■ PAPER ■

PRELIMINARY ESTIMATION OF ACTIVATED CORROSION PRODUCTS IN THE COOLANT SYSTEM OF FUSION DEMO REACTOR

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The second phase of the national program for fusion energy development in Korea starts from 2012 for design and construction of the fusion DEMO reactor. Radiological assessment for the fusion reactor is one of the key tasks to assure its licensability and the starting point of the assessment is determination of the source terms. As the first effort, the activities of the coolant due to activated corrosion product (ACP) were estimated. Data and experiences from fission reactors were used, in part, in the calculations of the ACP concentrations because of lack of operating experience for fusion reactors. The MCNPX code was used to determine neutron spectra and intensities at the coolant locations and the FISPACT code was used to estimate the ACP activities in the coolant of the fusion DEMO reactor. The calculated specific activities of the most nuclides in the fusion DEMO reactor coolant were 2-15 times lower than those in the PWR coolant, but the specific activities of ^{57}Co and ^{57}Ni were expected to be much higher than in the PWR coolant. The preliminary results of this study can be used to figure out the approximate radiological conditions and to establish a tentative set of radiological design criteria for the systems carrying coolant in the design phase of the fusion DEMO reactor.

Keywords: Activated Corrosion Product, FISPACT, Fusion DEMO Reactor, MCNPX

1. INTRODUCTION

As the governmental investment to the development of fusion energy had grown up, a dedicated law “Act of Promoting Fusion Energy Development” was legislated in 2007 in Korea [1]. According to the Act, a national long-term program addressing development of fusion energy technology was established in the same year. In the first phase of the plan covering 5 years from 2007 to 2011, the life cycle of the program was defined and the strategic plans for the program was developed. In the second phase covering 10 years from 2012 through 2021, technologies required for the design and construction of a fusion DEMO reactor will be developed. In this phase, prediction of the radiological source terms, which is the first step in assessment of radiological conditions imposed on workers and public, is one of the important tasks to determine licensability of the reactor. The source terms also provide constraints in setting a tentative set of general design criteria.

According to the tentative specification of the fusion DEMO reactor, the power level is 600 MW_e and the coolant of the reactor is pressurized light water [1]. Unlike fission reactors where fission products are the main source of activity in the coolant, radionuclides produced by activation reactions comprise the activity of structural materials and the coolant in case of a fusion reactor. In addition, it is expected that corrosion products (also known as CRUD) are produced and activated as experienced in water-cooled fission reactors. Furthermore, the activated corrosion products (ACPs) would form the major part of the source terms in the coolant together with the tritium diffused from plasma facing components.

In this study, we attempted to estimate the ACPs by neutronics calculation with modeling of the fusion DEMO reactor and by adopting or extrapolating the operating experiences of pressurized water reactors (PWRs), where specific information is lack for the fusion reactor. Activities of radionuclides produced by activation of coolant itself and those of tritium diffused

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into the coolant are not included. This assessment should be regarded as a preliminary one because much of the detail designs which may affect the coolant activity are not finalized yet.

2. MATERIALS AND METHODS

The activities of ACPs in the coolant system were estimated using MCNPX 2.6.0 [2] and FISPACT 2007 [3] codes. Even in fission reactors for which extensive experiences are accumulated, calculation of the amount and behavior of CRUD by theoretical modeling does not provide reasonable estimates and data from operating experiences are used in radiological assessments. As there is no operating experience in fusion reactors, however, we applied the methods and the related data from fission reactors for estimation of ACPs in the coolant of the fusion DEMO reactor. This procedure is regarded reasonable because the coolant temperature of the fusion DEMO reactor, which largely affects production of ACPs, will be similar to that of PWRs since the fusion DEMO reactor will have similar thermal efficiency of the PWRs. In addition, the heat transport system of the fusion DEMO reactor will use similar type of material to that of PWRs.

