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Activation and decay heat analysis of the European DEMO blanket concepts

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HIGHLIGHTS

- Activation and decay heat analysis of the four European breeder blanket concepts.
- MCNP, FISPACT-II and ACAB used to calculate the activation and decay heat.
- Variations in material composition and neutron spectrum between blanket concepts leads to difference in activation and decay heat.
- HCLL blanket concept had the lowest decay heat at short decay times.

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ABSTRACT

Demonstrating tritium self-sufficiency is an important goal of the European tokamak demonstration fusion reactor. Currently four breeder blanket concepts are being considered: the Helium Cooled Pebble Bed (HCPB), Helium Cooled Lithium-Lead (HCLL), Dual Cooled Lithium-Lead (DCLL) and Water Cooled Lithium-Lead (WCLL). Differences in materials and construction of the four breeder blanket concepts lead to differing nuclear responses. As well as affecting tritium breeding this is also of particular importance in safety analyses, such as the modelling of loss of coolant accidents, as it affects the blanket's decay heat and nuclide inventory.

This paper presents and discusses analysis performed for each of the 2014 designs of the blanket concepts to ascertain the decay heat and nuclide inventory for the entire reactor. It was found that the total decay heat at short decay times for the HCLL concept (17.5 MW at 1 s) was between 17% and 22% lower than the HCPB, WCLL and DCLL. At longer decay times (~100 years) it was found that the DCLL and WCLL blankets had decay heats in the region of 2–3 orders of magnitude above the HCPB and HCLL blankets. The differences noted between the blanket concepts are discussed in terms of neutron spectrum and material composition.

1. Introduction

In order to demonstrate that Deuterium–Tritium (D–T) fusion is a sustainable energy source it will be necessary for power reactors to demonstrate tritium self-sufficiency. This will be an important goal for the European demonstration tokamak (DEMO). It is currently envisaged that tritium will be bread from lithium using neutrons produced during the D–T fusion reaction. The lithium will be incorporated into breeder blankets situated around the outside of the plasma chamber in areas of high neutron flux. There are currently several design concepts of breeder blankets being assessed for use in DEMO. These include: Helium Cooled Pebble Bed (HCPB) – uses a helium coolant and a ceramic lithium orthosilicate breeding material with a beryllium neutron multiplier; Helium Cooled Lithium-Lead (HCLL) – uses a helium coolant with a lithium-lead eutectic breeding material and neutron multiplier; Dual Cooled Lithium Lead (DCLL) – uses a helium and lithium-lead eutectic as coolant, and a lithium-lead eutectic breeding material and neutron multiplier; and Water Cooled Lithium-Lead (WCLL) – uses a water coolant with a lithium-lead eutectic breeding material and neutron multiplier.

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During operation the breeder blankets will be subjected to high neutron fluxes. This leads to material activation and damage, and the subsequent generation of decay heat. As the different breeder blanket concepts differ in layout, construction and materials their nuclear responses while under neutron irradiation will differ. This results in differing amounts of activation, damage and decay heat for each of the breeder blanket concepts. This is particularly important for safety analysis where the amount of decay heat will play an important role in the assessment of loss of coolant accidents (LOCA). It is also important for decommissioning and waste disposal as higher activities and longer lived isotopes affect the disposal route for irradiated material.

This paper describes the activation analysis carried out on all four of the 2014 breeder blanket design concepts which are currently under development. The decay heat and active nuclide inventory have been calculated to allow comparison of the four different blanket module concepts.

2. Modelling methodology

2.1. Computer codes and nuclear data

To calculate the neutron flux and energy spectra across each of the blanket components, MCNP [1] has been utilised. MCNP uses a Monte-Carlo technique to track particles throughout a 3-D geometry and estimate nuclear quantities such as flux, dose rate and nuclear heating. During the particle transport, interactions with material are controlled by nuclear cross-section data. Many cross-section libraries exist for various particle types and energy ranges. This work was focused on neutron activation so the JEFF-3.2 [2] and FENDL-2.1 [3] cross section libraries have been used.

