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Activation analysis for the European HCPB blanket module in DEMO

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Abstract

The activity and decay heat inventories were assessed for the HCPB DEMO blankets making use of a code system that enables performing 3D activation calculations by linking the Monte Carlo transport code MCNP and the fusion inventory code FISPACT through an appropriate interface. The dedicated full scale geometry MCNP model of a 10 degree HCPB DEMO torus was adapted to the requirements for the coupled 3D neutron transport and activation calculations. The sensitivity analyses were performed to assess the effect of the homogenized geometry cells to the final results. The importance of the use of the impurities in the material definitions was pointed out and accounted for in the simulations. The activity of the HCPB blanket modules is dominated by the tungsten protecting layer up to one month after shutdown. After that it's dominated by the breeding zone mixture of Eurofer, breeder ceramic and beryllium pebbles with impurities. The decay heat generation in blankets is especially high in the casing that requires intensive cooling efforts for their treatment after the shutdown. The accumulation of the poisoning ^{239}Pu could make complicated the recycling of the beryllium pebbles extracted from the blankets.

Keywords

HCPB, DEMO, Activation, Decay Heat

1 Introduction

The Demonstration Fusion Power Reactor (DEMO) is a key step following the International Thermonuclear Experimental Reactor (ITER) towards the future commercial fusion power station [1]. Several design concepts, such as the Helium Cooled Pebble Bed (HCPB), Helium Cooled Lithium-Lead (HCLL), Water Cooled Lithium-Lead (WCLL) and the Dual Coolant Lithium-Lead (DCLL) are the near-term options for a breeding blanket in the considered DEMO [2].

The analyses of a neutron-induced activation of HCPB DEMO materials can provide detailed information required for an assessment of the safety issues related to the DEMO fusion technology. The objective of the present work was to provide detailed activation and decay heat data required for quality assured safety analyses of the HCPB DEMO. In the following, the computational approach used for coupled 3D neutronics calculations is presented and the results of the activation calculations for the HCPB DEMO blankets are given and discussed.

2 HCPB DEMO Neutronics Model

The HCPB DEMO blanket is based on a solid breeder and neutron multiplier technology with inert helium gas used as a coolant and purge gas [3]. The current HCPB concept assumes a module segmentation scheme suitable for a flexible installation, maintenance and disassembling of the plasma in-vessel components by means of remote access tools. For the arrangement in a blanket space around the plasma two HCPB DEMO blankets were developed for an inboard (IB) and an outboard (OB) sides.

Shown in Fig.1 is the CAD model of the HCPB blanket model version v.1.2 [3]. The blanket box is built by a 25 mm thick U-shaped first wall (FW), 25 mm caps and a 30 mm thick back wall, the FW is being covered with a 2 mm W protecting layer. The total radial thickness of the breeder zone from the FW up to back plate is 45 and 82 cm in the inboard and outboard sides, respectively. The thickness of the back supporting structure with feeding pipes (BSS) is 43 and 23 cm in the inboard and outboard sides, respectively. The breeder zone (BZ) is stiffened with parallel horizontal cooling plates of 5 mm thick. The Li_4SiO_4 breeder ceramic pebbles with 0.63 package factor are arranged between two cooling plates forming an 11 mm thick breeder bed. The neighbouring breeder beds are separated with 33 mm thick Be pebbles layer (the package factor is 0.64). Such a structure is repeated to fill the internal blanket space. All structural elements of the blanket are assumed to be manufactured with Eurofer [4] steel. The module is assumed to be maintained with a He cooling flow of ~80 bar pressure.

The principal parameters of the DEMO reactor are presented in the Table 1 [5]. The CAD geometry model of the HCPB DEMO represents a 10 degree toroidal sector extracted from full DEMO model assuming its symmetry. This sector represents a half of the 18 times repeated toroidal DEMO segments. Empty HCPB blanket casings with BSS were arranged in the breeder blanket space of the DEMO CAD model assuming gaps around the modules as follows: 10 mm in poloidal and 20 mm in toroidal directions. Finally 7 full inboard modules, 7 full and 7 half outboard modules were arranged around the plasma.

Table 1 Main parameters of the DEMO reactor.

