Comparative Analysis of WCLL to Different European DEMO Blanket Concepts in Terms of Activation and Decay Heat after Exposure to Neutron Irradiation

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Abstract. The study revealed that WCLL have the highest (~2-3 orders of magnitude) total decay heat at longer decay times in comparison to HCLL design which has the lowest total decay heat (17.5 MW) at short decay times. In addition, major nuclides were identified for WCLL in W armor (W187 and W185), Eurofer (Fe-55, Mn-56, Cr-51, W-187, Ta-182) and LiPb excluding tritium (Pb-207 and Pb-203). In addition, the great attention has been dedicated to the analysis of the decay heat and activity both from the different WCLL blanket modules for the entire reactor and from each WCLL blanket module separately.

1. Introduction

Neutronic effects are the major operational concern of large scale nuclear fusion reactors that work in DD/DT/TT regimes. Fusion neutrons, in addition to its main role as energy carrier, also actuate undesired effects that are unavoidable; however they can be mitigated by using apt design of reactor components. One of such effects is neutron activation, which not only could disturb reactor operation, but also is primary hazard for personnel and auxiliary systems, furthermore activated materials poses many risks after reactor shutdown and decommissioning. This comparative paper describes the activation and decay heat calculations for WCLL (Water-Cooled Lithium-Lead) [1, 2] performed in the frame of the EURO*fusion* WPSAE programme in comparison to other European DEMO blanket concepts, i.e. DCLL (Dual-Coolant Lithium-Lead) [3], HCLL (Helium-Cooled Lithium-Lead) [4] and HCPB (Helium-Cooled Pebble Bed) [5], on the basis of using a three dimensional neutronics calculation model, developed within the WPBB (Breeder Blanket) of the PPPT programme. Results are provided for a range of decay times of interest for maintenance activities, safety and waste management assessments.

In this work, the main attention was dedicated to the calculation and analysis of the decay heat and activity for different WCLL blanket modules, both for the entire reactor and for each individual WCLL blanket module. Activation calculations were also performed for blanket manifolds. Blanket module was divided into five components: W armor, first wall (FW), caps, breeding blanket module (BB) and back plate (BP). Following materials used in blanket module design were examined: Eurofer steel, LiPb, tungsten and water. In conjunction with this certain impurities were also taken into account. For the convenience, analysis of activation and decay heat calculations as well as identification of dominant radionuclides was performed for equatorial outboard module.

2. WCLL blanket design and computational model

The design model of the WCLL BB includes 7 IB and 16 OB modules (8 of them integer and 8 half modules) [1]. This amounts to 23 BB modules that have been integrated into the 22.50º sector of the generic MCNP_DEMO1 model [6] filling the available breeder space.

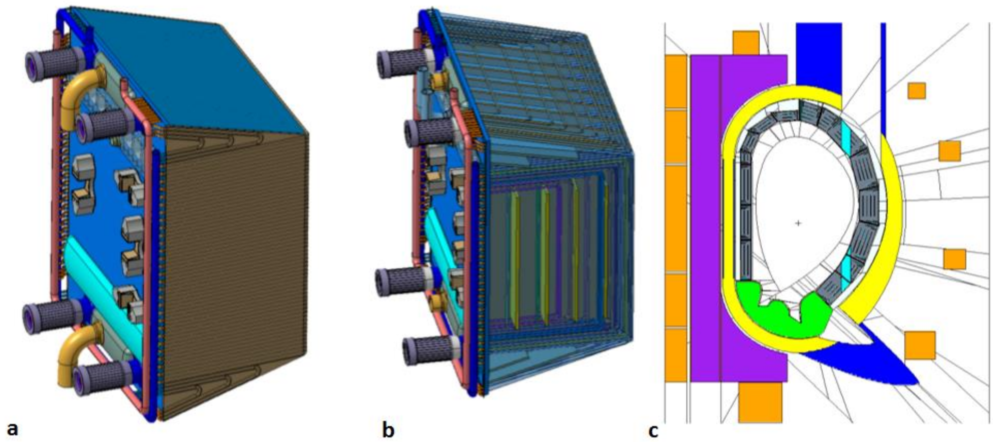

FIG. 1. Conceptual WCLL model: a) outer structure, b) inner structure and c) MCNP model [1, 3].

