Estimation of Decay Heat in Fusion DEMO Reactor*)

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The decay heat of activated materials is important in safety assessment of fusion DEMO reactor against loss of coolant-flow accidents. Decay heat for reactor main components of the SlimCS DEMO reactor was studied with a one-dimensional code THIDA-2. The reactor main components consist of the inboard (IB) blanket module, outboard (OB) blanket module and divertor. For a reactor with a fusion output of 3.0 GW, the decay heat of IB blanket, OB blanket, divertor and radiation shield were estimated to be as high as 8.6 MW, 30.9 MW, 10.6 MW and 1.8 MW, respectively, immediately after the shutdown of operation. The total decay heat was as high as 52 MW immediately after the shutdown and 3.1 MW one month later. The blanket produces the largest portion of decay heat, about 76 %.

Keywords: decay heat, neutronics, safety, DEMO, SlimCS

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1. Introduction

The decay heat of the activated materials is important in safety assessment of fusion DEMO reactor against loss of coolant/flow accidents (LOCA/LOFA). Moreover, there is a concern that the temperature of blanket and divertor may increase when cutting the cooling pipe during maintenance because the situation is same as LOCA. Thus, estimation for decay heat after shutdown is required for safety assessment and maintenance. On the other hand, the decay heat must be handled at the moment when the operation of a fusion reactor is halted and maintenance is started for periodic replacement of blanket and divertor. The blanket and divertor favorably need to be replaced shortly after shutdown of the reactor for high plant availability. In this sense, nuclear characteristics of the blanket and divertor need to be understood to define criteria or the maintenance.

2. Calculation Model

A neutronics calculation was carried out for a fusion DEMO reactor SlimCS [1]. The major parameters of the reactor are a plasma major radius of 5.5 m, aspect ratio of 2.6 and fusion power of 3.0 GW. The main reactor components are the inboard (IB) and outboard (OB) blanket modules, the divertor and the radiation shield as shown in Fig. 1. The number of IB and OB blanket modules, and divertor is 18, 36 and 2 per a sector, respectively. The volumes of the IB blanket, OB blanket and divertor per sector are 4.9 m^3, 23.3 m^3 and 5.3 m^3, respectively. The number of sector is 12. The decay heats of IB blanket, OB blanket and divertor are calculated under the neutron wall loading of 2.5 MW/m^2, 3.5 MW/m^2 and 1.5 MW/m^2, respectively. It is assumed that the replaceable blanket modules and divertor are changed over at every two years during the operation. Here, the blanket is assumed to be composed of structural material with reduced-activation martensitic steel (F82 H), tritium breeder with Li_2TiO_3 pebbles and neutron multiplier with $Be_{12}Ti$ pebbles. The blanket is filled with the mixture of Li_2TiO_3 pebbles and $Be_{12}Ti$ ones [2]. Tungsten coating is required on first wall (FW) surface to suppress erosion by physical sputtering. For the purpose, the surface of the blanket is covered with 0.2 mm-thick tungsten (W). The divertor is assumed to be made of W mono-block and F82H cooling tubes and substrates. In the calculation, the cooling channel area was modeled with a homogeneous mixture of W and F82 H. The blanket and divertor were approximated by a slab model as shown in Fig. 2. The slab models are in the minor radial direction of

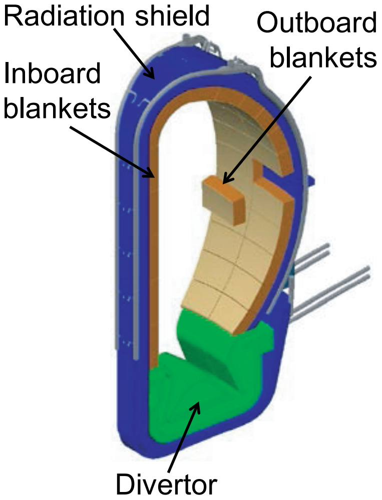

Fig. 1 Torus configuration of SlimCS per sector.