In order to accurately calculate the decay heat and dominant active nuclides, nuclear inventory codes are required. With given neutron spectra, irradiation schedule and material composition the codes solve the Bateman equation [4] in order to calculate the nuclear inventory at given decay times. There are several nuclear inventory codes available for this type of calculation, however FISPACT [5] was chosen to perform inventory calculations for the HCPB, HCLL and WCLL blanket concepts and ACAB [6] was chosen for the DCLL blanket concept. Like neutron transport calculations, nuclear cross-sections play an important role in nuclear inventory calculations. In order to ensure consistent results between models, all blanket concepts use the European Activation Files (EAF) 2007 [7] and EAF2010 [8].

The current baseline DEMO design will include, in the first phase, the deployment of a so called ‘starter blanket’ with a maximum displacement damage of 20 dpa in the steel contained in the first wall followed by a second phase employing a second blanket with can withstand at least 50 dpa. This study only considered the ‘starter blanket’, as these are the blankets currently under design, and as such the irradiation schedule only covers the first 5.2 calendar years of operation. A pictorial representation of the irradiation schedule used in the inventory calculations is given in Fig. 1. It should be noted that in these calculations no account has been taken for the flowing nature of the lithium-lead eutectic and it has been irradiated with the entire first phase blanket irradiation schedule.

2.2. Radiation transport models

MCNP models of the DEMO reactor and blanket modules were required in order to calculate neutron flux and spectra throughout the blanket modules. The model [9] used for the HCLL blanket calculations can be seen in Fig. 2. This model has been developed as part of the EUROfusion Power Plant Physics & Technology project and relates to a reactor with a D–T fusion power of 1572 MW. As each D–T reaction releases a 14.1 MeV neutron this equates to approximately 5.581×10^{20} n/s for the entire reactor. Due to the symmetrical nature of the DEMO design, instead of a full 360° tokamak, it is possible to model only a 11.25° sector of the tokamak with vertical reflecting planes at 0° and 11.25°.

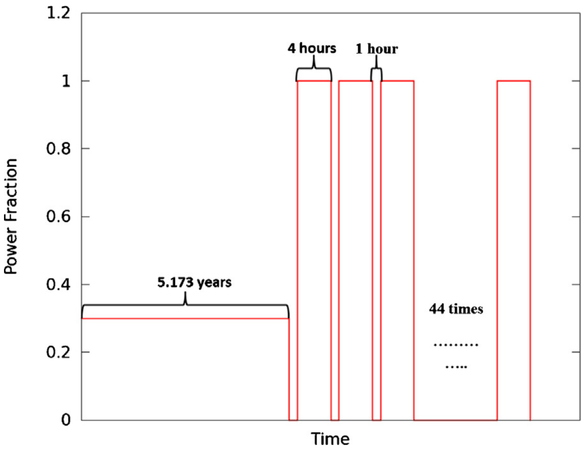


Fig. 1. First blanket phase irradiation schedule.

The MCNP DEMO reactor model includes all of the main features of a demonstration power plant including the Toroidal Field (TF) and Poloidal Field (PF) coils, Vacuum Vessel (VV), blanket modules, divertor and ports. The majority of these systems are still pre-conceptual designs and as such are only represented by homogeneous blocks. The models used for the other blanket concepts varied slightly but contained all of the same major features.

Activation calculations were carried out on each of the homogeneous finite-elements of the blanket modules. These finite-elements include the first wall armour (FWA), first wall (FW), breeder material, caps and lateral walls, back plate and the manifold. The finite-elements making up the blanket modules are shown in Fig. 2. Averaged neutron Flux values were calculated across each of these finite-elements and along with the homogeneous material definitions these were fed to the inventory code in order to calculate decay heat and active nuclide inventory.