The reference WCLL detailed module is 91 cm thick. As specified for the task, it was decided to maintain constant the thickness of the modules, fixing it to 91 cm for all the OB modules and reducing to 50 cm for the IB side. Breeder material consists of pure LiPb (80.1%), containing 90% enriched Li in ^{6}Li, with a considerable percentage of steel (18.00%) and some water (1.9%) to take into account the presence of the cooling channels. MCNP [7] calculations were performed with use of the JEFF-3.1 data library [8]. For calculations with FISPACT [9] the EAF 2010 [10] library was used. 10^{9} neutron source histories were run in the MCNP calculation. The average statistical error for the total neutron flux is below 1%, and well below 15% for the group fluxes in the VITAMIN-J group structure. The assumed fusion power of DEMO is 2119 MW [11]. The irradiation scenario assumes a DEMO operation over 5.2 years minus 10 days at 30% of the nominal fusion power. For the subsequent 10 days 48 pulses are assumed each lasting 4 hours at full power with 1 hour dwell time in between [11].

3. Simulation results

WCLL decay heat calculations for the entire reactor displayed value equal to 22.7 MW after 1s of cooling time after the shutdown [2]. The paper contains the representation of dominant nuclides for individual components with greatest contributions to the total decay heat induced by neutron activation for WCLL concept reactor. In tungsten based armor segment few days after end of irradiation W-187 is principal radionuclide, it is being surpassed at later periods by W-185 radionuclide which attributes largest fraction of total decay heat for about a year after shutdown. For the First Wall segment, Mn-56 and W-187 are dominant nuclides in short period, while Fe-55 nuclide together with others have more significance during later periods and maintain it till all the observed time after the shutdown. Mn-56 and W-187 nuclides constitute majority of the decay heat for Breading Blanket mixture for the entire cooling time after the end of irradiation, in addition Ta-182 contribution should be also noted.

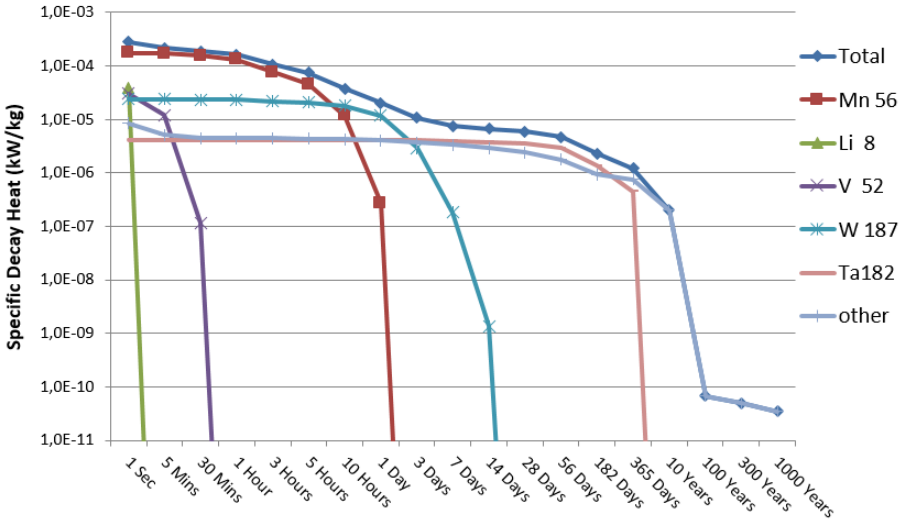

FIG. 2. Specific decay heat break-down of the afterheat of BB mixture into dominant nuclides for WCLL.

Similar to WCLL, DCLL total decay heat for all blanket modules (excluding tritium) ranges from ~23 to 12 MW in 1 hour period; drops below 1 MW after 2 months, and about 0.3 MW after 1 year [3]. It reaches 4.5 W and 3.0 W after 100 and 1000 years of cooling respectively. Obtained total activity values ranges from $1 \cdot 10^{14}$ to $1 \cdot 10^{12}$ MBq for 10 years period, it decreases to $2 \cdot 10^{8}$ MBq in 100 years; for longer cooling times, values are around 10^{7} MBq. As expected, the outboard and inboard equatorial blanket modules have the highest values in both activity and decay heat. Outboard section has the highest integrated values of investigated characteristics, while inboard section has the highest volumetric values.

