Activation analysis for the HCSB-DEMO reactor in China

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The Neutron induced activity and decay heat are very important for the nuclear design of fusion reactor. In this paper, activation analysis of DEMO reactor with helium-cooled solid blanket (HCSB-DEMO) was performed. Ceramics Li_4SiO_4 and Beryllium options were considered as tritium breeding material and neutron multiplier, respectively. Chinese low-activation ferritic steel (CLF-1) developed in South Western Institute of Physics (SWIP) was applied as structural materials of blanket. Activation analysis was performed using FDKR code with activation cross section data file FENDL/A-2.0. Neutron fluxes as the input of FDKR were calculated with MCNP Monte Carlo code and FENDL/MC-2.1 neutron cross section data. The activity inventories and decay heat in HCSB-DEMO were examined. The contributions of radionuclides of structural materials, Li_4SiO_4 and Beryllium in blanket were discussed, respectively.

Keywords: Activation analysis, DEMO, Solid breeder blanket, CLF-1, Impurity.

1. Introduction

In recent 50 years, China has made an effort to develop the fusion energy. China DEMO (CN DEMO) study is the important aspect of long-term national program [1]. DEMO reactor with Helium-cooled solid breeder (HCSB) blanket (HCSB-DEMO) concept is an option of China DEMO design study [1, 2]. Tritium breeding blanket is one of the key components of fusion reactor. The main requirements for DEMO blankets are tritium self-sufficiency and extraction of high-grade heat. Some of HCSB-DEMO related blanket technologies will be tested with ITER [2].

In HCSB-DEMO design, the low activation ferritic/martensitic steel of CLF-1, which was developed in SWIP of China, was chosen as structure material. Beryllium was used for neutron multiplication. Li_4SiO_4 ceramic tritium was chosen as tritium breeder due to its high lithium content and good thermal stability. Li_4SiO_4 ceramic pebble bed was adopted in blanket to improve the tritium release and to reduce the thermal stress due to low conductivity of Li_4SiO_4.

The radioactivity of fusion materials induced in D-T neutron field is very important in terms of maintenance and radioactive waste management. In this paper, we report the investigation of the induced radioactivity and decay afterheat in the components of HCSB-DEMO.

2. Calculation procedure

The neutron transport calculation was performed using MCNP Monte Carlo code and FENDL/MC-2.1 neutron cross section data [4, 5]. The calculated neutron fluxes were used as input file for activation analysis. FDKR code was used for activation analysis [6]. FDKR code is based on DKR code which originated at the University of Wisconsin in 1976 [6, 7]. With the supplements of decay chain of fission products and actinides and related libraries, FDKR code can perform the activation calculation for fission, fusion and hybrid reactors. In this analysis, the recent activation cross section data file FENDL/A-2.0 was used [8].

Table 1 Radial build of HCSB-DEMO

	Thickness (cm)	Composition
FW	3.0	CLF-1, 54%; He, 46%
Blanket	37.0 (IB)	CLF-1, 12.2%; He, 38.0%; Be, 18.7%; Li_4SiO_4, 31.1%
	47.0 (OB)	
Shield	45.0	CLF-1, 70%; B4C, 20%; H_2O, 10%
V.V	20.0	CLF-1, 90%; H_2O, 10%

Major radius and minor radius of HCSB-DEMO are 7.2 m and 2.1 m respectively. Fusion power is 2550 MW. The neutron wall loading is 2.3 MW/m^2. A torus model was used in the activation analysis. Table 1 shows the radial build of HCSB-DEMO. The inboard and outboard total thicknesses of First Wall (FW), blanket and shield are 85 cm and 95 cm, respectively. Vacuum Vessel (V.V) in 20 cm thickness is consisting of CLF-1 structure and water. The water in shield and V.V was used as both of coolant and shield material. Activation analysis was assumed for a full power continuous operation 4 years, which is the predicted life of blanket. The chemical

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composition of CLF-1 is: 8.3 Cr, 1.5 W, 0.3 V, 0.11 C, 0.5 Mn, 0.08 Ta, 0.001 O, 0.007 N (wt. %) and Fe for balance [3]. The impurities in CLF-1 were considered in activation analysis.

