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Impacts of Fuel Deformation on LOCA Safety: A Multi-Rod Modeling Approach

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1. Introduction

Fuel deformation caused by fuel rod ballooning and burst can significantly alter core coolability during a large break loss-of-coolant accident (LBLOCA) [1,2]. Excessive deformation may change the flow geometry within the assembly, which, in turn, affects the thermal-hydraulic volume. Additionally, fragmented and pulverized UO_2 pellets can be relocated within the cladding, modifying the heat sources [3]. If cladding deformation is severe enough to cause adjacent fuel rods to come into contact, convective heat transfer will be impeded, and conductive heat transfer will occur.

Previous studies by the authors have preliminarily examined the impact of these phenomena on LOCA safety [4]. However, there are limitations to that work. For instance, cladding deformation in a hot assembly was not directly assessed but was instead estimated based on hot rod properties, and the cladding contact fraction was determined using an empirical model previously developed by the authors [5]. Moreover, the effect of heat conduction due to contact between adjacent rods was not considered.

Recently, KINS has been enhancing the multi-rod modeling capabilities within the FAMILY computer code, focusing on core coolability analysis. FAMILY is an integrated computational code that combines the thermal-hydraulic capabilities of MARS-KS with the fuel performance analysis of FRAPTRAN [6-8]. This paper provides a brief overview of the models related to fuel deformation and presents a preliminary evaluation of fuel performance during a LOCA in the APR1400 reactor.

2. Implemented Models

To evaluate the impact of fuel deformation on core coolability, the following factors are considered: 1) hydraulic volume change, 2) form loss, 3) cladding contact, including the assessment of contact fraction and its effects on 3-1) convective and 3-2) conductive heat transfer, and 4) fuel relocation models. Some of these models have been introduced in the authors' previous works [4]. Below is a brief overview of these models.

Thermal-Hydraulic (TH) Volume Change: The thermal-hydraulic volume change in FAMILY is formulated by incorporating the concept of porosity (γ), treated as a variable responsive to cladding deformation. The parameter γ is integrated into the governing equations for mass, energy, and momentum (2 fields, 6 equations) [9]. The definition of γ is as follows:

$$\gamma = 1.0 - \frac{L}{V}\left[\pi(r_{clad}^2 - r_{clad,o}^2)\right] \qquad (2\text{-}1)$$

Where L and V stand for the axial length and initial volume at the deformed node, respectively, while r_{clad} and $r_{clad,o}$ represent the deformed and initial radius of the fuel cladding.

Form loss: Form loss due to fuel rod deformation is considered using the following correlation, which is already employed in MARS-KS [7].

$$[K_E, K_C]^T = [(1-B)^{2.0}, 0.45(1-B)]^T \qquad (2\text{-}2)$$

Here, K represents the loss coefficient, with subscripts E and C denoting expansion and contraction, respectively. The variable B represents the ratio of the flow area compared to the original undeformed state.

Cladding contact: Accurately assessing the cladding contact fraction (CAF) due to adjacent fuel rods is challenging because the fraction varies depending on the deformation shape, even when the same cladding strains are applied. Therefore, for simplicity, an idealized correlation is used. Fig. 1 shows a schematic of cladding contact between rods, and the CAF surrounded by four rods can be derived using the following correlation. This model was activated when cladding contact occured.

$$CAF = \sum_{i=1}^{4}\left\{2 \times cos^{-1}\left[\left(r_o^2 + p^2 - r_i^2\right)\Big/ 2r_i^2 p\right]\Big/ 2\pi\right\} \qquad (2\text{-}3)$$

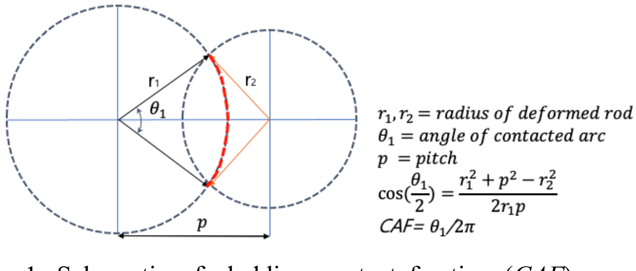

Fig. 1. Schematic of cladding contact fraction (*CAF*) between two deformed rods.

Here, r_o, r_i represent the outer radius of deformed fuel rod, with subscripts o and i denoting the evaluated rod and the surrounding four fuel rods, respectively. p is the pitch length.

