Benchmark on EBR-II Experiment for Verification of FRAPCON-SFR Alpha Version

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1. Introduction

In KINS (Korea Institute of Nuclear Safety), to prepare audit calculation of PGSFR (Prototype Gen-IV Sodium Cooled Fast Reactor) licensing review, the project has been started to develop the regulatory technology for SFR system including a fuel area. [1] Also, 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 and improve the FRAPCON-SFR alpha version, some models for SFR metal fuel are improved. And the benchmark analysis for verification is performed. In the benchmark, X447, X430 EBR-II experiment data are used.[3],[4],[5]

2. Structure of FRAPCON-SFR alpha version[1],[2]

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. The constituent re-distribution of U-Zr fuel, the cladding wastage due to FCCI (Fuel Clad Chemical Interaction) and the anisotropic deformation of fuel slug are important phenomena of SFR fuel. In addition to SFR fuel specific phenomena, a general fuel performance model such as temperature evaluation, stress-strain analysis, fission gas release, swelling and FCMI (Fuel Clad Mechanical Interaction) for the large deformation of SFR fuel slug are must be implemented in a SFR fuel performance code system. [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.

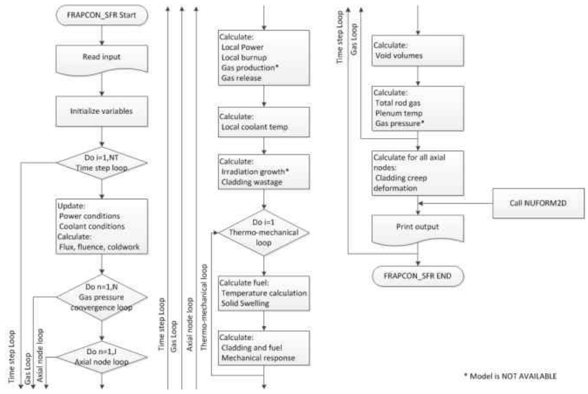

Fig. 1. Calculation flow diagram of FRAPCON-SFR.

3. Modification of FRAPCON-SFR Alpha Ver.

In this study, based on the existing benchmark results [6], some of the models that need improvement are modified.

3.1 Burn-up model [7]

In case of UO_2 fuels for LWR, in FRAPCON code, the linear heat generation rate (LHGR) and time step duration are input values, the burnup increment for the time step is prescribed and can be related to the flux, the fission cross sections, and the concentrations of fissile isotopes. Therefore, the burnup is calculated by the following burnup increment.

$$\mathrm{dbu} = \frac{q' \ dt}{\rho_{fuel}} = \frac{\alpha}{\rho_{fuel}} \sum_k \sigma_{f,k} \overline{N_k} \emptyset dt \quad \text{[eq .1]}$$

where,

q' =volumetric heat generation rate
ρ_{fuel} = fuel density
σ_f = fission cross section
α = a conversion constant

However, in the case of metal fuel for SFR, it is difficult to simulate the burnup model with a simple equation because of the large density change. Therefore, in this study, with reference to the FEAST-M code, the code is modified so that the burnup values calculated by using neutronics code can be used as an input.

3.2 Improvement of Sodium Properties

FRPACON calculates bulk coolant temperatures assuming a single, closed coolant channel according to

$$T_b(z) = T_{in} + \int_0^z \left[\frac{(\pi D_0)q"(z)}{C_p G A_f}\right] dz \qquad \text{[eq.2]}$$

Where,

$T_b(z)$ = bulk coolant temperature at elevation z on the rod axis (K)

T_{in} = inlet coolant temperature (K)

q" = rod surface heat flux at elevation z on the rod axis (W/m^2)

C_p = heat capacity of the coolant (J/kg·K)

G = coolant mass flux (kg/s·m^2)

A_f = coolant channel flow area (m^2)

D_0 = outside cladding diameter (m)

Finally, the coolant outlet temperature is calculated by adding the heat generated at each axial node to the inlet temperature.

The FRAPCON-SFR alpha version has difficulties in simulating the behavior of sodium coolant because the coolant properties are used the values of the heat capacity and the density for water which is the properties of the existing FRAPCON code.

Therefore, the source code is modified to replace the properties of liquid sodium coolant shown in Table I.