In order to estimate the ACPs in the fusion DEMO reactor, the composition data of CRUD published by US DOE [4] and the design and experience data (e.g. an area ratio of a core and primary coolant system, concentration of CRUD in coolant) in the Final Safety Analysis Report (FSAR) of Younggwang unit 5 and 6 [5] were used. Since Younggwang unit 5 and 6 have been recently constructed and use Inconel 600 as the material of steam generator tubes, we decided the plants as appropriate reference reactors. In the FSAR, the activities of ACPs per unit mass of CRUD on the surface of reactor core (A_i) are estimated using the following equation.

$$A_i = \Sigma_i \Phi (1 - e^{-\lambda_i T_{res}}), \mathrm{Bq(g - crud)^{-1}} \qquad (1)$$

where $\sum_i$ is the macroscopic cross section of activation reaction (cm^2g^{-1}) for nuclide i, Φ the neutron flux ($cm^{-2}sec^{-1}$), λ_i the decay constant (sec^{-1}), and T_{res} the average value of maximum retention time in the core for the CRUD (sec).

First, the composition of corrosion products described in the DOE report was applied to calculate the cross section of activation reaction, $\sum_i$. This report includes composition of corrosion products from early PWRs and recent PWRs in which Inconel alloy is used as the material of steam generator tubes as shown in Table 1. Because Inconel alloy has very low content of cobalt, it is used to reduce production of ^{60}Co which is a major source causing occupational exposures. For this reason, the fusion DEMO reactor will also use Inconel alloy as the material of steam generator tubes. Thus, composition of corrosion products from recent PWRs in the Table 1 was used to estimate the ACPs from the fusion DEMO reactor coolant system. It was assumed that chromium and other metals in recent PWRs data of Table 1 are substituted by only chromium, i.e., chromium accounts for 16% of corrosion products. Even if Inconel alloy originally does not have cobalt, it is known that slight amount of cobalt exists as an impurity in nickel with concentration of 0.014 mass percent [6]. This cobalt impurity was applied when estimating the ACPs.

Table 1. Composition of Corrosion Products from Early PWRs and Recent PWRs in the US.

	Early PWRs	Recent PWRs
Fe	78%	14%
Ni	20%	70%
Cr and Others	2%	16%

In addition to the composition of corrosion products, the neutron energy spectrum is also a key factor because the activation reaction rates vary greatly depending on the neutron energy spectrum. While neutrons emitted from fission reaction have the energy spectrum with average of about 2 MeV, neutrons emitted from fusion reaction have the discrete energy of about 14 MeV. Because neutron energy spectrum in the coolant system is also significantly different, the neutron energy spectrum in coolant of the fusion DEMO reactor should be calculated.

In order to calculate the neutron spectrum in the coolant of the fusion DEMO reactor, the major structures and components of the fusion DEMO reactor were modeled using MCNPX 2.6.0 code. As the fusion DEMO reactor has not been specifically designed, we simplified the reactor based on the design of ITER (International Thermonuclear Experimental Reactor) which is the first large-scale experimental fusion reactor and under construction in France. ITER has torus shaped tokamak consisting of magnets, vacuum vessel, blanket, divertor, cryostat, etc as shown in Fig. 1. The blankets provide shielding to the vacuum vessel and the superconducting magnets against the heat and neutrons from fusion reactions. The divertors are component to exhaust the major part of the alpha particle power as well as helium and impurities from the plasma. The vacuum vessel provides a high quality vacuum for the

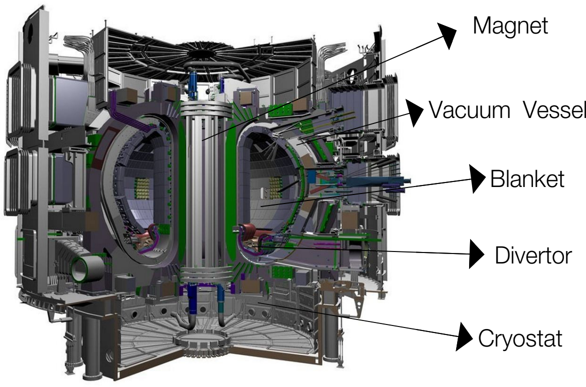

Fig. 1. Structure and components of the ITER.

plasma and cryostat provides the vacuum environment to stop convective heat transfer to the superconducting magnets and cold structures.

