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Fuel Dispersal and Recriticality Safety Analysis during LOCA in APR1400

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1. Introduction

During a large-break loss-of-coolant accident (LBLOCA) in nuclear power plants, fuel pins can be bursted in a core-wide due to excessive deformation of cladding at high temperature [1]. When the cladding burst occurs, the fragmented fuel pellets may be dispersed into the core through the burst opening. If the amount of fuel dispersal is significant, potential safety issues defined by U.S.NRC can arise [2].

- Recriticality of dispersed fuel fragments
- Energetic fuel-coolant interactions
- Core coolability and long-term decay heat removal
- Radiological impacts, including control room dose and equipment qualification

Among the above safety issues, this paper deals with recriticality safety. To address this issue, following three areas have to be studied:

- amount of fuel pin burst in a core-wide during LOCA,
- mass of fuel deposition into the core bottom from the bursted fuel pins, and
- critical mass of dispersed fuel for recriticality.

In this paper, evaluation methodology and results of each area for recriticality analysis in APR1400 during LOCA are described. Recriticality safety analysis also performed based on the three research areas.

2. Fuel Pin Burst Fraction

2.1 Evaluation Methodology

The 16x16 PLUS7 fuel with ZIRLO cladding in APR1400 was modeled for a large-break LOCA safety analysis. Initial states of fuel pin before accident initiation are calculated by FRAPCON-4.0 fuel performance code [3]. Transient fuel behaviors for a LOCA period are analyzed by the FAMILY code [4]. For the LOCA analysis, reactor core in APR1400 is divided into one hot channel and one average channel, and single fuel pin was allocated in the hot channel. Considered fuel and thermal-hydraulic uncertainties are 38 and 21 parameters, respectively. Monte Carlo method is used to get the cladding burst probability at 8 different fuel burnups from 0 to 60 MWd/kgU [5].

Power to burst probability curves are constructed in a fuel burnup domain, shown in Fig. 1. These curves are constructed with 95 % confidence interval. Fuel pin burst fraction during LOCA was evaluated by the comparison between the burst probability curves and each fuel pin power in the core during reactor operation. Fig. 1 also shows the comparison between constructed cladding burst probability curves and evolutions of each fuel pin power during reactor operation at the initial core (cycle 1) of APR1400.

2.2 Evaluation of fuel pin burst fraction

In a regulatory analysis, fuel failure is counted deterministically based on the given failure criterion for the assurance of conservatism. As shown in Fig. 2, if 1 % pin burst probability curve is employed as a deterministic burst criterion, the burst fraction at beginning of cycle (BOC) of initial core is 14.4 %. The fraction is increased continuously with burnup increase. It reaches 26.6 % at 8 MWd/kgU burnup (core average) and reduces to 19.0 % at end-of-cycle (EOC). As 5 % probability curve is used as the criterion, the fraction is 1.75 % at BOC, and it increases to 3.8 % at 2 MWd/kgU, then reduced to 0.8 % at EOC.

Results of fully probabilistic approach of the fuel pin burst is also shown in Fig. 2. Fully probabilistic means that the fuel pin burst fraction in the core is counted as the summation of each fuel pin burst probability at the given power and burnup. The analyzed fraction is 0.6 % at BOC, and it increases to 0.8 % at 8 MWd/kgU, then reduced to 0.5 % at EOC. Details on the methodology and evaluation results are described in authors' previous work [5].

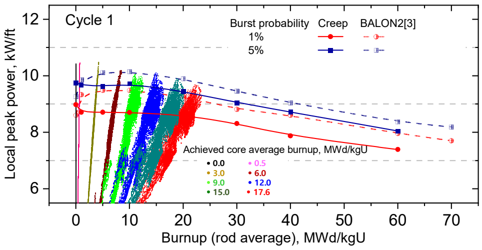

Fig. 1 Power to burst curves and local fuel pin powers in APR1400 initial core (cycle 1) [5]

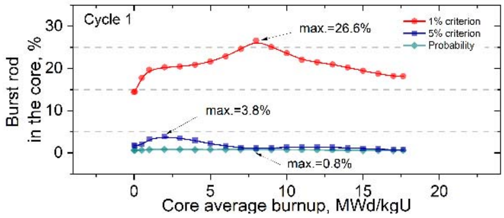

Fig. 2 Evolution of fuel pin burst fraction in APR1400 initial core (cycle 1) [5]

3. Dispersed Fuel Mass

3.1 Pin based dispersed fuel mass

Pin based fuel dispersal can be evaluated by the comparison of following three factors; the size of fuel fragment, size of burst opening, and allowable axial fuel relocation. In general, the size of the fragmented fuel pellets can be divided into two groups such as fine fragments and coarse fragments. According to the LOCA simulation test the coarse fragments are mostly observed below ~60 MWd/kgU burnup [6]. Size of coarse fragment was 2.78 mm (average), which is observed at FR2 test with fuel burnup 2.5~35 MWd/kgU [7]. Size of burst opening in the cladding shows huge uncertainty [6]. The width and length of the opening are ranging up to ~ 20 mm and ~ 40 mm, respectively. Thereby, with conservative assumptions coarsely fragmented fuel pellets can escape through this burst opening.