Table I. Heat Capacity and Density of Sodium [8]

Temp. (K)	C_p (kJ·kg^{-1}·K^{-1})	C_v (kJ·kg^{-1}·K^{-1})	*Density*1) (kg·m^3)	*Density*2) (kg·m^3)
371	1.383	1.262	-	-
400	1.372	1.241	919	1.24 x 10^{-9}
500	1.334	1.170	897	5.03 x 10^{-7}
600	1.301	1.104	874	2.63 x 10^{-5}
700	1.277	1.045	852	4.31 x 10^{-4}
800	1.260	0.994	828	3.43 x 10^{-3}
900	1.252	0.951	805	1.70 x 10^{-2}
1000	1.252	0.914	781	6.03 x 10^{-2}
1100	1.261	0.885	756	0.168
1200	1.279	0.862	732	0.394
1300	1.305	0.844	706	0.805
1400	1.340	0.830	680	1.48
1500	1.384	0.819	653	2.50
1600	1.437	0.811	626	3.96
1700	1.500	0.803	597	5.95
1800	1.574	0.795	568	8.54
1900	1.661	0.784	537	11.9
2000	1.764	0.768	504	16.0
2100	1.926	0.768	469	21.2
2200	2.190	0.791	431	27.7
2300	2.690	0.872	387	36.3
2400	4.012	1.172	335	49.3
2469	8.274	2.463	-	-
2500	39.279	16.371	239	102
2503.7	-	-	219	219

1) Liquid density
2) Vapor density

4. X447, X430 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 II gives the fuel specification for X447 assembly.[4],[5]

Table II: 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

In this study, we also performed the benchmark calculation using the X430 test results to verify the combustion model. According to the FRAPCON-SFR alpha version benchmark results, [9] experiments with high linear power have larger errors in the calculation of burnup. Therefore, the X430 experiment with relatively high linear power was selected as the benchmark problem. Table III gives the fuel specification for X430 assembly.[4]

Table III: X430 fuel data

Parameter	Value
Fuel Composition	U-19Pu-10Zr
Clad Material	HT-9
Fuel slug radius (mm)	2.86
Clad inner radius (mm)	3.28
Clad outer radius (mm)	3.68
Fuel Smear Density (%)	76.1
Fuel Active Length (cm)	34.3
Plenum to Fuel Ratio	1.4
Peak Linear Heat Rate (kW/m)	48

5. Benchmark Results

In this study, for verification of the FRAPCON-SFR improved alpha version, the benchmark analysis is performed using FRAPCON-SFR. In the benchmark, X447, X430 EBR-II experiment data are used.

5.1 X447 EBR-II Benchmark Result

For X447 experiment data and result of code calculations, irradiation history is showed in Fig.2. The result showed that calculated results are similar to X447 data. For a performance test with a low linear power, such as X447, there is little difference in the burnup results between the existing alpha version and the improved alpha version.

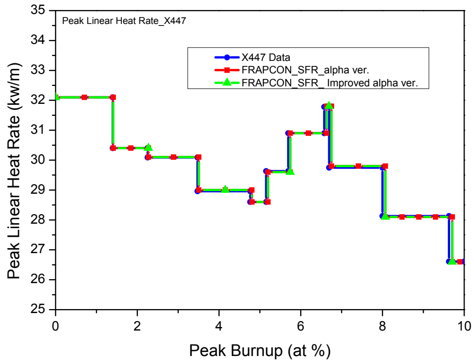

Fig. 2. Irradiation history of X447 data and code calculation

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%. There is no difference between the existing alpha version and the improved alpha version.

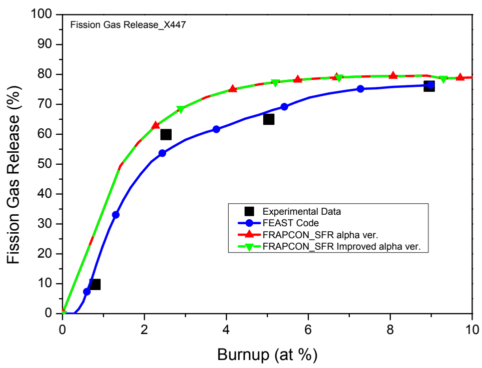

Fig. 3. Fission gas release behavior of X447 data and code calculations

Figure 4 shows the bulk coolant, cladding average, and fuel centerline temperature calculated by the existing alpha version and the improved alpha version at 10 (at %) burnup.

As you can see from the Fig. 4, the bulk coolant temperature cannot be predicted properly because of the water properties applied to the existing FRAPCON-SFR alpha version. However, in the case of the improved alpha version reflecting the properties of sodium, it showed proper prediction results. It can also be seen that the cladding average and the fuel centerline temperature are also changed due to this effect.