In this study, only the blanket, divertor, vacuum vessel, and magnet were modeled because they are considered to affect the neutron energy spectrum in the coolant. Fig. 2 shows the vertical sections of the model. The modeled reactor is largely segmented into torus region, cylindrical region, and divertor region. The torus region and cylindrical region consist of the blanket, the vacuum vessel, and the TF (Toroidal Field) coil. Table 2 shows composition and materials of the cylindrical region along the AA line shown in Fig. 2 and the torus region has same composition and materials except for the TF coil. The divertor region comprises of tungsten. All regions were segmented into several layers to apply the geometry splitting method in MCNPX code because it takes time to obtain statistically reliable results at the region far from the source such as the coolant system of the vacuum vessel. Although the actual design of blanket and divertor coolant systems of ITER has a very complex configuration including a large number of narrow pipes, it was assumed that the coolant and pipes are replaced by the material of components surrounding them. Unlike the blanket and the divertor, the vacuum vessel has simpler coolant system that coolant flows between inner shell and outer shell of vacuum vessel. Thus, the coolant of vacuum vessel cooling system was separately modeled.

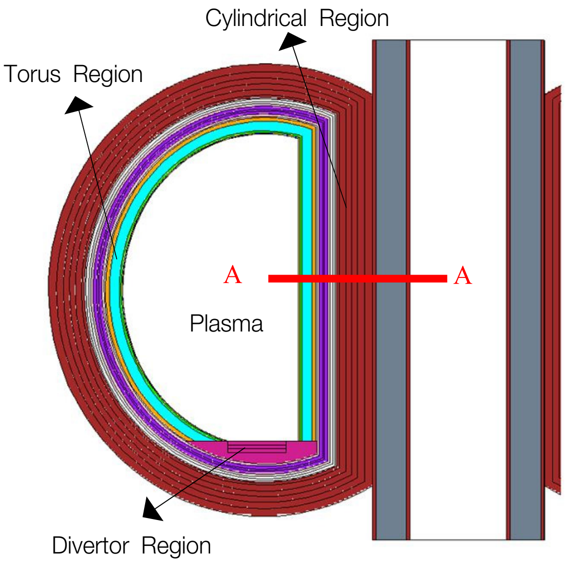

Fig. 2. Vertical section of the modeled fusion DEMO reactor using MCNPX.

The ITER neutron source [7] was used as the neutron source term in the MCNPX simulation. The neutron emitted from D-T fusion reaction has mono-energy of 14.1 MeV. Because the results from MCNPX code are produced as value per history (one neutron), it is needed to calculate the number of neutron per second to obtain neutron flux. The number of neutron per second is calculated from dividing a thermal power by produced energy per D-T reaction, 17.6 MeV. In this study, thermal power of the fusion DEMO reactor is assumed as 1800 MW_{th} based on the electric power of 600 MW_e and assumed efficiency of 33%. For the neutron cross sections, the ENDF/B-VII library [2] was used

In order to calculate the neutron energy spectrum in the cooling systems, we specified representative region for each coolant system as shown in Fig. 3 and these regions were assigned for tally cell in the MCNPX simulation. When the neutron energy spectrum is calculated at each region, the neutron energy range was divided into 175 energy bins of VITAMIN-J library [3] used for activation calculation using FISPACT code. VITAMIN-J library is one of the most widely used libraries for fusion application [8-10].

Table 2. Composition and Materials of the Cylindrical Region.

Region	**Plasma**	**Blanket First Wall**	**Blanket**	**Blanket**	**Void**	**Inner Vacuum Vessel**	**Vacuum Vessel Coolant**	**Outer Vacuum Vessel**	**TF Coil**
Material	Void	Beryllium	CuCrZr	SS316L	Void	SS316L	Water	SS316L	SS316-LN