Major radius, (m)	*9.072*
Minor radius, (m)	2.927
Plasma elongation	1.59
Plasma triangularity	0.333
Fusion power, (MW)	2037
Net electric power, (MW)	500

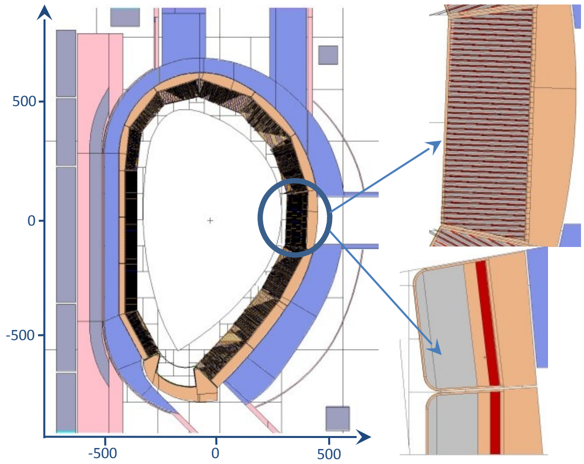

Fig.1. MCNP model of HCPB DEMO with detailed blanket structures

The CAD model of the HCPB DEMO with empty blanket boxes was converted into the MCNP geometry model using the McCad conversion tool [6]. The final MCNP geometry model was developed making use of the MCNP internal tools. The fine heterogeneous structure of one HCPB blanket module was developed using an inbuilt repeated structure option of the MCNP. Once the geometry model of the breeder zone for one separate blanket module was finished all other blankets were filled with the same structure applying proper transformation cards. Shown in Fig.1 is the MCNP geometry model of the HCPB DEMO with detailed blanket structures.

3 Methodological approach

3.1 Coupling of neutronics and inventory calculations

The activation and decay heat simulations in the HCPB DEMO are performed in two steps:

- A particle transport simulation to assess the neutron spectra in the different locations
- Inventory calculations based on the neutron spectra mapped over the geometry and irradiation scenario to quantify the generation of the radioactive nuclides in different materials.

The step 1 in this procedure requires neutron spectra in all geometry cells where then the activation analyses will be performed. To this end the set of the geometry cells of interest must be specified in the MCNP input file to tally the neutron spectra. Special attention should be paid to an accuracy of the nuclear responses. This can be achieved by applying of the proper variance reduction technique.

To facilitate the activation analyses an interface code developed by KIT was applied for numerous activation calculations. This computer interface is based on MCNP5 code for particle transport simulations and FISPACT code [7] for activation inventory analysis of the irradiated materials. FISPACT code makes use of EAF library and in the present version it is EAF-2007 [8]. The inventory results of the FISPACT outputs are collected by a versatile post-processing code.

3.2 Materials specifications

The blankets of the HCPB DEMO employs the Eurofer RAFM steel [4] as structural material, Li_4SiO_4 pebbles (60 at % Li-6 enrichment) as breeder material and beryllium pebbles as neutron multiplier. The activation behaviour of these materials is affected to a large extent by impurities and other minor elements. For the activation and decay heat calculations, it is therefore important to take proper account of impurities and minor constituents of the materials considered. The elemental composition of Eurofer, Beryllium, Li_4SiO_4 and tungsten are listed in the Table 2 [9-11]. The impurity elements such as Mn, Cr, Co, Ag, etc. in these materials may have severe impact on the activity. It is essential that Be contains about 0.01% Uranium that may have a risk for an environment and for a waste management.

Based on the detailed engineering CAD model of the HCPB blanket module discussed above a homogeneous mixture representing the breeder zone of the blanket was derived: 11.76 vol.% Eurofer, 13.04 vol.% breeder ceramic, 37.9 vol.% beryllium and the rest is the helium coolant. The helium volume fractions in the different blanket components like FW or BSS were included in the MCNP geometry model and accounted for in the activation calculations.

Table 2 Material specification of Eurofer, breeder ceramic, Beryllium and Tungsten (Unit: wt%).

Eurofer		Lithium		Beryllium		Tungsten	
Fe	89.0026	**Li**	22.415	**Be**	98.749	**W**	99.9595
B	0.001	**Si**	24.077	**O**	0.9	**Ag**	0.001
C	0.1049	**O**	53.39	**Al**	0.09	**Al**	0.0015
N	0.04	**Al**	0.003	**Fe**	0.1	**As**	0.0005
O	0.001	**C**	0.1	**Mg**	0.08	**Ba**	0.0005
Al	0.004	**Ca**	0.003	**Si**	0.06	**Ca**	0.0005
Si	0.026	**Co**	0.0002	**Mn**	0.01	**Cd**	0.0005
P	0.002	**Cr**	0.0001	**U**	0.01	**Co**	0.001

S	0.003	**Cu**	0.0001	**Co**	0.001	**Cr**	0.002
Ti	0.001	**Fe**	0.0005			**Cu**	0.001
V	0.01963	**K**	0.0001			**Fe**	0.003
Cr	9.00	**Mg**	0.0005			**K**	0.001
Mn	0.55	**Mn**	0.0001			**Mg**	0.0005
Co	0.005	**Pt**	0.009			**Mn**	0.0005
Ni	0.01	**Na**	0.002			**Na**	0.001
Cu	0.003	**Ni**	0.0002			**Nb**	0.001
Nb	0.005	**Ti**	0.0005			**Ni**	0.0005
Mo	0.003	**Zn**	0.0002			**Pb**	0.0005
Ta	0.12	**Zr**	0.0001			**Ta**	0.002
W	1.0987					**Balance**	0.022

3.3 Neutron transport simulations

The neutron transport calculations were carried out making use of the geometry model discussed above and the MCNP5-1.60 code [12] with nuclear data from the FENDL-2.1 library [13]. The toroidal fusion neutron plasma source was simulated making use of the specially developed source subroutine [14] linked to the MCNP executable. The results for neutron spectra were obtained with a standard VITAMIN-J 175-grouped structure.

