Activity and Decay Heat Estimates for the European DEMO Divertor with Respect to WCLL and HCPB Breeder Blanket Module Integration

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Introduction

Divertor in nuclear fusion reactor is a multi-purpose inner vacuum vessel structure designed mainly for heat and helium ash extraction. The structure is subject to high thermal loads caused by energetic particle interactions during device operation. Heating in nuclear fusion reactor is primarily caused by immediate collisions resulting in kinetic energy transfer. In addition to that, fraction of heating is caused by decay processes in activated material. Decay heat component tend to increase as device operation continues. Accordingly, decay heat estimation is required in order to evaluate divertor performance, more so activated material is considered to be a hazardous waste.

Main Objective of This Work

Work presented was carried out under EUROfusion/Power Plant Physics and Technology (PPPT) Safety and Environment (SAE) project. Its goal is to provide estimates for activities and decay heats for European DEMO device. MCNP neutron transport and FISPACT inventory calculation codes were used for the activation calculations of Divertor cassette. Divertor cassette calculations were performed with three different sets of breeder blanket models that include: Water Cooled Lithium Lead Multi-module Segment (WCLL MMS), Water Cooled Lithium Lead Single-module Segment (WCLL SMS), and Helium Cooled Pebble Bed (HCPB). Calculations and analyses were performed in compliance with PPPT guidelines for neutronics.

Methodology and Model Descriptions

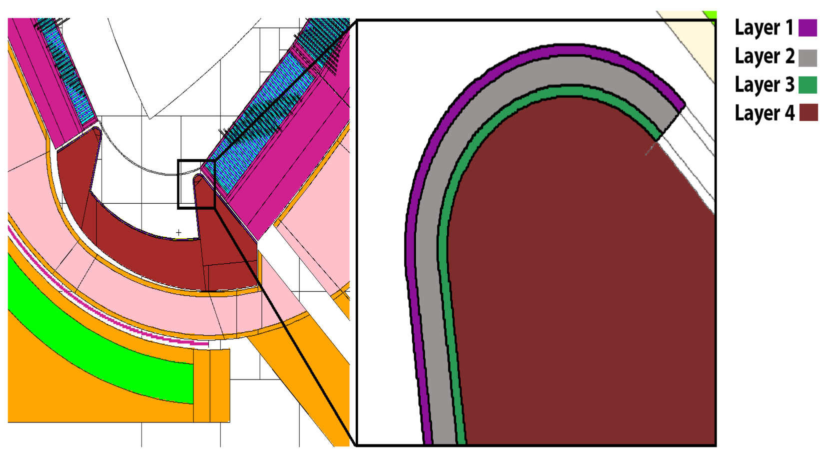

Fig 1. MCNP model of European DEMO Divertor with HCPB breeder blanket.

European DEMO1 2015 baseline model for MCNP was used as a basis for calculations. The model represents 10^0 slice segment of whole reactor. Neutron source description was generated by CEA TRANSGEN toolkit. For further calculations three different breeder blanket modules were integrated to the baseline model:

- **Helium Cooled Pebble Bed (2016/2MK7GG);**
- **Water Cooled Lithium Lead Single-module Segment (2017/2L4EL8);**
- **Water Cooled Lithium Lead Multi-module Segment (2015/2MKXCC).**

SMS model for WCLL is less homogenized compared to MMS. Whole blanket is divided into layers as opposed to functional segments in MMS.

Water cooled Divertor was the main focus of this neutronic analysis. Divertor cassette was divided into 62 segments and four different layers (Tab. 1 for volumes). First layer represent plasma facing components and consists of tungsten (Fig. 2) (density 19.23 g/cc). Second is pipe layer and it is made of CuCrZ, copper alloy, water and tungsten composites (Fig. 3) (density 8.53 g/cc). Third layer is tungsten inner shell structure with different density - 11.55 g/cc. Last layer (Fig. 4) represents cassette body made of EUROFER 97-3 reduced activation steel (54 %) and water (46 %) with aggregate density equal to 2.73 g/cc.

