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Evaluation of the Effect of Fuel Relocation on the current LBLOCA Safety Analysis using SPACE

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1. Introduction

Oxide fuel cracks into many pieces during normal operation. In a loss-of-coolant accident (LOCA) transient, pellet fragmentation can occur because of the thermal-mechanical response. In addition, cladding deformation can occur due to a difference in pressure inside and outside the cladding and an increase in cladding temperature. If sufficient cladding deformation occurs, fuel fragments will be relocated into a ballooned region in the fuel rod. The heat source will increase due to the effect of relocation and consequently, increase the cladding temperature and local cladding oxidation. Therefore, the fuel fragmentation and relocation (FFR) phenomenon should be considered for LOCA safety analysis.

In this paper, the effect of FFR phenomenon on LOCA safety analysis is assessed using the SPACE FFR model developed by KAERI [1].

2. FFR Model

2.1 Space FFR model [1]

The SPACE FFR model was designed and implemented to simulate fragmentation and relocation phenomenon based on the Quantum Technology (QT) model [2] which is composed of the sub-models related to the ‘fuel fragmentation’, ‘fuel relocation’ and ‘fuel heat conduction and axial power’.

The sub-model related to the axial relocation of SPACE FFR model is identical to that of the QT model. The QT model is known as conservative because it is designed that all fuel fragments can be relocated, even if only a minor cladding deformation occurs. This is because the inter action between fuel fragments is not considered.

2.2 Additional assumption

The cladding deformation causes the increase of the heat transfer area between the outer wall surface and coolant. For this reason, the increase of the cladding temperature during the LOCA transient is suppressed until the strain reaches up-to specific value even though the heat source is increased by axial relocation of the fuel fragments. According to Ref. [3], the cladding temperature can increase as the effect of the axial relocation on the increase of the heat source in ballooned region when the strain of the cladding exceeds 35 percent at the coplanar location.

Therefore, in the FFR effect evaluation of this paper, excess of the cladding strain 35% is added as a condition for relocation to occur.

3. Analysis Details

3.1 Analysis conditions and assumptions

The FFR phenomenon is related to ballooning and rupture of the cladding which occurs in reflood period. To confirm this, series of LBLOCA break spectrum analyses with FFR model are performed for two representative burn-up conditions of 30 MWd/kgU and 60 MWd/kgU. These are expected to be conservative in terms of power and burn-up. As shown in Fig.1 through Fig.2, relocations occur in the reflood period of guillotine break cases and show the increases in the reflood peak cladding temperature (PCT). In both burn-up conditions, the relocation occurs because the cladding is sufficiently deformed. However, 30 MWd /kgU case is more affected by the FFR phenomenon because the 30 MWd/kgU case before applying the FFR model has a higher reflood PCT than the 60 MWd/kgU case before applying the FFR model. In addition, the reflood PCT when relocation occurs is also higher for 30 MWd/kgU case than for 60 MWd/kgU case. Therefore, among the results of LBLOCA break spectrum analysis, the case showing the highest reflood PCT (30 MWd/kgU, 81% Cold-leg guillotine, and hereafter ‘PCT base case’) is selected as the base case for FFR evaluation from the perspective of PCT.

In addition, the effect of the FFR model on peak local oxidation (PLO) of the break spectrum calculations for LBLOCA analysis of APR1400 plant is shown in Fig.3 through Fig.4. The case showing the highest PLO (60 MWd/kgU, 85% Cold-leg guillotine, and hereafter ‘PLO base case’) is selected as the base case for the uncertainty quantification of the FFR evaluation from the perspective of PLO. The basis for selection of the PLO base case is the same as basis for selection of the PCT base case.

In the analysis, the following conditions and assumptions are used.

- APR1400 plant [4] is selected for the FFR analysis.
- The effects of pulverization are not considered. According to Ref. [5], there is little possibility of

pulverization under the current licensing burn-up condition.

- Several uncertainty parameters and ranges are used, which are the same as those used in the APR1400 LBLOCA analysis [4].
- ZIRLO high temperature creep model is used.
- ZIRLO cladding failure criterion is used.
- The variables excluding 'fragmentation packing fraction' among user inputs of the SPACE FFR model are applied as a default value.

3.2 Uncertainty analysis

The major uncertainty variables to represent the FFR phenomenon are as follows.

- Cladding deformation
- Gap pressure
- Fragmentation packing fraction
- Effective thermal conductivity of crumbled fuel

Among the above variables, cladding deformation and gap pressure are already included in the LBLOCA uncertainty variables. Effective thermal conductivity is not selected as an uncertainty variable because effective thermal conductivity is a function of fragmentation packing fraction. Consequently, fragmentation packing fraction is selected as an additional uncertainty parameter for the FFR evaluation, and its uncertainty is set as 0.62 ~ 0.79 based on Ref. [3]. The fragmentation packing fraction distribution is assumed as uniform for conservatism at higher values.

