A Preliminary Study of Impurity Effect on Activation for the K-DEMO HCCR Blanket

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1. Introduction

Nuclear fusion based on the deuterium-tritium (D-T) fusion reaction is believed as a promising clean energy source due to the actinide-free operation, which induces elimination of high level radioactive waste. However, high energy neutrons, causing considerable activation in both of functional and structure materials for the breeding blanket, are produced during deuterium-tritium fusion reaction. Since these activated materials in breeding blanket can play an important role in operating or radioactive waste management, a rigorous evaluation of the activation level for such materials are an essential work especially for a high neutron fluence operation system such as demonstration fusion power reactor (DEMO). To remedy activation issue of structural material in the fusion devices, reduced activation ferritic martensitic (RAFM) steels have been developed by control of their elemental compositions. However, the impurities remained in both of the developed RAFM steels and functional materials, such as breeder or multiplier materials in breeding blanket, may induce unexpected activation.

Hence, in this paper, the activation characteristics of functional and structural materials were studied considering effect of impurities.

2. K-DEMO with HCCR Blanket Model

In the South Korea, a Korean demonstration fusion power reactor (K-DEMO) has been studied to aim at demonstrating a fusion power reactor as a future energy source. The main parameters of the K-DEMO studied so far are reported in the Ref. [1]. Currently, two types of DEMO breeding blanket concepts were proposed for the K-DEMO, helium-cooled ceramic reflector (HCCR) blanket and water-cooled solid breeder (WCSB) blanket [2] for tritium self-sufficiency. Although both concept of bleeding blankets are being studied, in this paper, we focused on the HCCR blanket.

The HCCR blanket adopted the block type graphite reflector as a neutron reflector, which plays a role of reducing beryllium multiplier amount while maintaining sufficient tritium breeding ratio (TBR), Li_2TiO_3 as a tritium breeding material, beryllium as a neutron multiplier, and Advanced Reduced Activation Alloy (ARAA) as the structural material. The detailed design and performance of the HCCR blanket for the K-DEMO were reported in Refs. [2] and [3]. A neutronic calculation model was established by inserting HCCR blanket model into the 3-D K-DEMO model as shown in Figs. 1 and 2 [3, 4, 5]. The MCNP6.1 code with FENDL ver.3.0 library were used for neutron and photon transport calculation while the FISPACT-II code were used for activation calculation [6, 7].

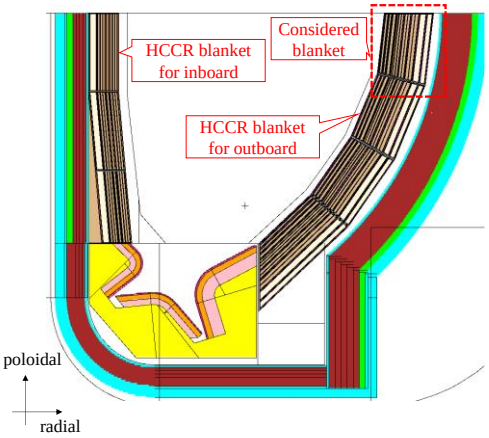

Fig. 1. Neutronics calculation model of K-DEMO HCCR Blanket (poloidal view)

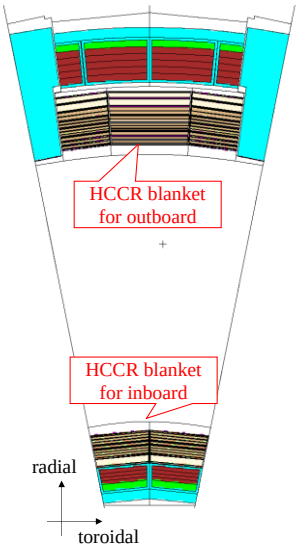

Fig. 2. Neutronics calculation model of K-DEMO HCCR Blanket (toroidal view)

For the structure material, the most significant irradiation is occurred at the “first wall (FW)” position,

hence activation analysis is performed focused on the FW region at outboard blanket position shown in Fig. 1. For the functional material, the most significant irradiation is occurred at the breeder region rather than multiplier or reflector region as reported in Ref. [3], hence activation analysis is performed focused on the first breeder at outboard blanket position shown in Fig. 1. Tables I and II shows compositions of pure structural and breeder materials. Figs. 3 and 4 shows impurity compositions of those materials based on the Ref.[8]. The 2,200 MW fusion power was assumed for the HCCR blanket loaded K-DEMO, consequently, 4.2 MW/m^2 neutron wall loading was expected for the blanket considered as reported in Ref. [4].

Table I: Composition of ARAA steel

Isotope	Mass fraction, %
C	0.10
Si	0.10
Mn	0.45
Cr	9.00
W	1.20
V	0.20
Ta	0.07
N	0.01
Ti	0.01
Zr	0.01
Fe	others

