Evaluation of the Effect of the Burned Fuel Initial Conditions for the MARS-KS code

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1. Introduction

Highlight of the revision of Emergency Core Cooling (ECCS) performance rule [1] is consideration of burnup effect of the modeled fuel in the design base accident such as Lager Break Loss of Coolant Accidents (LBLOCA).

According to the proposed revised rule, irradiated fuel conditions, such as degraded fuel pellet conductivity and fuel rod geometry changes should be considered in the model of safety analysis codes.

MARS-KS code [2] have its own fuel rod model, but still limitations are remained in the specific modeling. So, KINS has been developing the integrated code, combining the S-FRAPTRAN module developed based on the FRAPTRAN code for the transient fuel performance calculation into the MARS-KS code. [3]

As well as the current standalone MARS-KS code, the integrated code also uses irradiated fuel conditions, which were calculated with FRAPCON code[4] for the modeling of core fuel conditions.

Major results of the fuel performance calculation provide information including the cold-state fuel geometry, power history, axial power profile, rod internal pressure (RIP), average and local fuel burnup, pellet density, fuel and clad deformation and clad oxide thickness and hydrogen concentration. Modeling methodology of the above irradiated fuel conditions in safety analysis code can give effect on the safety analysis result.

In this study, the modeling methodology using FRAPCON code result is reviewed and improvements for MARS-KS code is identified for the modeling multi-burned fuel conditions. The modified APR-1400 model for LBLOCA case was used in which 14-burned fuel heat structures (HS) are added in the hot assembly hydraulic channel. Burnup ranges of the modeled fuels are from the fresh to 60 GWd/MTU.

2. Fuel Performance Calculation Results

Fuel performance calculation result for the PLUS7 fuel of OPR-1000 and APR-1400 plant was reviewed in this chapter.

Used code is FRAPCON 4.0 version and the maximum RIP case is used as an input.

2.1 End-of-life cladding oxidation and RIP

Major fuel performance parameters of FRAPCON code calculation are the cladding oxidation and the RIP built up by fission gas release (FGR) at the End-of-life (EOL).

FRAPCON calculation results are shown in Fig. 1 for the clad oxide thickness and the hydrogen concentration.

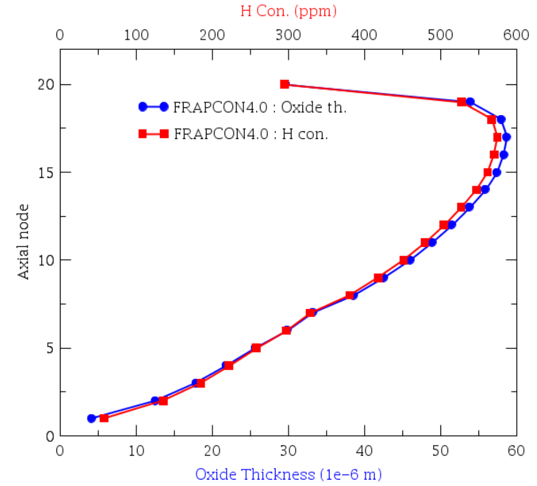

Fig. 1. Calculated oxide thickness and hydrogen concentration for the maximum RIP case at EOL

The calculated EOL fission gas release was 9.4%. Accumulation of fission gas in the free volume of the fuel resulted in the increase of the internal pressure, the hot condition RIP was calculated 11.2MPa as shown in Fig. 2

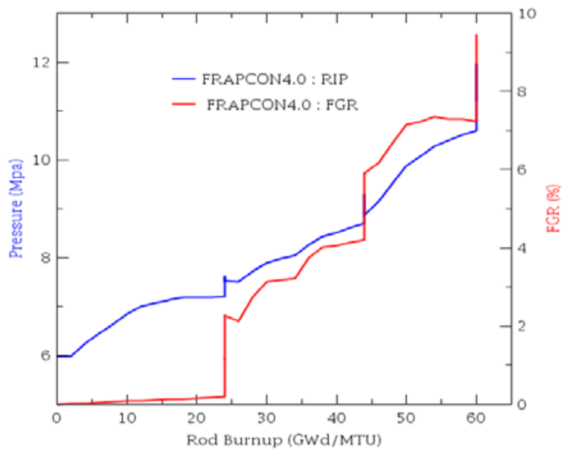

Fig. 2. Calculated RIP and FGR vs. burnup

2.2 Fuel condition parameters for DBA initial condition

Fuel geometry and thermal characteristics are changed as the fuel irradiation increase by densification, swelling and relocation of the pellet and FGR. Cladding is also affected by the oxidation, creep and thickness thinning as shown in Fig 3.

