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Supplementary neutronics analysis of DEMO WCLL including activity and decay heat

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This paper presents the analyses performed within the SAE (Safety and Environment) project of EUROfusion/PPPT aimed at providing up-to-date estimates of the activity inventories and the decay heat generation in the WCLL. Detailed evaluation of the WCLL PPPT reactor concept based on the generic Multi-Module-Segment (MMS) model was performed by calculating the decay heat and activity inventories for the central inboard and outboard modules separated into the segments in order to evaluate heterogeneity for the WCLL MMS reactor model. Following, the estimation of radial distribution of decay heat and activity in reactor geometry and in BB module material mixture. And finally, the preliminary approach to evaluate Li flow inside the breeder zone is presented in this paper. Additional calculations were performed to identify dominant nuclides after the irradiation

Keywords: DEMO, WCLL, neutronics, Monte Carlo, activity, decay heat

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1. Introduction

The WCLL (Water Cooled Lithium Lead) is an European breeder blanket (BB) design dedicated for DEMO fusion power reactor as being developed within the frame of EUROfusion's Power Plant Physics and Technology (PPPT) programme. The intense neutron radiation produced inside the reactor vessel will result in a strong activation of the breeder blanket structural elements. The activity and decay heat generation of the WCLL components are in need for assessment for the maintenance, decommissioning and waste management purposes and preceding safety analyses.

This paper presents the analyses performed within the SAE (Safety and Environment) project of EUROfusion/PPPT aimed at providing up-to-date estimates for the activity inventories and the decay heat generation in the WCLL module. A detailed investigation based on a set of coupled MCNP neutron transport and FISPACT inventory calculations was performed using the WCLL MMS (Multi-module Segment) model and the JEFF nuclear cross-section data library. Activity inventories and decay heat data were assessed for the different breeder blanket segments due to module heterogeneous structure.

This paper discuss the results obtained for the activity and the decay heat as a function of the decay time after irradiation and also addresses the issue of the radiation dose loads that have to be expected due to the activated components/systems.

2. WCLL MS model

Previous study was carried out using homogeneous structure of the BB [1]. In addition, separate study was performed with the rough segmentation of the breeding zone in order to estimate the radial distance impact for the total decay heat/activity in the breeder zone volume. In [1] neutronic studies were carried out based on the DEMO1 2015 configuration. Moreover, from engineering CAD files were extracted homogenized compounds with volume percentage of each materials and they represented integrated a WCLL breeding blanket [2].

Upgraded MCNP WCLL MMS geometry model for DEMO design was used in current studies, presenting comprehensive description of the breeding blanket in the Inboard and Outboard equatorial modules. In order to validate WCLL blanket and to improve its eligibility for neutronics calculations, studies were carried out which are presented in Ref [2], where contains information on integration of segmented Inboard and Outboard equatorial modules for the WCLL DEMO model, which is based on the generic Multi-Module-Segment (MMS) geometry representing a 10° sector of the actual machine. According to the design specifications [3] specific homogenized compounds have been defined to represent the former blanket modules (Table 1).

Eurofer steel box with first wall (FW), caps, back plate and a back supporting structure (BSS) with inlet/outline pipes for the water and the LiPb were included in the layout of the blanket module. The box is filled with the LiPb liquid metal and reinforced by horizontally and vertically arranged stiffening plates [2].

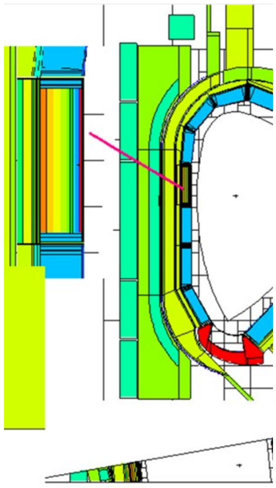

Figure 1. Overview of the WCLL MMS geometry model segmentation for DEMO [2]

The original CAD file was pre-processed and simplified by the means of 3D modelling software and detailed MCNP model of the WCLL Outboard #4 blanket module has been developed. Single breeding unit (BU) contain 21 cooling water pipes embedded in the LiPb breeder and they has been isolated. The single breeding unit has been recursively integrated filling the DEMO MCNP generic model Inboard and Outboard (full and halved) blanket modules #4 [2].

Previously mentioned design alteration of the BB modules was performed by ENEA taking the OB equatorial CAD module (WCLL DEMO 2015 homogeneous BB Model based on WCLL Blanket & manifold design) as a reference [2]. Subsequently 7 IB and 14 OB modules (7 of them integer and 7 half modules) were developed taking into account simplifications required for the neutronics analysis.

3. Computational Tools, Data and Geometry

Neutron transport calculations were performed by utilizing 3D Monte Carlo particle transport simulations with recommended code MCNP, which is widely benchmarked and validated code for fusion neutronics application. Variety of nuclear cross-section data libraries the specified DEMO neutron source and the recommended geometry model(s) were used for the calculations.