- Convective heat transfer: Convective heat transfer change due to cladding contact is accounted for by modifying the heat transfer coefficient (h').

$$h' = h \times (1 - CAF) \quad (2\text{-}4)$$

Here, h, h' denote the heat transfer coefficient before and after cladding contact, respectively.

- Conductive heat transfer: Heat transfer due to conduction between surrounding fuel rods is modeled based on the following assumptions. First, the outer cladding temperature at the contact area between two claddings is averaged from the temperatures of the two outer claddings. Second, heat conduction between the contacted and uncontacted outer cladding areas is assumed to occur instantaneously, resulting in temperature equilibrium between these areas. This assumption does not reflect the actual situation, as instantaneous heat conduction across the outer cladding surface is not feasible without thermal dissipation to the coolant. Nevertheless, based on these assumptions, the following conduction model is derived for the calculations:

$$T_{surf} = T_{surf,o} + \sum_{i=1}^{4}\left\{\left[\frac{(T_{surf,i} - T_{surf,o})}{2}\right] \times CAF_i\right\} \quad (2\text{-}5)$$

Here, T_{surf}, $T_{surf,o}$ represent the cladding outer surface temperature after and before considering cladding contact, respectively. $T_{surf,i}$ and CAF_i are the cladding surface temperature and cladding contact fraction of surrounding fuel rod i, respectively.

Fuel Relocation: Fuel relocation model developed by Quantum Technology (QT) is employed in this analysis [10]. The heat source distribution at an axial location and the mass fraction of fine fragments are slightly modified. Further details can be found in reference 11.

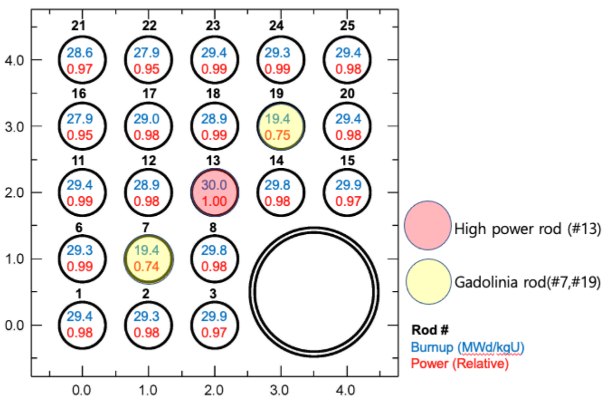

Fig. 2. 5x5 fuel rod array considered for LOCA analysis in a hot assembly. Rod numbers, burnup (MWd/kgU), and fuel power (relative to maximum power) is given.

3. Modeling for Multi-Rod Analysis

The APR1400 reactor was selected for the LOCA assessment, with the reactor core partitioned into a hot channel and an average channel. A 16x16 PLUS7 fuel assembly with ZIRLO cladding was used. To simulate fuel deformation and blockage in the hot channel, a 5x5 fuel rod array was employed instead of the full 16x16 array (236 rods), as illustrated in Fig. 2. The simulation included two gadolinia rods and a guide tube.

The LOCA analysis was performed at a hot fuel rod burnup of 30 MWd/kgU, as this burnup has the most significant impact on peak cladding temperature (PCT) [11]. The highest local peak fuel power, observed in rod number 13 in Fig. 2 before the accident initiation, was set at 14.1 kW/ft. The power and burnup for each fuel rod are depicted in Fig. 2.

The initial conditions of the fuel rods prior to the accident were determined using the FRAPCON4.0P1 fuel performance code [12]. The transient behavior of the fuel during the LOCA was analyzed using the FAMILY code, which incorporates the models described in Section 2. Changes in thermal-hydraulic properties due to volume changes in the hot channel were calculated at the assembly unit rather than at the subchannel level.

Limitations on cladding deformation were imposed based on both local subchannel and average flow area reduction criteria. Cladding deformation was halted when the flow area reduction reached 85% in the local subchannel and 65% on average in the 5x5 simulation. The strain-based NUREG-0630 burst criterion was applied [13]. This study is based on the 69th LOCA input out of 124 inputs from the authors' previous uncertainty analysis work [4], because this input results in a relatively higher reflood PCT.

4. Fuel Performance

4.1 Sensitivity Analysis

The effects of each fuel deformation model described in Section 2 on PCT during a LOCA were assessed. In the base case, where these models were excluded, the blowdown and reflood PCTs of the hottest fuel rod (No. 13) were 1208.3 K and 1108.0 K, respectively, as shown in Fig. 3.

