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Preliminary Study on the Application of Booster Fuel for HANARO Irradiation Facility

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1. Introduction

Recent research trends of materials applied to the nuclear industry are focused on maintaining integrity under severe environment in consideration of operating condition of future nuclear system such as sodium-cooled fast reactor (SFR), very high temperature reactor (VHTR) and fusion reactor [1]. The integrity of reactor core materials of commercial nuclear power plant and research reactor is also interested to enhance safety and to produce licensing database [2]. The higher neutron fluence than before are needed to demonstrate the in-core performance of above materials. Since the neutron flux of HANARO, which has been used for the irradiation testing [3], is respectively low, it is expected to take a long time to meet the required neutron fluence. Therefore, we propose the application of booster fuel to overcome the inherent limitation of HANARO and to reduce the irradiation period. The applicability of candidate fuels was evaluated based on previous experience and their boosting performance was analyzed in this study.

2. Irradiation testing at HANARO

In-core test has been carried out by the device called 'Irradiation Capsule' that is inserted in the irradiation hole for the irradiation of specimen [3]. Since the central thimble (CT) is located at the center of the core, the neutron flux in CT is the highest among the others. The fast neutron flux (> 1MeV) is 1.5 x 10^{14} n/cm^2-sec and the maximum neutron fluence rate is 0.0174 DPA/EFPD considering the irradiation in CT. Research reactor materials such as Zircaloy-4, beryllium and graphite were irradiated during the longest duration of 202.5 EFPDs and 474 days for calendar days throughout the irradiation testing experience [2]. In order to meet the neutron fluence of 10 DPA, the irradiation period of 574.7 EFPDs (3.69 years for calendar days) is necessary. It should be shortened because the irradiation period is too long. Therefore, the neutron flux boosting is needed for the effective irradiation at HANARO.

3. Application of booster fuel

3.1 Candidate fuels as a booster

Table 1 shows the specification of candidate fuels as a booster. All fuels can be manufactured by atomization technology, which is developed and applied by Korea Atomic Energy Research Institute (KAERI) [4]. Since the fuel test name of HANARO fuel (U_3Si/Al) has been used as the HANARO driver fuel, its performance was proven through numerous applications. KOMO test series were successfully conducted and the fuels showed a good performance up to 85% U-235 burnup [5]. Although HAMP test was conducted only a few times for the production of licensing database of Kijang research reactor [6], it is contained as a candidate fuel due to its prospectiveness. The fuel and matrix composition of U-7Mo/Al-5Si is mainly considered as a fuel material.

Table 1. The specification of candidate fuels

Type	Fuel test name	Fuel and matrix composition	Uranium density (g-U/cm^3)
Rod	HANARO fuel	U_3Si/Al	3.15
	KOMO fuel	U-7Mo/Al-5Si	5
	HAMP fuel	U-7Mo/Al-5Si	6.5
		U-7Mo/Al-5Si	8
Plate	HAMP fuel	U-7Mo/Al-5Si	8

3.2 Conceptual design of booster fuel and irradiation device

The hexagonal irradiation holes are considered as a target because they have a high neutron flux. Fig. 1 shows the cross-sectional schematic diagram of booster fuel and irradiation device considering plate and rod-type fuels assuming they are installed. In the case of plate-type booster fuel, the design of fuel was determined by the consideration of remaining space excluding specimen installation. Total twelve plate fuels can be installed. In the case of rod-type booster fuel, the structure of HANARO driver fuel was applied as much as possible. We proposed the installation of outermost 18 rods of HANARO driver fuel.

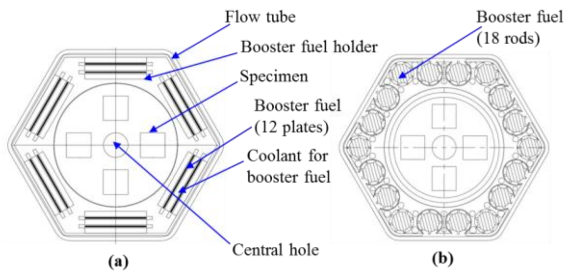

Fig. 1. The cross-sectional schematic diagram of booster fuel and irradiation device: (a) Plate type, (b) Rod type

3.3 Boosting performance

We evaluated the boosting performance assuming the booster fuel is applied by the consideration of above conceptual design. We used MCNP version 6 [7] to calculate the neutron flux and spectrum of specimen and the power generation rate of booster fuels during the irradiation. Although the actual irradiating environment is variable by the withdrawal of control absorber rod (CAR) and the depletion of HANARO driver fuel, the fixed condition at the middle of cycle (MOC) was considered in this calculation.