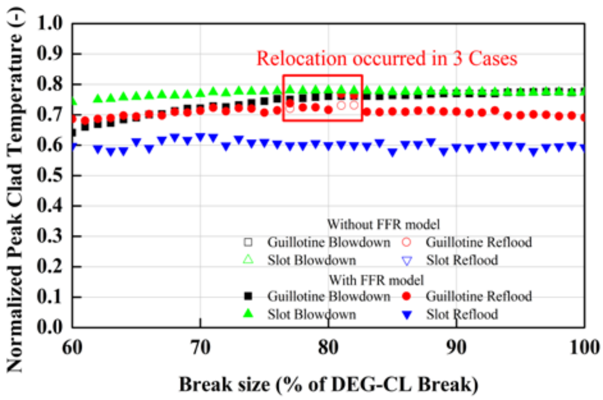

Fig. 1. 30 MWd/kgU break spectrum analysis result of PCT

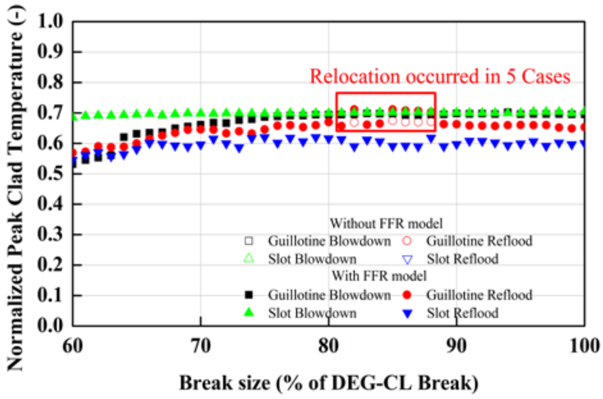

Fig. 2. 60 MWd/kgU break spectrum analysis result of PCT

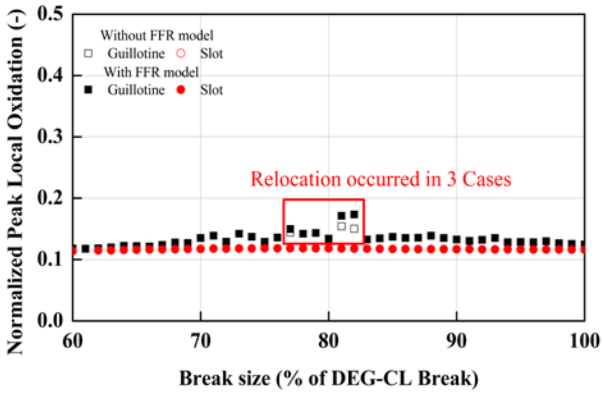

Fig. 3. 30 MWd/kgU break spectrum analysis result of PLO

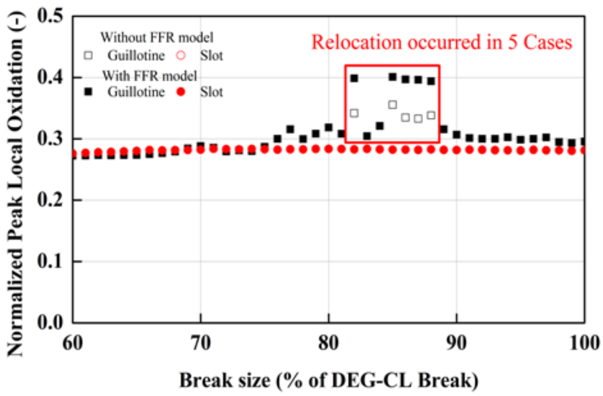

Fig. 4. 60 MWd/kgU break spectrum analysis result of PLO

4. Analysis results

Fig.5 shows the typical simple random sampling (SRS) PCT when relocation model is not applied to the PCT base case. Fig.6 shows the SRS PCT when relocation model is applied to the PCT base case. As expected, blowdown PCT is the same regardless of whether relocation model is applied. However, many relocations occur in the low burn-up condition, differently as expected. The movement of the heat source due to unexpected relocation increases the reflood PCT, total 3rd PCT and PLO. Fig.7 shows the

SRS PCT when relocation model and strain limit of 35% are applied to the PCT base case. It shows a similar behavior as the results of Fig.6, but the number of relocation cases is significantly reduced, and accordingly, reflood PCT is also reduced. The detailed results are summarized in Table 1.

