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Exploratory tritium breeding performance study on a water cooled lead ceramic breeder blanket for EU DEMO using Serpent-2

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ABSTRACT

Innovative Water cooled Lead Ceramic Breeder (WLCB) blanket concepts are being developed at Karlsruhe Institute of Technology (KIT) to explore alternative options for the European demonstration fusion power plant (DEMO). Compared to the Helium Cooled Pebble Bed blanket (HCPB, which is one of the two driver blanket concepts of the European DEMO), Lead/ Lead-alloy is used as neutron multiplier instead of Be/Be-alloy and pressurized subcooled water is used as coolant instead of Helium in the WLCB. The tritium self-sufficiency is the vital function that a Breeding Blanket has to achieve. The absorption of neutrons by water leads to a decrease in the number of neutrons, so the requirement to improve the tritium breeding capacity of the water-cooled blankets is particularly prominent. The Monte Carlo neutron transport code Serpent-2 developed by VTT in Finland has already been benchmarked to be applicable to neutronics calculations in the fusion reactors in a previous study. In this paper, an exploratory TBR study on Water cooled Lead Ceramic Breeder Blanket is presented.

Introduction

The Helium Cooled Pebble Bed (HCPB) breeding blanket (BB) [1] is one of the two driver blanket candidates for the European demonstration fusion power plant (EU DEMO) [2]. The research on HCPB BB has made great progress in recent years [3–8]. At the same time, the EU is pursuing also water cooled concept based on PbLi as functional material [9]. A water cooled concept based on solid breeder ceramics could be envisaged. However, the presence of Be/Be-alloy as neutron multiplier represents a safety (H_2 production) issue if water is ever to come in contact with this material in an accidental event. A way to circumvent this issue is by using Pb/Pb-compounds as substitute for Be-based neutron multiplier. Such innovative concept, a Water cooled Lead Ceramic Breeder (WLCB) blanket [10], is being developed at Karlsruhe Institute of Technology (KIT) for the European DEMO and it derives from the HCPB architecture (i.e. arrangement of fuel-breeder pins).

The tritium self-sufficiency is a necessary mission of WLCB that has to be achieved. The absorption of neutrons by water leads to a decrease in the number of neutrons, so the requirement to improve the tritium breeding capacity of the water-cooled blanket is particularly prominent. Serpent [11] is a three-dimensional continuous energy Monte Carlo particle transport code developed at VTT Technical Research Centre of Finland, and the code has been publicly distributed since 2009. The features of Serpent-2 such as neutronics modeling, neutron source definition, and neutron and photon flux spectra, nuclear heating and tritium breeding ratio (TBR) calculations have all been benchmarked with MCNP5 [12]. An exploratory tritium breeding performance study of WLCB BB is carried out in this paper, such as the impacts of material compositions of breeder zone and first wall (FW) and different architecture of blanket on TBR.

WLCB model

The blanket casing is built by a U-shaped FW, caps and a back plate, the FW is being covered with a 2 mm armor (tungsten is assumed). The radial length of the inboard and the outboard WLCB breeding zone is

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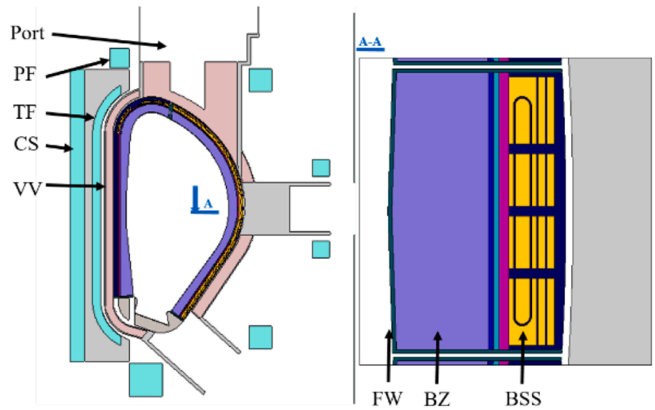

Fig. 1. Poloidal cut of WLCB Serpent-2 model (left) and horizontal cuts in OB side (right).

Table 1
TBR parametric analysis.

