ACCEPTED MANUSCRIPT Published at:
https://www.sciencedirect.com/science/article/pii/S0920379615303793
DOI: 10.1016/j.fusengdes.2015.11.051

Neutronic Performance Issues of the Breeding Blanket Options for the European DEMO fusion power plant

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This paper presents nuclear performance issues of the HCPB, HCLL, DCLL and WCLL breeder blankets, which are under development within the PPPT (Power Plant Physics and Technology) programme of EUROfusion, with the objective to assess the potential and suitability of the blankets for the application to DEMO. The assessment is based on the initial design versions of the blankets developed in 2014. The Tritium breeding potential is considered sufficient for all breeder blankets although the initial design versions of the HCPB, HCLL and DCLL blankets were shown to require further design improvements. Suitable measures have been proposed and proven to be sufficient to achieve the required TBR ≥ 1.10. The shielding performance was shown to be sufficient to protect the super-conducting TFC provided that efficient shielding material mixtures including WC or borated water are utilized. The WCLL blanket does not require the use of such shielding materials due to a very compact BSS/manifold configuration which yet requires design verification. The vacuum vessel can be safely operated over the full anticipated DEMO lifetime of 6 full power years for all blanket concepts considered.

Keywords: Neutronics, DEMO, Tritium breeding, shielding

1. Introduction

The European Power Plant Physics and Technology (PPPT) programme, organised within the EUROfusion Consortium, aims at developing a conceptual design of a fusion power demonstration plant (DEMO) within the time period of the "Horizon 2020" roadmap [1 - 3].

The DEMO power plant will rely on the availability of a technically mature breeding blanket providing the Tritium required for its operation ("Tritium self-sufficiency") and producing nuclear heat for the conversion into electricity. Four different design options of a breeder blanket are under investigation in the PPPT programme [4]: a solid breeder blanket with Beryllium as neutron multiplier and Helium gas as coolant (HCPB – Helium Cooled Pebble Bed), a liquid metal blanket with PbLi as breeder and Helium gas as coolant (HCLL – Helium Cooled Lithium Lead), a liquid metal blanket with PbLi as breeder and water as coolant (WCLL – Water Cooled Lithium Lead), and another liquid metal blanket with PbLi acting both as breeder and coolant, and employing additionally Helium gas as coolant for the blanket steel structure (DCLL – Dual Coolant Lithium Lead).

In this paper an evaluation of the nuclear performance of these breeder blanket concepts is presented with regard to their potential and suitability for application in DEMO. The evaluation builds on the analyses performed within the PPPT breeder blanket programme for the initial design versions of the blankets produced in 2014. Results of previous studies are also taken into account as well as the inherent nuclear characteristics of the considered blanket configurations and the materials employed. This approach allows proposing design improvements in an early development phase of the blanket designs.

The paper is organized as follows. First a brief overview is presented of the different blanket design variants and the DEMO power plant. Next the inherent neutronics characteristics of the blankets are discussed and the methodological approach is described for assessing the nuclear performance issues of the breeder blankets. Results obtained for DEMO are presented to conclude on the nuclear performance of the considered blanket designs.

2. Breeder blanket concepts for DEMO

2.1 Common design features

The current design approach for DEMO assumes a vacuum vessel (VV) with integrated shielding function [5], sufficient to protect the superconducting Toroidal Filed Coils (TFC) over the entire DEMO plant lifetime of 6 full power years (fpy). The VV is thus a lifetime component to which replaceable in-vessel components such as the breeder blankets are directly attached. The breeding blankets are designed for vertical maintenance and are separated into removable segments. A torus sector of 22.5°, defined by the reactor configuration with 16 TFCs, contains 3 outboard and 2 inboard segments. The currently adopted Multi Module Segmentation (MMS) scheme typically employs 6 to 8 modules arranged in poloidal direction on either side of the plasma chamber, as shown in Fig. 1. The modules are attached to a Back Supporting Structure (BSS) that acts as mechanical support and hosts the main manifolds for the coolant and the Tritium carrier. The space available in radial direction for the breeder blankets, including manifold and blanket support structure, is about 80 cm and 130 cm, inboard and outboard, respectively. The blankets need to be designed for a maximum neutron wall loading (NWL) corresponding to the DEMO peak values at the inboard and outboard side. For the DEMO 2014 configuration with a fusion power of 1572 MW, a major radius of 9 m and a minor radius of 2.25 m, these NWL peaking values are at 1.15 and 1.35 MW/m^2, inboard and outboard, respectively.