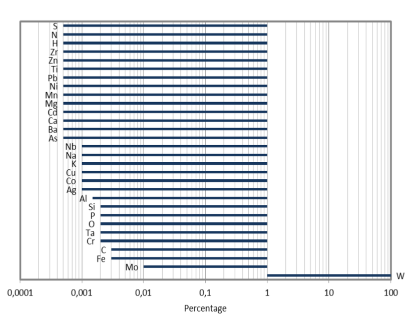

Fig 2. Material composition of plasma facing components and inner shell structures.

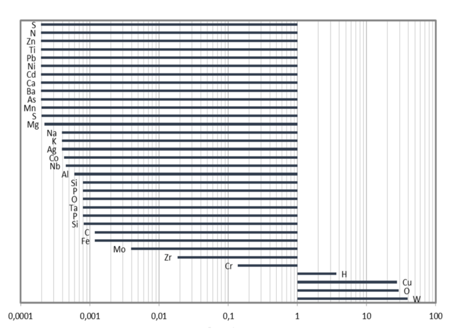

Fig 3. Material composition of pipe layer.

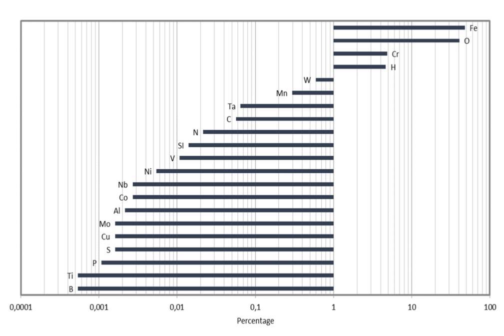

Fig 4. Material composition of cassette body.

Table 1. Volumes of divertor cassette layers.

	Layer 1	Layer 2	Layer 3	Layer 4
Volume, cc	2.40E+04	7.41E+04	2.38E+04	2.24E+06

Neutron flux densities were calculated with help of MCNP 5 equipped with JEFF-3.1.2 nuclear data library. Activation calculations were performed by means of FISPACT-II using TENDL-2015 nuclear data library. For each divertor segment Neutron flux distribution in 175 energy groups was obtained by performing Monte Carlo transport calculations with statistical error lesser than 10% and 10^9 generated particles histories

5.2 years long DEMO operation cycle is considered due to necessity to replace divertor cassettes. Simulated irradiation scenario consists of two sequences: continuous operation lasting for 1888 days at 30% of the nominal fusion power followed by 10 days pulse mode (48 pulses with 4 hours at full power and 1 hour dwell time in between). Such sequence corresponds to actual predicted operation of device and provides more accurate estimates for short half-life radionuclide production.

The decay times considered for the calculation of the activity inventories and the decay heat are: 0 s, 1 s, 5 min, 30 min, 1 hr, 3 hr, 5 hr, 10 hr, 1 day, 3 days, 1 week, 2 weeks, 4 weeks, 6 months, 1 year, 10 years, 50 years, 100 years, 300y and 1000 years.

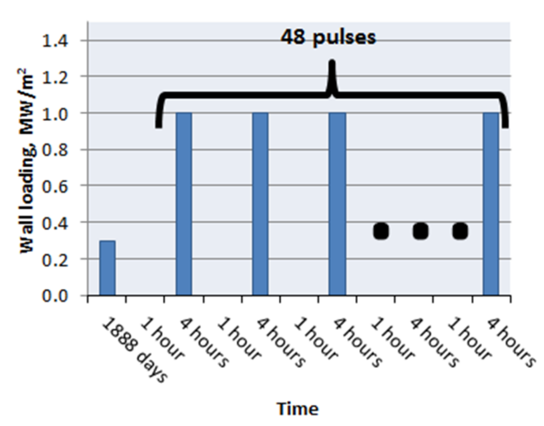

Fig 5. Irradiation sequence.

Calculation Results and Analyses

In terms of total activity, difference between HCPB and both WCLL model configurations vary from around 20% within first day after the end of irradiation, around 10 percent within first year of irradiation and within 5 percent for the rest of investigated time. In all instances divertor with HCPB exhibit lower activity compared to WCLL modules. There is also a slight difference between WCLL MMS and SMS configurations. Within first 3 days after the end of irradiation the difference is insignificant between two and fits within 2 percent, but after one week the divertor with MMS configuration has ~ 5 percent higher activity compared to SMS.

