ANALYSIS OF THE WCLL EUROPEAN DEMO BLANKET CONCEPT IN TERMS OF ACTIVATION AND DECAY HEAT AFTER EXPOSURE TO NEUTRON IRRADIATION

by

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This comparative paper describes the activation and decay heat calculations for water-cooled lithium-lead performed part of the EURO fusion WPSAE programme and specifications in comparison to other European DEMO blanket concepts on the basis of using a three-dimensional neutronics calculation model. Results are provided for a range of decay times of interest for maintenance activities, safety and waste management assessments. The study revealed that water-cooled lithium-lead has the highest total decay heat at longer decay times in comparison to the helium-cooled design which has the lowest total decay heat. In addition, major nuclides were identified for water-cooled lithium-lead in W armour, Eurofer, and LiPb. In addition, great attention has been dedicated to the analysis of the decay heat and activity both from the different water-cooled lithium-lead blanket modules for the entire reactor and from each water-cooled lithium-lead blanket module separately. The neutron induced activation and decay heat at shutdown were calculated by the FISPACT code, using the neutron flux densities and spectra that were provided by the preceding MCNP neutron transport calculations.

Key words: Monte Carlo calculation, activation method, fusion, neutron irradiation

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 their main role as energy carriers, also actuate undesired effects that are unavoidable. However, they can be mitigated by using apt design of reactor components. One such undesired effects is neutron activation, which not only could disturb reactor operation, but also is a primary hazard for personnel and auxiliary systems. Furthermore, activated materials pose many risks after fission or fusion reactor shutdown and decommissioning. This comparative paper describes the activation and decay heat calculations for water-cooled lithium-lead (WCLL) [1, 2] performed as part of the H2020 EURO fusion WPSAE (Safety and Environment) programme in comparison to other European demonstration fusion power reactor (DEMO) blanket concepts, *i. e.*, dual-coolant lithium-lead (DCLL) [3], helium-cooled lithium-lead (HCLL) [4], and helium-cooled pebble bed (HCPB) [5], on the basis of using a three-dimensional neutronics calculation model, developed within the breeder blanket (WPBB) of the power plant physics and technology (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 the WCLL breeder blanket concept for the entire fusion reactor. Activation calculations were also performed for blanket manifolds. The blanket module was divided into five components: Warmour, first wall (FW), caps, breeding blanket module (BB), and back plate (BP). The following materials used in blanket module design were examined: Eurofer steel, LiPb, tungsten, and water. For the purpose of convenience, analysis of activation and decay heat calculations, as well as identification of dominant radionuclides, was performed for the main components from the WCLL concept.

WCLL BLANKET DESIGN AND COMPUTATIONAL MODEL

The design model of the WCLL breading blanket (BB) includes 7 inboard and 16 outboard modules (8 of them integer and 8 half modules) [1]. This amounts to 23

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Table 1. Volume percentages of materials in the blanket module for neutronic analysis of the WCLL DEMO

WCLL DEMO						
Vol. [%]	Armour (2 mm)	FW (21 mm)	Breeder module	Caps	Breeder module backplate	Manifold
Eurofer	–	89.5	18	95.2	100	74.4
Water	–	10.5	1.9	4.8	–	4.8
PbLi (90 % ^{6}Li)	–	–	80.1	–	–	9.2
Tungsten	100	–	–	–	–	–
Void (vacuum)	–	–	–	–	–	11.6

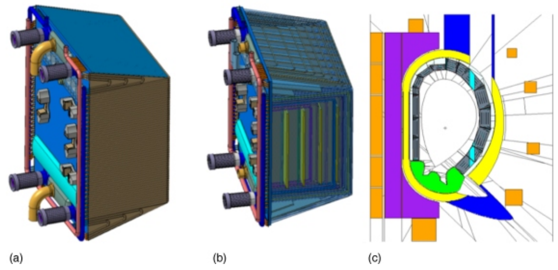

Figure 1. Conceptual WCLL model, (a) outer structure, (b) inner structure, (c) MCNP model [1, 2]

BB modules that have been integrated into the 11.25 ºC sector of the generic MCNP_DEMO1 model [6] filling the available breeder space.

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 it to 50 cm for the IB side. The breeder material consists of pure LiPb (80.1 %), containing 90 % enriched Li in ^{6}Li, with a considerable percentage of steel (18 %) and some water (1.9 %) taking into account the presence of the cooling channels (see fig. 1 or ref. [1] for more details). Material compositions are presented in tab. 1.

MCNP [7] calculations were performed with the use of the JEFF-3.1 data library [8]. For calculations with FISPACT [9], the EAF 2010 [10] library was used. In total, 10^9 neutron source histories were run in the MCNP calculation. The average (1) statistical error for the total neutron flux density is below 1 %, and well below 15 % for the group flux densities in the VITAMIN-J [11] group structure. The assumed fusion power of DEMO is 2119 MW [2]. 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 [2].