For the assessment of fuel dispersal in a pin, axially relocatable fuel pellets should be evaluated. Axial relocation of fuel pellet is governed by the cladding hoop strain. U.S.NRC reports that 3% cladding hoop strain is required for axial relocation in high burnup fuels [6]. Therefore, strain distribution along the fuel pin should be known.

Fig. 3 shows cladding hoop strain distribution after pin burst. Average cladding strain is obtained from the analysis of 4915 bursted cases in PLUS7 fuel during LOCA. It is calculated by FAMILY code. When the 3 % strain criterion is applied and the upper part of fuel pellets from the burst in the fuel pin is considered, 10.0 % fuel pellets along the pin can be relocatable. Consequently 205.4 g fuel can disperse through the burst opening at maximum. This amount is used as the dispersed pellet mass from a pin for the conservative analysis.

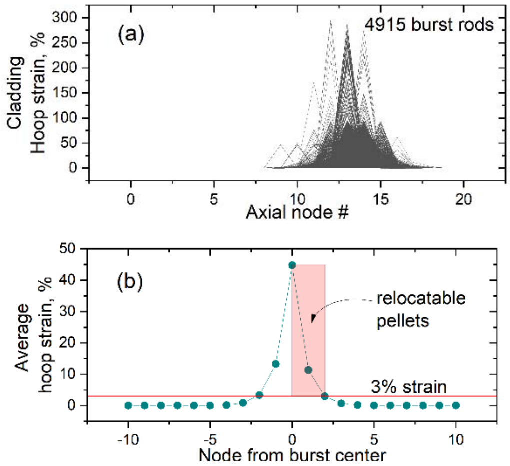

Fig. 3 (a) Cladding hoop stain of 4915 burst cases, and (b) average hoop strain from the burst center in PLUS7 fuel

3.2 Dispersed fuel mass in a core-wide

Dispersed fuel mass in a core-wide can be evaluated simply by considering the number of bursted fuel pins and dispersed fuel mass from a pin. Fig. 4 shows the results of total dispersed fuel mass. When 1 % probability curve is employed as a burst criterion, the total dispersed mass at BOC of initial core is estimated as 1936.7 kg. The mass is increased with burnup increase. It reaches 3590.2 kg at 8 MWd/kgU burnup (core average) and reduces to 2448.4 kg at EOC. As 5 % probability curve is used as the criterion, the mass is 236.8 kg at BOC, and it increases to 517.5 kg at 2 MWd/kgU, then reduced to 100.2 kg at EOC.

Result of probabilistic analysis is also shown in Fig. 4. The total dispersed mass is 76.3 kg at BOC, and it increases to 105.4 kg at 8 MWd/kgU, then reduced to 71.0 kg at EOC.

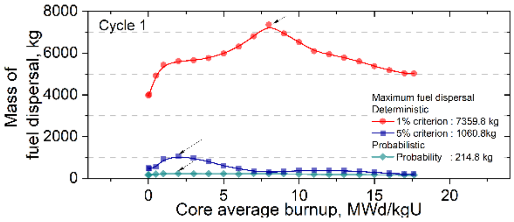

Fig. 4 Total dispersed fuel mass into the core during LOCA in APR1400 (cycle 1)

Among the dispersed fuel into the core, the important things for recriticality assessment are deposited pellets into the core bottom. There is possibility that the dispersed fuel pellets can escape from the core due to the steam/water coolant flow. For the determination of fuel pellet escape, authors have analyzed critical size of fuel pellet by utilizing force balance between buoyancy and drag during LOCA [8]. In this analysis uncertainties caused by thermal-hydraulics including shape of fragmented fuel pellet are considered.

Fig. 5 shows the evaluated critical size distribution. Critical radius of dispersed fuel pellet shows log-normal distribution. Lower and upper limit with 95%/95% probability/confidence level are estimated as 0.2403 mm and 1.479 mm, respectively. Details on this analysis can be found in ref. 8.

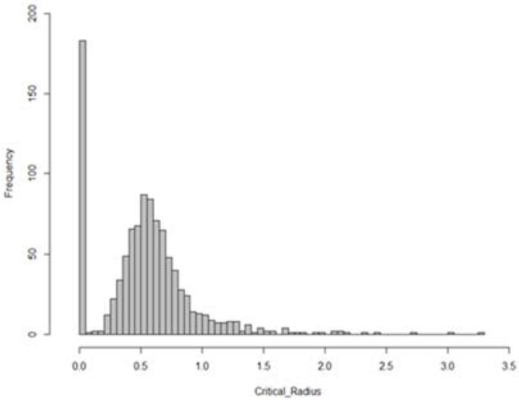

Fig. 5 Histogram of maximum critical radius of dispersed fuel particle (mm) [8]

For the recriticality analysis, maximum pellet deposition in the core is necessary. Thereby, the lower limit of 0.2403 mm was used. Under this criterion, all coarsely fragmented fuel pellets will be deposited in the core. This means that all dispersed fuel masses, as shown in Fig. 4, should be used for the recriticality assessment.