As for decay heat (fig. 6) the differences between blanket configurations are even more pronounced. HCPB at the end of irradiation has more than two times lower decay heat values than MMS and SMS. Differences between MMS and SMS range within 10 %. Divertor with SMS has higher decay heat within first week after irradiation while MMS has higher decay heat values after first week. Such discrepancy might be caused by different neutron energy spectra profile.

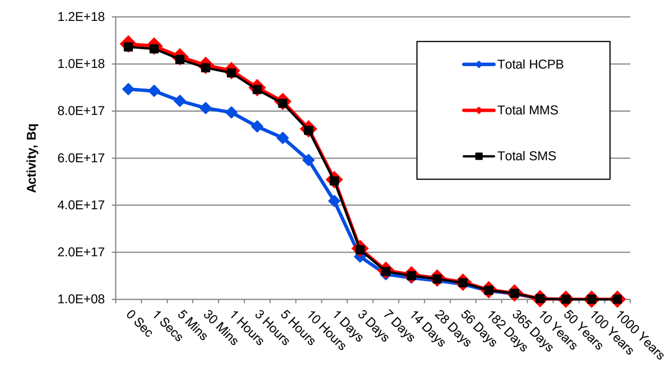

Fig 6. Total decay heat for divertor with different breeder blanket modules.

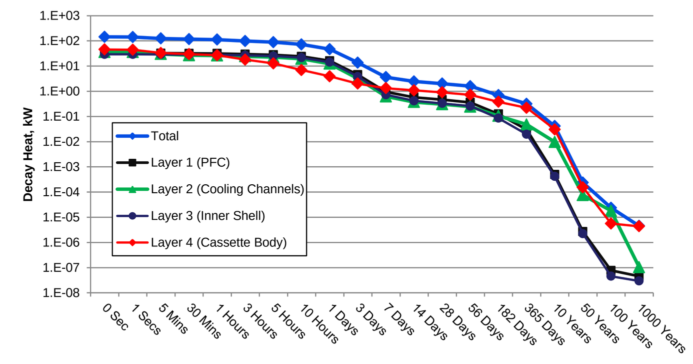

Fig 7. Total activities for divertor with WCLL SMS. Layer breakdown.

Largest amount of activity is produced in tungsten based materials. Plasma facing component (layer 1) and inner shell structure (layer 3) has highest activity (Fig. 7) and decay heat within first few days at the end of irradiation. Cassette body (layer 4) is responsible for majority of total activity after few days of cooling. Beyond that piping (layer 3) remains most active till the end of investigated time largely due to Co-60 and Ni-63 radionuclides.

Layers 1 and 3 are made of tungsten. The most dominant radionuclide in terms of specific activity within first 3 days after the end of irradiation is W-187 is solely produced from W-186 (n, g) reaction. The other relevant radionuclides for mentioned time period are W-185, Re-188, Re-186. Their values remain close to each other and there is a slight variation in hierarchy between the layers and layer segments. W-185 is being produced from multiple decay schemes. ~80 % of it comes from W-184 (n, g), ~ 10 % from W-186 (n, 2n) reactions, rest are produced from more complex decay schemes and recurring activation e.g. W-183 (n, g) -> W-184 (n, g). Re-186 comes mostly from W-185 decay schemes: W-185 b- decays into Re-185 and Re-185 is activated (n, g) into Re-186. Likewise Re-188 is a product of W-187 b- decay and subsequent Re-187 (n, g) reaction. W-187 is replaced by W-185 as the most dominant radionuclide and remains so for about 1 year of cooling period. After one year total activity steeply decline and other radionuclides start to dominate. As for decay heat radionuclides the trends are very similar, with few exceptions. For example Re-188 decay specific heat output is marginally larger in comparison to W-185 and Re-186.

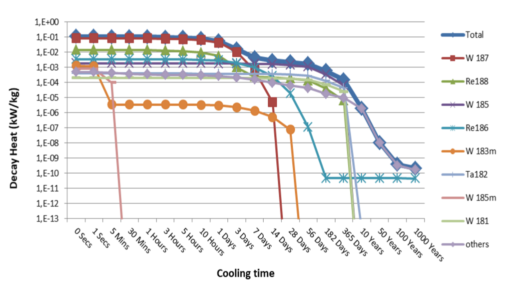

Fig 8. Specific decay heat. Layer 1 radionuclide breakdown.