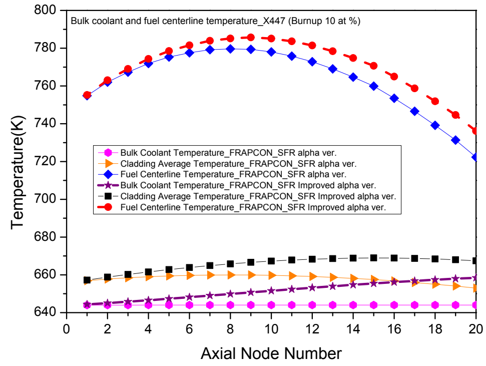

Fig. 4. Code calculation results of bulk, cladding and fuel centerline temperature – X447

5.2 X430 EBR-II Benchmark Result

As mentioned earlier, experiments with high linear power, such as X430 fuel, have failed to predict the burnup properly in the existing alpha version. However, in the case of the FRAPCON-SFR improved alpha version, the burnup values are treated as an input, and the calculation results of the burnup are shown in accordance with the experimental results.

Fig. 5 shows the irradiation history of X430 data and calculation results by the existing alpha version and improved alpha version.

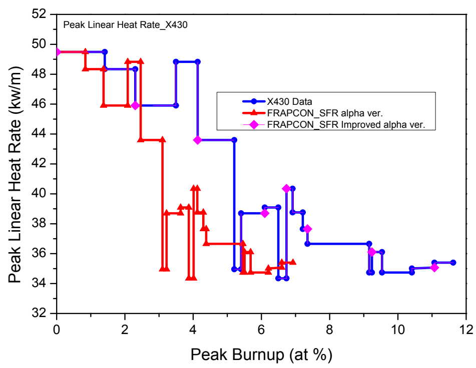

Fig. 5. Irradiation history of X430 data and code calculations

Fig. 6 shows fission gas release behaviors of X430 data and calculated code results. In this graph, like the X447 benchmark, FEAST code is used as a reference code for a comparison between new code and existing metal fuel performance code.[4]

In the case of the fission gas release for the X430 fuel assembly experiment, due to the improvement in the burnup model, the initial behavior between the existing alpha version and the improved alpha version is different. However, the values of fission gas release at the end of life for the X430 are calculated to be in agreement with the experimental data.

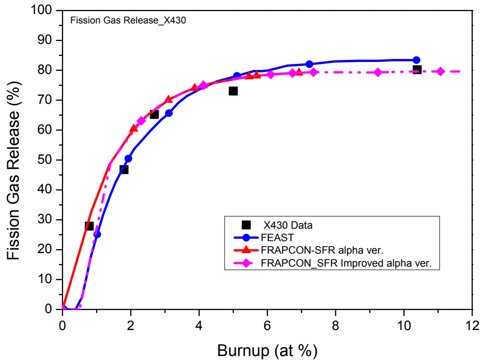

Fig. 6. Fission gas release behavior of X430 data and code calculations

Figure 7 shows the bulk coolant, cladding average, and fuel centerline temperature calculated by the existing alpha version and the improved alpha version at 11.62 (at %) burnup for X430 experiment. As with the X447 experimental benchmark results, the bulk temperature of the coolant did not increase significantly in the existing alpha version, which did not reflect the sodium properties. However, in the improved alpha version, which reflects the sodium properties, a proper temperature rise of the coolant occurs.

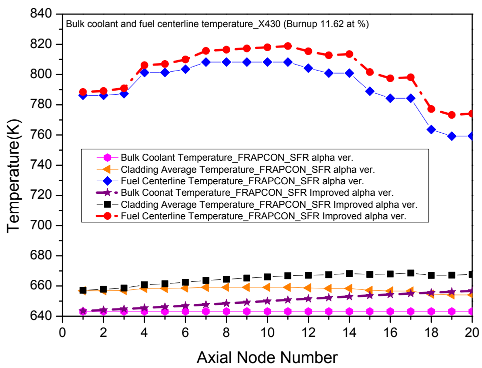

Fig. 7. Code calculation results of bulk, cladding and fuel centerline temperature – X430

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, based on the existing benchmark results, [9] some models are improved in the source code of the FRAPCON-SFR where the error occurred. To verify the effect, benchmarks are also performed for the EBR-II experiments X447 and X430 fuel assembly. And, in terms of verification, it is considered that the results of benchmark are reasonable. However, in order to improve the accuracy of metal fuel performance analysis, it is necessary to improve the additional models reflecting the SFR characteristics. Also it is considered that additional verification process is needed.

ACKNOWLEDGEMENTS

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