4. Recriticality Assessment

4.1 Critical mass change

Serpent physics codewith an ENDF/B VII.0 library is used for the determination of critical mass and burnup calculation. Burnup calculation has been performed up to 60 MWd/kgU with assumptions of a two-dimensional infinite fuel array and an initial 5 wt% U^{235} enrichment in PLUS7 fuel. Boron concentration and power density are 1,000 ppm and 38.36 W/gU, respectively. For the assessment of critical mass following conditions are prescribed.

- Shape of pellet deposit: conical shape
- Composition:
    - Cone interior: homogeneous mixture between fuel and coolant
    - Exterior: coolant without boron
- Fuel/coolant mixing ratio: 5 %, 10 %, 15 %

Fuel/coolant mixing ratio is defined as the percentage of UO_2 mass with respect to UO_2 plus coolant.

Table 1 shows the assessed critical mass with fuel burnup and mixing ratio. Critical mass increases as the burnup increases. When the mixing ratio is 10 %, smaller critical masses are observed. In this study, critical masses analyzed with 10 % mixing ratio are used as the recriticality mass criteria for conservative analysis.

Table 1. Critical mass with burnup and mixing ratio

Burnup MWd/kgU	Critical mass, kg		
	Fuel mixing ratio		
	5%	10%	15%
0	253.6	175.8	201.3
5	327.2	217.4	251.5
10	441	277.3	326.4
15	610.6	364.3	435.3
20	889	497.5	603.9
25	1364	717.9	879.2
30	2320.8	1126.1	1370.1
35	4511.3	1936.2	2366.3
40	11830.2	4152	4841.7
45	80852.6	13865.2	14551.6

4.2 Assessment of recriticality

Possibility of recriticality can be assessed simply by comparison between deposited fuel mass and critical mass with the given burnup, which are shown in Fig. 4 and Table 1, respectively. When 1 % probability curve is employed as a burst criterion, the total deposited fuel mass is ranging 1936.7 kg ~ 3590.2 kg from 0 MWd/kgU to 18 MWd/kgU burnup. These are well above the critical masses shown in Table 1. Therefore, possibility of recriticality may exist. As 5 % probability curve is used as the criterion, the deposited mass from 0 MWd/kgU to 6 MWd/kgU burnup is larger than the critical masses of the given burnup. So recriticality in this burnup may be possible. As probabilistic burst analysis considered, the dispersed fuel mass is ranging 71.0 kg ~ 105.5 kg. These are below the critical masses, suggesting that the recriticality is impossible.

Fig. 6 shows the location of bursted fuel pins in the core during LOCA. As can be seen in the figure, bursted pins are located throughout the core. When 1 % and 5 % criterion is used, maximum dispersible fuel mass in an assembly is estimated 40.0 kg and 19.7 kg, respectively. These are well below the critical mass, as shown in Table 1. Therefore, possibility of conical shape accumulation of dispersed fuel pellet at the core bottom is very low. Furthermore, conservative assumptions such as the zero-boron concentration in coolant, fuel/coolant mixing ratio are used for the critical mass analysis. Based on this information, criticality safety seems to be maintained during LOCA in APR1400.

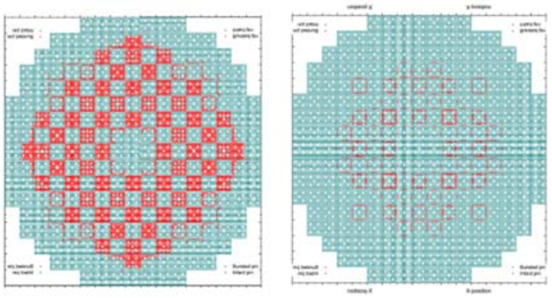
(a) (b)

Fig. 6 Location of bursted fuel pins as (a) 1% and (b) 5% probability curves applied as burst criterion

5. Summary

Fuel dispersal and subsequent criticality safety analysis during LOCA in APR1400 has been performed. Fuel pin burst analysis in a core-wide, evaluation of deposited fuel mass, recriticality safety analysis have been performed with the help of computer codes, experimental evidences and various conservative assumptions. Followings are main results obtained temporarily.

- Fuel mass deposited in the core during LOCA is successfully evaluated by the assessment of fuel pin burst, dispersed fuel mass from the pin, and critical size of fuel pellet for core deposit.
- Fuel mass deposited in the core exceeds the critical mass depending on the burst criterion and the core condition. However, criticality safety seems to be maintained because several conservative assumptions are employed in this analysis.

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