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Preliminary Heating Rate Evaluation of Control Assembly in Fast Reactor

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1. Introduction

To secure the sufficient shutdown margin on PGSFR(Proto-type Gen-IV Sodium-cooled Fast Reactor) core design, the control assembly design was modified recently to enhance control rod worth by increasing the volume of neutron absorber. The diameter of B_4C absorber pin can expand 1.85 times as the number of absorber pins is reduced from 61 to 19. However, a lager pin diameter leads higher absorber centerline temperature and cladding mid-wall temperature which are major criteria on thermal hydraulic design. To confirm the integrity of absorber pins, the proper heating rate at control assemblies is evaluated considered with dominant heat source - $^{10}B(n, \alpha)^7Li$ as well as inelastic scattering effect of fast neutrons and the thermal hydraulic analysis - temperature criteria and floatation margin - is performed in this study.

2. Evaluation Methodology

2.1 Heating rate

To evaluate the thermal hydraulic integrity at a control assembly, the heating rate is calculated previously. The heating rate in a medium is expressed in follow equation (1) [1].

$$H = \sum_{i,g} N_i K_{i,g} \phi_g \qquad (1)$$

N_i : the number density of nuclide i
$K_{i,g}$: KERMA (Kinetic Energy Release in Materials) for nuclide i and energy group g
Φ_g : the neutron scalar flux of energy group g.

The number density is fixed value and the neutron flux can be obtained from core calculation as fixed value in group g. But KERMA factor depends on assumptions to affect it. Thus, the heating rate can be changed according to KERMA factor.

2.2 KERMA

KERMA means the sum of kinetic energy considered with all particles and γ-ray after any reactions multiplied by the reaction cross-section. Generated energy after reaction is same with Q-value. Therefore, KERMA of control assembly is described by

$$K_{i,g} = Q_{c,i} \sigma_{c,i,g} \qquad (2)$$

Q_c means Q-value during absorption reaction (fission excepted) Q-value and σ_c is microscopic absorption cross-section. Equation (2) is widely used in thermal reactor because thermal neutron energy is too small compared with Q-value. In fast reactor, however, it is proper to include neutron kinetic energy at KERMA because neutron energy is not negligible[2]. Therefore, equation (3) considered with incident neutron energy term as well as neutron scattering term is suggested for KERMA [1].

$$K_{i,g} = (Q_{c,i} + Em_g)\sigma_{c,i,g} + \left(Em_g \sigma_{s,i,g} - \sum_{g'} Em_{g'} \sigma_{s,i,g\to g'} \right) \qquad (3)$$

$\sigma_{s,i,g\to g'}$ is microscopic scattering matrix, and Em_g is mean neutron energy of group g as shown in equation (4) [1].

$$\sigma_g \phi_g Em_g = \int_{E^L}^{E^H} E\sigma(E)\phi(E)dE \qquad (4)$$

It can be simplified to equation (5) by assuming that the energy dependence is almost constant.

$$Em_g = \frac{E^H - E^L}{\ln(E^H/E^L)} \qquad (5)$$

2.3 Q-value

The Q-value for the reaction is the amount of energy released by that reaction. It can be determined from the masses of reactants and products. Considering the energy conservation of the simple reaction, the definition of Q-value based on mass-energy equivalence can be represented by equation (6) where incident particle is 'a', target nuclear is 'x', daughter products after reaction are 'b' and 'y'.

$$Q = [(Ma + Mx) - (Mb + My)] \times \frac{931.5}{amu}\ (MeV) \qquad (6)$$

M is atomic mass of each particle. For example, Q-value of $^{10}B(n, \alpha)^7Li$ is

$$Q_{^{10}B} = [(1.008665 + 10.012937) - (4.002603 + 7.016004)] \times 931.5 = 2.79\ MeV.$$

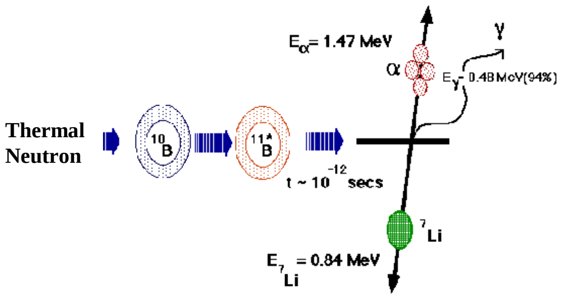

Fig. 1. Kinetic energy release due to ^{10}B(n, α)^{7}Li reaction

The Q-value calculated by mass-energy equivalence reveals to kinetic energy and it divides to each particles with different energy such as 1.47MeV for alpha particle, 0.84MeV for ^{7}Li, and 0.48MeV for gamma-ray. It means all released gamma-ray energy is deposited at the medium without any loss in Q-value.