Table II: Composition of Li_2TiO_3

Isotope	Mass fraction, %
Li 6	10.03
Li 7	1.30
O	44.35
O 17	44.33

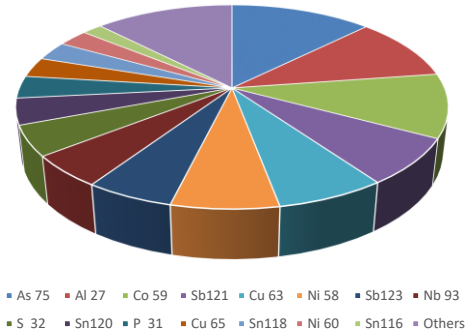

Fig. 3. Impurity composition of ARAA steel

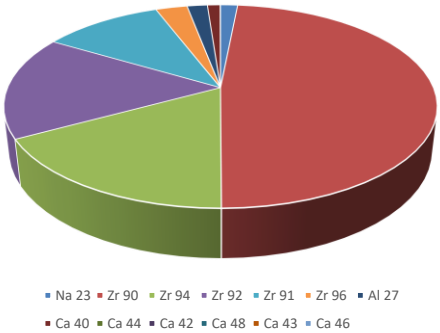

Fig. 4. Impurity composition of Li_2TiO_3

3. Activation Analysis

In Fusion reactors, solid type blankets are considered to be regularly replaced from 2 to 5 years. However in the present activation calculation, HCCR blankets are assumed to be operated during 20 effective full power years (EFPYs) at conservative manner. For the breeder materials, iterative depletion calculations are performed between MCNP neutron transport calculation and FISPACT-II irradiation calculation at every 5 EPFY time step to reflect depletion feedback effect. Figs. 5 and 6 shows behaviors of volumetric decay heats and specific activities for the FW (ARAA structure) and Li_2TiO_3 breeder materials.

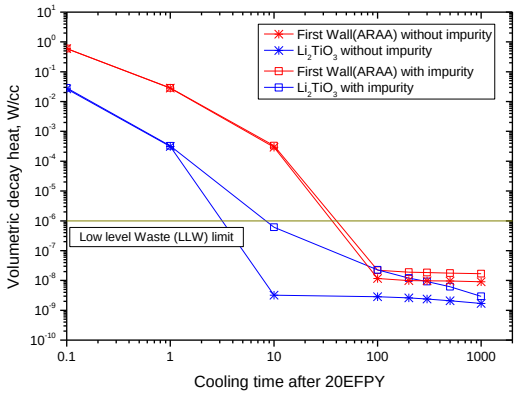

Fig. 5. Behavior of volumetric decay heats after 20 EFPY operation

The results of structural and breeder materials with impurities were identical to those reported in the Ref. [3]. The limitations of radioactive waste in Figs. 5 and 6 are based on the limitation considered in Ref. [9]. In this calculation, we assumed that all of tritium produced in the breeder regions are extracted before cooling.

In both of structural and breeder materials, the effect of impurities are negligible up to 1 years cooling time. However, significant impurity effects are observed after 10 years cooling time at the breeder region while relatively small impurity effects are resulted at the FW region. Table III and IV show activity contributions and decay heat contributions after 10 years cooling time.

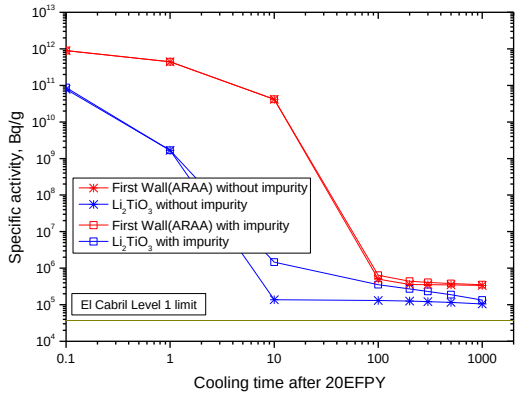

Fig. 6. Behavior of specific activities after 20 EFPY operation

Table III: Activity contribution in Li_2TiO_3 after 10 years cooling

Without impurity		With impurity	
Isotope	Activity contribution, %	Isotope	Activity contribution, %
C 14	84.5	Na 22	47.4
Ar 39	14.6	Ar 39	15.3
Ca 45	0.8	Y 90	14.4
Ca 41	0.1	Sr 90	14.4
-		C 14	7.6
		Zr 93	0.6
		Nb 93m	0.2
		Ca 45	0.1

Table IV: Decay heat contribution in Li_2TiO_3 after 10 years cooling

Without impurity		With impurity	
Isotope	Decay heat contribution, %	Isotope	Decay heat contribution, %
C 14	56.1	Na 22	85.0
Ar 39	43.0	Y 90	10.1
Ca 45	0.9	Ar 39	2.5
-		Sr 90	2.1
		C 14	0.3

Due to the production of Na-22 (2.6 y half-life), Y-90 (64.6 h half-life), Ar-39 (269 y half-life), and Sr-90 (28.8 y half-life) by impurities, specific activity of breeder material are increased by a factor of 10. Similarly, due to the radioactive products by impurities, decay heat of breeder material are also increased by a factor of 200 as shown in table IV. Considering impurity compositions of Li_2TiO_3, it is clearly understood that Y-90 and Sr-90 are generated by irradiation of Zr, Ar-39 is generated by irradiation of Ca, and Na-22 is generated by Na-23.

4. Conclusions

In this paper, activation analyses were performed to evaluate impurity effect on breeder and structural materials for the HCCR loaded K-DEMO reactor.

As reported in the Ref. [3], the ARAA structural material requires about 40 years cooling time and the Li_2TiO_3 breeder material requires about 10 years cooling time considering LLW limit suggested in Ref. [9]. In case of the Li_2TiO_3 breeder material without impurity, about four years cooling time will be sufficient. In addition to that, controlling of Na-23 impurity will provide considerable improvement in lowing specific activity of breeder material. Comparing to the Li_2TiO_3 breeder material, impurity effect on activation for structural material is not significant (about 10 % difference in required cooling time).

The information of impurities for both of breeding and structure materials will be updated continuously by an improvement in the material production and impurity control technology.

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