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X447 EBR-II Experiment Benchmark for Verification of Audit Code of SFR Metal Fuel

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1. Introduction

In order to prepare the licensing of a prototype reactor for a SFR (Sodium-cooled Fast Reactor), regulatory audit technologies, reviewing the safety of system of SFR must be secured. In KINS (Korea Institute of Nuclear Safety), to prepare audit calculation of PGSFR licensing review, the project has been started to develop the regulatory technology for SFR system including a fuel area. [1] To evaluate the fuel integrity and safety during an irradiation, the fuel performance code must be used for audit calculation.[2]

In this study, to verify the new code system, the benchmark analysis is performed. In the benchmark, X447 EBR-II experiment data are used.[3],[4],[5] Additionally, the sensitivity analysis according to mass flux change of coolant is performed.

2. Structure of Audit Code for SFR Metal Fuel[1],[2]

In this section, the structure of SFR fuel performance code (FRAPCON-SFR) is described.

In case of LWR fuel performance modeling, various and advanced models have been proposed and validated based on sufficient in-reactor test results. However, due to the lack of experience of SFR operation, the current understanding of SFR fuel behavior is limited. But there are several phenomena which will affect to the in-reactor behavior of SFR fuel. For example, the constituent redistribution is the key phenomenon which can be occurred in a mixed metal fuel system. In case of U-Zr fuel, re-distribution of Zr changes the thermal and mechanical property of fuel slug. The cladding wastage due to FCCI (Fuel Clad Chemical Interaction) and the anisotropic deformation of fuel slug are important phenomena of SFR fuel as well. In addition to SFR fuel specific phenomena, a general fuel performance model such as temperature evaluation, stress-strain analysis, fission gas release and swelling are must be implemented in a SFR fuel performance code system.

Especially, FCMI (Fuel Clad Mechanical Interaction) must be evaluated because of the large deformation of SFR fuel slug. In case of LWR fuel performance modeling, the FE (Finite Element) modeling technique is under development to solve the complex interaction between the fuel and the cladding. However, FE model causes long solving time and some non-linear material behavior model must be newly developed. Therefore, the simplified 1D model for FCMI analysis is presumed to be valuable and its modeling will be considered.[1][2]

Based on the method discussed above, the alpha version of SFR fuel performance code (FRAPCON-SFR) was developed. FRAPCON-SFR code has been developed based on FRAPCON 3.4 which is fuel performance analysis code for light water reactor. So the basic structure of FRAPCON-SFR is similar to the structure of FRAPCON 3.4. Also, the specific models which can calculate behaviors of metallic fuel are applied to a suitable location and time. And furthermore, NUFRORM2D model has been developed for calculation of FCMI for metallic fuel. The detailed FCMI calculations can be performed with using this model on a specific time step and axial node. Fig.1 shows calculation flow diagram of FRAPCON-SFR.

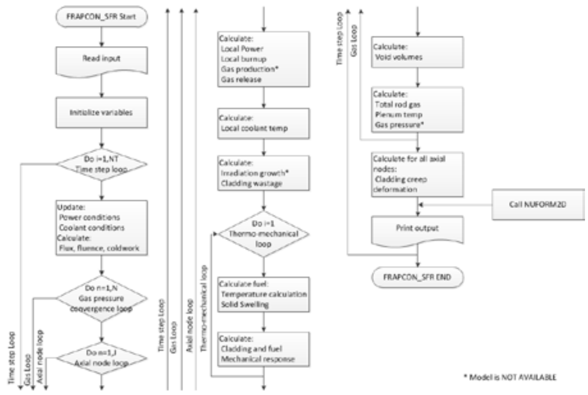

Fig. 1. Calculation flow diagram of FRAPCON-SFR.

3. X447 EBR-II Experiments

In this study, X447 EBR-II Experiment data are used for benchmark. The fuel composition of X447 assembly is U-10Zr and PGSFR also uses this composition in initial phase. So we select X447 EBR-II experiment for benchmark analysis.