Table 1: Summary of results about PCT base case SRS

	Non-Relocation	Relocation	Relocation with 35 % strain limit
Blowdown PCT[1)]	Base	Base + 0.0 K	Base + 0.0 K
Reflood PCT[1)]	Base	Base + 170.5 K	Base + 115.7 K
3rd PCT[2)]	Base	Base + 123.9 K	Base + 94.4 K
PLO[3)]	Base	Base + 1.898 %	Base + 1.923 %
Number of Relocation [4)]	-	59	28

1) The first highest PCT in each phase among 124 runs
2) The third highest PCT among 124 runs
3) The first highest PLO among 124 runs
4) The number of cases where relocation occurred among 124 runs

Fig.8 shows the typical SRS PCT when relocation model is not applied to the PLO base case. Fig.9 shows the SRS PCT when relocation model is applied to the PLO base case. Fig.10 shows the SRS PCT when relocation model and strain limit of 35% are applied to the PLO base case. The detailed results are summarized in Table 2. The analysis results show a similar tendency as the SRS results of PCT base case. However, PCT is relatively low due to the influence of burn-down curve, and PLO is relatively high because the initial oxidation is higher than PCT base case.

As shown in Table 1 and 2, the change in 3rd PCT and PLO does not show a clear tendency when the 35% strain limit is applied. This is because the influence of delayed relocation timing has a complex effect on PCT and PLO. An analysis of the impact associated with the timing of the relocation is currently being conducted. However, the main purpose of applying the 35% strain limit in this paper is to reduce the number of relocation occurrences.

It is notable that the 3rd PCT with a 35% strain limit does not decrease as expected in the SRS results of PLO base case. It is because the applied strain restriction is not the actual modeling of heat transfer area increase but only the relocation timing delay. It is believed that the actual heat transfer area increase modeling would decrease PCT and PLO further because the heat source movement is already made before the actuation of the FFR.

Table 2: Summary of results about PLO base case SRS

	Non-Relocation	Relocation	Relocation with 35 % strain limit
Blowdown PCT	Base	Base + 0.0 K	Base + 0.0 K
Reflood PCT	Base	Base + 141.8 K	Base + 129.0 K
3rd PCT	Base	Base + 37.8 K	Base + 49.3 K
PLO	Base	Base + 0.276 %	Base + 0.239 %
Number of Relocation	-	44	26

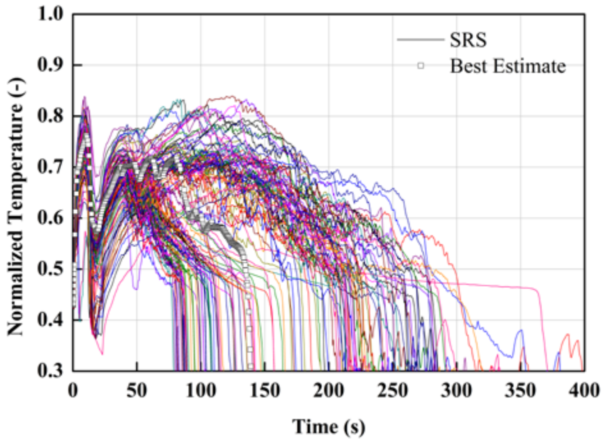

Fig. 5. 124 PCT results without relocation model (PCT base case)

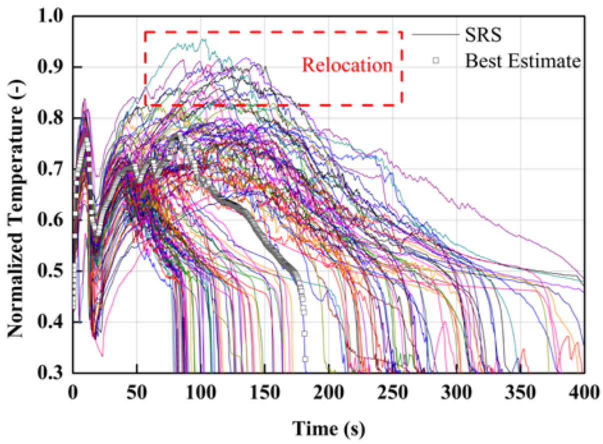

Fig. 6. 124 PCT results with relocation model (PCT base case)

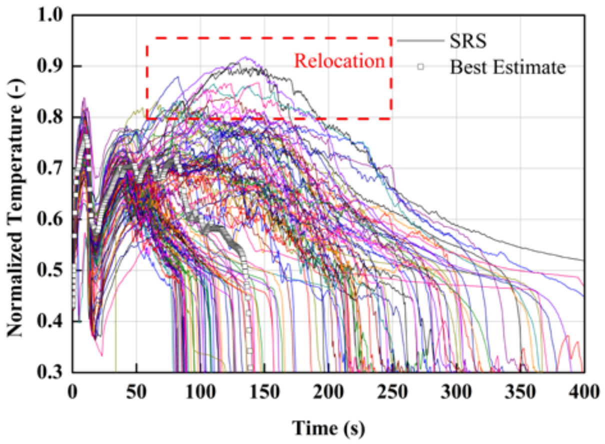

Fig. 7. 124 PCT results with relocation model and strain limit of 35% (PCT base case)