In the present study only the activation of the breeder blanket modules were analysed. Therefore the tallying of the neutron spectra was performed in different geometry cells that belong to the blanket structure including BSS. The statistical uncertainty in all calculations of the total neutron flux does not exceed 1%. For some low energy bins, for instance, $1\cdot10^{-7} \sim 1\cdot10^{-4}$ MeV, the relative error was found to be as high as ~10%. Normalization of the nuclear responses was done to the DEMO fusion nuclear power of 2037 MW (Table 1) that results in $7.24\cdot10^{20}$ s^{-1} neutron source intensity.

3.4 Activation calculation

For the activation calculations a following irradiation scenario is assumed: during the first 5.2 years minus 10 days the DEMO is supposed to operate at an average level of 30% total fusion power, in the last 10 days 48 pulses of 4-hours at 100% fusion power and 1-hour dwell time are considered, shown in Fig. 2. The cooling time steps adopted in the FISPACT calculations are 1 second, 1 hour, 1 day, 1 week, 1 month, 1 year, 10 years, 100 years and 1000 years after the shutdown.

The computer interface used in the activation analyses uses a MCNP5 input file for neutron transport calculations as a main repository to get full information on materials used in the calculations. The interface assures proper preparation and execution of the big amount of FISPACT calculations according to the geometry cells numbers specified in the MCNP neutron transport calculations. For the numerous activation calculations the interface prepares automatically the FISPACT input files for each geometry cell using the proper fine material composition and the irradiation scenario. It submits then automatically the batch jobs for each geometry cell for the execution.

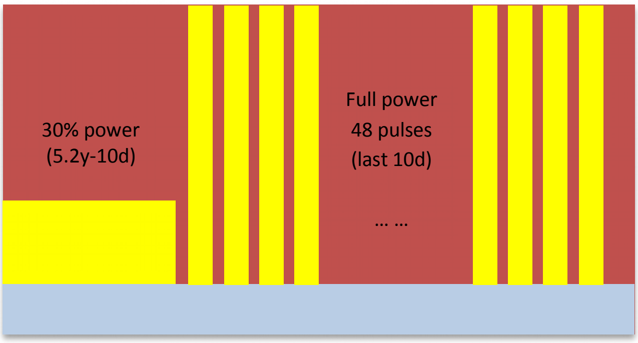

Fig. 2. Irradiation scenario for HCPB DEMO during operation.

3.5 Effect of the material impurities to the activity of the blankets

To assess the effect of the material impurities to the blanket activity the activation analyses have been performed by replacing of commercial beryllium, lithium ceramic and tungsten (Table 2) with pure elemental compositions without any minor impurities. For this case the one central inboard blanket module was considered. The BZ was filled with the homogeneous structure representing HCPB breeder zone mixture. The comparison of the results for these two options is shown in Fig. 3. The impurities apparently have a significant effect in the activity. The radioactive isotopes ^{239}Np ($T_{1/2}$=2.36d), ^{237}Pu ($T_{1/2}$=45.25d) coming from the uranium impurity as well as ^{54}Mn ($T_{1/2}$=312.05d), ^{55}Fe ($T_{1/2}$=2.73y) dominate the activity in beryllium, shown in Fig. 4. ^{31}Si ($T_{1/2}$=2.62h), ^{193}Pt ($T_{1/2}$=50.7y), ^{195m}Pt ($T_{1/2}$=96.47h), ^{60}Co ($T_{1/2}$=5.27y) dominate the activity in breeder ceramic, shown in Fig. 5. The specific activity of the pure tungsten 10 years later after the shutdown is much lower compared to the commercial tungsten mainly due to the radioactive nuclides ^{179}Ta ($T_{1/2}$=1.82y), ^{106m}Ag ($T_{1/2}$=8.28d), ^{108m}Ag ($T_{1/2}$=418y), shown in Fig. 6. The inclusion of the impurities in the material specification for the neutron transport calculations does not affect the results for the neutron fluxes and spectra. The comparison done for the activity calculations using commercial and pure materials shows the importance of the impurities that supports the significant increase of the final results.