The homogeneous material specifications for each of finite-element of each blanket concept is given in Table 1. These are given as the percentage volume for each material. As can be seen the HCLL, DCLL and WCLL all contain PbLi for the neutron multiplier and tritium breeder whereas the HCPB design uses beryllium for the neutron multiplier and Li_4SiO_4 as the tritium breeder. There

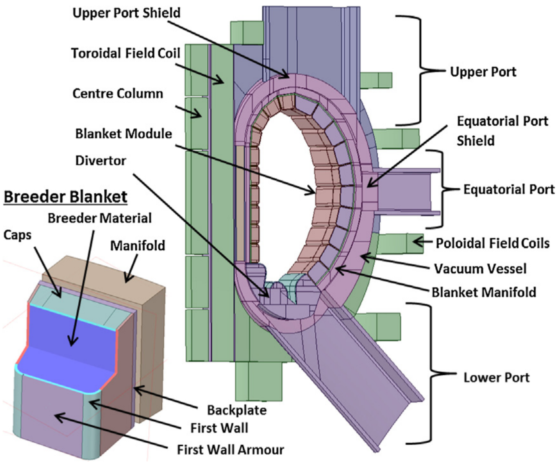


Fig. 2. DEMO generic HCLL MCNP model with homogeneous blanket modules.

Table 1
Blanket modules material specification.

Vol (%)	Armour		First wall				Breeding material							
	Vol (m^3)	W	Vol (m^3)	Eurofer	Water	He 80 bar	Vol (m^3)	Eurofer	Be	Water	Li_4SiO_4	PbLi	He 80 bar	He 1 bar
HCLL	1.6	100	21	70	–	30	606	13	–	–	–	78	8	–
HCPB	2.5	100	29	70	–	30	765	11.76	37.9	–	13.04	–	8.7	28.6
DCLL	2.2	100	20	85.54	–	14.46	767	17.85	–	–	–	73	9.15	–
WCLL	2.2	100	20	89.5	10.5	–	767	18	–	1.9	–	80.1	–	18

	Caps				Backplate				Manifold					
	Vol (m^3)	Eurofer	Water	He 80 bar	Vol (m^3)	Eurofer	PbLi	He 80 bar	Vol (m^3)	Eurofer	Water	PbLi	He 80 bar	Void
HCLL	52	90	–	10	26	24	8	68	179	29	–	11	60	–
HCPB	47	70	–	30	44	95.3	–	4.7	311	67.8	–	–	32.2	–
DCLL	49	85.54	–	14.46	23	85.54	–	14.46	451	51.29	–	44.36	4.35	–
WCLL	49	95.2	4.8	–	23	100	–	–	451	74.4	4.8	9.2	–	11.6

are also differences in the amounts of stainless steel (Eurofer) and helium coolant between designs. The WCLL design contains water which may have a significant effect on the neutron flux and spectrum as it is a relatively good moderator and neutron absorber. It should be noted that the material definitions used for Eurofer, PbLi, Tungsten, beryllium and Li_4SiO_4 all contained impurities which can be important for activity and decay heat results at longer decay times.

