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Improvement of RELAP5 Rod Models for High Burnup Phenomena

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1. Introduction

The current trend in the nuclear industry has been focused upon high-burnup fuel to improve the economy. Long-term burnup fuel has resulted in the new phenomena which were not observed at lower burnup [1]. To address the performance of the high-burnup fuel under LOCA, RELAP5/MOD3.3/K currently used in LOCA analysis [2] should be revised relevant with major phenomena occurring at long-term burnup such as pellet thermal conductivity, pellet/cladding direct contact, and rod internal pressure (RIP) considering dynamic gap volume.

It is announced that the thermal conductivity data of UO_2 pellet generally indicates a degradation of approximately 5 to 7 percent for every 10 GWD/MTU of exposure [3]. A lower fuel pellet conductivity results in higher fuel temperatures at a given linear heat-generation rate due to the increase of the initial stored energy in the fuel. Because of fuel swelling and thermal expansion with burnup, the surface contact between the pellet and cladding could occur after about 15 GWD/MTU [4]. Because the gap-gas pressure is estimated based on the assumption of a constant volume, RELAP5 could not simulate the RIP transient with a varied gap volume during LOCA. Therefore, the improved rod models were incorporated in RELAP5 to account for high burnup phenomena. Also, high burnup fuel behavior for large-break LOCA was simulated using the modified code for verification.

2. Implementation of New Rod Models

2.1 Fuel Thermal Conductivity Degradation Model

In order to consider the effects of burnup, the Modified Nuclear Fuels Industries (NFI) Model [5] is applied in RELAP5/MOD3.3/K. The thermal conductivity of UO_2 can be deduced from its relation with thermal diffusivity, density and heat capacity. NFI model is shown below:

$$\lambda_{95} = \frac{1}{A+BT+f(Bu)+(1-0.9\exp(-0.04Bu))g(Bu)h(T)} + \frac{E}{T^2}exp\left(-\frac{F}{T}\right) \quad (1)$$

$$h(T) = \frac{1}{1+396\exp\left(-\frac{6380}{T}\right)} \quad (2)$$

where λ_{95} is thermal conductivity of unirradiated 95% theoretical density (TD) of UO_2 (W/m-K), Bu is burnup (MWD/MTU), T is temperature (K), and h(T) represents the effect of radiation damage. The coefficients of the equation (1) are defined in Table 1.

Table 1. Coefficient of NFI Model

Coef.	A	B	E	F
Value	0.0452	2.46E-4	3.5E9	1.6361E4

2.2 Gap Closure Model

The RELAP5 gap conductance model employs an assumption as the direct contact of the fuel pellet and the cladding is not explicitly considered. The gap closure generally occurs due to the enlarged fuel swelling and thermal expansion according to increasing burnup [6]. Therefore, the contact conductance model of FRAPCON [5] has been incorporated into RELAP5/MOD3.3/K. The total gap conductance upon contact is given by:

$$h_{gap} = h_{g,open} + h_{contact} \quad (3)$$

The contact conductance model provides a relatively smooth transition between the open and closed gap conductance.

2.3 Rod Internal Pressure Model

The legacy RIP model is based on a constant volume assuming ideal gas. The gas composition is initially the fill gas, which should be an inert gas such as helium, but is gradually altered with burnup by the addition of gaseous fission product such as xenon and krypton and then the gap volume is increased. Therefore, RIP model considering the dynamic gap volume should be used in the calculation of the high-burnup fuel. The improved RIP model is based on the assumption of the changed fuel rod gap volume except for the plenum volume. Thus, the equation is

$$P_g = P_{g,i} \cdot \frac{T_f}{T_{f,i}} \cdot \frac{V_{p,i}+V_{g,i}}{V_{p,i}+\sum_{j=1}^{N}(V_{g,j})} \quad (4)$$

where V is volume, T is temperature, N is total number of axial nodes, and P is pressure. f, g, p, j, and i subscripts indicate fluid, gap, plenum, axial node number, and initial value, respectively.

3. Preliminary Assessment of New Rod Models

For the assessment of the improved rod model, LBLOCA analysis of APR1400 plant has been performed. Plant nodalization and modeling in this study are the same as those of CAREM [2]. The limiting burnup in terms of initial stored energy occurred at beginning of cycle (BOC). Therefore, there were hot pin and hot assembly rods with the burnup of 1.0 GWD/MTU. On the other hand, average rods are assumed by core-average burnup (20.0 GWD/MTU). Through these assumptions, the thermal conductivity obtained the modified rod model compared well with an analytic solution as shown in Fig. 1. The gap width and gap conductance of average rods are shown in Fig. 2. The gap contact took place between 17 and 25 kW/m of the linear heat generation rate (LHGR) at transient time zero. The calculated gap conductance via gap closure model was higher than legacy result due to the consideration of direct contact conductance. Fig. 3 shows the RIP behavior calculated for the hot rod. The result of new model showed similar to FRAPTRAN [7] and appeared to be quite reasonable. On the other hand, the legacy result was relatively higher than others. A comparison of the peak cladding temperature is shown in Fig. 4. In the case of average rods, the calculated value using improved rod models tended to be higher than legacy result. The temperature difference is 58K. For the hot rod, the result using improved rod models tended to be slightly higher than legacy result by 10K.