3. Results and discussion

3.1 Radioactivity inventory

Radioactive inventories in HCSB-DEMO include the bred tritium and activated materials. Figure 1 shows the activity generated in the component of FW, blanket, shield and V.V. The results are given as a function of cooling time after shutdown. First, the activity from blanket dominates for about 60 s. Then the activity generated in FW is dominant up to about 10 years. Finally, the activity from blanket dominates up to 1000 years. The activity in V.V is one order lower than that in other components. The decay curves of FW and V.V activity are very close.

The radioactivity in FW is responded by the activation of CLF-1. The FW activity is dominated by ^{55}Fe ($T_{1/2}$=2.72 y) up to 10 years as shown in Fig. 2. ^{55}Fe is mainly produced through ^{56}Fe(n, 2n)^{55}Fe reaction. After about 100 years cooling, the dominant radionuclide

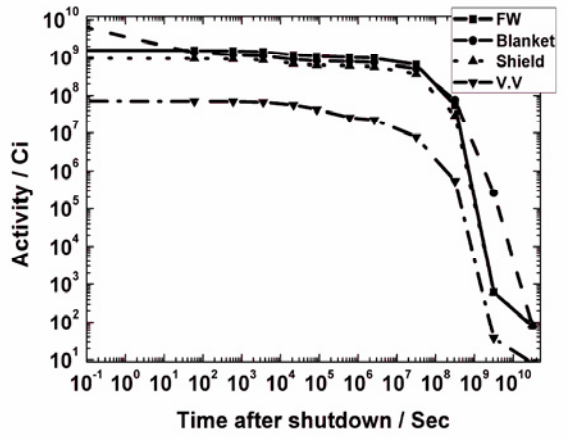

Fig. 1 Total activity generated in FW, blanket, shield and V.V

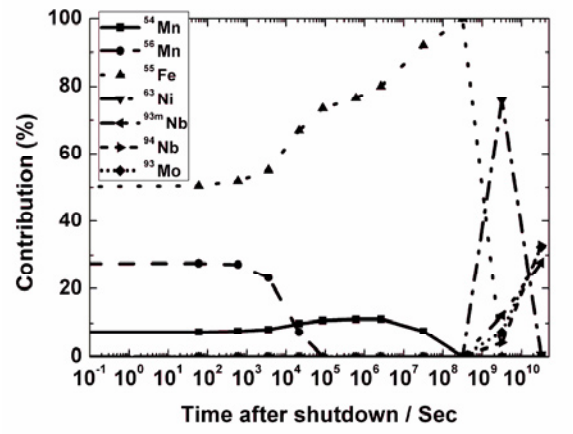

Fig.2 Major radionuclides contributing to FW activity

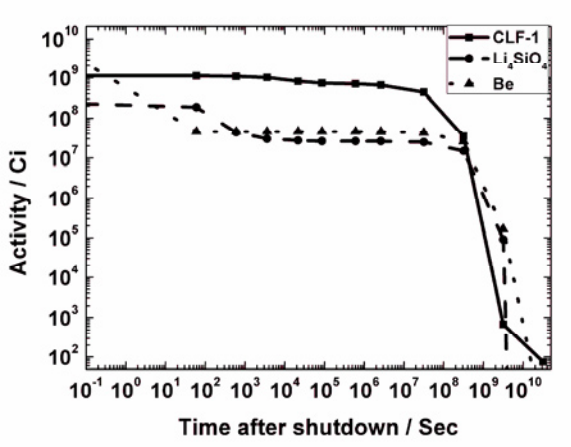

Fig.3 Total activity generated in CLF-1 structure, Li_4SiO_4 breeder and Be neutron multiplier of blanket.