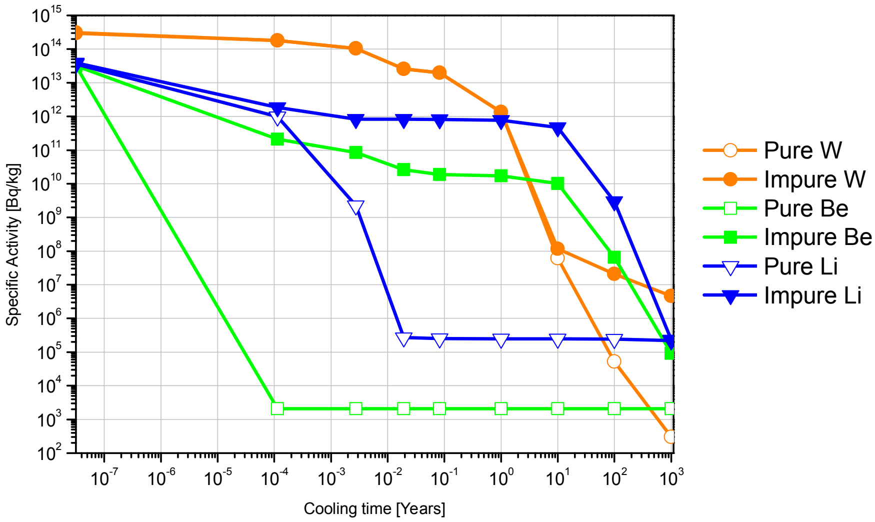

Fig. 3. Impurity effects of Beryllium, Lithium and Tungsten.

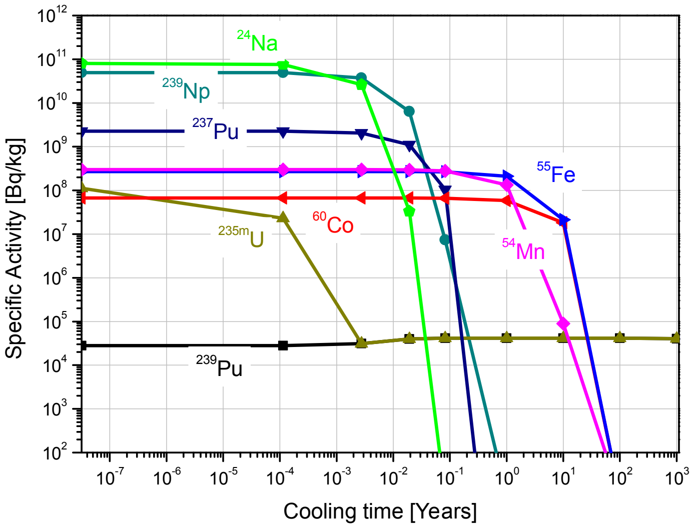

Fig. 4. Specific activity of dominant nuclides in Beryllium.

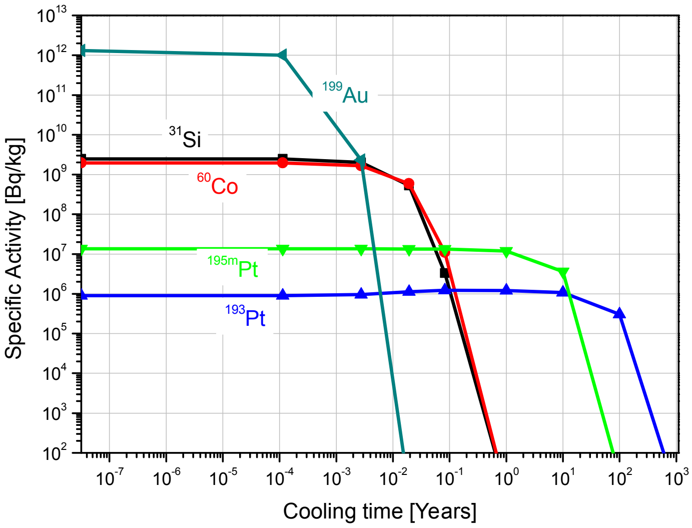

Fig. 5. Specific activity of dominant nuclides in Lithium ceramic.