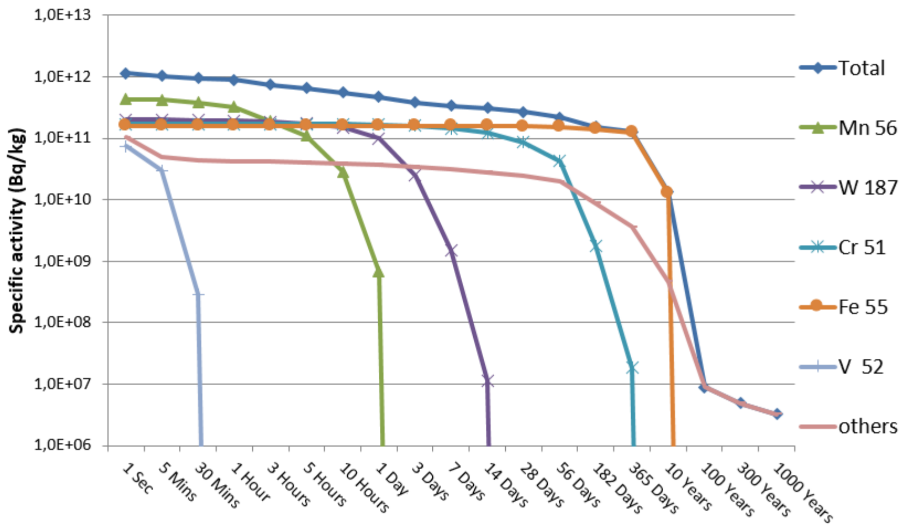

FIG. 3. Specific activation break-down of the afterheat of BB mixture into dominant nuclides for WCLL.

The activated LiPb (tritium excluded) is the key contributor to the total decay heat after first second of shutdown and after a 100-year cooling period. Thereafter Eurofer material from the breeding blanket module display the highest values of the decay heat. In terms of activity, LiPb (tritium excluded) contributes the most and reigns in 1 second 300 years cooling time interval, later on Eurofer material from the breeding blanket module exhibits highest values at the remaining times. Total decay heat values of manifold segment ranges from $6\cdot10^{2}$ to $1\cdot10^{2}$ kW from initial shutdown till 1 day of cooling; about 10 kW after 1 year and finally, it decreases to $3\cdot10^{-4}$ kW after 1000 years. Total activity value ranges from $3\cdot10^{12}$ to $1\cdot10^{12}$ MBq during the first day of the shutdown; around $3\cdot10^{11}$ MBq after 1 year and then it drops to $4\cdot10^{6}$ MBq after 1000 years of cooling. For both activation responses, the inboard region shows higher values than the outboard one, in most of the considered times.

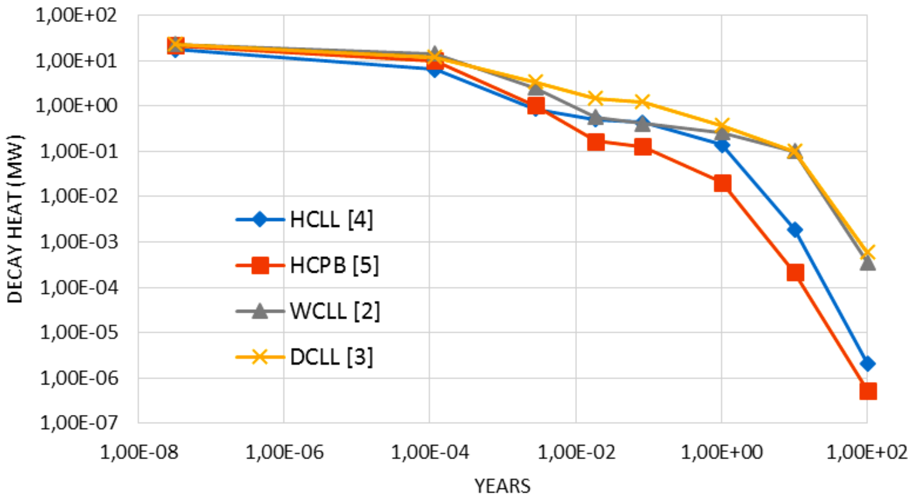

FIG. 4. Comparison of WCLL [2] *decay heat to different blanket concepts* [3-5].