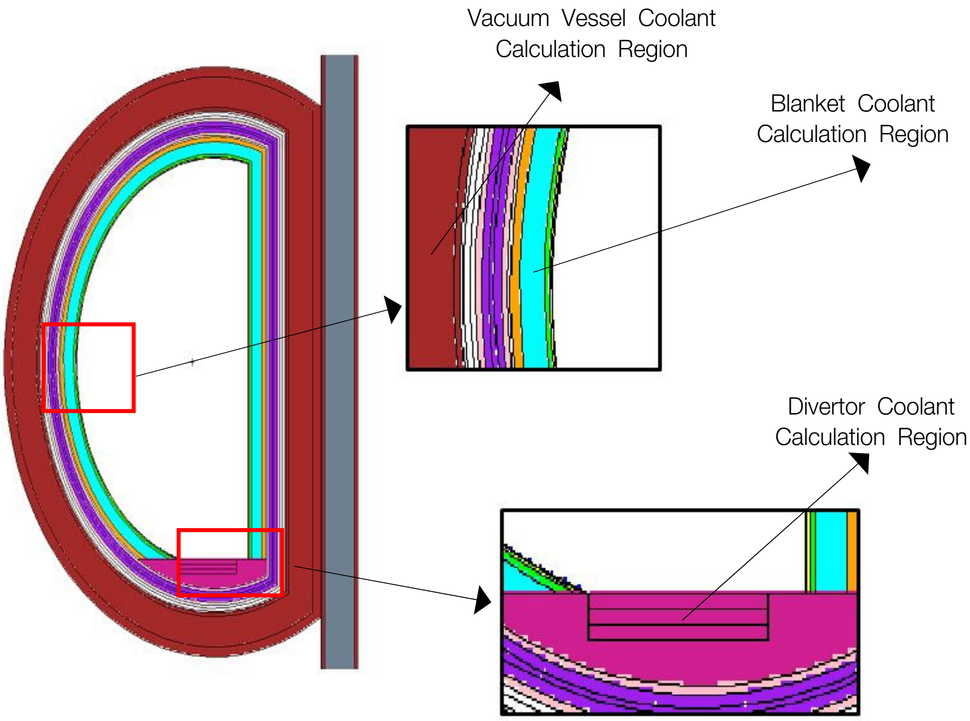

Fig. 3. Representative regions for calculating neutron energy spectra in the coolant of blanket, divertor, and vacuum vessel.

Using calculated spectrums and the composition of corrosion products, activation of corrosion products was estimated using FISPACT code. The FISPACT code requires neutron energy spectrum, total neutron flux, mass of each element, irradiation scenario such as irradiation and cooling time as the input data and provides activities of radionuclides produced by neutron irradiation as output. In other words, FISCAT code does the calculations using Eqn. (1). In Eqn. (1), T_{res} is the average value of maximum retention time in the core for each nuclide, which is based on the operation experience of the reference PWRs as described in the FSAR. Since there is no operation experience of the fusion DEMO reactor, however, T_{res} in the FSAR, 74 days, is applied to the fusion DEMO reactor. After irradiation by neutrons, activated corrosion products were assumed to have cooling time of 1 day in order to exclude radioisotopes having very short half-life.

With the activity of ACP per unit mass of the CRUD on the surface of reactor core, we assessed the activity of each ACP in the coolant. In the FSAR, the activity of ACP per unit mass of the CRUD transferred from the surface into the coolant (A_{ic}) was calculated using following equation.

$$A_{ic} = A_i \frac{A_c}{A_t}, \mathrm{Bq(g-crud)^{-1}} \qquad (2)$$

where A_i is the activity of nuclide i per unit mass of the CRUD on the surface of reactor core [$\mathrm{Bq(g\text{-}crud)^{-1}}$], A_c is the total area of the core surface(cm^2), and A_t is the total area of the primary coolant system (cm^2). It was assumed that A_c/A_t in the coolant system of the fusion DEMO reactor is 0.238, the same value given for the reference PWR since the coolant system of the fusion DEMO reactor has not been designed in detail. The activity of each ACP per unit mass of the coolant is calculated by multiplying A_{ic} and the concentration of corrosion products in the coolant. In case of the reference PWR, the average concentration of corrosion products in the coolant, 7.5×10^{-2} ppm is used to calculate the specific activity of ACP in the coolant. This concentration was also used to estimate the specific activity of ACP in the coolant of the fusion DEMO reactor.

In order to compare specific activity of ACPs in the coolant system of the PWR and the fusion DEMO reactor, the ACPs in the coolant system of PWR was also estimated using FISPACT code. The composition of corrosion product in the DOE report with the cobalt impurity was used. To obtain the neutron energy spectrum in the PWR core, the MCNP input modeling the reactor of Younggwang unit 3 performed in the previous study [11] was used. The neutron energy spectrum was calculated at the center of core and the neutron energy range was divided into 69 energy bins of WIMS library [3] used for activation calculation using FISPACT code. In the analysis for the FSAR, only 2 energy groups were used. The WIMS library is an appropriate library for fission application. Using calculated neutron energy spectrum, the activities of each ACP per unit mass of the CRUD and per unit mass of the coolant were calculated with the same procedure used in the case of the fusion DEMO reactor.

