phase varied from +41 K to -23 K, respectively. These changes are relatively smaller than the changes caused by the packing fraction or burst strain variables. And about 120 s after LOCA initiation, centerline temperatures of relocated fuels reduced rapidly. These are due to the improved heat conduction from crumbled fuel to coolant. QT relocation model assumes contact between fuel and cladding as relocation happens basically.

4.4 Size of gap

Fig 4 shows the packing fraction variations with the size of gap, which is used for the criterion of axial fuel relocation. The results are obtained from the given 35 % burst strain, 0.69 packing fraction, 20 axial nodes along the fuel rod. If the gap width is smaller than the 100 μm, the desired packing fraction of 0.69 is attained, but if the size is in between 100 and 400 μm, or even larger than 400 μm, the desired fraction cannot be achieved.

4.5 Axial node

Fig 5 shows the distribution of packing fraction along the fuel rod with change of number of axial node. As the failure strain is given as 35 %, the minimum required number of axial node to attain the packing fraction of 0.69 is lying in between 30 to 35. And the failure strain is given as 73 %, the minimum node is above 60. And 94 % failure strain, the required node is in between 150 and 200. These analyses are performed with the 200 μm size of gap threshold and 0.69 packing fraction condition. Thus the results must be varied depending on the size of gap and packing fraction.

4.6 Further research

Through this study several important parameters that can affects fuel performances can be founded. But followings need to be studied further.

- For the uncertainty quantification, ranges of uncertainty such as packing fraction, size of gap for relocation, effective thermal conductivity etc. should be determined.
- Axial nodding of fuel rod needs to be determined carefully based on the experimental results.

5. Summary

Fuel relocation and its impacts on fuel performances for a LOCA period have been evaluated preliminary. Following results can be drawn.

- There is a threshold cladding strain for axial fuel relocation. Size of fragmented fuel pellets and formation of pulverization is related to the fuel burnup and temperature.
- Packing fraction and cladding failure strain have significant impacts on cladding temperature and oxidation
- Axial nodding and size of gap for relocation can influence the total mass of fuel relocation significantly.
- For the uncertainty quantification, ranges of uncertainty on key parameters should be determined.

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