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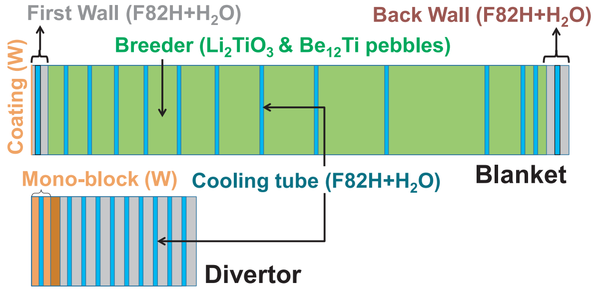

Fig. 2 Slab model structures of the blanket and divertor for the analysis.

a torus.

The cooling tubes were replaced with slabs having the equivalent cross section. In the one dimension (1D) calculations of the neutronic for the blanket and divertor, a THIDA-2 code [3] with the nuclear data library FENDL-2.0 [4] was used.

The neutronic calculation includes the nuclear heating and decay heat density in the blanket and divertor. A temperature of blanket and divertor were evaluated by solving the 1D thermal conduction equations. The thickness of each layer was determined to satisfy the operation temperature of materials. The upper operation temperature of Li_2TiO_3, $Be_{12}Ti$ and F82H was limited to 900°C, 900°C and 550°C, respectively. The coolant was assumed to be water with the pressurized water reactor conditions of 15 MPa and $\Delta T = 40$°C (290-330°C). The upper coolant velocity was limited to 5 m/s. The thickness of IB blanket, OB blanket and divertor were 30 cm, 60 cm and 18 cm, respectively.

3. Total Decay Heat in Fusion DEMO Reactor

The total decay heat for OB and IB blanket, divertor and radiation shield in the reactor is shown in Fig. 3. For the reactor with the fusion power of 3.0 GW, the decay heat of OB blanket, IB blanket, divertor and radiation shield are estimated to be as high as 30.9 MW, 8.6 MW, 10.6 MW and 1.8 MW, respectively, immediately after the shutdown of operation. The total decay heat was as high as 52 MW immediately after the shutdown and 3.1 MW one month later. A month after the shutdown, the total decay heat decreases to 6.0 % of the initial one. It was found that the blanket produces the largest portion of decay heat in the total decay heat, about 76 %. Thus, estimation of decay heat for blanket is important as described in section 3.1.

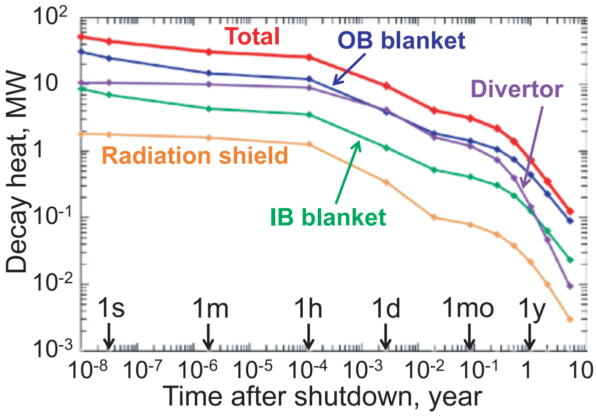

Fig. 3 Total decay heat in fusion DEMO reactor for fusion power of 3.0 GW.

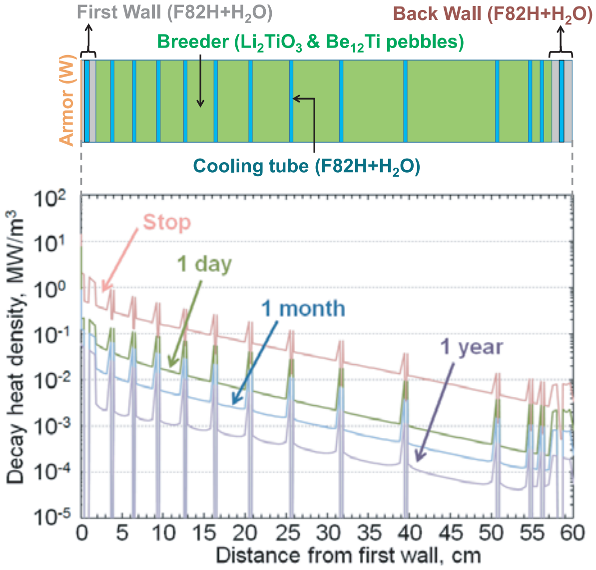

Fig. 4 Decay heat density distribution of the OB blanket.