3. Results

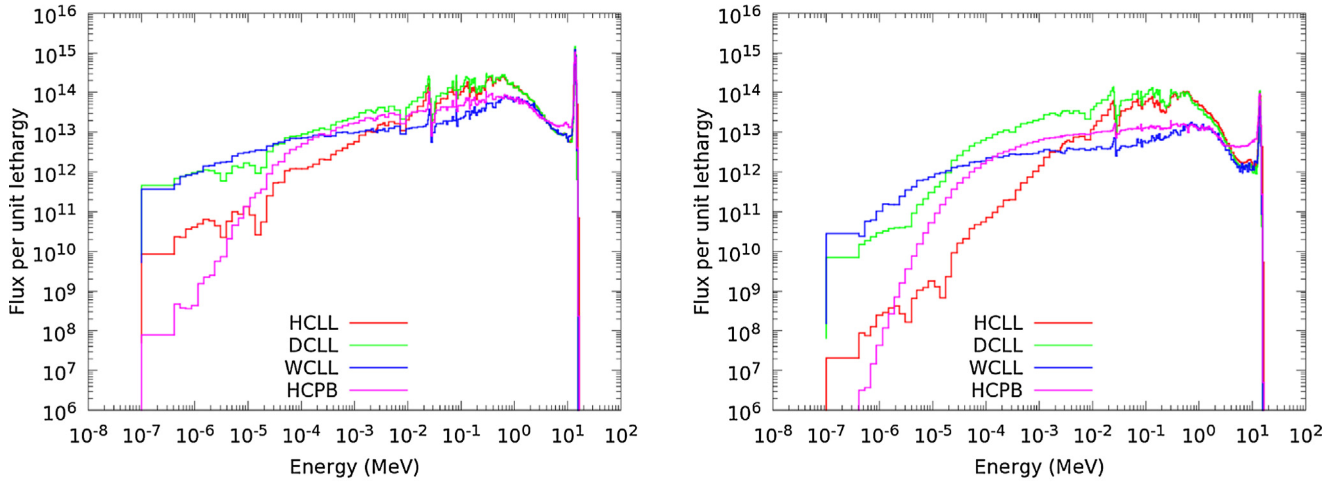
3.1. Neutron flux and spectra

An average neutron flux and spectra were calculated in each of the finite-elements of the breeder blankets. This was done for all blanket modules in the 11.25° sector. Due to the differing material compositions the neutron spectra differ considerably between concepts. They also differ considerably between the parts of the blanket modules. Examples of the types of differences can be seen in Fig. 3a and b.

For all blanket module concepts, as would be expected, the 14.1 MeV peak is higher in the first wall when compared to the breeder material. As the neutrons pass through the first wall and interact with the material some lose some of their energy and some are absorbed; this results in the lower 14.1 MeV peak in the areas deeper within the blanket. The HCLL and DCLL concepts have similar high energy spectra in both the FW and breeder material. However the HCLL blanket has significantly lower low energy tails to the spectra for both the FW and breeder material. This may be due to the DCLL concept containing a larger fraction of Eurofer (steel) and helium coolant when compared to the HCLL. These are likely to be a better moderator than the PbLi leading to a greater number of lower energy neutrons. The WCLL blanket concept has the most thermalised spectrum in both the first wall and breeder material mainly due to the presence of water as the coolant. The HCPB has fewer very low energy neutrons although it is not exactly clear what is the cause of this. It also has a greater number of neutrons in the range 1–10 MeV compared to the other three concepts. This is most likely due to the higher neutron capture cross sections for lead (used in the other three concepts) compared to beryllium.

3.2. Decay heat and dominant nuclides

The shutdown decay heat after first phase irradiation for each blanket concept has been calculated for all blanket modules within the 11.25° sector. The results from this have been multiplied by 32 to give the total decay heat for all blankets in the complete 360° tokamak. The decay heat against decay time for each of the reactor concepts can be seen in Fig. 4. Please note that the decay heat values given in Fig. 4 do not contain any decay heat generated by tritium in



(a) First Wall (b) Breeder Material

Fig. 3. Neutron energy spectra at the first wall and breeder material for each of the four blanket concepts, given in neutron fluxes per lethargy interval.