Neutron fluxes and energy distributions for each WCLL BB segment were calculated. The complete analysis was performed by means of MCNP [4] with JEFF-3.1.2 [5] nuclear data. Activation calculations were performed by means of FISPACT [6] using EAF-2010 [7]. FISPACT is a nuclide inventory code benchmarked/validated for fusion nuclear inventory calculations and is capable of handling the fusion-specific activation cross-section data libraries. Neutron flux distribution in 175 energy group was provided by preceding Monte Carlo transport calculations, where statistical error is about 0.1% with 1.00E+09 generated particles histories.

The foreseen operation will consist of 20 calendar years at an average availability of 30%. This results in a total DEMO plant lifetime of 6 full power years. The operation phase is assumed: the phase will run over 5.2 CY and reach 1.57 FPY. The irradiation scenario for the activation calculations is the 1st DEMO operation, i.e. continuous operation over 5.2 years (CY) minus 10 days at 30% of the nominal fusion power followed by 10 days pulsed operation with 48 h pulses of 4 hours at full power and 1 hour dwell time in between.

The decay times considered for the calculation of the activity inventories and the decay heat are: 1 s, 5 min, 0.5, 1, 3, 5 and 10 hours, following 1 day, 3 days, 1, 2, 4 and 8 weeks, 6 months, 1 year together with 10, 100 , 300 and 1000 years.

4. Calculation results

4.1 Decay heat and activation for the mid. modules

In order to evaluate the radial profile of decay heat inside the breeder blanket mixture, the OB module was divided into 14 (32 in total) volume segments as shown in Figure 4 and 10 segments of IB (see also Figure 5). The decay heat was calculated in each new cell. The decay heat profile is represented in Figures 6 and 9 and for activation – in Figures 2 and 3 for IB #4 and OB #4 accordingly.

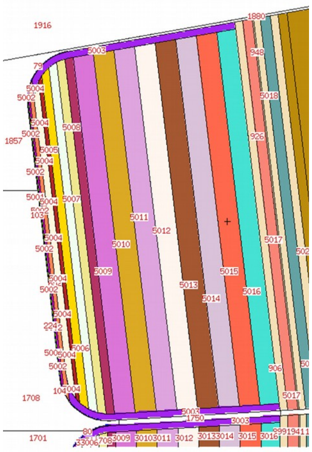

Figure 2. Segmentation of the MCNP model for WCLL blanket OB4 module.

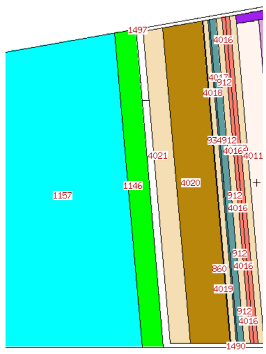

Figure 3. Segmentation of the MCNP model for WCLL blanket IB4 module.

Neutron spectra was obtained for each cell of WCLL MMS model and it was provided as input data for FISPACT inventory calculations. Consequently, specific activity and specific decay heat were calculated for each BB segment with different material composition specified. The following graphs represent radial distribution of the decay heat and activation along WCLL DEMO reactor. Calculations results for radial distribution can be seen in Figures 4 and 5 by reactor structure.

Table 1: *Segmentation and cell numeration*

Zone	OB
Tungsten	103/79/104
FW	224
	5001
	5002
BZ	652
	5004
	5005
	5006
	5007
	5008
	5009
	5010
	5011
	5012
	5013
	5014
	5015
	5016
PBLi manifold	906
	926
	5017/948
	5018
Back Plate	5019
Manifolds	5020/873/882
BSS	5021/5022

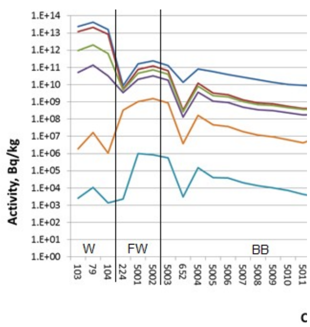

Figure 4. The radial distribution of the specific activity by OB4 segments.

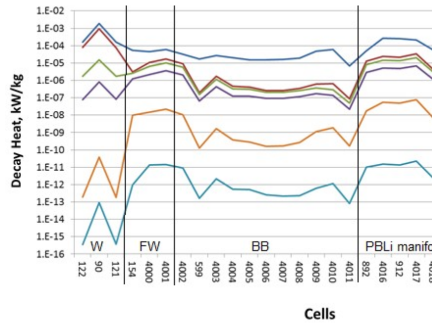

Figure 5. The radial distribution of the specific decay heat by IB4 segments.

4.2 Nuclide vector for activation and decay heat

Figures 6 and 7 represent dominant nuclides for individual components, which contribute the most to the total activation of the WCLL reactor. Previous study [1] indicated that in case of armor (made of pure tungsten), principal radionuclide after few days of shut down is W-187 which is later surpassed by W-185 in terms of total contribution. 1 year and after, Re-186 and other nuclides are more relevant, however the total activity stay relatively low level.