3.1 Decay heat density of breeding blanket

The decay heat density for OB blanket is shown in Fig. 4. The decay heat density of W coating and F82H in FW was estimated to be 12.1 MW/m^3 and 2.0 MW/m^3 for OB blanket, respectively, immediately after shutdown of operation. The average decay heat density of OB blanket from breeder and multiplier pebbles was 0.1 MW/m^3 immediately after shutdown of operation. Here, W has the highest decay heat density. The decay curves of the decay heat density for W coating are shown in Fig. 5.

The dominant nuclides determining the decay heat density were ^{187}W and ^{188}Re which originated from ^{186}W in W coating. The ^{187}W activity is prominent during one day after shutdown of operation. One day after shutdown, the dominant nuclides determining the decay heat density was ^{185}W and ^{186}Re which originates from ^{185}W. The ^{185}W activity is prominent for a cooling time from 1 day to 1 year. In the case of W coating, the dominant reaction determining decay heat density are ^{186}W (n, γ) reaction within a few days, respectively. When the back scattering is increased, neutron spectrum becomes soft inside the plasma. Thus, the decay heat density should increase with the number of thermal neutrons. When beryllium is used in blanket, the decay heat density of W coating will be an increase of the thermal neutrons.

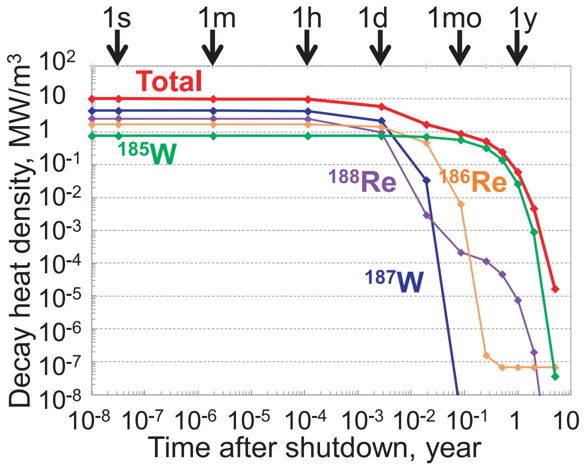

Fig. 5 Decay curves of decay heat density in W coating.

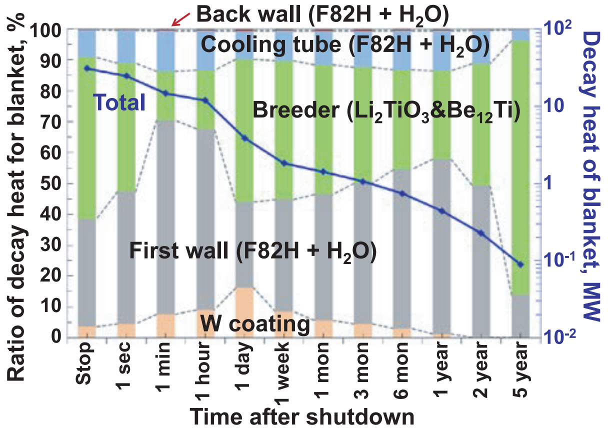

Fig. 6 Ratio of decay heats in OB blanket structure.

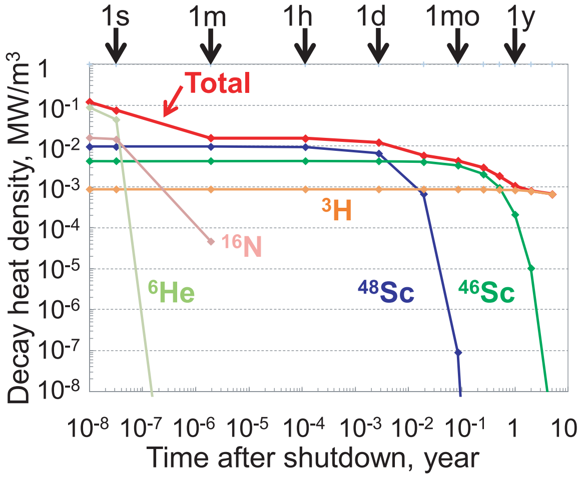

Fig. 7 Decay heat density in breeder.