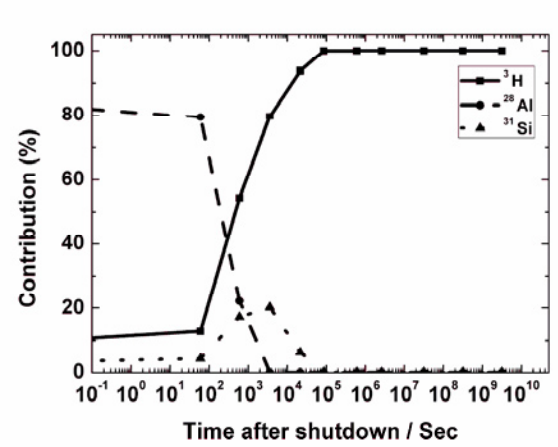

Fig.4 Major radionuclides contributing to Li_4SiO_4 breeder activity in blanket.

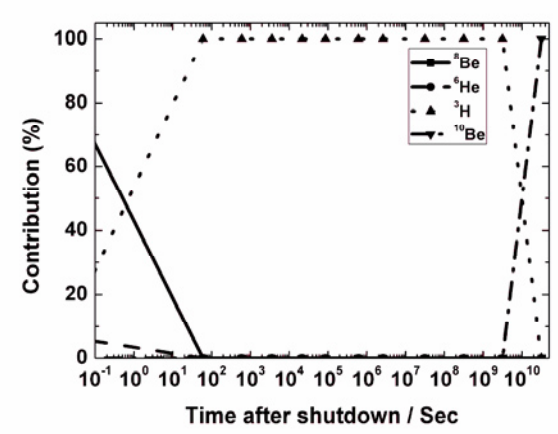

Fig.5 Major radionuclides contributing to Be neutron multiplier activity in blanket

is ^{63}Ni ($T_{1/2}$=92 y) which is produced by ^{63}Cu(n, p)^{63}Ni, ^{62}Ni(n, γ)^{63}Ni and ^{64}Ni(n, 2n)^{63}Ni reactions. The long-term radioactivity in FW is determined by the long-lived radionuclides of ^{93}Mo ($T_{1/2}$=3.5 x 10^3 y) and ^{94}Nb ($T_{1/2}$=2.0 x 10^4 y, product of ^{93}Nb (n, γ) reaction). ^{93}Mo is form through ^{92}Mo(n, γ)^{93}Mo and ^{94}Mo(n, 2n)^{93}Mo reactions.

The total activity generated in blanket materials is shown in Fig. 3 as a function of cooling time following shutdown. After a few seconds, the activity from CLF-1 structure dominates up to 10 years. During 10-100 years, the activity from Li_4SiO_4 breeder and Be neutron multiplier is higher than the activity from CLF-1 because of the bred tritium ($T_{1/2}$=12.33 y) as shown in Fig. 4 and 5.

Induced radioactivities in Li_4SiO_4 breeder are dominated by ^{28}Al($T_{1/2}$= 2.27 m) and by tritium, respectively. ^{28}Al is the activation production of ^{28}Si (n, p)^{28}Al reaction.

The short and intermediate radioactivity in Be neutron multiplier is dominated by ^{8}Be ($T_{1/2}$=7 x 10^{-17} s, product of ^{9}Be(n, 2n)^{8}Be reaction) and by tritium. Long-term activity in Be is due to ^{10}Be ($T_{1/2}$=1.51 x 10^6 y), which is produced by ^{9}Be(n, γ)^{10}Be reaction.

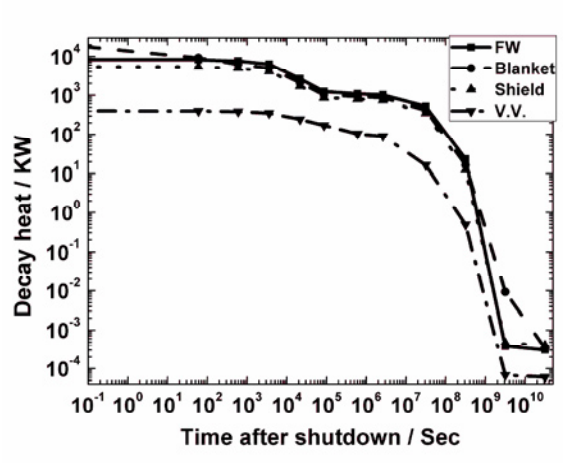

Fig.6 Total decay heat generated in FW, blanket, shield and V.V.