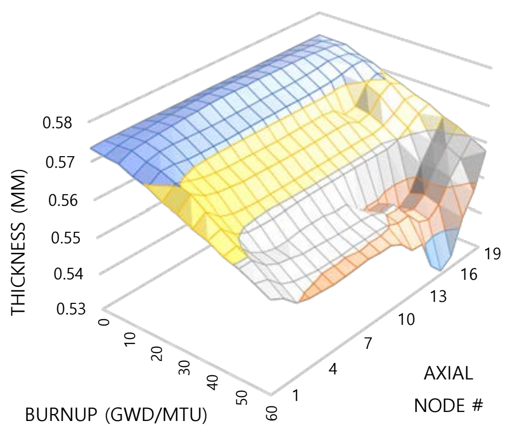

Fig. 3. Axial clad thickness vs. burnup

Fuel geometry parameters including radius of pellet and clad, thicknesses of the clad and oxide are used for the initial core fuel modeling including the RIP and plenum gas compositions at each burnup conditions.

3. Evaluation of the initial fuel conditions for the DBA assessment

For the 14-burned fuel HSs of the APR-1400 LBLOCA model, each of local fuel conditions calculated by the FRAPCON code were reviewed. Their accident transient effect were also assessed.

14-burnup cases were selected for every 5GWd/MTU from the FRAPCON code results at the 0~ 60GWd/MTU burnup range as shown in Fig. 4

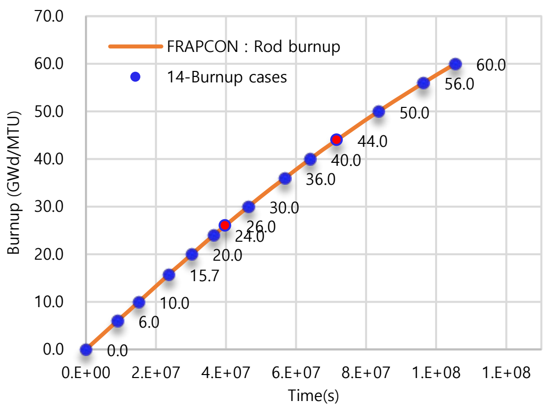

Fig. 4. 14-burnup cases for the hot assembly hydraulic channel

3.1. Fuel power and temperature conditions

FRACON code calculation uses the limiting power history considering the normal condition and AOO. For the DBA assessments, the hottest fuel pin power as well as core total power are increased considering conservative core power condition in the DBA assessment. So, HS powers for the burned-fuels were selected in Fig. 5.

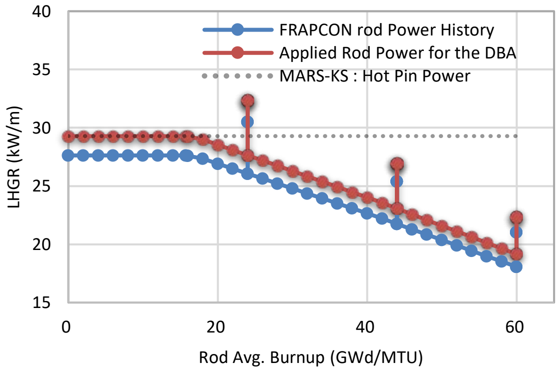

Fig. 5. The burned fuel powers for DBA assessment

Different power condition between the FRAPCON and MARS-KS codes could resulted in different temperature condition. Initial temperature input values are re-calculated in the steady-state calculation of the MARS-KS code with the accident power condition. Therefore, the importance of initial fuel node temperatures is minimized.

3.2. Burned fuel pellet conductivity

Thermal properties of the UO_2 is changed by irradiation.

Current modeling method for the burned fuel properties is using the material property table including the conductivity and the heat capacity using the modified Nuclear Fuel Industry (NFI) model [5] as shown in Fig. 6.

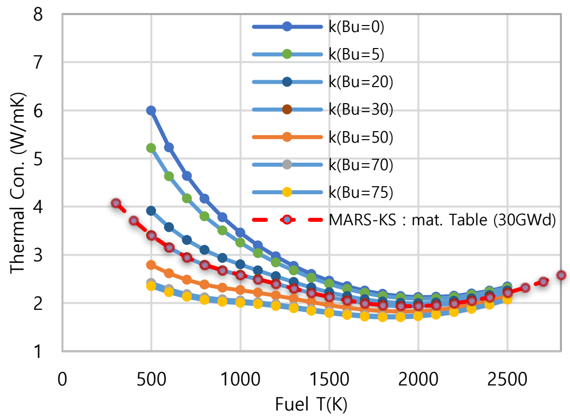

Fig. 6. Fuel pellet thermal conductivity degradation by burnup

It is inconvenient for the modeling multiple burned fuel modeling case, since as much as material property tables should be required.