3. RESULTS AND DISCUSSION

Fig. 4 shows the calculated neutron energy spectrums in the coolant system of blanket, divertor, and vacuum vessel. All results have relative error less than 5%. As shown in Fig. 4, the total neutron flux in the coolant system of blanket is slightly higher than that of divertor, but the lower energy neutron flux in the coolant system of divertor is higher than that of blanket because neutrons reaching the divertor coolant are further moderated than neutrons reaching the blanket coolant. The neutron flux in the coolant of vacuum vessel is much lower than others because of the longer distance between plasma and the coolant.

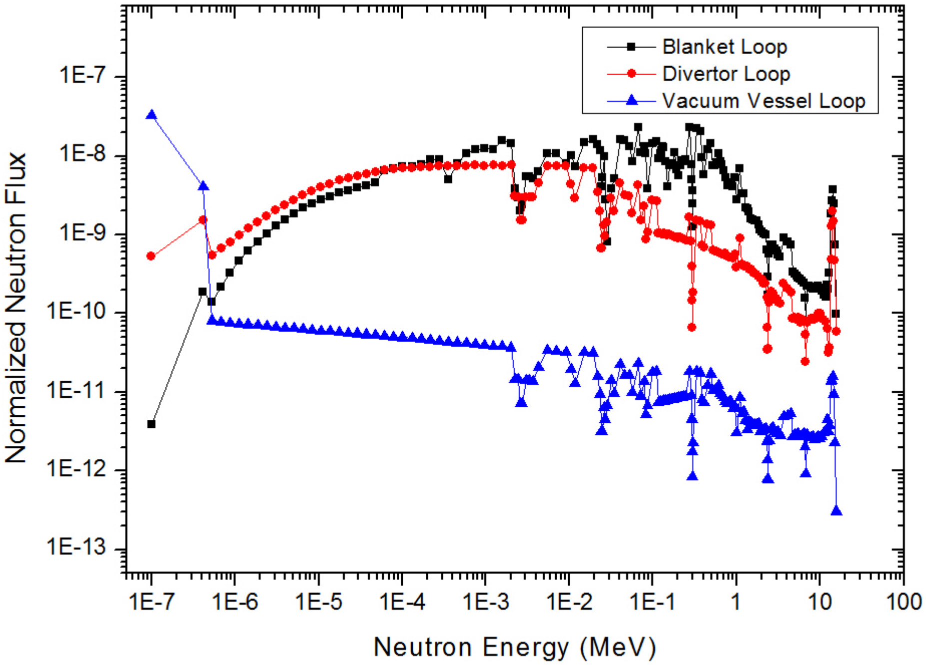

Fig. 4. Calculated neutron spectrum in the coolant system of blanket, divertor, and vacuum vessel.

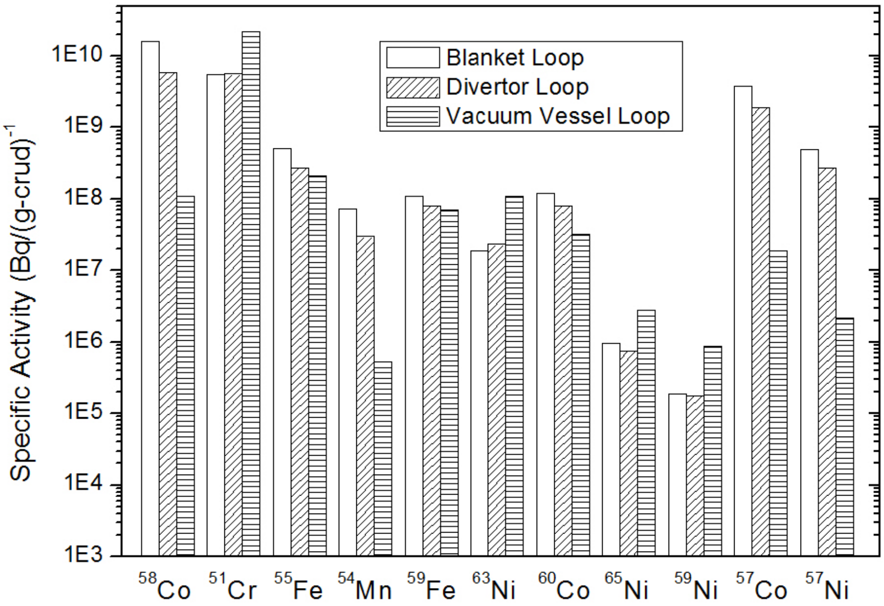

Fig. 5. Activity of major ACPs per unit mass of CRUD in the coolant system of the blanket, divertor, and vacuum vessel.

