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Induced activity of several candidate superconductor materials in a tokamak-type fusion reactor

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Abstract

The induced activity and compositional change of several superconducting materials such as Nb-based alloys, V-based alloys and MgB_2 have been evaluated with a numerical calculation. We assume that the materials are irradiated for 10 MW a/m^2 at the magnet of the inboard position of a tokamak-type fusion reactor with a neutron wall loading of 1 MW/m^2. The materials are Nb_3Sn, Nb_3Al, NbTi, NbZr, V_2Zr, $V_2(Zr,Hf)$, V_3Ga, V_3Si and MgB_2. Most of the induced activity of V-based alloys and MgB_2 after the shutdown of the reactor is controlled by the ^{60}Co formed from Cu. After the irradiation, the dose rate decreases to a safe level of 10 μSv/h within 30 years. However, Nb-based alloys are predicted to emit gamma rays for tens of thousands years. The compositional changes and irradiation damage of V-based alloys and MgB_2 are minimal.

1. Introduction

A superconductor is an important component in magnetic fusion reactors. In ITER, magnet coils, including toroidal (TF), poloidal (PF), and central solenoid (CS) coils, which confine, stabilize, and heat plasma, are designed with NbTi and Nb_3Sn superconductors [1,2]. These Nb-based superconductors are also candidates for commercial reactors. Results of the evaluation of damage and induced activity of TF and CS coils for 3 MW a/m^2 indicated that the design criteria for the biological shielding have been satisfied [3]. However, Nb has a potential to produce a long-lived nuclide, such as ^{94}Nb, depending on the neutron spectrum and fluence during the service period of the reactor. Especially for a long operation, it is necessary to consider the radioactivation of components of the fusion reactor, even of the magnets, from the viewpoints of radiological and environmental safety.

For the magnet coils, several new superconductor materials that improve the magnetic properties and irradiation resistance have been proposed [4–7].

In the present study, the induced activity and compositional change of several superconductor materials, such as Nb-based alloys, V-based alloys, and MgB_2 [8], of the magnets of a tokamak-type fusion reactor have been evaluated with a numerical calculation.

2. Numerical calculation of induced activity

Transmutation and induced radioactivity calculations were performed using the IRAC code [8]. Nuclear data in 42 energy groups covering the range energy from 0 to 15 MeV, were taken from FENDL/A-2.0 [9] and EAF-99 [10,11]. The neutron spectra were calculated using ANISN for the superconductors adjacent to the vacuum wall of a one-dimensional fusion reactor model [2].

Fig. 1 shows a typical one-dimentional model of a midplane of a tokamak-type reactor for the calculation.

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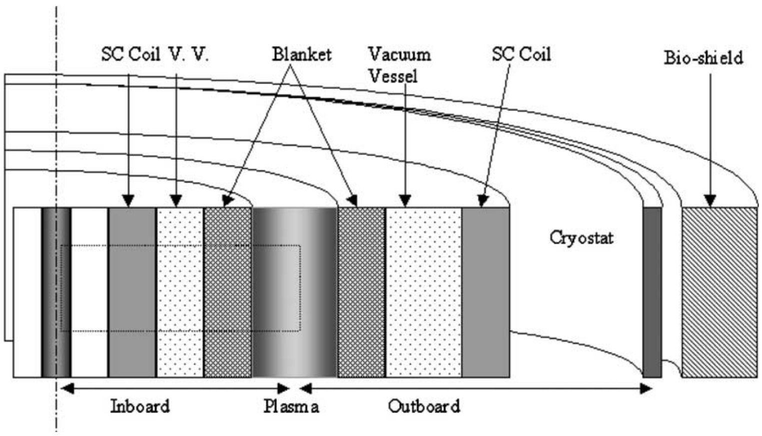

Fig. 1. One-dimensional model of a tokamak-type fusion reactor.