3. Heating Rate of Control Assembly

3.1 Core condition

Figure 2 shows 1/3 PGSFR core configuration. To calculate heating rate at control assembly, it is assumed that the primary control system is fully inserted and the secondary control system locates at the top of core. One control assembly which is close at core center is selected because it has higher heating rate.

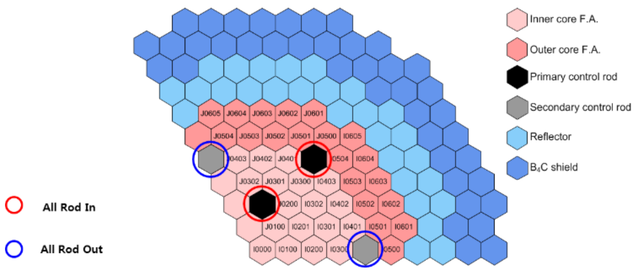

Fig. 2. PGSFR Uranium Core Configuration (1/3 symmetry)

3.2 Results

The analysis results of heating rate about the assembly with the number of 19 absorber pins are shown in this chapter 3.2.

To figure out the effects of the incident neutron energy and the scattering, heating rate comparison was conducted depend on equation (2) and equation (3).

First of all, heating rate integrated with all control assembly region is compared by nuclides at Table 1.

Considering only absorption reaction like equation (2), heat is almost generated due to ^{10}B. But the value using equation (3) shows 40.4% higher value compared with equation (2). Especially, ^{10}B, ^{11}B, and ^{nat}Fe are significantly increased because the number density of them are dominant in the control assembly. In this result, the effects of incident neutron energy and inelastic scattering is very significant in the core condition.

Table 1. Heating rate by nuclides using Eq. (2) and (3) (Unit: MW)

Nuclides	Eq. (2)	Eq. (3)	Diff., (3)-(2)
B-10	0.239	0.261	0.022
B-11	0.000	0.032	0.032
C-nat	0.000	0.010	0.010
Mo-nat	0.000	0.000	0.000
Si-nat	0.000	0.000	0.000
Mn-55	0.000	0.000	0.000
V-nat	0.000	0.000	0.000
Nb-93	0.000	0.000	0.000
Na-23	0.000	0.008	0.007
Fe-nat	0.007	0.031	0.024
Cr-nat	0.001	0.004	0.003
Ni-Nat	0.000	0.000	0.000
N-15	0.000	0.000	0.000
W-nat	0.000	0.001	0.001
B-nat	0.000	0.000	0.000
sum	0.248	0.348	40.4%

For the distinguish the heat production by incident neutron energy term and inelastic scattering term, each term on 25 neutron energy groups of KERMA is analyzed for ^{10}B isotope at Table 2.

Table 2. KERMA increase of ^{10}B by neutron energy group (Unit: MeV-barn)