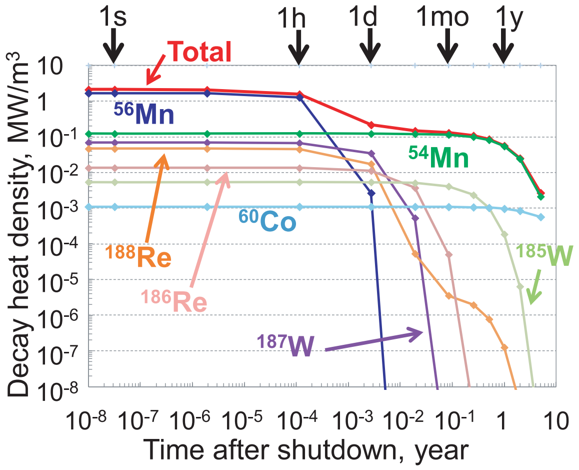

Fig. 8 Decay heat density in first wall.

3.2 Ratio of decay heat for blanket

Ratio of the decay heat in total decay heat for OB blanket is shown in Fig. 6. The dominant component determining the decay heat of blanket was FW of F82H and H_2O, and breeder of Li_2TiO_3 and $Be_{12}Ti$. Here, the decay heat of W is lower than FW and breeder. This is because the total volume is lower than those of the other components.

Decay curves of the decay heat density for breeder are shown in Fig. 7. In the Li_2TiO_3 employed as tritium breeder, the activity of ^{16}N and ^{6}He produced through sequential ^{16}O (n, p) and ^{6}Li (n, p) reactions becomes prominent 10 sec after shutdown as shown in Fig. 7. Thus, contributory the dominant decay heat of breeder decreases in one minute as shown in Fig. 6. The ^{48}Sc activity from ^{48}Ti in breeder is prominent during cooling times between 1 minute and 3 day after shutdown. Three days after shutdown, the dominant nuclides determining the decay heat density was ^{46}Sc during the prominent time from 3 days to 1 year which originates from ^{46}Ti.

Decay heat density for F82H in the first wall is shown in Fig. 8. In the F82H employed as blanket structural, the activity of ^{56}Mn produced through sequential ^{56}Fe (n, p) reaction becomes prominent in 3 hours after shutdown. Thus, contributory the dominant decay heat of breeder increases as one days as shown in Fig. 6. Three hours after shutdown, the dominant nuclides determining the decay heat density was ^{54}Mn during the prominent time from 3 days to 1 year which originated from ^{54}Fe. Here, the F82H is most feasible material in fusion DEMO reactor. However, there is a concern that the dominant material determining decay heat is F82H in first wall. One year after shutdown, on the other hand, ^{3}H becomes increasingly a major part of decay heat in breeder as shown in Fig. 6 and Fig. 7. However, tritium activity can be ignored from the calculated results although it is produced especially in breeder because the recovery of tritium would be possible in the breeding zone. Moreover, reducing the neutron wall load is effective in decreasing the decay heat from threshold reactions of ^{56}Fe (n, p), ^{54}Fe (n, p) and ^{48}Ti (n, p) reactions.

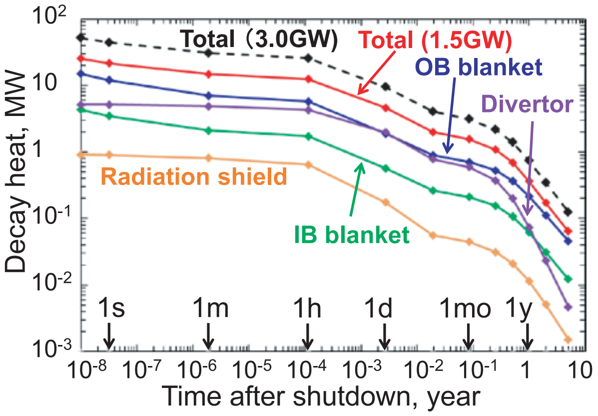

Fig. 9 Total decay heat for 1.5 GW fusion power.