When the TH volume change model was applied, the blowdown and reflood PCTs increased to 1212.1 K and 1191.1 K, which are 3.8 K and 82.8 K higher than the base case, respectively. The application of the form loss model did not affect the blowdown PCT, but it increased the reflood PCT to 1134.8 K, 26.8 K higher than the base case. The cladding contact model, along with the convective and conductive heat transfer models, had no impact on PCT due to the minimal cladding deformation, which prevented the activation of the contact model. Finally, when the fuel relocation model was applied, the reflood PCT increased to 1141.9 K, 33.9 K higher than the base case.

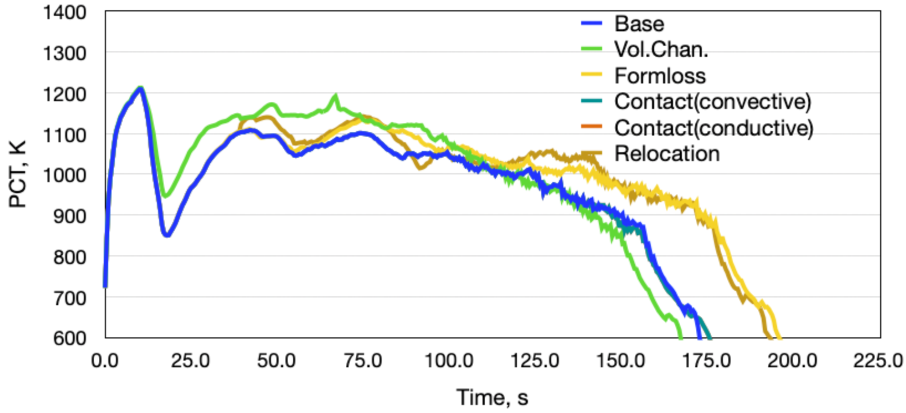

Fig. 3. Sensitivity of each model on the PCT of the high-power fuel rod (No.13)

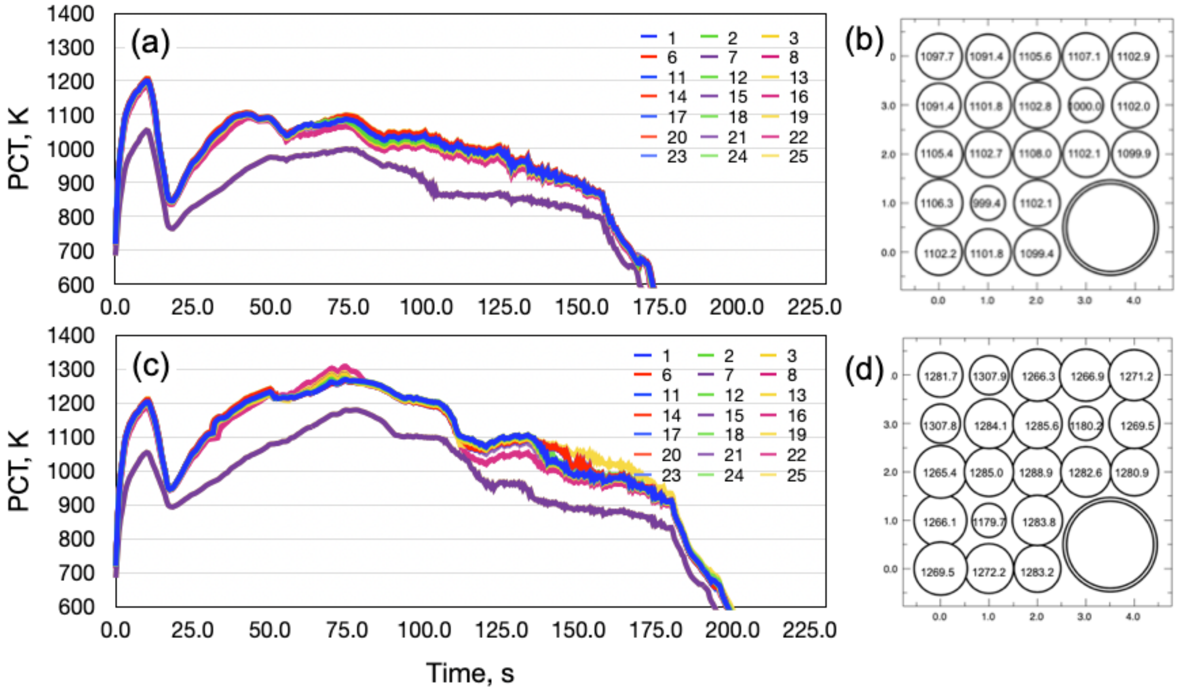

Fig. 4. PCT evolutions of 21 fuel rods in the 5x5 array: (a) before and (c) after the application of the models. (b) and (d) show the maximum reflood PCT before and after the factorization of the models, respectively.