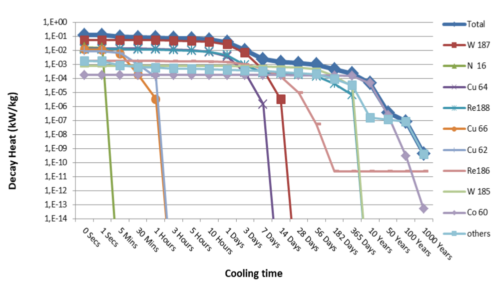

Fig 9. Specific decay heat. Layer 2 radionuclide breakdown.

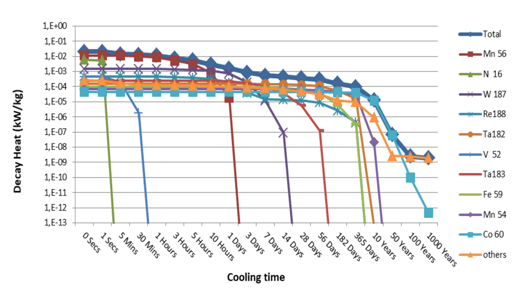

Fig 10. Specific decay heat. Layer 3 radionuclide breakdown.

Layer 2 is made of CuCrZr, Water, Tungsten and Copper. The key radionuclides within 3 days after the end of irradiation in terms of specific activity are W-187, Cu 64, W-185, Re-188, while W-185, W-181 stays relevant for whole year. More so Ni-63 stays relevant for whole investigated period and contributes majorly to specific activity from 10 years to 1000 years. Tungsten radionuclide production was described in previous paragraph. Cu 64 can be either produced from Cu-63 (n, g) (~93%), or Cu-65 (n, 2n) (~7%). ~87% of Ni-63 is produced from Cu-63 (n, p) reaction while the rest come from complex decay schemes and recurring activation. As for decay heat, N-16 emerges from O-16(n, p) water fraction and stays relevant for few minutes. Decay heat from Ni-63 is not relevant and rest of the trends follows the specific activity in terms of radionuclide constituents.

Layer 4 is made of EUROFER steel and water. The key contributors for specific activity are Mn-56, Fe-55, Cr-51, W-187 and N-16. Mn-56 is the most relevant for the first day after the end of irradiation, Cr-51 is significant contributor for few months and Fe-55 stays relevant and a major radionuclide for up to 10 years after the end of irradiation. ~72% of Mn-56 is produced from Mn-55(n,g) reaction, while 13 % from Fe-56 (n, p),rest comes from complex decay schemes. Cr-51 comes from Cr-50 (n, g) reaction (~95 %), Cr-52 (n, 2n) (~5 %) and Fe 54 (n, a) (1%). Fe-55 comes from Fe 54 (n, g) (~75%) and Fe 56 (n, 2n) (~25 %). As for specific decay heat tungsten impurities play marginally larger role as well as N-16 covered in previous paragraph. However 4th period metals are still constitute the most to activation characteristics in all time periods of cooling. Besides the formerly mentioned radionuclides V-52 has slight impact in decay heat for first few days after the end of irradiation while Co-60 dominates periods from 1 year to 50 year.

European DEMO Divertor with three different blanket module configurations (HCPB, WCLL MMS/SMS) was examined and following findings were made:

- **Plasma facing components, cooling channels and inner shell structure in divertor cassette exhibit highest activities and decay heats within few days after the end of irradiation..**
- **In piping layer, Ni-63 and Co-60 are major contributors after 10 years of cooling and further. N-63 mainly produced from Cu-63 (n,p) reaction.**
- **Mn-56 and Fe-55 are the key activity contributors in divertor cassette body.**
- **Total HCPB activity of divertor cassette is ~1.1-1.15 times lower compared to WCLL MMS and WCLL SMS. Differences between WCLL MMS and WCLL SMS range within few percent.**

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