In this model, the fusion reactor is mainly composed of plasma, a blanket, a vacuum wall, magnets, and a cryostat. Since the vacuum wall at the inboard is thinner than that at the outboard, because of the narrower space, the neutron flux is higher for the magnets of the inboard position than for those of the outboard position. In the present study, the transmutation and induced activity of the superconductors were examined for the magnet coils adjacent to the vacuum wall of the midplane of the inboard, considering the case of the severest neutron irradiation condition. The structure and composition of the one-dimensional model at the midplane of the inboard position, indicated as the area surrounded with dotted lines in Fig. 1 are shown in Fig. 2 for the calculation of the neutron spectra. The armor is carbon and the blanket is composed of SUS316, water and lithium oxide. The vacuum wall and the vessel of liquid He consist of SUS316. Superconductor materials, copper, epoxy resin and liquid He, which make up the magnet, are placed behind the vacuum wall.

Fig. 3 shows the neutron spectra at the blanket first wall, the vacuum wall, and the magnet adjacent to the vacuum wall under the neutron wall loading of 1 MW/m^2. Nb_3Sn was assumed as a superconductor in this calculation. The flux of neutrons decreases as the distance from the first wall increases. The flux of 14 MeV neutrons at the magnet is lowered by about 5–6 orders of magnitude from that of the first wall.

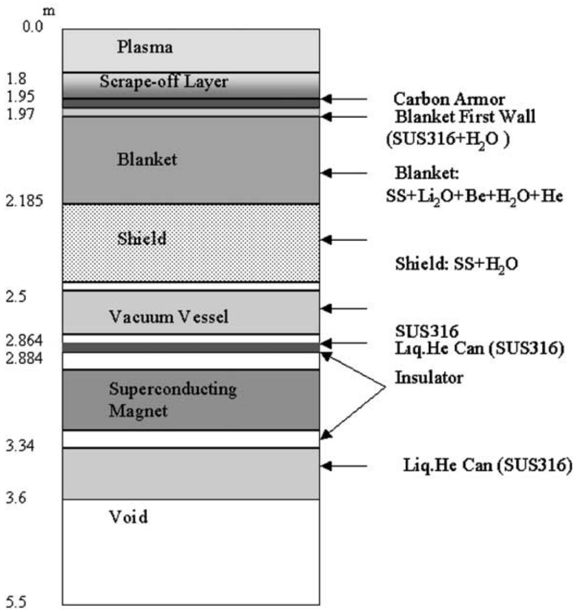

Fig. 2. Structure and composition of a tokamak-type reactor for neutron spectra calculations. Typical scale for the midplane of the inboard of the reactor is indicated.

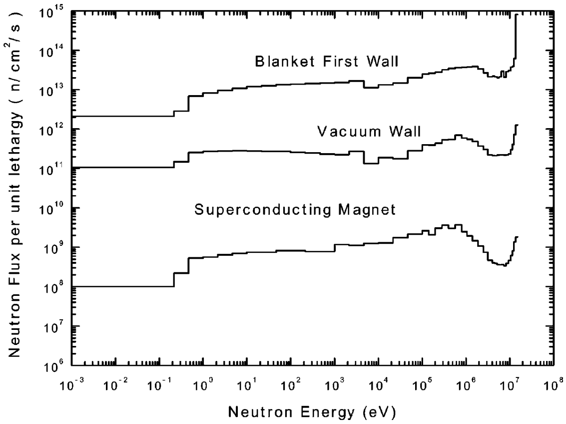

Fig. 3. Neutron spectra at the first wall of blanket, the vacuum wall, and the superconducing magnet adjacent to the vacuum wall.

Using the neutron spectrum at the magnet as shown in Fig. 3, the activation and transmutation calculations for the superconductor materials were made assuming 10 years of irradiation. The materials considered were Nb_3Sn, NbTi, Nb_3Al, NbZr, Nb_3(Al,Ge), Nb_3(Al,Si), V_2Zr, V_2(Zr,Hf), V_3Ga, V_3Si, and MgB_2. Modified Nb-based alloys such as Nb_3(Al,Ge) and Nb_3(Al,Si) were recently developed [4] to improve the critical magnetic field (H_c) and current (I_c). V-based superconductors are attractive because of their low activity of vanadium in addition to their irradiation resistance [7]. MgB_2 [8] is also a candidate low-activation superconductor.