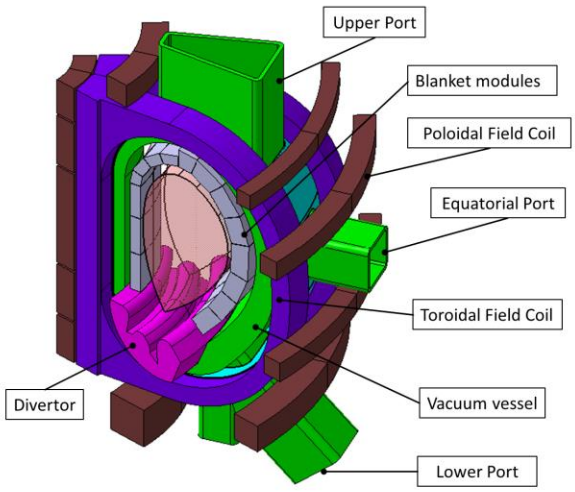

Fig.1: 22.5° torus sector of DEMO showing the arrangement of the blanket modules inside the vessel.

2.1 Helium Cooled Pebble Bed ("HCPB") Blanket

The HCPB 2014 MMS blanket design [6] employs 6 blanket modules both for the inboard and the outboard segment. A blanket module consists of a steel box made of the Eurofer low-activation steel and includes the U-shaped First Wall (FW), a stiffening grids (SG) with breeder units (BU), a box manifold with a back wall, two caps at the top and the bottom of the box, and the integrated BSS, see Fig. 2.

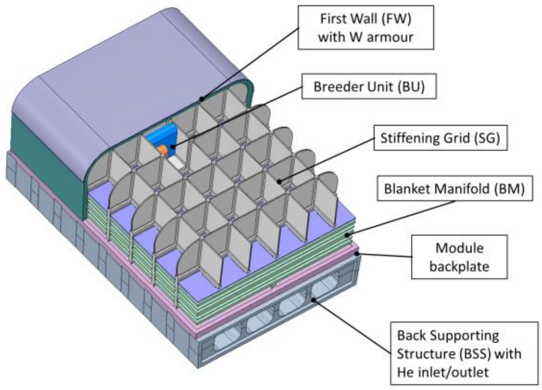

Fig. 2: HCPB breeder blanket module. The breeder units are filled in the open spaces of the stiffening grid.

The dimensions of a module amount to 509 mm x 1184 mm x 1706 mm (radial x toroidal x poloidal) at the inboard mid-plane and 840 mm x 1576 mm x 2141 mm at the outboard mid-plane. Li_4SiO_4 ceramics is used as breeder material with ^{6}Li enriched to 60 at% and Beryllium as neutron multiplier. Both materials are filled in the form pebble beds in the space between the cooling/stiffening plates. High pressure He gas is used for the cooling of the breeder units, the FW and the box structure.

2.2 Helium Cooled Lithium-Lead ("HCLL") Blanket

The HCLL blanket concept [7] uses the Pb-15.8Li eutectic alloy as breeder and neutron multiplier material and Helium gas as coolant. 7 blanket modules are assumed for the inboard and 8 modules for the outboard segment. The design of the breeder module boxes is similar to the HCPB box design including a stiffening grid whose open space is filled with the PbLi eutectic alloy for the Tritium breeding. Lithium is enriched to 90 at% ^{6}Li in the PbLi. Cooling of the PbLi and the structure is provided by high pressure Helium gas flowing in the horizontal cooling plates (CP) connected to the back plate of the BUs. The liquid PbLi is circulated at low velocity for the extraction of Tritium. A rather complex manifold scheme is thus required for the circulation of both the Pb-Li and the He gas, see Fig. 3.