For the MARS-KS code improvement, the modified NFI model as a function of burnup, theoretical density (TD : 10.96 g/cm^3) and gadolinium weight fraction was implemented in the MARS-KS 1.5 version(Sub-version number 146).

3.3. Fuel clad oxide thickness

Calculated clad oxide thickness by the FRAPCON code have different values in each axial nodes as shown in Fig. 1. MARS-KS 1.5 code uses single oxide thickness for a HS model. The oxide thickness input value is used as an initial value for the metal-water reaction model and it is not used for heat conduction calculation for the fixed 3-layer (pellet, gap and clad) fuel rod model.

Considering the oxide layer on clad surface in fuel temperature calculation, MARS-KS code have been modified to have 4-layer fuel rod model [6]. In this study, the modified MARS-KS version was used in which 6-layer fuel rod modeling is possible.

The oxide thickness input scheme of the MARS-KS code also improved to specify axial thicknesses for the metal-water reaction calculation.

In the 14-burned fuel model, an axial maximum oxide thickness was applied for the oxide layer and different axial oxide thicknesses were used for the metal-water reaction model.

Radial temperature distributions were compared in Fig. 7 for the 1.5 version (3-layer) and the modified MARS-KS version (4-layer) for the steady-state.

Oxide thickness modeled case in the layer (4-layer) showed higher centerline temperatures than the 3-layer model as much as 0.0K, 18.2K and 27.5K for each 0 µm, 58.7 µm and 19.8 µm oxide thickness models.

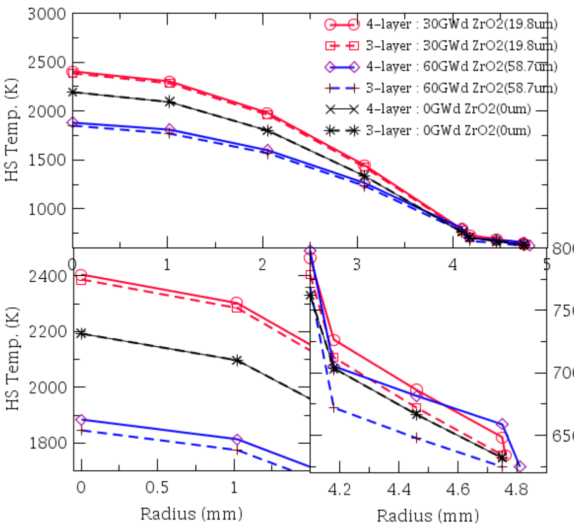

Fig. 7. Fuel radial temperature comparison between MARS-KS code versions

3.4. Burned fuel geometry

FRAPCON code provide results such as pellet outer radius, clad inner radius, clad and oxide thickness at the hot condition. Each of the permanent radius changes by densification, swelling and relocation is provided for the pellet and the permanent radial change by the creep for the clad also.

The Fuel rod model of MARS-KS code requires information of the cold state fuel geometry and deformed radius of the pellet and clad for each axial nodes excluding the radius changes by thermal and recoverable elastic deformations. Thicknesses of the burned fuel clad and oxide also applied in the fuel geometry model. Extracted permanent pellet and clad radius are shown below figures.

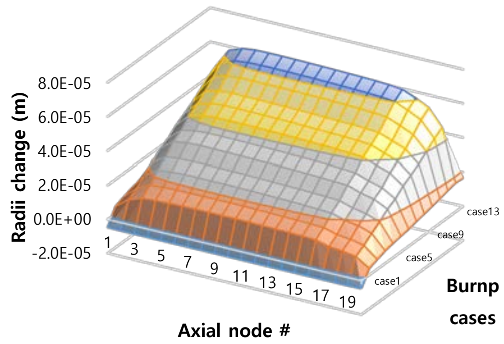

Fig. 8. Permanent fuel pellet surface radius change

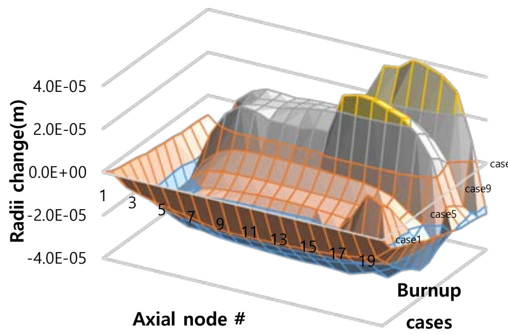

Fig. 9. Permanent clad outer radius change

Clad thickness also differ in axial nodes from the FRAPCON code result due to the clad thinning by the local oxidation of the clad. The minimum axial clad thickness was used for burned fuel HS model conservatively.