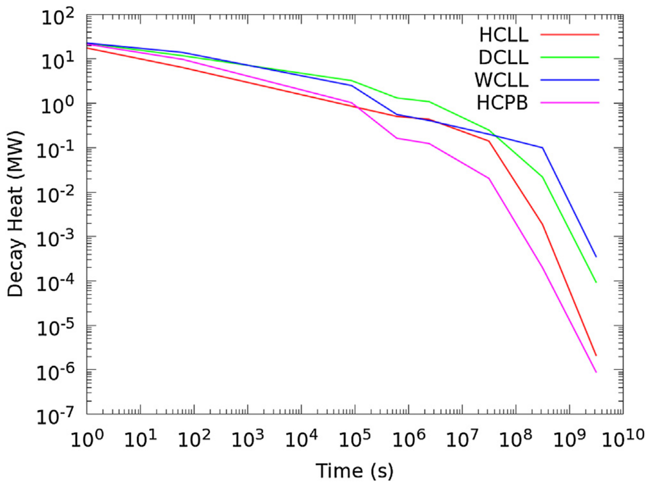
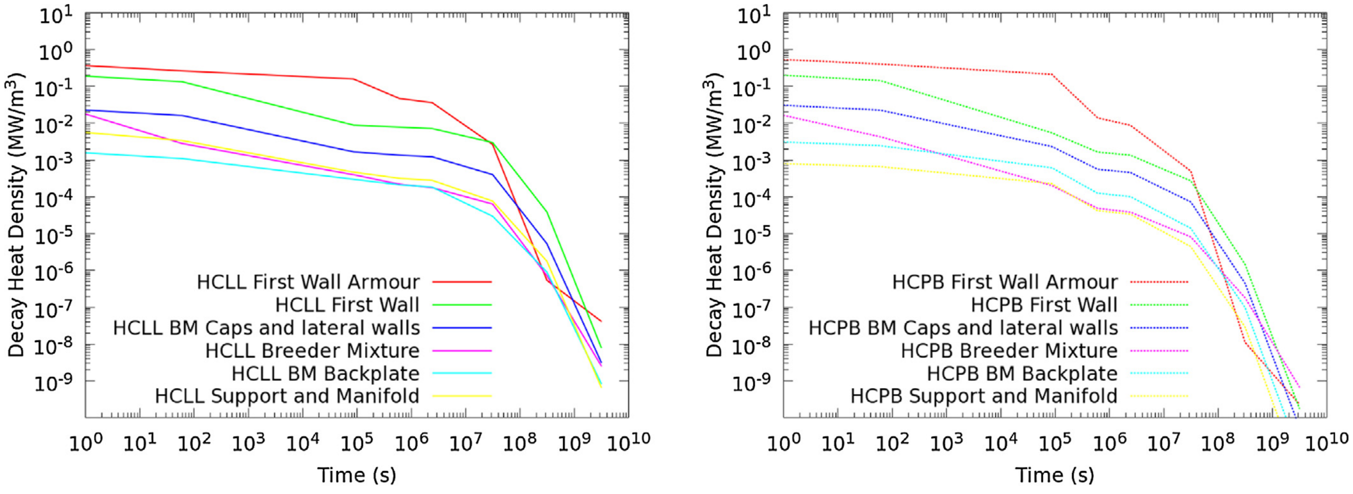


Fig. 4. Total blanket decay heat (MW) at various cooling times for each concept.

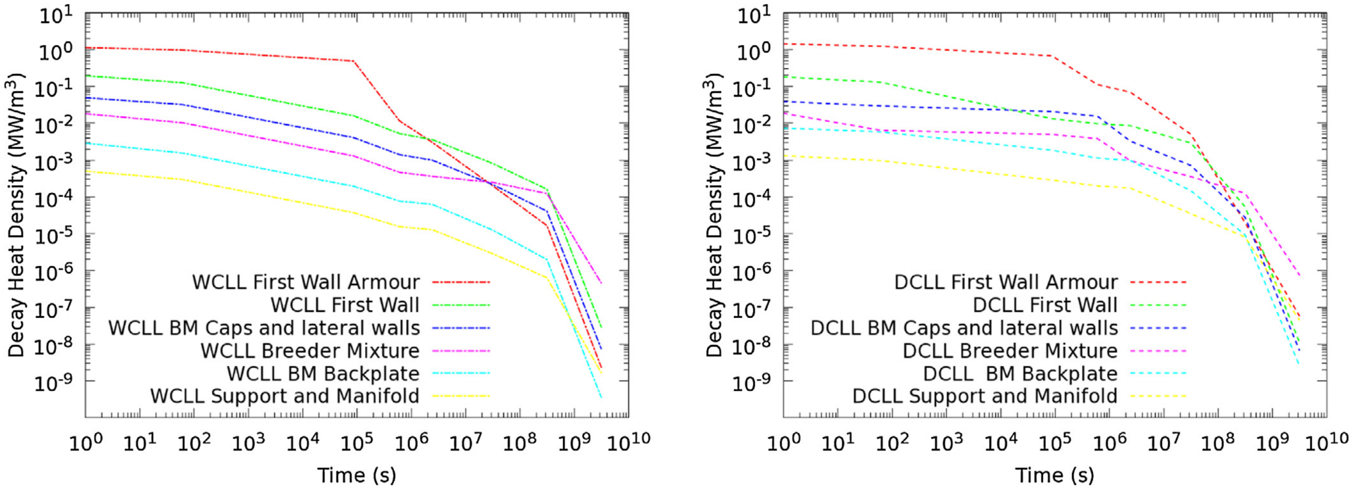
the breeding material. Tritium will be constantly extracted from the breeding material of all blanket concepts. This will lead to steady state level of tritium contributing to the decay heat. However due to the design still being pre-conceptual the amount of tritium present in this steady state is unknown. If all of the generated tritium was left in the blanket module it would dominate the decay heat results at certain decay times making them unrealistic. Although not necessarily conservative, the decision was taken to remove all of the tritium in order to have more realistic results.