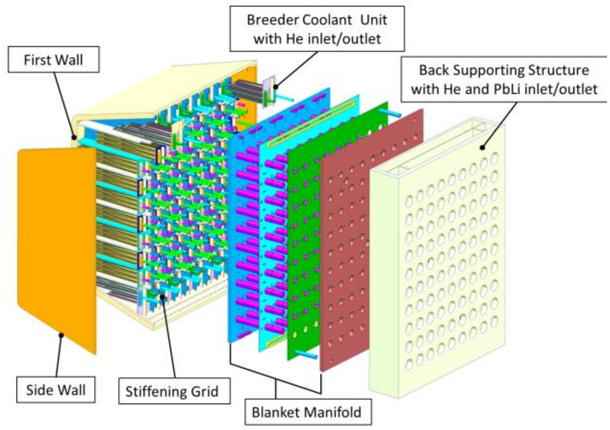

Fig. 3: Exploded view of the HCLL breeder blanket module with PbLi/He manifolds and BSS.

2.3 Dual Coolant Lithium-Lead ("DCLL") Blanket

The DCLL blanket concept [8] employs the Pb-15.8Li eutectic alloy both as breeder/multiplier and coolant. The PbLi is circulated at higher velocity in large sized coolant channels made of Eurofer steel and covered with thin flow channel inserts removing the heat from the breeding zone. The Eurofer structure including the first wall is cooled by Helium gas. The MMS scheme assumes 7 blanket modules for the inboard and 8 modules the outboard segment. Fig 4 shows a cut-away model of a DCLL outboard blanket module.

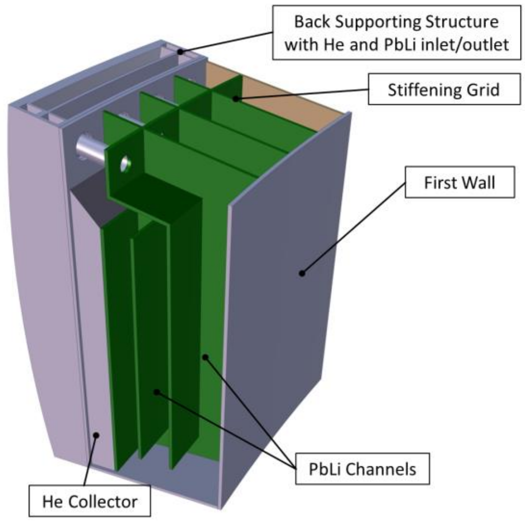

Fig. 4: DCLL breeder blanket module showing a cut-away view of the liquid metal channels and the attached BSS with manifolds.

2.4 Water Cooled Lithium Lead ("WCLL") Blanket

The WCLL blanket concept [9] employs the Pb-15.8Li eutectic for the Tritium breeding and the neutron multiplication. Cooling is provided by pressurized water flowing in small pipes through the PbLi pool at similar conditions as those of a fission Pressurized Water Reactor (PWR). The module design is based on the WCLL design elaborated by CEA in the frame of the preceding EFDA PPPT work programme [10]. Within the 2014 WCLL design activities, ENEA proposed an improved PbLi/water manifold scheme with a compact BBS which was assumed for the shielding performance assessment in this work.

The WCLL MMS scheme assumes 7 blanket modules both for the inboard and the outboard segment. The design of the blanket module is based on the same principles as the other blanket concepts and includes a Eurofer steel box with FW, caps, back wall and BSS with inlet/outline pipes for the water and the PbLi. The box is filled with the PbLi liquid metal and reinforced by horizontal and vertically arranged stiffening plates.