The irradiation experiment, designated subassembly X447, was performed in the EBR-II (Experimental Breeder Reactor II) at a maximum linear power of 33 000 W/m (33 kW/m) to a peak heavy metal burnup of 10 at%. The upward sodium coolant flow of 2.52 kg/s within the subassembly, with a core inlet temperature of 644 K, resulted in peak cladding temperatures in the range of 903 to 933 K occurring at the top of the fuel pin. Post-irradiation examinations were performed at 5 at% peak burnup, reached after ~ 284 EFPDs (effective full power days) and 10 at% after ~ 619 EFPDs. [3]

Table I gives the fuel specification for X447 assembly.[4],[5]

Table I: X447 fuel data

Parameter	Value
Fuel Composition	U-10Zr
Clad Material	HT-9
Fuel slug radius (mm)	2.16
Clad inner radius (mm)	2.54
Clad outer radius (mm)	2.92
Fuel Smear Density (%)	75.0
Fuel Active Length (cm)	34.3
Plenum to Fuel Ratio	1.4
Peak Linear Heat Rate (kW/m)	33
Peak Clad Temperature (K)	933

4. Benchmark Results

In this study, as a part of verification of the new code, the benchmark analysis is performed using FRAPCON-SFR. In the benchmark, X447 EBR-II Experiment data are used. Also, to assess effects of mass flux changes of coolant, the sensitivity analysis is performed.

4.1 X447 EBR-II Benchmark Result

For X447 experiment data and result of code calculation, irradiation history is showed in Fig.2. The result showed that calculated result is similar to X447 data.

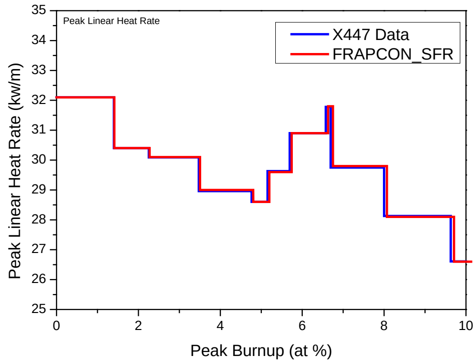

Fig. 2. Irradiation history of X447 data and code calculation

Fig. 3 shows fission gas release behaviors of X447 data and calculated code results. In this graph, FEAST code is the reference code for a comparison between new code and existing metal fuel performance code.[4] The fission gas release at the end of life for the X447 fuel assembly is to be between 72-76%. The FEAST prediction for the peak fuel rod is 75%. But FRAPCON-SFR code calculated higher fission gas release than FEAST and data. Also peak value of gas release calculated by FRAPCON-SFR is 79%.

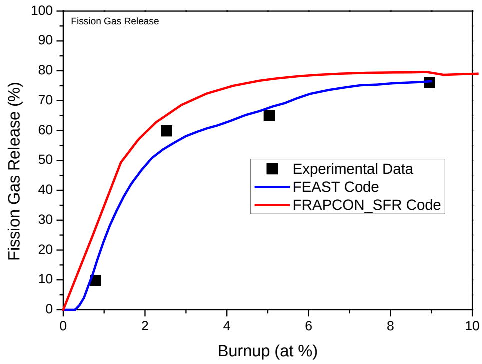

Fig. 3. Fission gas release behavior of X447 data and code calculations

The FEAST-predicted cladding strain for the X447 fuel assembly matches well with the experimental cladding strain data, as shown in Fig.4. But, in case of FRACON-SFR, the result shows nearly same values at all axial points. It is considered that there is no strain model by irradiation in FRAPCON-SFR code.

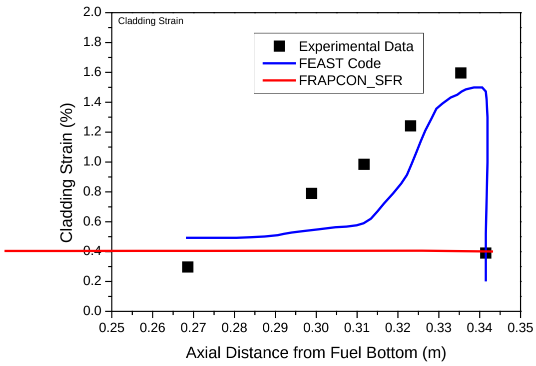

Fig. 4. Peak cladding strain of X447 data and code calculations

4.2 Sensitivity Analysis Results

In this study, 6 cases with change of mass flux in coolant are performed for sensitivity analysis. The results of sensitivity analysis are showed in Fig. 5~8.