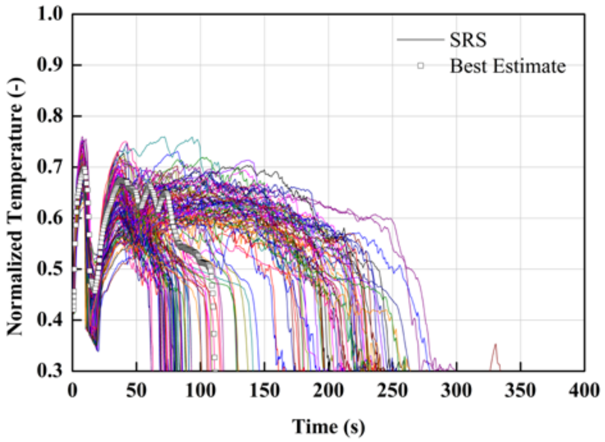

Fig. 8. 124 PCT results without relocation model (PLO base case)

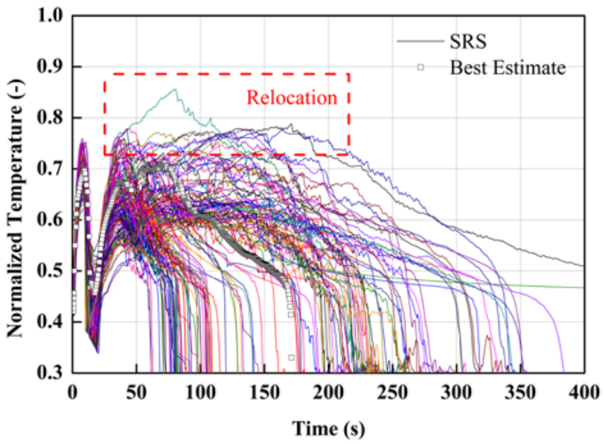

Fig. 9. 124 PCT results with relocation model (PLO base case)

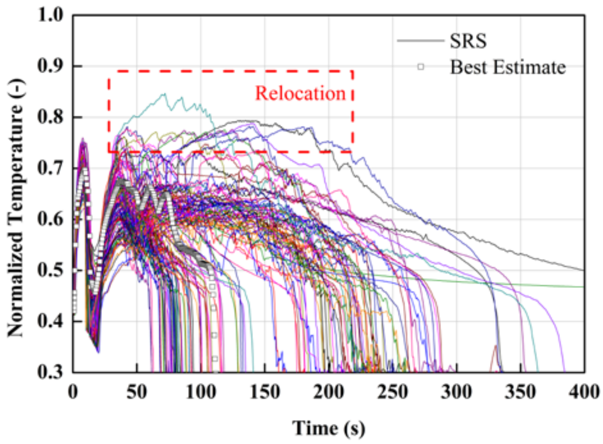

Fig. 10. 124 PCT results with relocation model and strain limit of 35% (PLO base case)

5. Conclusions

The effect of FFR phenomenon on LOCA safety analysis is assessed using the SPACE-FFR model. From the results of evaluation, it is confirmed that the relocation model affects the reflood phase where sufficient deformation may occur.

In the analysis applying the FFR model to the APR1400 plant, many relocations occur, but still meet the acceptance criteria. In addition, applying a 35% strain limit as the additional condition for FFR model, the number of relocation cases is significantly reduced, and accordingly, PCT is also reduced.

Although it is not plausible for the FFR to occur in regard of the current fuel discharge burn-up limit, the evaluation with FFR shows several FFR occurrences. Continuous efforts to secure the safety margins such as strain limits are being considered.

Additionally, the FFR model applicability is being evaluated for OPR1000 and WH plants as well as APR1400.

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REFERENCES

[1] Jong Hyuk Lee et al., “Assessment of model uncertainty for effective thermal conductivity of the SPACE in crumbled fuel”, Transactions of the KNS virtual spring meeting, May, 13-14, 2021.

[2] Lars Olof Jernkvist, Ali Massish, “Models for axial relocation of fragmented and pulverized fuel pellets in distending fuel rods and its effects on fuel rod heat load”, SSM 2015:37, 2015.

[3] L.J. Siefken, “Axial Fuel Relocation in Ballooning Fuel Rods”, 7th International Conference on SMiRT-7, August 22-26, Chicago, IL, USA.
[4] TR-KHNP-0030, “LBLOCA Best-Estimate Evaluation Model for APR1400 Type Nuclear Power Plants Using the SPACE Code”, August 2017.
[5] RIL 2021-13, “Interpretation of Research on Fuel Fragmentation, Relocation, and Dispersal at High Burnup”, December 2021.