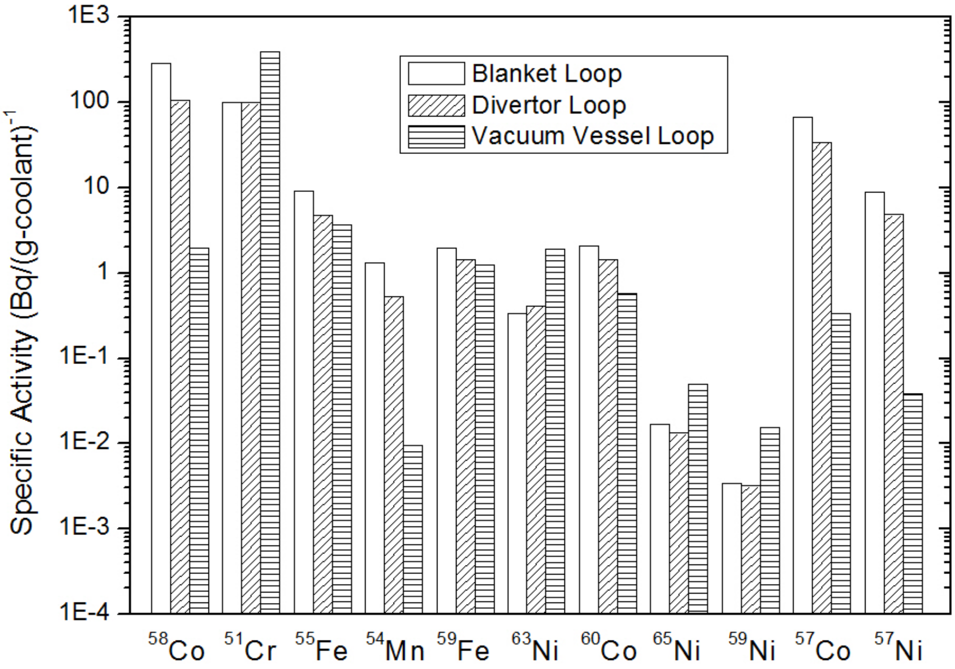

Fig. 6. Activity of major ACPs per unit mass of coolant in the blanket, divertor, and vacuum vessel.

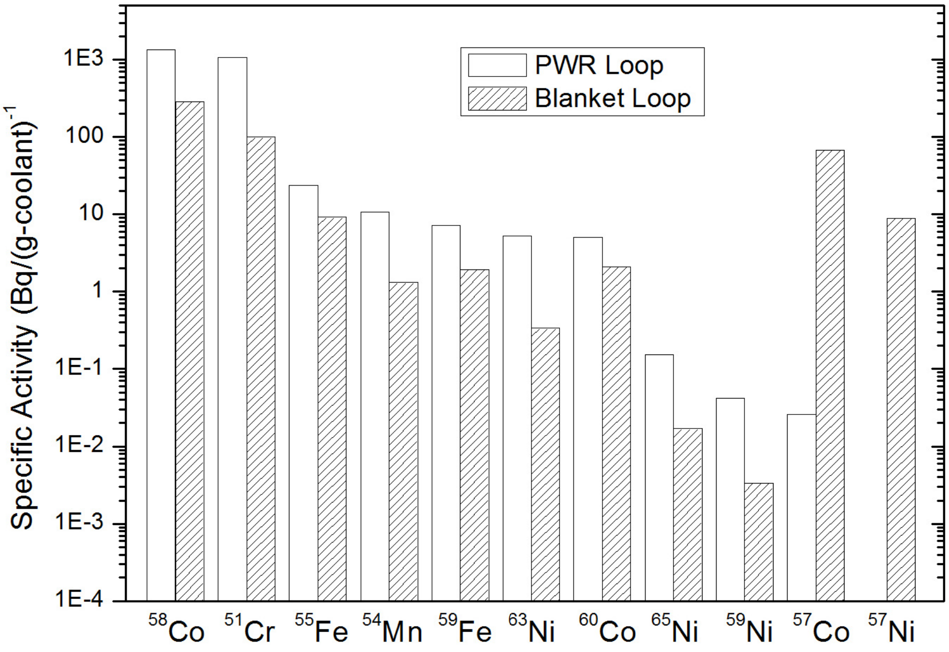

Fig. 7. Comparison of specific activity in the coolant of the PWR and that of the blanket.