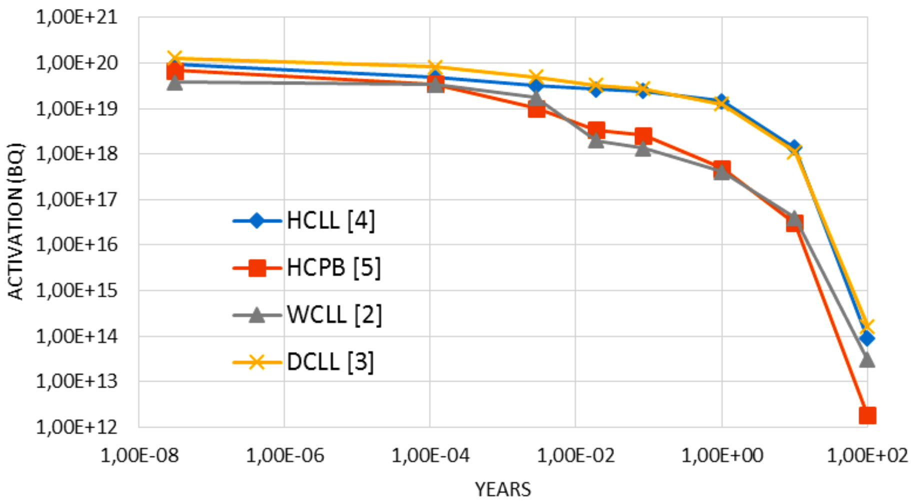

FIG. 5. Comparison of WCLL [2] *activation to different blanket concepts* [3-5].

Activation calculations were performed using HCLL blanket DEMO neutronics model in [4]. The decay heat and nuclide activation inventories were calculated for each material making up the blanket modules and the blanket manifold. The decay heat from the blanket modules and manifold for the entire reactor is in the region of 17 MW for a decay time of a second. This is mainly due to the activation products contained in the Eurofer and PbLi. The decay heat decreases as the decay time increases and corresponds to few hundred W in 100 years and to few hundred of mW in 1000 years after discontinuation of irradiation. The total activity for all blanket modules and the entire manifold at 1s decay time is dominated by the activities of Eurofer and PbLi which are in the region of $4{\cdot}10^{19}$ and $8{\cdot}10^{19}$ Bq respectively. Principal nuclides at 1s are H-3, Pb-207m, Fe-55 and Mn-56. At longer decay times, in the region of 1000 years, long-lived isotopes such as C-14, Nb-94, Pb-205 and Nb-91 exhibits highest activity.

HCPB blanket modules and manifolds for the entire reactor produces about 21 MW power of decay heat shortly after the shutdown of the reactor [5]. Activation products contained in the Eurofer and breeder mixture contribute most to the total decay heat. After 100 years of cooling decay heat falls under 1 W. For the entire investigated time period, the highest activity in blanket modules of HCPB DEMO concept is caused by the functional materials made of Eurofer steel.

4. Conclusions

In the first several days after the end of irradiation, WCLL blanket concept armor section made of tungsten exhibits highest activity and decay heat. Subsequently, breeder mixture and Eurofer steel from other sections become more prominent and remains biggest contributors of these properties for the remaining investigated time.

Comparison of the total decay heat profiles (MW) for all blanket concepts showed that the total decay heat expected to be in the 10 MW for all blanket concepts in the seconds and minutes after shutdown. In addition, short decay times ($<1\times10^5$ s) HCLL gives the lowest decay heat, while longer decay times ($>10^5$ s) HCPB gives the lowest decay heat. Also short decay times ($<10^3$ s) and long decay times ($>10^8$ s) WCLL gives highest decay heat while middle decay times ($>10^3$ and $<10^8$ s) DCLL gives highest decay heats. Analysis of four different breeding blanket concepts showed that WCLL and DCLL blanket modules have the highest (~2-3 orders of magnitude) total decay heat values at longer (~100 years) cooling periods compared to other concepts. Also HCLL and HCPB designs has the lower total decay heat (17.5 MW) at (1 s) short cooling periods. Total decay heat is expected to be around 10 MW for all blanket concepts in the seconds and minutes after shutdown. Major radionuclides were identified for WCLL: in tungsten armor – W187 and W185; in Eurofer structural steel – Fe-55, Mn-56, Cr-51, W-187, Ta-182; in LiPb breeder mixture (excluding tritium) – Pb-207 and Pb-203.

In WCLL armor section, 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 breeder mixture Mn-56, W-187, Cr -51 and Fe-55 are the dominant nuclides accounted for the decay heat for the investigated time.

5. Acknowledgments

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