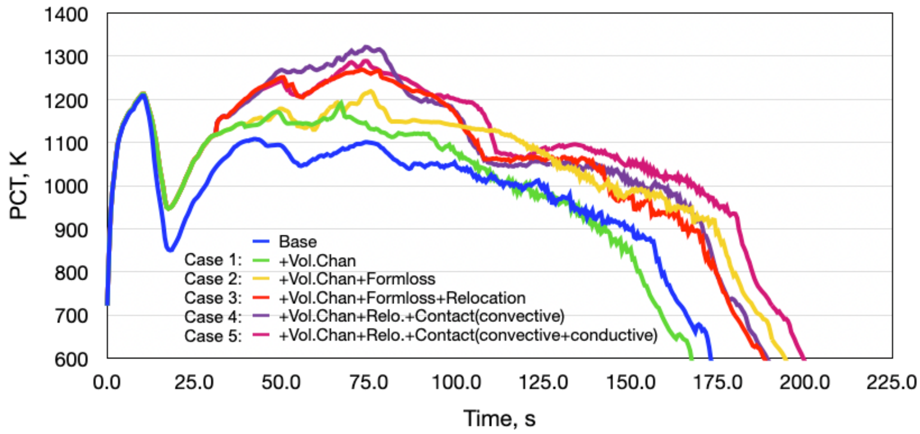

Fig. 5. Influence of combined fuel deformation-related models on the PCT evolution in the hottest fuel rod (No. 13).

4.2 Combined model effects

Fig. 4 illustrates the evolution of PCT across 21 fuel rods during the LOCA, both before and after model activation. When the models were excluded, as shown in Fig. 4(a) and (b), the blowdown and reflood PCTs for all rods, except the two gadolinia rods, ranged from 1183.8 K to 1208.3 K and 1091.4 K to 1108.0 K, respectively. However, after model activation, as depicted in Fig. 4(c) and (d), the blowdown and reflood PCTs increased to a range of 1186.2 K to 1212.3 K and 1265.4 K to 1307.9 K, respectively. This indicates an average increase of approximately 3 K for blowdown PCT and 180 K for reflood PCT. For the highest power rod (No. 13), the blowdown and reflood PCTs increased by 4.0 K and 180.9 K, respectively.

Fig. 5 shows the cumulative impact of the models on the PCT of the highest power fuel rod (No. 13). When only the volume change model was applied (case 1), the reflood PCT increased to 1191.1 K. With the inclusion of the form loss model (case 2), the reflood PCT rose to 1218.9 K. When the relocation model was activated under these conditions (case 3), the reflood PCT further increased to 1268.6 K. Adding the cladding contact model with convective heat transfer alone (case 4) caused the PCT to rise to 1321.6 K. However, when conductive heat transfer model was considered (case 5), the PCT decreased to 1288.9 K. This clearly demonstrates the influence of each model on PCT.

These preliminary analysis results underscore the significance of fuel deformation-induced models, such as thermal-hydraulic volume change, fuel relocation, and cladding contact, as well as their effects on heat transfer models. This also highlights the need for more refined analysis methodologies and the development of advanced computer codes, particularly with the capability for multi-dimensional analysis in terms of heat transfer and fuel deformation.

5. Summary

The impacts of fuel deformation-related models on LOCA safety analysis have been preliminarily investigated under a 5x5 multi-rod analysis condition. The main findings are as follows:

- For the multi-rod LOCA safety analysis, fuel deformation-induced models, including thermal-hydraulic volume change, form loss, cladding contact, and fuel relocation, were successfully developed and implemented in the FAMILY computer code.
- The incorporation of these models led to significant effects on fuel performance, particularly an increase in reflood PCT by approximately 186.6 K in the hottest fuel rod.
- These findings underscore the critical role of fuel deformation-induced models in LOCA safety analysis. There is a clear need for more refined analysis methodologies and models, as well as enhanced computer code capabilities to support multi-dimensional analysis.

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