SIMULATION RESULTS

WCLL decay heat calculations for the entire DEMO fusion reactor displayed a value equal to 22.7 MW after 1 s of cooling time after the shutdown. The paper contains the representation of dominant nuclides for individual components with the greatest contributions to the total decay heat induced by neutron activation for the WCLL concept reactor. In the tungsten-based armour segment a few days after the end of irradiation ^{187}W is the principal radionuclide, which is surpassed at later periods by the ^{185}W radionuclide which contributes to the largest fraction of total decay heat for about a year after shutdown. For the First Wall segment, ^{56}Mn and ^{187}W are dominant nuclides in short (up to one hour) period, while the ^{55}Fe nuclide, together with the other ones, has more significance during a later period and maintains it during all the entire observed time after the shutdown. ^{56}Mn and ^{187}W nuclides constitute the majority of the decay heat for the Breading Blanket mixture for the entire cooling time after the end of irradiation. In addition the ^{182}Ta contribution should be also noted (see fig. 2 for more details).

Similar to WCLL, the DCLL total decay heat (fig. 4) for all blanket modules (excluding tritium) ranges from ~23 MW to 12 MW in a 1 hour period; drops below 1 MW after 2 months, and about 0.3 MW

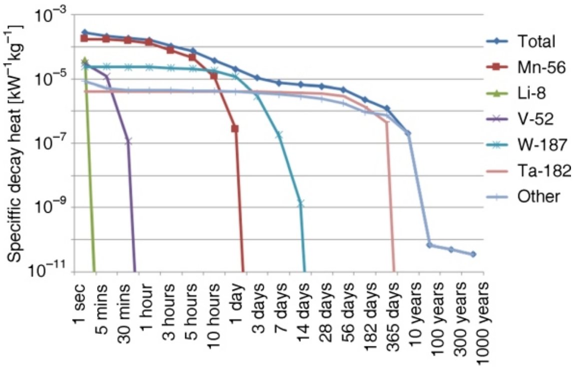

Figure 2. Specific decay heat break-down of the afterheat of the BB mixture into dominant nuclides for WCLL

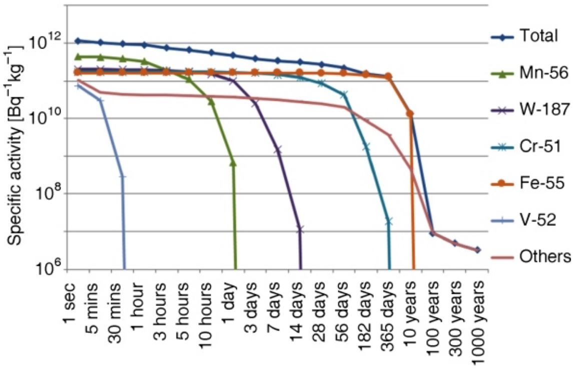

Figure 3. Specific activation break-down of the afterheat of the BB mixture into dominant nuclides for WCLL

after 1 year [3]. It reaches 4.5 W and 3.0 W after 100 years and 1000 years of cooling respectively. The obtained total activity values ranges from 10^{14} MBq to 10^{12} MBq for a 10 years period, itthey decreases to $2 \cdot 10^{8}$ MBq in 100 years; for longer (more than 100 years) cooling times, the 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. The outboard blanket section has the highest integrated values of investigated characteristics, while the inboard blanket section has the highest volumetric values.

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

Activation calculations were performed using a 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 a few hundred watts in 100 years and to a few hundred of milliwatts in 1000 years after discontinuation of irradiation. The total activity for all blanket modules and the entire manifold at 1 s decay time is dominated by the activities of Eurofer and PbLi which are in the region of $4 \cdot 10^{19}$ Bq and $8 \cdot 10^{19}$ Bq, respectively. Principal nuclides at 1 s are ^{3}H, ^{207m}Pb, ^{55}Fe, and ^{56}Mn. At longer decay times, in the region of 1000 years, long-lived isotopes such as ^{14}C, ^{94}Nb, ^{205}Pb, and ^{91}Nb exhibits the highest activity.

HCPB blanket modules and manifolds for the entire fusion 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 the decay heat falls under 1 W. For the entire investigated time period, the highest activity in blanket modules of the HCPB DEMO concept is caused by the functional materials made of Eurofer steel (figs. 4 and 5).