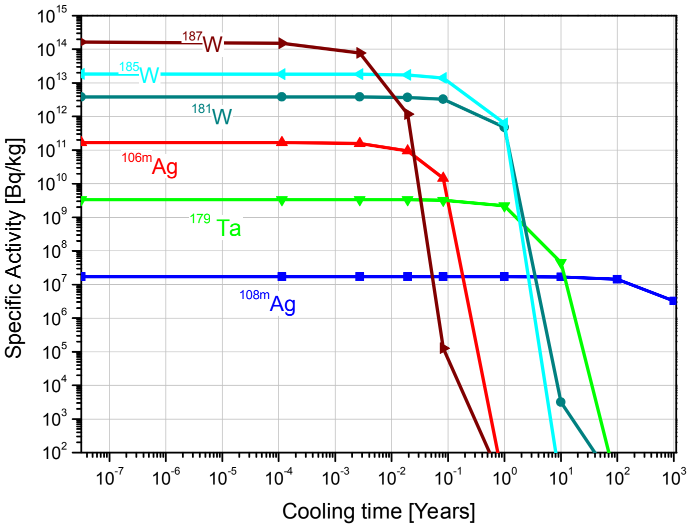

Fig. 6. Specific activity of dominant nuclides in FW Tungsten.

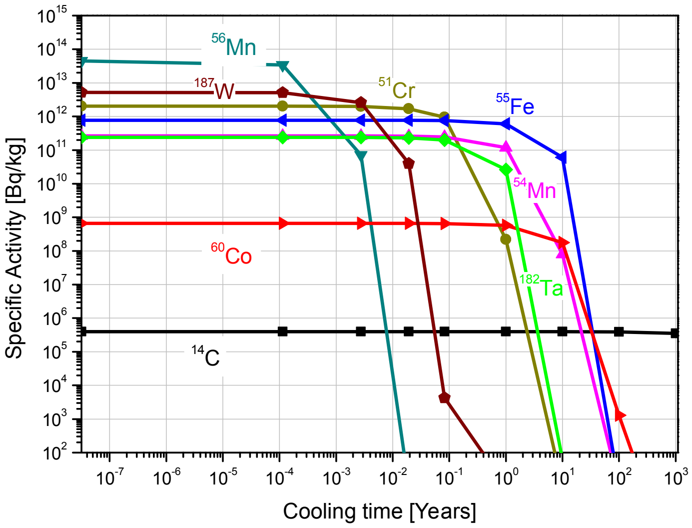

Fig. 7. Specific activity of dominant nuclides in Eurofer steel.

4 Inventory calculations

4.1 Sensitivity analyses

The results of the activation simulations depend to high extent from the size of the irradiated geometry cell. Due to the attenuation of the neutron flux the averaging of the results over the cell volume could result in overestimations of the responses. To analyse this effect the activation calculations were performed in one central IB blanket of the HCPB DEMO. To this end three options of the blanket breeder zone were investigated: original design with the sandwich-like fully heterogeneous structure, a fully homogeneous breeder zone with the material composition discussed above and the radially segmented homogeneous breeder zone, shown in Fig. 8.

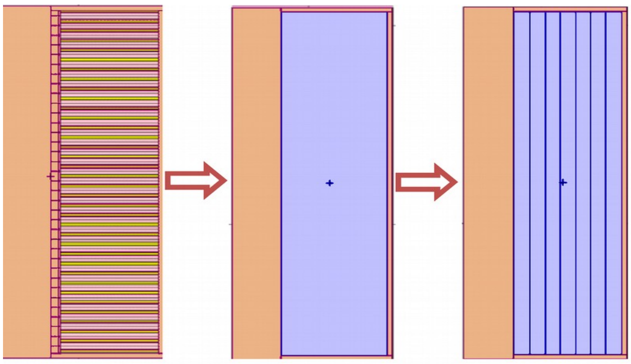

Figure 1 HCPB detail neutronics model, the simplified structure and incised cell.

Fig. 8. Different geometry options applied for activation calculations

The neutron transport and following inventory calculations were performed both with the detailed and simplified models. Shown in Fig. 9 is the activity of the constituent breeder zone materials as they calculated for the case with the original detailed and homogeneous BZs. The slight differences were found for Be and Eurofer for the cooling times up to 30 days, they do not exceed ~15%. The activity of the Li in detailed and homogeneous model has good agreement for all cooling times.

Additional study was done to find the effect of the use of the radially segmented homogeneous BZ instead of one big cell. The devoted coupled neutron transport and activation analyses were performed in such breeder zone, see Fig. 8. In this option the BZ was segmented with the parallel vertical planes keeping the 6 cm radial distance between them. In the poloidal direction no segmentation was applied because the change of the neutron flux within the height of the blanket is small. Respectively, the full activation analyses including neutron transport simulations, was performed for each layer in BZ separately. The Table 3 results show that the total activity of the segmented BZ is almost the same compared to the fully homogeneous BZ, the differences not exceeding ~0.3%. The total activity of the BZ for the detailed geometry and for the BZ with homogeneous mixture differs not more than ~4%, Table 3. These results enable to make a conclusion that the use of the homogeneous instead of the heterogeneous BZ of the HCPB blanket leads to the very close results for the activity. Such approach can be used with the reasonable fidelity for the activity assessment in the HCPB DEMO.