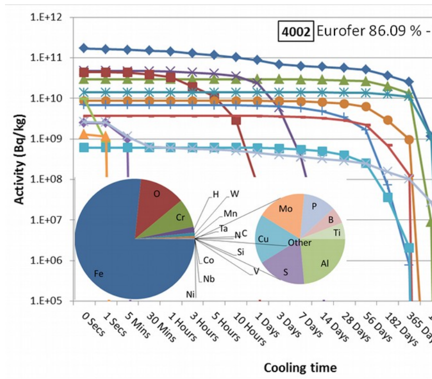

Figure 6. Specific activity break-down of the afterheat of OB #4 module into dominant nuclides.

Activation analysis was performed for the segmented BB zone (both OB #4 and IB #4) with particular interest in

BB most inner segment, Mn-56 and W-187 are the key radionuclides in short period after the end of irradiation, while Mn-54 together with Fe-55 are consistently significant within 10 years after the shutdown as seen in Figures 6 and 7. Materials specifications are also provided in the mentioned figures.

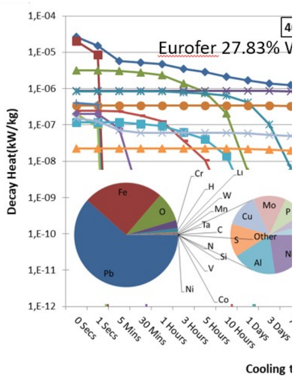

Figure 7. Specific decay heat break-down of the afterheat of OB4 module BB mixture into dominant nuclides.

Total decay heat table were analyzed in details, however in OB #4 Pb207m, Mn-56 and Ta-182 are most dominant nuclides in BB deeper levels all the time for decay heat. IB #4 gives slightly different results, where Mn-56 and Mn-54 are dominating in up to 3 hours and 10 year accordingly. See Figures 6 and 7 for more details and material specification.

4.3 Approach to consider the impact of LiPb flow

An approach to estimate the impact of the LiPb flow was proposed and some preliminary results are presented in this paragraph. In order to make straight forward comparison, three conservative cases were analyzed, i.e 1) a continuous irradiation of 30 days; 2) as LiPb flows, another approach was assumed, i.e. 4 hours of irradiation and 1 hour of decay 3) and 235s of irradiation and 91s of decay.

The preliminary results (see details in Figure 8 for decay heat and in Figure 9 for activation) did not highlighted significant differences, especially in longer cooling times (more than few hours). The slight impact could be observed just after the shut-down of the irradiation, where few percent of the decay heat and activation values differences can be observed.

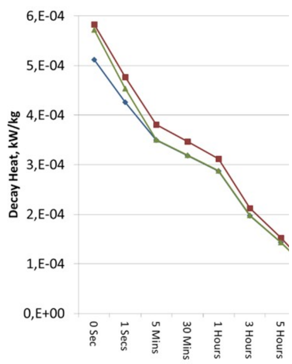

Figure 8. Estimated specific decay heat by approaches to estimate the impact of the LiPb flow

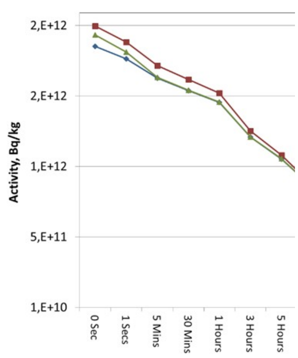

Figure 9. Estimated specific activity by approaches to estimate the impact of the LiPb flow

These results could lead to the simple conclusion that in case of WCLL (using heterogeneous MMS model), the impact of LiPb flow is influenced by fast decaying nuclides. In order to identify main isotope contributors to the mentioned discrepancy, further analysis is needed.

4. Conclusions

Activity inventories, decay heat and shut-down radiation doses are important nuclear quantities which are in need to be assessed on a reliable basis for the safe operation of a fusion nuclear power reactor and its final decommissioning. This report describes the activation and decay heat calculations performed in the frame of the European Power Plant Physics and Technology (PPPT) programme, for DEMO MMS WCLL blanket module for the tritium breeding and Eurofer reduced activation steel as structural material. Neutron induced activities and dose rates at shutdown were calculated by the FISPACT code, using the neutron fluxes and spectra provided by the preceding MCNP neutron transport calculations.

The activities and dose rates at different cooling times were investigated. In the first several days after the end of irradiation, WCLL blanket concept armor segment made of tungsten exhibits highest activity and decay heat. Subsequently, heterogeneous breeder mixture and Eurofer steel from other sections become more prominent and remains key contributors of these characteristics for the remaining investigated time.

Major radionuclides were identified for WCLL: in tungsten armor (with 100% of tungsten) – W-187 and W-185; in Eurofer structural steel – Fe-55, Mn-56, Cr-51, W-187 and Ta-182.

In WCLL armor segment, there are three principal nuclides that reign in different time intervals: W-187, W-185 and Re-186. Respectively, their contribution in total activity is highest for few days, one year and rest of the investigated time after the shutdown. Furthermore in FW section, Mn-56 and W-187 exhibits highest activity and decay heat in first few days after shutdown and later on are being overtaken by Fe-55 in terms of importance. In heterogeneous breeder Pb207m, Mn-56, W-187, Mn-54 and Ta-182 are the dominant nuclides accounting for the decay heat for the investigated time.

Acknowledgments

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