4. Summary

RELAP5/MOD3.3/K currently used in LOCA analysis rarely adopts models relevant with major phenomena occurring at high-burnup fuel. To simulate the phenomena, RELAP5/MOD3.3/K was revised relevant with the thermal conductivity degradation (TCD) model, gap closure model, and improved RIP model. The best-estimate LBLOCA analysis was accomplished using the fuel adopting the improved rod models.

It was observed in the average rods, that the calculated cladding temperature using new rod models was significantly higher than the legacy result due to the effect of TCD. For the hot rod, there was no significant difference between the result from the legacy and improved rod models. For hot pin, the effect of TCD was weakened since a BOC condition was assumed. A code modification for improved rod models results in more realistic prediction via the preliminary assessment.

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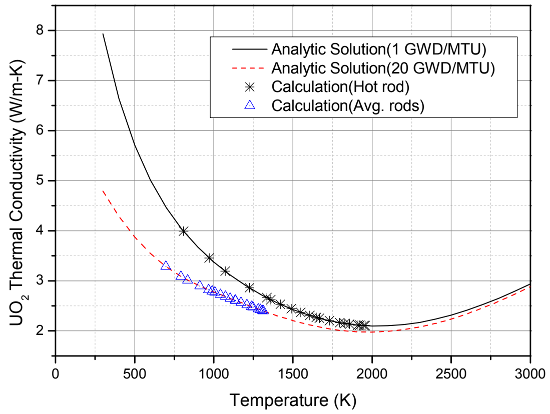

Fig. 1. Comparison of UO_2 Thermal Conductivity at Time Zero

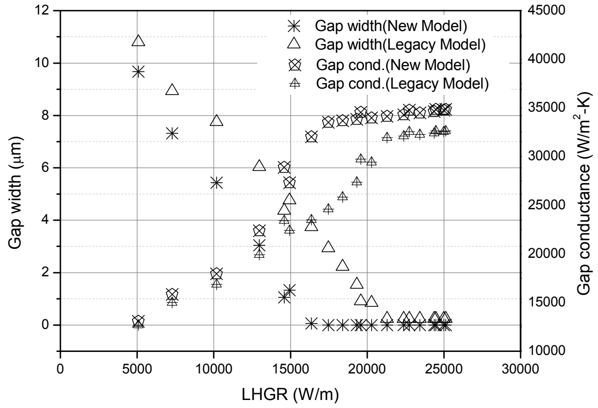

Fig. 2. Comparison of Gap Conductance at Time Zero (Average Rods)

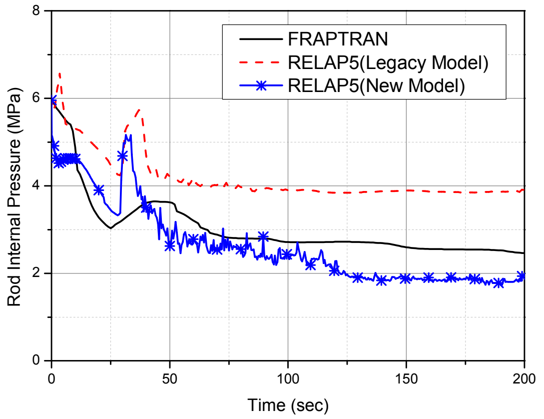

Fig. 3. Comparison of Rod Internal Pressure (Hot Rod)

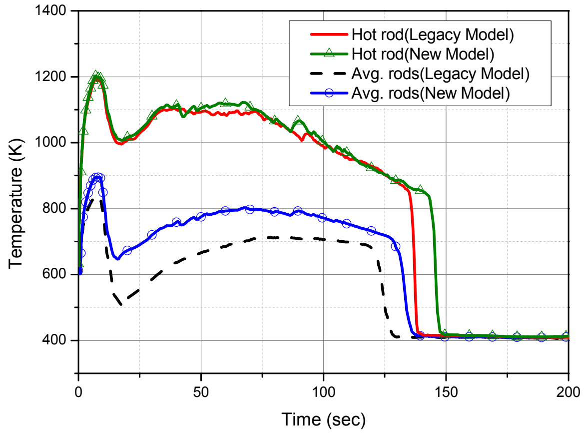

Fig. 4. Comparison of Peak Cladding Temperature