	Effect of incident neutron energy	Effect of inelastic scattering	Increase of KERMA	
Energy Group	$Em_g\sigma_{c,i,g}$	$Em_g\sigma_{s,i,g} - \sum_{g'} Em_{g'}\sigma_{s,i,g\to g'}$	Total	Total/ Eq.(2)
1	1.94E+00	4.66E+00	6.59E+00	14.27
2	1.28E+00	9.90E-01	2.27E+00	3.04
3	9.73E-01	8.70E-01	1.84E+00	1.97
4	6.95E-01	4.77E-01	1.17E+00	1.06
5	2.53E-01	4.48E-01	7.02E-01	1.06
6	3.55E-01	3.85E-01	7.40E-01	0.48
7	3.51E-01	2.18E-01	5.70E-01	0.23
8	3.07E-01	1.55E-01	4.62E-01	0.14
9	2.90E-01	1.14E-01	4.03E-01	0.10
10	2.60E-01	7.80E-02	3.38E-01	0.08
11	2.28E-01	5.80E-02	2.86E-01	0.06
12	1.97E-01	4.22E-02	2.39E-01	0.04
13	1.70E-01	3.10E-02	2.01E-01	0.03
14	1.47E-01	2.23E-02	1.69E-01	0.02
15	1.29E-01	2.11E-02	1.50E-01	0.02
16	1.07E-01	1.12E-02	1.19E-01	0.01
17	8.26E-02	5.81E-03	8.84E-02	0.01
18	6.41E-02	3.23E-03	6.73E-02	0.00
19	5.06E-02	2.20E-03	5.28E-02	0.00
20	3.89E-02	1.06E-03	4.00E-02	0.00
21	3.18E-02	1.09E-03	3.29E-02	0.00
22	2.43E-02	6.64E-04	2.50E-02	0.00
23	1.67E-02	1.47E-04	1.68E-02	0.00
24	7.83E-03	9.77E-06	7.84E-03	0.00
25	5.05E-04	0.00E+00	5.05E-04	0.00

In thermal neutron energy range(included in the last group of 25), the effects can be ignored because the increment of KERMA is almost zero. The more neutron energy is higher, however, the effects of both terms effects become larger. The incident neutron energy effect is bigger than the scattering effect except energy group 1.

3.3 Thermal hydraulic integrity

The CRBR(Clinch River Breeder Reactor) design criteria is used as a reference on thermal hydraulic design criteria of the PGSFR and it is evaluated by MATRA-LMR code[3]. The calculated heating rate considered with both effects is assigned uniformly to each absorber pin in the control assembly. And it is assumed that the absorber pin contacts with the cladding.

The temperature distributions of the assemblies consisted of 19pins and 61pins are shown at Figure 3. The cladding mid-wall temperature at the edge of assemblies are relatively low due to higher flow rate. The pin temperature difference in case of 19pins is bigger than the case of 61 pins.

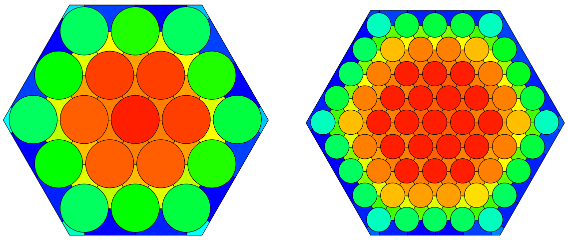

Fig. 3. Temperature distributions at the assemblies of 19 pins and 61 pins.

Table 3 shows the thermal hydraulic characteristics and design limits at three different designs about a control assembly. The higher flow rate is assigned because the assembly with 19 pins has a higher heating rate. And it is also increased to meet the design requirement of maximum cladding mid-wall temperature. Thus, the outlet temperature is lower than in case of 61pins.

Table 3. Thermal hydraulic design characteristics of three cases- CRBR, 19pins and 61pins.

	CRBR 37 Pins	PGSFR 19 pins (0.348MW)	PGSFR 61 pins (0.323MW)	Limit
Flow rate (kg/s)	-	2.27	1.68	-
Outlet Temp. (℃)	531.1	509.8	538.7	-
Max. mid-wall Temp. (℃,2σ)	652.2	661.0	660.3	< 662.7
Max. absorber centerline Temp. (℃, 3σ+115%)	1197	869.8	750.0	< 2450
Margin for floatation	-	1.859	1.862	> 1.3

The centerline temperature of B_4C absorber is higher in case of 19 pins but it has sufficient tolerance in spite of applying the 15% overpower as uncertainty. The flotation margins of PGSFR control assembly designs are satisfied with the limit value by 1.3.

4. Conclusion

The most important thing is to consider the incident neutron energy and inelastic scattering to prevent underestimating the heating rate when the heating rate is evaluated at control assembly in the fast reactor. It is appropriate to apply only absorption reaction in a thermal reactor. In fast reactor, however, the heating rate at all rod-in condition in this study is about 40% bigger when the both effects are taken into account.

The heating rate at the control assembly that consists of 19 absorber pins is about 5.3% bigger than the case of 61 pins. But thermal hydraulic integrities in the both designs can satisfy the design requirements by modifying flow rate.

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