Table 2 shows the increase rate of neutron flux of specimen by the application of booster fuels. In case of rod-type booster fuels, both reduced and standard fuel rods were considered using the design of HANARO driver fuel. The neutron flux was divided into four energy ranges. The epithermal and fast neutron fluxes are increased by the application of booster fuel. The neutron flux is generally increased as the increase of uranium loading. On the contrary, the thermal neutron flux is decreased. It can be also shown in fig. 2 that is the change of neutron spectrum by the application of booster fuel. If the thermal neutron generated by HANARO driver fuels is diffused into the irradiation device, the outermost booster fuels are interacted with thermal neutrons and fission neutrons are emitted. Therefore, the neutron spectrum is hardened by the booster fuel.

Table 2. The increase rate of neutron flux of specimen by the application of booster fuels

Type	Density (g-U/cc)	U loading (g)	E < 0.625eV	0.625eV < E < 0.1MeV	0.1MeV < E < 1MeV	1MeV < E
Rod (reduced)	3.15	938.5	-32.49%	7.29%	19.45%	25.12%
	5	1491.2	-40.34%	8.54%	24.41%	30.73%
	6.15	1938.7	-44.99%	9.21%	27.35%	33.70%
	8	2386.0	-48.49%	9.67%	30.06%	36.38%
Rod (standard)	3.15	1255.6	-38.30%	8.49%	23.36%	29.51%
	5	1994.9	-46.75%	9.47%	28.64%	35.10%
	6.15	2593.7	-51.34%	9.92%	31.78%	38.15%
	8	3192.0	-54.86%	10.17%	34.21%	40.23%
Plate	8	746.6	-32.98%	8.40%	24.62%	27.41%

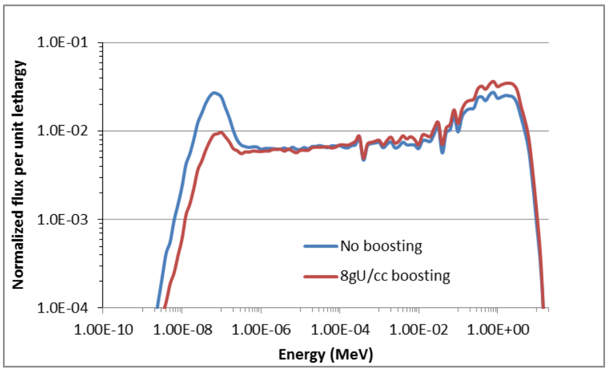

Fig. 2. The change of neutron spectrum by the application of booster fuel

Table 3 shows the comparison of neutron fluence of specimen by the depletion of rod-type booster fuel (3.15 g-U/cc). Displacement per atom (DPA) calculated by SPECTOR [8] was used for the quantification of neutron fluence using the neutron spectrum calculated by MCNP. The boosting performance is decreased due to the depletion of uranium in the fuel. From this calculation, the DPA increase of 33.8% is evaluated at the beginning of irradiation. Assuming the booster fuel is depleted to the maximum, the DPA increase of 22% is evaluated.

Table 3. The comparison of neutron fluence (DPA) of specimen by the depletion of booster fuel (3.15 g-U/cc)

Burnup	DPA
No fuel	0.467
Fresh fuel	0.625
25 GWD/MTU	0.615
50 GWD/MTU	0.603
75 GWD/MTU	0.588
100 GWD/MTU	0.570

4. Discussions

The boosting performance was evaluated by the neutronic calculation for the candidate fuels. Although high density uranium is contained in the plate-type booster fuel, its uranium loading is generally less than rod-type fuels. The plate-type fuel has more boosting performance than rod-type fuel of 3.15 g-U/cc despite less uranium amount as shown in table 2. However, the boosting performance by the plate-type fuel is limited because it is hard to accommodate more uranium. Therefore, the rod-type fuel is more effective as a booster for HANARO irradiation facility.

Since the performance of fuel during not only normal operation but also accident condition is important, it is verified by the in-core test and analysis. The reduced fuel rod of 5 g-U/cc was demonstrated by KOMO-5 irradiation testing [5], however, the in-core test for the fuel rods more than 5 g-U/cc is not conducted until now. The limitation of uranium density might be caused by the consideration of application as the HANARO driver fuel. In case of the booster fuel, the uranium loading can be increased than HANARO driver fuel because the reduction of heat source that is generated by inside fuels. Therefore, the in-core performance evaluation of fuel rods more than 5 g-U/cc is necessary for the feasibility assessment.

5. Conclusions

To increase the neutron flux for the reduction of irradiation period, the application of booster fuel was proposed. The candidate fuels were selected by the consideration of irradiation experience and in-core performance. We conceptually designed booster fuel and irradiation device. It was used as the basic information for the performance evaluation during irradiation. From this evaluation, the performance of rod-type fuel is more effective than the plate-type as the booster fuel. To determine the limitation of uranium loading of rod-type booster fuel, more detailed performance evaluations are needed.

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