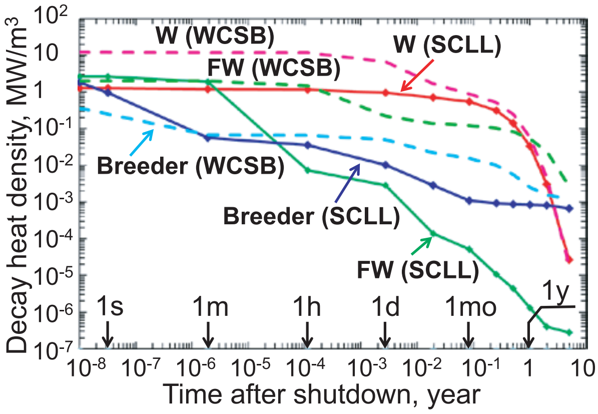

Fig. 10 Comparison of decay heat for WCSB and SCLL.

4. Discussion

4.1 Reduced fusion power

The decay heat depends on the fusion power, or the neutron wall load. Thus, reduced fusion power decreases the decay heat. The fusion power was changed to 1.5 GW from 3.0 GW. The decay heats of IB blanket, OB blanket and divertor were calculated under the neutron wall loading of 1.2 MW/m^2, 1.7 MW/m^2 and 0.6 MW/m^2, respectively.

The total decay heat for OB and IB blanket, divertor and radiation shield for the 1.5 GW fusion power is shown in Fig. 9. The total decay heat was as high as 26 MW immediately after the shutdown and 1.6 MW one month later. It was found that the decay heat was proportional to neutron wall load. With decreasing the neutron wall load, moreover, the local tritium breeding ratio is improved because of a reduction of the coolant area in the blanket.

4.2 Modification of a blanket concept

Blanket concept needs to be adopted to show low decay heat. For example, the blanket concept is selected to be Self Cooled Lithium Lead, SCLL [5]. Here, the SCLL blanket is assumed to be composed of structural material with SiC/SiC, tritium breeder with LiPb without neutron multiplier. The decay heat density of SCLL blanket for 3.0 GW fusion power is shown in Fig. 10.

The decay heat density of W coating and SiC/SiC in FW was estimated to be 1.3 MW/m^3 and 2.7 MW/m^3 for SCLL blanket, respectively, immediately after shutdown of operation. The decay heat of W decreases to 10 %, immediately after shutdown. Moreover, the F82H of WCSB (Water Cooled Solid Breeder) blanket and SiC/SiC of SCLL almost is equal within 1 minute. Because of the dominant nuclides determining the decay heat was ^{28}Al which originate from ^{28}Si in SiC/SiC. An hour after shutdown, the decay heat for FW decreases to 1 %.

5. Summary

Estimation for decay heat after shutdown is important for safety assessment and maintenance. In this sense, nuclear characteristics of the blanket and divertor need to be understood to define criteria or the maintenance. A neutronic calculation was carried out for a fusion DEMO reactor SlimCS. In the 1D calculation of the neutronic for the blanket and divertor, a THIDA-2 code with the nuclear data library FENDL-2.0 was used. For the reactor with the fusion power of 3.0 GW, The total decay heat was as high as 52 MW immediately after the shutdown and 3.1 MW one month later. It was found that the decay heat of blanket accounted for nearly 76 % of total decay heat. The reducing the fusion power or the neutron wall load is effective in decreasing the decay heat. It was found that the decay heat was proportional to neutron wall load. Moreover blanket concept needs to be adopted to show low decay heat. For example, the blanket concept was selected to a SiC/SiC-based blanket concept. As a result, the decay heat of W decreases to 10 %, immediately after shutdown. An hour after shutdown, the decay heat for FW decreases to 1 %.

In the future work, safety assessment is performed on the decay heat. The estimation of LOCA/LOFA accident is important for the safety. Considering these points, the blanket assumed that several ribs were located in the blanket module. Therefore, the analysis of the accident needs to be done in near future and reconfirm the effectiveness. Moreover, the safety oriented blanket designs with advanced materials will be studied.

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