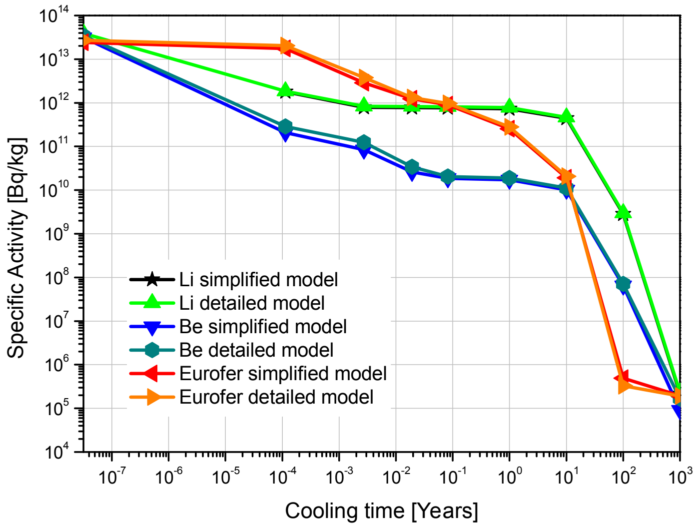

Fig. 9. The activity of the different constituent materials for the detailed and the homogeneous BZ.

Table 3 Total activity (Bq) for different breeder zone options.

Cooling time	Detailed model	Simplified model	Simplified model with radial segmentation
1.0 Secs	4.76E+16	4.70E+16	4.71E+16
1.0 Hours	1.44E+16	1.40E+16	1.40E+16
1.0 Days	2.31E+15	2.27E+15	2.27E+15
7.0 Days	1.12E+15	1.15E+15	1.15E+15
30.0 Days	8.65E+14	8.95E+14	8.97E+14
365.0 Days	3.89E+14	4.07E+14	4.08E+14
10.0 Years	1.35E+14	1.40E+14	1.40E+14
50.0 Years	1.28E+13	1.32E+13	1.32E+13
100.0 Years	7.71E+11	7.93E+11	7.95E+11

4.2 Results for the HCPB DEMO

4.2.1 Total activity of the HCPB blankets

The activation calculations for the HCPB DEMO breeder blanket modules including BSS were performed assuming the homogeneous breeder zone in all modules using the material compositions specified in Table 2. The results were obtained for the total activity and decay heat of all modules as well as the results for different constituent materials. In all simulations the HCPB BZ mixture was considered as a separate artificial material. The total masses of the different pure constituent materials of the HCPB blankets are listed in the Table 4. The data refers to the whole HCPB DEMO reactor. The total mass of the breeder zone was found to be $2.1 \cdot 10^3$ tons. The mass of the back supporting structure is as heavy as $3.1 \cdot 10^3$ tons.

Table 4 Total mass of HCPB modules in whole reactor.

Materials	Mass [t]
First Wall Tungsten	6.64E+01
First Wall front Eurofer	2.82E+02
Caps and lateral walls	2.94E+02
Breeding zone mixture	2.10E+03
Back supporting structure	3.10E+03
Total	5.84E+03

Shown in Fig. 10 is the total activity (Bq) of the different components of the HCPB blankets including the total activity in entire reactor. The total activity of the HCPB blankets one second after the DEMO shut down is 8.04E+19 Bq. At this moment the activity in FW Tungsten contributes 26.6% to the total activity. FW front Eurofer, caps and lateral walls, breeding zone mixture and back supporting structure contribute 18.4%, 5.47%, 47.1%, 2.45% respectively. At shutdown, the Eurofer steel dominates total activity due to the radionuclides ^{56}Mn ($T_{1/2}$=2.58h), ^{187}W ($T_{1/2}$=23.85h), ^{51}Cr ($T_{1/2}$=665h), ^{55}Fe ($T_{1/2}$=2.73y), Fig. 7. From one hour to one month after shutdown, the nuclides in Tungsten ^{187}W ($T_{1/2}$=23.85h), ^{185}W ($T_{1/2}$=75.1d), ^{181}W ($T_{1/2}$=120.95h) will dominate the total activity. The activity of nuclides ^{55}Fe and ^{54}Mn ($T_{1/2}$=312.05d) in Eurofer are dominant for the cooling time longer than 1 year. For the cooling time longer than 100 years the ^{108m}Ag ($T_{1/2}$=418y) accumulated due to Ag impurity in tungsten dominants the total activity.