All of the blanket module concepts have decay heats in the tens of MW in the seconds after shutdown. The HCLL blanket has the lowest decay heat for short decay times ($<1\times10^5$ s) with 17.5 MW predicted 1 s after shutdown. This is approximately 17–22% lower than predicted for the other blanket concepts of 21.5–22.7 MW, 1 s after shutdown. For all concepts this is a significant amount of decay heat which will require dissipating in order to not over heat or melt components.

At longer decay times ($>1\times10^5$ s) the HCPB concept generates the least decay heat of all concepts. This is followed by the HCLL. The DCLL and WCLL have decay heats which are 2–3 orders of magnitude higher at times $>1\times10^5$ s. This may mean that forced cooling for the DCLL and WCLL may be required for longer after shutdown. The DCLL has the highest decay heat up to decay times of $\sim1\times10^8$ s



(a) HCLL (b) HCPB



(c) WCLL (d) DCLL

Fig. 5. Decay heat density (MW/m^3) for each of the four blanket concepts.

and the WCLL has the highest for decay times >1 $\times 10^8$ s. For all concepts the greatest amount of decay heat is generated in the breeder material region of the blanket modules. Although this area does not have the greatest decay heat density, see Fig. 5, it does have significantly more mass than any other region. The areas towards the back of the blanket modules, such as the backplate and manifold, tend to have the lowest contribution to the decay heat as they are in regions of relatively low neutron flux (leading to lower activation) and have relatively little mass.

In order to ensure adequate cooling is supplied to all blanket components, a study into which components generate the highest decay heat density has been performed. The decay heat density for the finite-elements of each of the blanket concepts can be seen in Fig. 5a–d. The decay heat densities are averaged over all blanket modules. Although there is some poloidal variation in the decay heat density the general trends are the same as the average.

As would be expected, due to the high neutron flux, the highest decay heat density (for decay times <1 $\times 10^8$ s for the HCLL, HCBP and DCLL and 1 × 10^5 s for the WCLL) occurs for the first wall armour (FWA) for all blanket concepts. The dominant nuclides in the FWA at shorter decay times appear to Tungsten isotopes; mainly ^{187}W with a 23.9 h half-life. At decay times longer than 10 years the products of the minor impurities in the Tungsten such as ^{60}Co and ^{39}Ar dominate the decay heat. It is therefore important to ensure these are minimised where possible. The decay heat density at short decay times for the FWA is slightly higher for the WCLL and DCLL than the HCLL and HCPB. The production of the dominant ^{187}W via the (n,γ) reaction with ^{186}W has the highest cross section at low neutron energies. As can be seen from Fig. 3a the WCLL and DCLL have greater neutron moderation in the first wall area which leads to higher production of ^{187}W and therefore a higher decay heat density.

The other blanket areas have similar decay heat densities between concepts apart from the manifold for the HCLL. For the HCPB, WCLL and DCLL the manifold has the lowest decay heat density. However for the HCLL the decay heat density for the manifold is above that of the backplate and breeder mixture for most decay times. This is likely due to the limited shielding that is offered by the HCLL blanket module design. This leads to a higher neutron flux with a ‘harder’ spectrum in the region of the manifold resulting in more activation and subsequent decay heat.

4. Summary

Neutron transport and activation simulations have been performed to analyse the decay heat and nuclear inventory for four DEMO blanket concepts. It was found that the HCLL blanket modules gave the lowest total decay heat, 17–22% lower than other three concepts. For most decay times, and all blanket concepts, the FWA has the highest decay heat density although the breeder material contributes the majority of the decay heat due to its large mass. The more thermalised spectrum in the DCLL and WCLL designs mean that more ^{187}W is created within the Tungsten FWA and the 1.2 atm.% Tungsten contained within Eurofer.

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