3. Results and discussion

3.1. Induced activity of superconductor materials

Fig. 4 shows the decays of the dose rate of Nb-based alloys, V-based alloys and MgB_2 after the shutdown of the reactor. The real superconductors are stabilized by Cu. However, only superconductor materials are considered in this figure to find which elements in the alloy control the induced activity. As seen in this figure, V-based and MgB_2 superconductors show very fast decays after the irradiation. On the other hand, Nb-based alloys require a longer cooling time than tens of thousand years, if the 10 mSv/h for the remote-handling recycling level is satisfied [12]. The dose rates of V-based alloys and MgB_2 are reduced to 10 μSv/h for the hands-on maintenance level [12] within 10 years. This suggests that the hands on maintenance of these materials is possible because of their short-time cooling. The activity that is maintained during a long time cooling is caused by the formation of long-lived nuclides such as ^{94}Nb ($t_{1/2} = 2 \times 10^4$ years), produced by $^{93}Nb(n,\gamma)^{94}Nb$ reaction, and ^{26}Al ($t_{1/2} = 7.2 \times 10^5$ years), produced by $^{27}Al(n,2n)^{26}Al$ reaction. A dose rate of around 10 mSv/h –100 mSv/h is kept at the magnet near the vacuum wall for a long time. This means that thicker shielding is necessary in front of the magnet if Nb-based superconductors are used for the long operation.

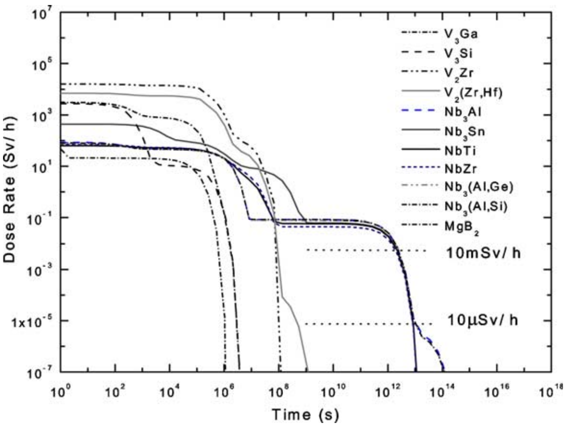

Fig. 4. Decay behaviors of the dose rate for V-based, Nb-based, and MgB_2 superconductors after 10 MW a/m^2 operation.

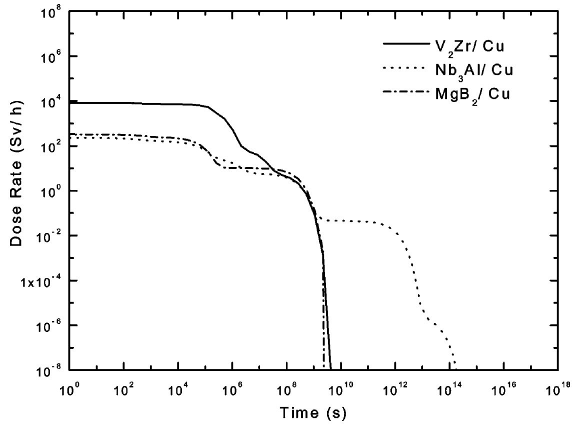

Fig. 5. Decay behaviors of the dose rate for V-based, Nb-based, and MgB_2 superconducting coils stabilized with Cu after 10 MW a/m^2 operation.

Fig. 5 shows the decay behaviors of the dose rate for real magnet coils stabilized by Cu. V_2Zr, Nb_3Al, and MgB_2 are selected as examples. In the case of V-based alloys and MgB_2, the dose rate for longer cooling is determined by the radioactive nuclides from Cu. The main nuclide is ^{60}Co ($t_{1/2} = 5.27$ years), produced by the reactions, $^{63}Cu(n,\alpha)^{60m}Co(IT)^{60}Co$ and $^{63}Co(n,\alpha)^{60}Co$. The dose rate decreases below 10 μSv/h of hands-on recycling within 30 years.