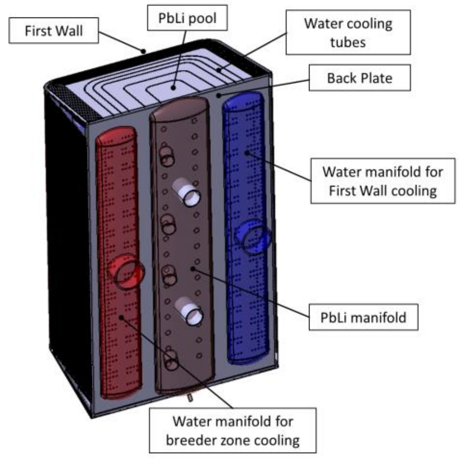

Fig. 5: Rear view of a typical WCLL blanket module with PbLi/water manifolds as proposed by ENEA.

3. Neutronics characteristics of the breeder blankets

The primary function of the breeder blanket is to breed the Tritium needed for maintaining the d,t fusion in the plasma chamber. Accordingly the blanket design needs to be optimised for neutron induced reactions producing Tritium. Among all such reactions, only the ^{6}Li(n,α)t reaction is of practical significance and necessitates the use of Lithium compounds as breeder material enriched in ^{6}Li. The breeder material needs to be cooled and enclosed in a solid container or box, in general made of (neutron absorbing) steel. As a consequence, parasitic neutron absorptions take place in these materials. This effect would prevent any blanket to achieve Tritium self-sufficiency unless the number of available neutrons per (d,t) fusion neutrons is increased with the addition of neutron multipliers such as Beryllium or Lead which provide neutron multiplication through (n,2n) reactions.

The choice of the breeder material and the neutron multiplier, and to a minor extent the coolant and the structural material, has a dominant impact on the neutronics characteristics of the blanket and its neutronic performance affecting the blanket design. The eutectic Pb-Li alloy, for example, combines the Tritium breeding and the neutron multiplication capability in one single material which is liquid at the operation conditions in the reactor. (This feature allows also its direct use as coolant as considered e. g in the DCLL blanket concept). The neutronics behaviour of Pb-Li based blankets is dominated by the nuclear properties of lead which shows a high neutron scattering power (due to the dominating elastic scattering cross-section) but a low neutron moderation power (due to its heavy mass). This results in a comparatively high fast neutron flux density and the fact that a larger radial blanket dimension (typically 70 to 80 cm for the breeding zone) is required to achieve a sufficiently high Tritium production. This is due to the cross-section of the ^{6}Li(n,α)t breeding reaction which increases with decreasing neutron energy and thus would benefit from a degraded neutron spectrum. The use of water as coolant in the WCLL blanket takes advantage of this effect although the amount of water, dictated by the cooling conditions, is rather low and not sufficient for efficient neutron moderation. (Cooling conditions actually call for a lower water fraction in the back of the breeder zone where the power density is lower. In contrast, from the neutronics point of view, it would be more favourable to have a low water volume fraction in the front and a much higher fraction in the back of the blanket).

The use of solid Lithium compounds such as the Li_4SiO_4 ceramics necessitate the use of a solid neutron multiplier. Beryllium is the optimal choice to this end since it provides the highest neutron multiplication and is solid at operation conditions. It is this therefore utilized as neutron multiplier in the HCPB blanket. For an optimal performance the amount of Beryllium needs to be very high with a Be/breeder volume ratio around 4:1. The neutronic performance of the HCPB blanket is thus dominated by the nuclear properties of the Beryllium multiplier which also acts as neutron moderator because of it slow mass. As a consequence, the neutron spectrum in the HCPB blanket is degraded in the breeder zone which is favourable for the Tritium generation in the Li ceramics. Lithium needs to be enriched to moderate levels only, typically to 30 to 60 at% ^{6}Li. Due to the high neutron multiplication power of Beryllium combined with its neutron moderating power, a minimal radial thickness of the breeder zone, in the range of only 30 to 50 cm, is required for a sufficient Tritium breeding.