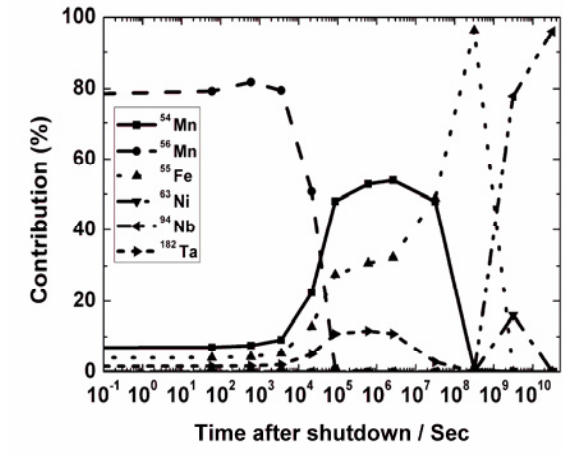

Fig.7 Major radionuclides contributing to FW decay heat.

3. 2 Decay heat

The total decay heat generated in the component of FW, blanket, shield and V.V is shown in Fig. 6 as a function of cooling time after shutdown. The decay heat generated in FW, blanket and shield are comparable up to 10 years following shutdown. The decay heat from blanket dominates during the period of 10-1000 years. The decay heat generated in V.V is about one order lower.

The FW decay heat is dominated by ^{56}Mn ($T_{1/2}$=2.578 h) up to several hours after shutdown as shown in Fig. 7. ^{56}Mn is mainly produced through ^{56}Fe(n, p)^{56}Mn reaction. Then ^{54}Mn ($T_{1/2}$=312.12 d), which is formed by ^{54}Fe(n, p)^{54}Mn reaction, dominates up to 1 year. During 1 year to several tens years after shutdown, the dominant nuclide is ^{55}Fe. Long-term decay heat is due to ^{94}Nb.

Figure 8 give the total decay heat generated in blanket materials as a function of cooling time after shutdown. The decay heat from CLF-1 structure dominates up to 1000 years. The decay heat from Li_4SiO_4 breeder and Be neutron multiplier are very low compared with that from CLF-1 structure.

Figures 9 and 10 show the major radionuclides contributing to the decay heat in Li_4SiO_4 breeder and Be neutron multiplier, respectively. For Li_4SiO_4, the dominant decay heat contributions are due to ^{28}Al, ^{29}Al ($T_{1/2}$=6.5 m, production of ^{29}Si (n, p)^{29}Al reaction) and bred tritium, respectively. The decay heat in Be neutron multiplier is dominated by ^{6}He ($T_{1/2}$=7 x 10^{-17} s, product

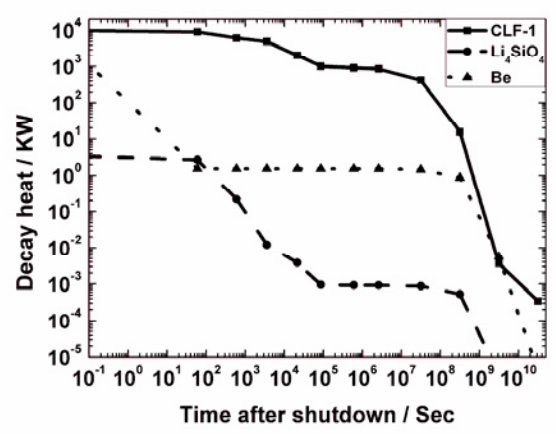

Fig.8 Total decay heat generated in CLF-1 structure, Li_4SiO_4 breeder and Be neutron multiplier of blanket.

of ^{9}Be(n, a)^{6}He reaction) , by tritium and by ^{10}Be, respectively.