3.5. Initial Rod internal pressure

The RIP of the FRAPCON code is calculated with buildup of fission gases (Xe, Kr) in the rod free volume and plenum temperature considering the heat transfer from the upper pellet to the plenum and again to the coolant faced at the fuel plenum region.

MARS-KS code uses the gas temperature of the plenum referenced volume for the gap pressure calculation from the initial RIP assuming the plenum volume is maintained during the calculation.

Plenum pressure at the hot condition of FRAPCON calculation may differ from the MARS-KS, but the steady-state coolant temperature difference of both code is relatively small, so the RIP calculated with FRAPCON code could be used for MARS-KS code initial condition directly.

A modeling case was preliminary assessed in which the plenum volume is modeled for the burned fuel rod at 24 GWd/MTU only. Its PCT calculation is showed in Fig. 8 (4-layer-plenum) that the blowdown PCT was not changed but the reflood PCT was affected and the quenching time is delayed than the normal case.

For more realistic calculation of plenum pressure during transient, proper reference volume need to be used for modeling for the plenum pressure calculation.

4. Initial fuel modeling effects on the LBLOCA case

APR1400 LBLOCA assessment result is shown in Fig. 8 with the modeling of burned fuel geometry changes including pellet and clad, as well as oxide thickness and the RIP and gap gas compositions.

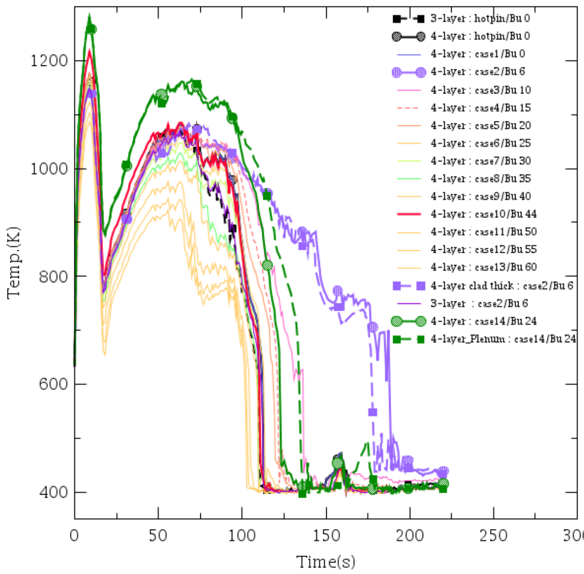

Fig. 8. Peak clad temperature calculations with burned fuel rods modeling

PCT calculation result has showed that the highest PCT was calculated the highest initial power rod (case 14: Bu24) and the higher burnup condition calculated the higher PCTs than the fresh fuel rod with the same power condition.

Oxide layer modeling with 4th oxide thickness layer increased the quenching time than the 3-layer fuel rod model. Thinned clad thickness model calculated slightly faster quenching time. (case 2 : Bu6)

Due to the PCT increase by the oxide thickness and thinned clad model, the transient oxidation and clad outer radius change were slightly increased.

5. Conclusions

Burned fuel condition modeling methodology was reviewed based on the calculation result of FRAPCON code. Improvements for MARS-KS code for multi-burnup fuel rod modeling was also identified for the changed burned fuel geometry and conditions by irradiation.

The modified NFI model and the axial oxide thickness input scheme for the metal-water reaction were improved for the MARS-KS 1.5 code in addition to the former multi-layer fuel rod model considering the oxide and crud layers.

APR1400 LBLOCA case results with the modified code showed that the higher initial power condition rod calculated the higher PCTs. Clad thinning modeling due to the oxidation affected the clad temperature response at the reflood region calculating earlier quenching time. Modeling plenum volume delayed the quenching time.

As a result of this study, further improvements were also identified for burned fuel model in MARS-KS code. Axial distribution of clad thickness and oxide layers need to be improved and the plenum temperature and pressure calculation for the transient clad deformation also need to be improved.

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