4. Space requirements for breeding and shielding in DEMO

The radial build of DEMO must be devised in such a way that the available space between the plasma and the vacuum vessel is sufficient to accommodate the integration of breeding blankets of any of the considered types with the constraint that sufficient Tritium breeding can be assured. This is crucial for the inboard side of the DEMO reactor where minimum space is available for the combined breeder/shield system. Shielding of the superconducting TFC is provided by the 57 cm thick VV with integrated shielding function. (The considered VV consists of 5 cm thick steel plates at the front and the back with 47 cm space in between utilized for shielding and providing the required thermal and structural-mechanical functions). The radial space available to the breeder blanket modules was set to 80 and 130 cm, inboard and outboard, respectively. The HCPB, HCLL, DCLL and WCLL breeder blanket modules including back supporting structure and manifolds were designed to fit to these dimensions. At the inboard side this constraint may result in a significantly reduced space available for the breeder zone itself since a large part of the available space is required for the BSS with the inlet/outline piping of the coolant and the Tritium carrier (either PbLi or He purge gas) as well as manifolds arranged inside the breeder modules. In case of the Pb-Li based blankets, however, the manifolds carrying the liquid metal will also contribute to the Tritium breeding.

5. Methodological approach for DEMO nuclear analyses

Within the EUROfusion PPPT programme, the design of the breeder blankets is being conducted by different design teams led by KIT (HCPB), CEA (HCLL), CIEMAT (DCLL) and ENEA (WCLL). The related nuclear analyses are performed within the design teams by the respective nuclear experts. The consistency of the analyses is ensured by a common methodological approach specified in the neutronic guidelines for DEMO nuclear analyses. An essential feature of this approach is the mandatory use of a generic DEMO model which is consistent with the DEMO design configuration and individually adapted to the different blanket concepts.

To this end a generic CAD neutronics model is generated from the Configuration Management Model (CGM) of DEMO. This model includes TFC, VV, divertor, blanket segment box, vessel ports, and plasma chamber, represented in a 22.5 ° torus sector with envelopes. All components are thus described by their bounding surfaces ("envelopes") without any internal structure specified. This model is converted to an analysis model for the MCNP [11] and the TRIPOLI4 [12] Monte Carlo codes using the McCad conversion software [13]. The resulting generic analysis model is used for the integration of specific blanket modules according to the design of the HCPB, HCLL, DCLL and WCLL blankets. The approach for the development of these blanket specific DEMO models, is to use the CAD models provided by the design teams for a single blanket module of the HCPB, HCLL, DCLL and WCLL type. Such a blanket module is converted to an MCNP or TRIPOLI analysis model and is then repeatedly filled into the empty blanket segment envelope of the generic DEMO model. This is done separately for the inboard and outboard blanket segments according to the poloidal segmentation scheme applied in the specific blanket designs.

The neutronics calculations are performed with the MCNP or the TRIPOLI-4 Monte Carlo codes using nuclear cross-section data from the JEFF-3.1.2/3.2 data library [14].

6. Tritium breeding potential

The capability of HCPB, HCLL, DCLL and WCLL type blankets to breed Tritium at the required level has been demonstrated in many previous studies including e. g . the European Power Plant Conceptual Study (PPCS) [15]. The current designs, however, suffer to some extent from severe design limitations such as the (mandatory) use of a very solid internal stiffening grid to sustain the pressure in case of a coolant leak inside a breeder module, and the assumed module segmentation scheme with a comparatively large number of blanket modules.

The TBR predicted for the 2014 initial design versions (without any modifications applied) amount to 1.04, 1.07, 1.04, and 1.13, for the HCPB, HCLL, DCLL and WCLL DEMO, respectively. In order to achieve the TBR design target for DEMO, TBR $\geq$ 1.10, design improvements are required for the HCPB, HCLL, and DCLL blanket concepts. Suitable measures, including the increase of the inboard breeder zone thickness (HCPB, HCLL) with an improved manifold scheme, a reduction of the number of stiffening plates, and the utilization of the manifold region for Tritium breeding (DCLL) have been already proposed [16, 17] and are being implemented in the advanced (2015) DEMO blanket design versions. Such measures were shown to be sufficient to ensure the required TBR.

6. Shielding performance issues

The shielding performance of the entire blanket/shield system is crucial at the inboard side of the DEMO tokamak where minimum space is available for the protection of the superconducting TFC from the penetrating radiation. The major shielding function must be fulfilled by the VV with integrated shield since the shielding performance of the breeder modules, optimised for the Tritium breeding, in general is poor.