For the Nb-based alloys stabilized with Cu, the main nuclide controlling the dose rate for a long cooling period is still ^{94}Nb. When Al is used as the alloying element, ^{26}Al also contributes to the dose rate for the long cooling time. In the present study, a neutron wall loading of 1 MW/m^2 and a maximum fluence of 10 MW/m^2 corresponding to around 100 dpa were assumed for the first wall. However, since the neutron wall loading and the fluence of the first wall for commercial reactors are expected to be around 5–10 MW/m^2 and 200 dpa at maximum, respectively [13], the use of Nb for a superconductor will lead to difficulties in maintenance and recycling from the viewpoint of induced activity.

3.2. Transmutation of superconductor materials

Although V-based alloys and MgB_2 are low-activation superconductors as discussed in the previous chapter, the irradiation damage should also be considered. In particular, B in MgB_2 is a neutron-absorbent material.

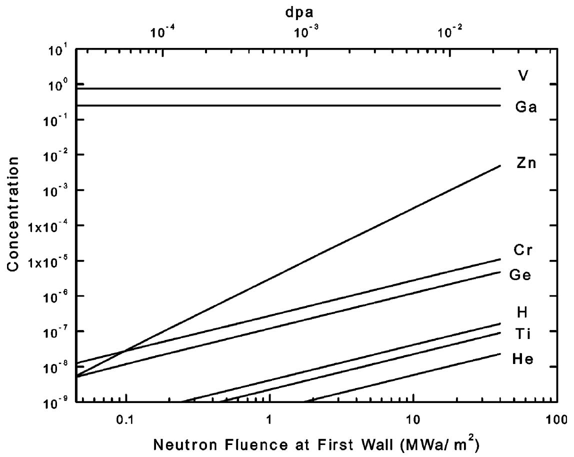

Fig. 6. Transmutation of V_3Ga as functions of neutron fluence and operation period.

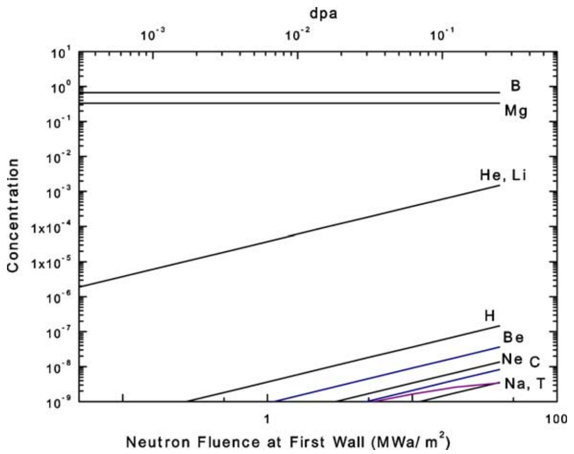

Fig. 7. Transmutation of MgB_2 as functions of neutron fluence and operation period.

Figs. 6 and 7 show the transmutation of V_3Ga and MgB_2 as functions of the neutron fluence at the first wall and the dpa of V_3Ga and MgB_2, respectively. After 10 MW a/m^2 operation, the neutron fluence for V_3Ga is around 5×10^{-3} dpa and only 0.01% of Zn is produced. The damage rate of MgB_2 is one order higher than that of V_3Ga. However, as seen in Fig. 7, about 0.1% of B transmutes after the 10 MW a/m^2 operation. This result indicates that the compositional change of MgB_2 in the magnet is minimal for the 10 years of operation under 1 MW/m^2 wall loading.

4. Conclusions

The induced-activity of several candidate superconductor materials under 10 MW a/m^2 operation condition was evaluated using numerical calculations. The following conclusions were derived.

1. Nb-based superconductors are expected to produce a long-lived γ emitter, ^{94}Nb, which limits the access for a long time after shutdown of the reactor.
2. V-based and MgB_2 superconductors are preferable from the viewpoint of low-induced activation.
3. The compositional change of MgB_2 after 10 MW a/m^2 operation is below 0.1 at.%.
4. A thick neutron shield is required if a Nb-based superconducer is used.

Acknowledgements

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