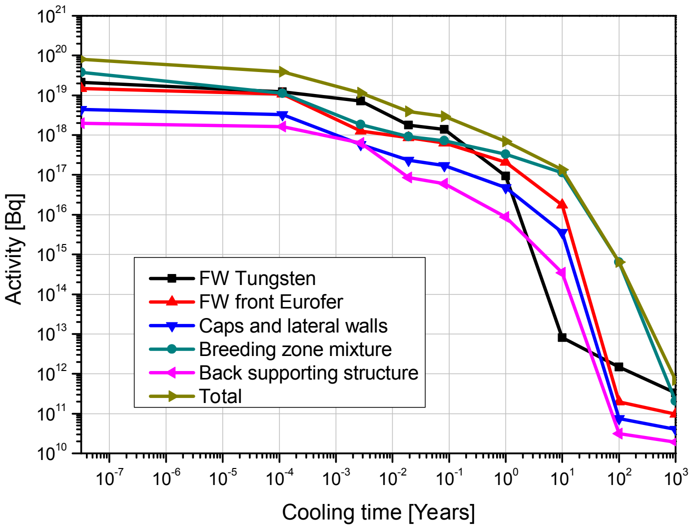

Fig. 10. Total activity of the different components of the HCPB blankets.

4.2.2 Balance of ^{235}U and ^{239}Pu

Due to the uranium impurity, Table 2, the irradiated beryllium of the HCPB blankets should be monitored for potential problems for its maintenance, storage and an effect to the environment. The presence of the long-lived isotopes ^{235}U ($T_{1/2}=7.04{\cdot}10^{8}$ y) and ^{239}Pu ($T_{1/2}=2.41{\cdot}10^{4}$ y) accumulated during the irradiation in the beryllium pebbles could result in additional difficulties with their recycling. In the original loading with fresh Be pebbles (~763 tons) the total mass of natural uranium is ~76 kg. At shut down, the mass of ^{235}U, which is burnt during irradiation, is about 550 g and the mass of ^{239}Pu , produced due to neutron absorption of ^{238}U and subsequent β-decays, is about 609 g. The ^{239}Pu content is considered as impurity since it is diluted over the large beryllium mass inventory.

4.3 Decay heat

The results for the decay heat in the blanket modules of the HCPB DEMO for different decay times are presented in the Table 5. For the present configuration the total nuclear power generated in all HCPB blankets during routine operation is 2031 MW [15]. The decay heat in all blankets right at the shutdown (0 sec) is ~26 MW. One day later, the total decay heat decreases to 1.03 MW.

Table 5 Decay heat density [MW/m3] in HCPB blanket modules in the HCPB DEMO reactor.

Time	0s	1 s	1 h	1 day	1 week	1 month	1 year	10 years	100 years	1000 years
Blanket casing										
W	5.33E-01	5.22E-01	3.75E-01	1.97E-01	1.30E-02	7.45E-03	4.33E-04	3.41E-07	1.04E-07	2.34E-08
FW	1.31E-01	1.31E-01	9.27E-02	1.68E-03	5.91E-04	4.90E-04	1.31E-04	7.39E-07	7.20E-11	4.08E-11
Caps	3.41E-02	3.41E-02	2.47E-02	1.16E-03	2.78E-04	2.26E-04	4.58E-05	3.13E-07	3.97E-11	2.40E-11
Lateral walls	1.29E-02	1.29E-02	9.41E-03	5.40E-04	1.26E-04	1.02E-04	1.93E-05	1.37E-07	1.88E-11	1.20E-11
Breeder zone										
	1.60E-02	1.29E-02	3.37E-03	1.39E-04	3.29E-05	2.67E-05	5.91E-06	3.86E-08	2.28E-11	2.12E-11
BSS										
	7.05E-04	7.05E-04	5.69E-04	1.32E-04	1.85E-05	1.43E-05	1.96E-06	1.57E-08	1.76E-12	1.52E-12
Total [MW]	2.64E+01	2.30E+01	1.01E+01	1.03E+00	1.28E-01	9.31E-02	1.64E-02	9.63E-05	3.88E-07	1.09E-07

The total decay heat generation in all components of the HCPB breeder blankets at 1 sec after the shutdown is presented in the Fig. 11. The decay heat density in different blanket components is shown in Fig. 12 for all 14 blankets. The blankets numbering starts on the lowest IB module then clockwise up to the lowest module in the OB side. The decay heat density is the highest for the W layer and it is the lowest for BSS. The specific decay heat differs for various blanket parts by several orders of magnitude. The specific decay heat in FW for different blankets varies by approximately factor 2. The same scale has the variation of the decay heat density in the homogeneous BZ mixture. The most loaded BSS was found to be in the central IB part of the reactor. In the OB side the BSS is much less loaded due to the big radial thickness of the outboard blankets that protects BSS from the intensive neutron irradiation. The same effect was found for the BZ mixture. Because the radial thickness of the IB blanket is much less compared to the one in the OB side and the BZ volume is greater here the specific decay heat is several time higher in the BZ of the IB blankets.