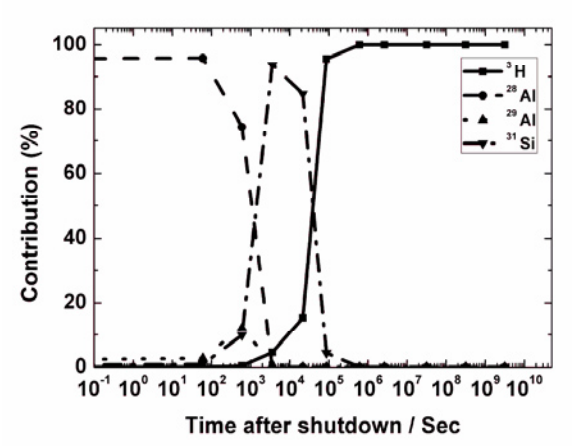

Fig.9 Major radionuclides contributing to Li_4SiO_4 breeder decay heat in blanket.

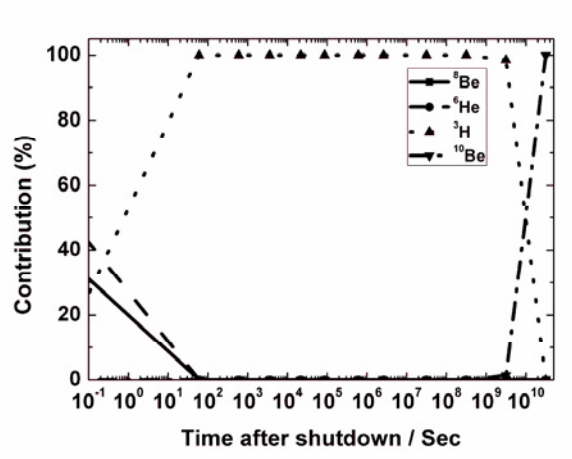

Fig.10 Major radionuclides contributing to Be neutron multiplier decay heat in blanket.

For Li_4SiO_4 and Be, the bred tritium contributes most of decay heat from several hours to hundreds years following shutdown. The decay heat from Li_4SiO_4 and Be are negligible if the tritium is removed.

4. Summary and conclusion

In this paper, the preliminary design of HCSB-DEMO was introduced. The neutron induced radioactivity inventories and decay heat in HCSB-DEMO were investigated. The contributions of radionuclides of structural materials, Li_4SiO_4 and Beryllium were discussed, respectively.

After several minutes cooling, the radioactivity and decay heat of FW, blanket and shield are comparable up to about 10 years following shutdown. On the other hand, the radioactivity and decay heat of V.V is bout one order lower. The radionulides of ^{54}Mn, ^{56}Mn, ^{55}Fe, ^{63}Ni, ^{94}Nb and ^{93}Mo dominate the radioactivity and decay heat level of CLF-1 FW. The long-lived rodionuclides of ^{63}Ni, ^{94}Nb and ^{93}Mo are the activation product of the impurities of Cu, Ni, Nb and Mo in CLF-1. Long-term activity in Be is due to ^{10}Be.

For Li_4SiO_4 and Be, the bred tritium contributes most of radioactivity and decay heat from several hours to hundreds years following shutdown. The activation of Li_4SiO_4 and Be are negligible if the tritium is removed.

Acknowledgements

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5. References

[1] C.H. Pan, *et al*., Fusion Eng. Des. **83,** 877 (2008).
[2] K. M. Feng, *et al*., J. Nucl. Eng. Des. **81,** 1219 (2006).
[3] WANG Pinghuai, *et al*., Plasma Science and Technology, **11**, 226 (2009).
[4] J F. Briesmeister. MCNP-A general monte carlo n-particle transport code [R]. LA-1265-M, (2000).
[5] D. Lopez Aldama and A. Trkov, INDC-NDS-467, (2004).
[6] Y. X. Yang, *et al*., CCC-541/FDKR, (1989).
[7] T.Y. Sung, *et al*., CCC-323/DKR, (1976).
[8] A.B. Pashchenko and H. Wienke, report IAEA-NDS-174 (1997).