The most crucial radiation loads to the TFC are the fast neutron fluence to the superconductor, the peak nuclear heating in the winding pack, the radiation damage to the copper insulator and the radiation dose absorbed by the Epoxy resin insulator [18]. The related radiation design limits are the criteria for assessing the shielding efficiency. The limits on the neutron fluences result, with the assumed DEMO conditions, in a limit for the fast neutron flux around $1{\cdot}10^9$ $cm^{-2}s^{-1}$. The most demanding criterion, however, is the extremely low power density limit of 50 W/m^3 as specified currently for the super-conducting TFCs of DEMO [17].

The irradiation induced damage accumulation of the VV, shielded only by the breeder modules, needs to be limited to prevent radiation induced degradation of the stainless steel strength. A limit of 2.75 dpa, accumulated over the full DEMO plant lifetime, has been specified to ensure that the fracture toughness is reduced by no more than 30% [18].

A shielding criterion of minor importance for DEMO is the accumulated He production of steel components which need to be re-welded e. g. the coolant feeding pipes. To enable re-welding, the He concentrations should be less than 1 appm in stainless steel [18]. The DEMO design goal, however, is to necessitate re-welding only at such locations where sufficient shielding can be provided, e. g. in the vessel ports or at the bottom of the blanket segments. Actually, the He production at the front of the VV (behind the blanket modules) is in the order of about 0.5 appm/fpy and less.

Radial profiles of the nuclear responses relevant for shielding are shown in Figs. 6a to 6c as obtained for the inboard mid-plane. The calculations were performed with the DEMO models developed for the HCPB, HCLL, DCLL and WCLL blankets as described above. Normalization was performed to the DEMO fusion power of 1572 MW. The resulting neutron wall loading at the inboard mid-plane first wall is about 1.15 MW/m^2.

The considered WCLL blanket version shows the best performance with regard to the radiation shielding. This is mainly due to the BSS/manifold configuration which, according to the design proposed by ENEA, is assumed as compact component with a homogenised material composition of 74.4% Eurofer, 4.8% H2O, 9.2 % LiPb and 11.6% void.

Specific comments and findings are given in the following for the nuclear responses obtained at the first wall, the front of the VV and the front of the TFC.

Fast neutron flux density: It is highest for the PbLi based blankets with no water included, typically around 6 to 7 10^{14} $cm^{-2}s^{-1}$ at the first wall, i. e. about a factor 2 higher than for the HCPB blanket. The attenuation across the blanket modules is about one order of magnitude except for the WCLL blanket, which provides another order of magnitude due to the assumed compact BSS/manifold including water as efficient neutron moderator. At the front of the TFC the fast neutron flux density is in the order of the specified limit, again with the lowest value for the WCLL.

Displacement damage in steel: The dpa rate at the first wall amounts to 8.1, 9.4, 10.4 and 10.4 dpa/fpy for the HCPB, HCLL, DCLL and WCLL blankets, respectively. At the front of the VV it is 0.22, 0.20, 0.15, and 0.042 dpa/fpy, respectively. Assuming 2.75 dpa as limit, as noted above, it is thus possible to operate the VV safely as lifetime component over the full anticipated DEMO lifetime of 6 fpy.