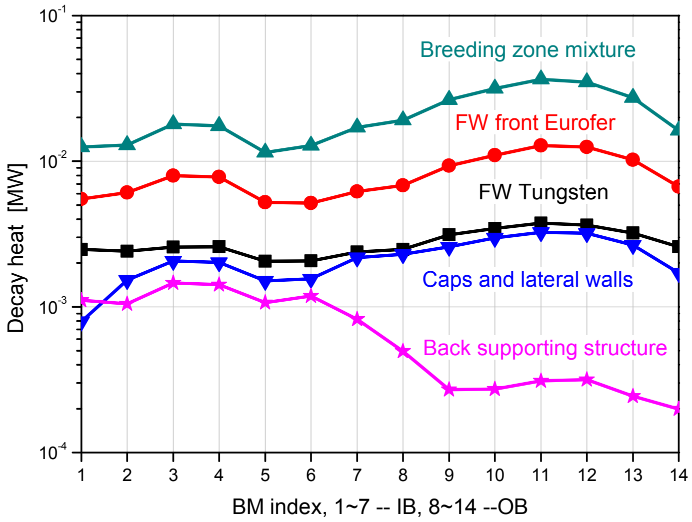

Fig. 11. Total decay heat in the different components of the HCPB modulse at 1 sec after shutdown.

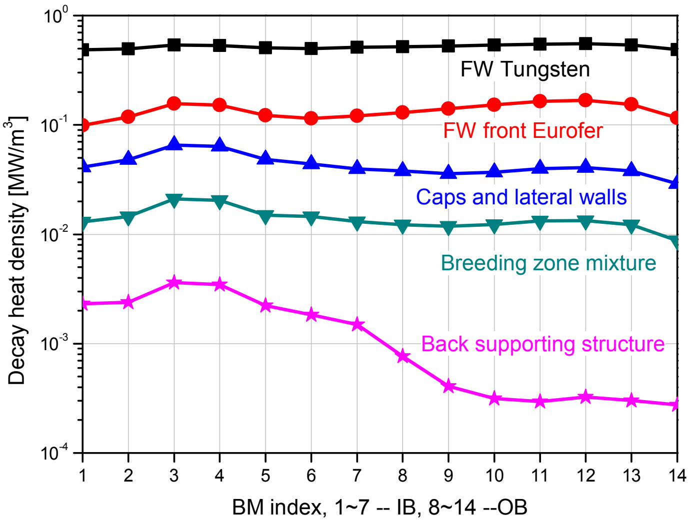

Fig. 12. The decay heat density in different blanket components of the HCPB modules at 1 sec after shutdown.

5 Conclusions

The activity and decay heat inventories were assessed for the HCPB DEMO blankets making use of a code system that enables performing 3D activation calculations by linking the Monte Carlo transport code MCNP and the fusion inventory code FISPACT through an appropriate interface. The dedicated full scale geometry MCNP model of a 10 degree HCPB DEMO torus was adapted to the requirements for the coupled 3D neutron transport and activation calculations. The analyses were done to assess the sensitivity of the results to the replacement of the real geometry with representative homogeneous material mixture. The corresponding effect was found to be not significant. The additional radial segmentation of the geometry cells does not result in the noticeable effect. Therefore the homogenized materials can be used in the DEMO activation calculations providing an acceptable accuracy of the final results. Special attention was paid to the use in the activation calculations of the commercial materials containing technological impurities. This has a severe effect on the results and the impurities must be accounted for in the calculations.

The activity and decay heat were assessed for the HCPB DEMO breeder blankets for several decay cooling times from 1 sec up to 1000 years. The method used enabled the calculations of the activity and decay heat for separate constituted parts of the HCPB blankets. The total activity of all blanket modules in the whole reactor was about 8.04E+19 Bq 1 second after the shutdown. The activity of the tungsten protecting layer dominates the total activity during 1 month after the irradiation and at the very long cooling time after 1000 years. For the cooling time from 1 month to 100 years the activity is dominated by BZs homogeneous mixture. The uranium impurity of 100 wppm in beryllium results in the generation of ~609 g ^{239}Pu in ~763 t beryllium. The generation of the decay heat in the HCPB blankets affects the design of the cooling system and recycling methods. After the shutdown the nuclear power generated in the blankets drops from 2031 MW (in routine operation) to 26 MW. The cooling system capacity required for the safe treatment of the blankets drops up to ~130 kW after 1 week cooling time. The most loaded parts of the HCPB blanket are the Eurofer casings (including W layers) that require serious attention to the cooling technology. The decay heat density in the BZ of the blankets is much less that makes easier its treatment.

Acknowledgments

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