Fig. 5 shows the activity of major ACPs per unit mass of CRUD produced in the coolant system of the blanket, divertor, and vacuum vessel. As shown in Fig. 5, ^{58}Co accounts for the greatest part in the blanket and divertor coolant system because almost 50% of CRUD is ^{58}Ni which is converted into ^{58}Co by (n,p) reaction. This reaction has larger reaction cross sections at higher neutron energy. The specific activities of several nuclides including ^{58}Co, ^{54}Mn, ^{57}Co and ^{57}Ni in the divertor and blanket coolant are over 100 times higher than those in the vacuum vessel coolant because these nuclides are produced by reactions having threshold energy of several MeV. On the contrary, ^{51}Cr accounts for the greatest part in the vacuum vessel coolant since neutrons are further moderated on the path reaching the vacuum vessel coolant, thereby having higher portion of thermal neutrons for which (n,γ) reaction cross sections are very large. Similar to the ^{51}Cr, specific activities of some nuclides such as ^{59}Ni, ^{63}Ni and ^{65}Ni, in the vacuum vessel coolant is over 3 times higher than those in the blanket and divertor coolant even if the total flux in the vacuum vessel coolant is much lower than that in the other coolant systems. Fig. 6 shows the activities of major ACPs per unit mass of coolant in the blanket, divertor, and vacuum vessel. Since this specific activity is calculated by just multiplying the values in Fig. 5 by constants, the pattern in Fig. 6 is same as that in Fig. 5.

Fig. 7 compares the specific activities in the coolant of the PWR and those of the blanket for major ACPs. The blanket coolant system was selected as the comparable coolant system because the neutrons reaching the blanket coolant system are less moderated to cause the greatest difference from fission neutrons. The specific activities of the most nuclides in the PWR coolant are 2-15 times higher than those in the blanket coolant because the thermal power of the PWR is higher than that of the fusion DEMO reactor and the PWR coolant is closer to the neutron source than the blanket coolant. For ^{57}Co and ^{57}Ni, however, the specific activity in the PWR coolant is much lower or negligible because ^{58}Ni(n,np)^{57}Co and ^{58}Ni(n,2n)^{57}Ni reaction have very high threshold energies of 8.03 MeV and 12.4 MeV, respectively. Unlike in the PWR, ^{57}Ni will be important radionuclide in the fusion reactor because ^{57}Ni emits high energy gamma rays of 1.37 MeV and 1.92 MeV and has half-life of 35.6 hours that is not short.

4. CONCLUSION

In this study, we calculated the specific activities of ACPs in the blanket, divertor, and vacuum vessel coolant of the fusion DEMO reactor. In order to estimate the specific activities of ACPs, the data and operating experience from the PWRs were employed because there is no operating experience of a fusion reactor. The MCNPX code was used to obtain the neutron energy spectrum in the coolant system. Using the calculated neutron energy spectrum and the composition data of CRUD, the specific activities of ACPs in the coolant of fusion DEMO reactor were estimated using FISPACT code. From the results, we identified the activity level of ACPs in the coolant of the fusion DEMO reactor and important radionuclides in each of the coolant system. In addition, we compared the specific activities of ACPs in the fusion DEMO reactor with the those in the reference PWR. Specific activities of most nuclides in the PWR coolant were significantly higher than those in the blanket coolant, but the specific activities of ^{57}Co and ^{57}Ni in the PWR coolant were much lower or negligible because of the threshold energy of reactions. Unlike in the PWR, ^{57}Ni will be important radionuclide in the fusion reactor.

It is expected that the results in this study will be used to figure out the approximate radiological conditions and to establish a tentative set of radiological design criteria for the systems carrying coolant in the design phase of the fusion DEMO reactor.

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