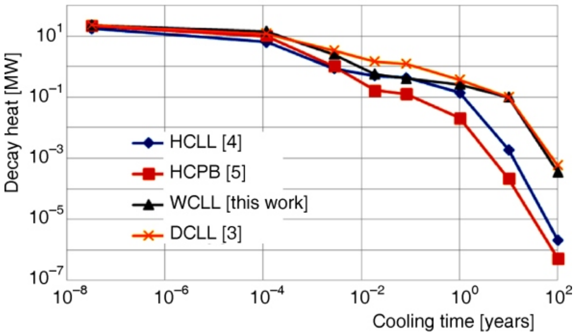

Figure 4. Comparison of WCLL total decay heat to different blanket concepts [3-5]

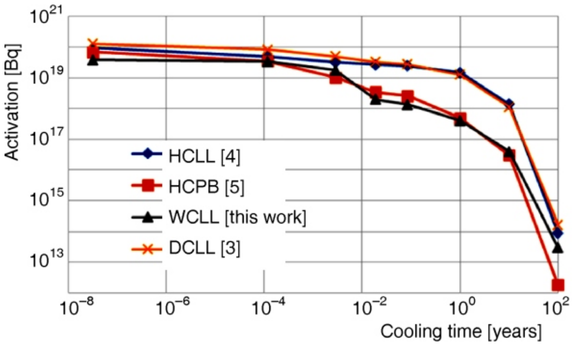

Figure 5. Comparison of WCLL total activation to different blanket concepts [3-5]

CONCLUSIONS

In the first several days after the end of irradiation, among the different components of the WCLL blanket concept, the armour section made of tungsten exhibits the highest activity and decay heat. Subsequently, the breeder mixture and Eurofer steel from other sections become more prominent and remains the 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 is expected to be 10 MW for all blanket concepts in the seconds and minutes after shutdown. In a ddition, short decay times (<10^{3} s) of HCLL gives the lowest decay heat, while longer decay times (>10^{5} s) of HCPB gives the lowest decay heat. Also short decay times (<10^{3} s) and long decay times (>10^{8} s) of WCLL gives the highest decay heat while middle decay times (>10^{3} s and <10^{8} s) of DCLL gives the 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 have a lower total decay heat (17.5 MW) at short (about 1 s) cooling periods. Major radionuclides were identified for WCLL:

- in tungsten armour: ^{187}W and ^{185}W,
- in Eurofer structural steel: ^{55}Fe, ^{56}Mn, ^{51}Cr, ^{187}W, and ^{182}Ta,
- in the LiPb breeder mixture (excluding tritium): ^{207}Pb and ^{203}Pb.

In the WCLL armour section, there are three principal nuclides that reign in different time intervals: ^{187}W, ^{185}W, and ^{186}Re, respectively, their contribution in to the total activity is highest for a few days, one year and the rest of the investigated time after the shutdown. Furthermore, in the FW section, ^{56}Mn and ^{187}W exhibit the highest activity and decay heat in the first few days after shutdown and later on are being overtaken by ^{55}Fe in terms of importance. In the breeder mixture ^{56}Mn, ^{187}W, ^{51}Cr, and ^{55}Fe are the dominant nuclides that contribute to the decay heat for the investigated time.

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AUTHORS' CONTRIBUTIONS

The neutron transport calculations were carried out by G. Stankunas and materials irradiation modelling was carried out by A. Tidikas. Both authors analysed and discussed the results. The manuscript was written by G. Stankunas and A. Tidikas, while the graphs were prepared by A. Tidikas.

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АНАЛИЗА WCLL ЕВРОПСКОГ ДЕМО КОНЦЕПТА ПРЕКРИВАЧА КРОЗ АКТИВАЦИЈУ И ЗАГРЕВАЊЕ ПОСЛЕ НЕУТРОНСКОГ ОЗРАЧИВАЊА

Овај компаративни рад описује прорачуне активације и загревања литијум-олова хлађеног водом (WCLL) спроведеног у оквиру EUROfusion WPSAE програма и спецификације у поређењу са другим европским DEMO концептима прекривача заснованих на примени тродимензионалног модела неутронског прорачуна. Приказани су резултати за опсег времена од интереса за потребе одржавања, сигурносног планирања и управљања отпадом. Студија показује да WCLL има највеће загревање на дужим временским интервалима у поређењу са хелијумским хлађењем које има јанмање загревања. Додатно, главни нуклиди су индентификовани за WCLL са W-штитом, Eurofer и LiPb. Велика пажња посвећена је анализи загревања и активацији од различитих модула WCLL прекривача за цео реактор, као и сваког модула прекривача WCLL понаособ. Активација индукована неутронима и загревање при гашењу прорачунати су применом програмског пакета FISPACT, користећи густине и спектра неутронског флукса који су добијени на основу претходних MCNP прорачуна транспорта неутрона.

Кључне речи: Монте Карло прорачун, активациона метода, фузија, неутронско озрачивање