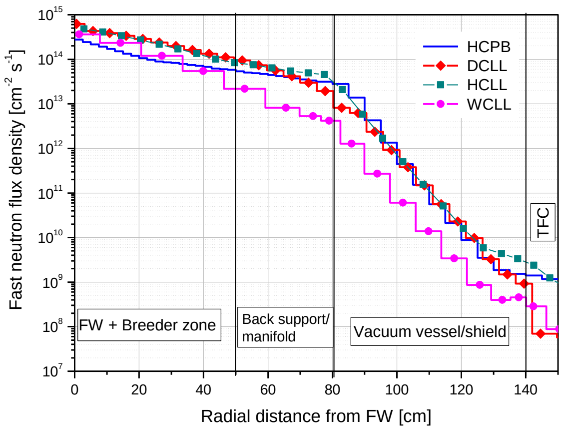

Fig. 6a: Fast (E>0.1 MeV) neutron flux density

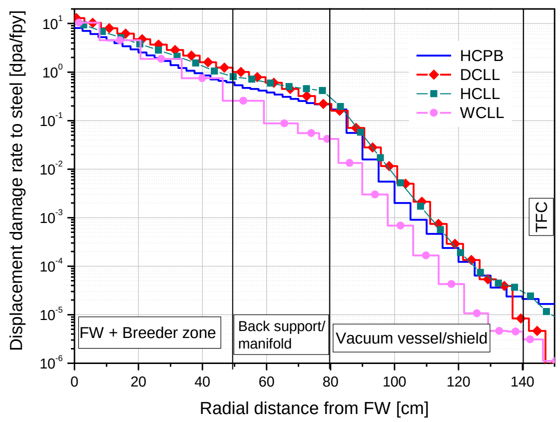

Fig. 6b: Displacement damage rate in steel [dpa/fpy]

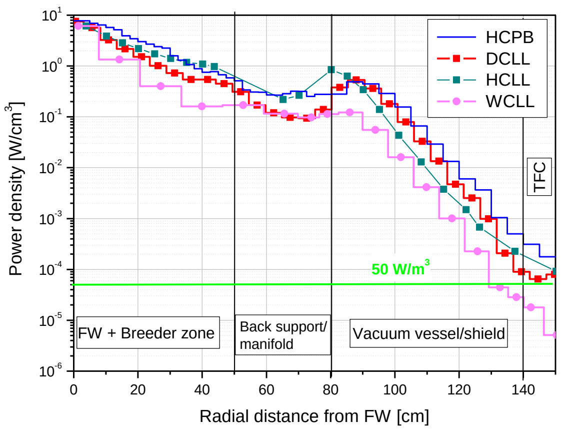

Fig. 6 c:Nuclear power density in steel [W/cm3]

Fig. 6 a- c: Radial profiles across the inboard mid-plane.

Nuclear heating in steel: The nuclear power density at the first wall is around 7 to 9 W/cm^3 and decreases to values in the order of 0.5 – 0.8 W/cm^3 (HCLL, HCPB) and 0.1 to 0.2 W/cm^3 (WCLL, DCLL) at the back of the modules. There is a discontinuous increase of the power density in the front plate of the VV due to the large amount of water present in the inner (shielding) part of the VV. The further attenuation of the power density across the VV depends predominantly on the material composition assumed for the inner (shielding) zone of the VV. With the standard material mixture (80% steel, 20 % water) the 50 W/m^3 limit in the TFC can be achieved only for the WCLL configuration. For the other blanket options, the utilization of more efficient shielding materials including WC or borated water is required. With such shielding materials employed in the VV, the power density in the TFC is further decreased by about one order of magnitude without modification of the dimensions [17, 19]. This is sufficient to keep the limit for the nuclear power density in the TFC.

7. Conclusions

Nuclear performance issues of the HCPB, HCLL, DCLL and WCLL breeder blankets, which are under development within the PPPT programme of EUROfusion, have been presented with the objective to assess the potential and suitability for the application of the blankets to a DEMO power reactor and provide feedback to the design teams to enable design improvements in an early development phase.

The Tritium breeding potential is considered sufficient for all breeder blanket options although the initial 2014 design versions of the HCPB, HCLL and DCLL blankets were shown to require further design improvements to achieve the required TBR $\geq$ 1.10. Suitable measures have been proposed and proven to be sufficient to ensure the required TBR.

The shielding performance was shown to be sufficient to protect the super-conducting TFC from the penetrating radiation provided that efficient shielding material mixtures including WC or borated water are utilized in the VV. The WCLL blanket, on the other hand, does not require the use of such shielding materials and is thus superior with regard to the shielding performance. This is mainly due to the considered BSS/manifold configuration which yet requires design verification.

The vacuum vessel can be safely operated over the full anticipated DEMO lifetime of 6 full power years for all blanket concepts considered.

Acknowledgement

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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