Fig. 5 shows the behavior of average fuel temperature with increase of burnup. As shown in Fig.5, if mass flux in coolant is decreased, average fuel temperature is increased. In terms of verification, it is considered that the result of temperature calculation is reasonable.

The behavior of fuel stack and cladding axial extension is showed in Fig. 6. In case of fuel stack axial extension, there is no effect according to change of mass flux in coolant. But, in case of cladding, the axial extension is increased by decrease of mass flux in coolant.

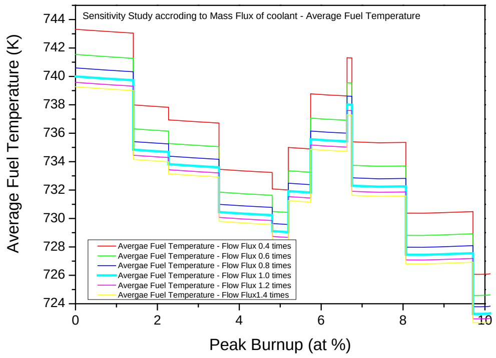

Fig. 5. Sensitivity analysis with change of coolant mass flux – average fuel temperature

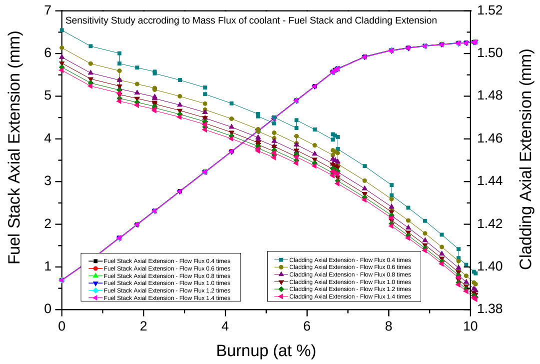

Fig. 6. Sensitivity analysis with change of coolant mass flux – fuel stack and cladding extension

Fig.7 shows the result of sensitivity analysis for fission gas release. As shown in Fig.7, the effect on fission gas release by change of mass flux in coolant is negligible.

The behavior of cladding axial strain is showed in Fig. 8. The cladding axial strain is increase with decrease of mass flux in coolant. However, there is little effect on strain because FRAPCON-SFR has only thermal strain model.

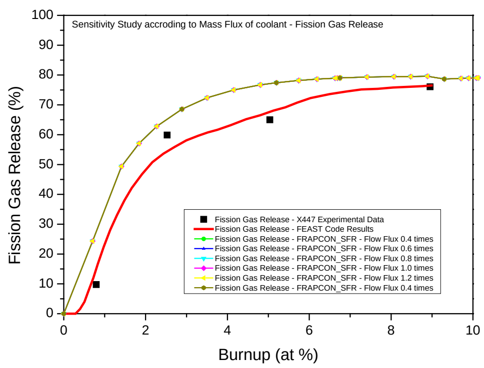

Fig. 7. Sensitivity analysis with change of coolant mass flux – fission gas release

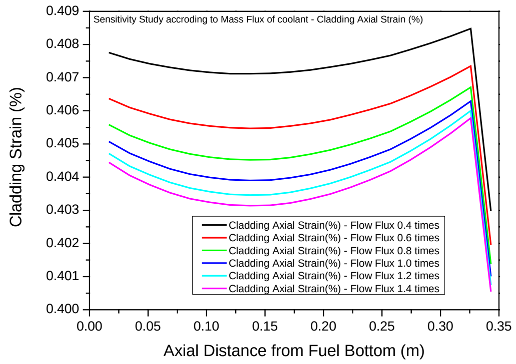

Fig. 8. Sensitivity analysis with change of coolant mass flux – cladding axial strain

5. Conclusions

Due to the lack of experience of SFR operation and data, the current understanding of SFR fuel behavior is limited. However, in order to prepare the licensing of PGSFR, regulatory audit technologies of SFR must be secured. So, in this study, to verify the new audit fuel performance analysis code, the benchmark analysis is performed using X447 EBR-II experiment data. Also, the sensitivity analysis with mass flux change of coolant is performed. In terms of verification, it is considered that the results of benchmark and sensitivity analysis are reasonable. However, in order to improve the accuracy of metal fuel performance analysis, complement and implementation of the specific models related to the SFR is necessary. Also it is considered that additional verification process is needed.

ACKNOWLEDGEMENTS

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