Group 1	Lithium ceramics	Lead	Water	Eurofer	TBR
1	5.00%	72.32%	8.44%	14.24%	1.023
2	20.00%	60.90%	7.10%	12.00%	1.168
3	35.00%	49.48%	5.77%	9.75%	1.179
4	50.00%	38.06%	4.44%	7.50%	1.153
5	65.00%	26.64%	3.11%	5.25%	1.105
6	80.00%	15.22%	1.78%	3.00%	1.039
7	95.00%	3.81%	0.44%	0.75%	0.956
Group 2	Lithium ceramics	Lead	Water	Eurofer	TBR
1	48.45%	5.00%	17.31%	29.23%	0.967
2	40.80%	20.00%	14.58%	24.62%	1.039
3	33.15%	35.00%	11.85%	20.00%	1.103
4	25.50%	50.00%	9.11%	15.39%	1.151
5	17.85%	65.00%	6.38%	10.77%	1.168
6	10.20%	80.00%	3.65%	6.15%	1.109
7	2.55%	95.00%	0.91%	1.54%	0.717
Group 3	Lithium ceramics	Lead	Water	Eurofer	TBR
1	20.36%	62.36%	5.00%	12.28%	1.162
2	17.14%	52.51%	20.00%	10.34%	1.170
3	13.93%	42.67%	35.00%	8.40%	1.143
4	10.71%	32.82%	50.00%	6.46%	1.096
5	7.50%	22.97%	65.00%	4.53%	1.031
6	4.29%	13.13%	80.00%	2.59%	0.943
7	1.07%	3.28%	95.00%	0.65%	0.787
Group 4	Lithium ceramics	Lead	Water	Eurofer	TBR
1	21.49%	65.83%	7.68%	5.00%	1.218
2	18.10%	55.44%	6.47%	20.00%	1.113
3	14.70%	45.04%	5.25%	35.00%	1.009
4	11.31%	34.65%	4.04%	50.00%	0.898
5	7.92%	24.25%	2.83%	65.00%	0.762
6	4.52%	13.86%	1.62%	80.00%	0.568
7	1.13%	3.46%	0.40%	95.00%	0.213

Table 2
TBR at different material radio in BZ.

Case Number	Lithium ceramics	Lead	Water	Eurofer	TBR
Case 1	20.65%	61.759	1.46%	16.13%	1.112
Case 2	20.58%	62.07%	3.52%	13.83%	1.129
Case 3	18.94%	62.07%	4.60%	14.37%	1.129
Case 4	21.30%	63.70%	6%	9.00%	1.169

483.6 mm and 667 mm, respectively. A mixture of Li_4SiO_4 and 35 mol% Li_2TiO_3 (90% ^{6}Li enrichment in both compounds) [13] and Lead/ Lead-alloy are used as tritium breeder and neutron multiplier, respectively. The packing factor of lithium ceramics is 63.5%. The 15.5 MPa water provides the cooling of the blanket and EUROFER97 steel [14] is used as structural material. The inlet water temperature was set at 300 °C, and the outlet temperatures of FW and breeder zone (BZ) were 330 °C. Design description of the WLCB is detailed in [10]. Fig. 1 shows the Serpent-2 neutronics model of the WLCB in outboard (OB) side.

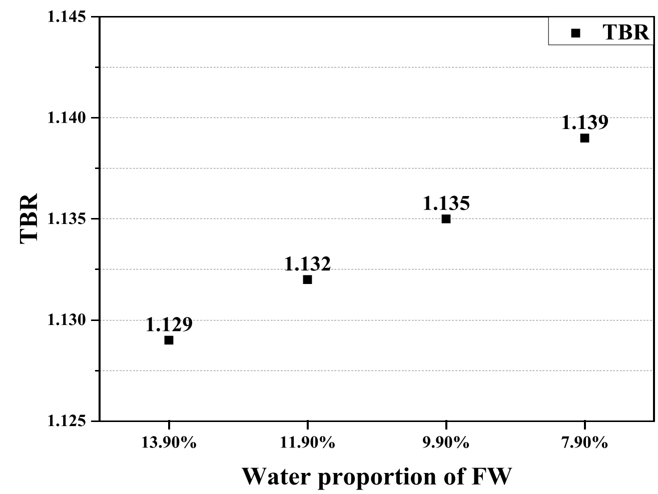

Fig. 2. Material sensitivity of TBR in FW.

TBR exploration

For water-cooled blanket, meeting the need for tritium self-sufficiency is one of the major challenges. In order to improve the TBR of WLCB BB, several explorations have been conducted in this work. The neutronics model is modified based on the EU-DEMO 2017 model [12]. An 11.25° torus model of WLCB blanket is generated for TBR exploration. In order to facilitate the parametric study, homogeneous material was adopted to the TBR analysis. Serpent v2.1.31 was used in all the calculations. The neutron cross-section data and photon cross-section data are from the FENDL-3.1d [15] data library and mcplib04 photon library, respectively. In order to ensure the accuracy of data, the statistical errors of all the TBR calculation results are within 0.0001.

Sensitivity analyses

TBR parametric analysis

Firstly, a parametric analysis of TBR has been done. In this parametric analysis, FW (the original 20 mm thick FW was used) is composed of 88.1% Eurofer and 11.9% pressurized water. The four materials (Eurofer, lithium ceramics, lead and water) of blanket were divided into four groups and analyzed sequentially. In each group, the proportion of one material gradually increases, while the relative proportions of the other three materials remain unchanged.

However, the design of the blanket must not only meet the requirements of tritium self-sufficiency, but also meet the requirements of thermal hydraulics and mechanical performances, so not all combinations have practical significance. In this way, we can roughly find out the influence of a single material on the TBR and screen out the combination that meets the requirements of tritium self-sufficiency (TBR >= 1.10). Table 1 shows the material proportions and TBR results of these four groups. The material proportions of lithium ceramics contains 36.5% of the purge gas.

Realizable configurations

TBR calculations for four cases of material composition are performed. The material composition of FW in all the cases are same (86.10% Eurofer and 13.90% water). The material composition of BZ in these cases and the TBR results are shown in Table 2.

It can be seen that after reducing the proportion of structural steel

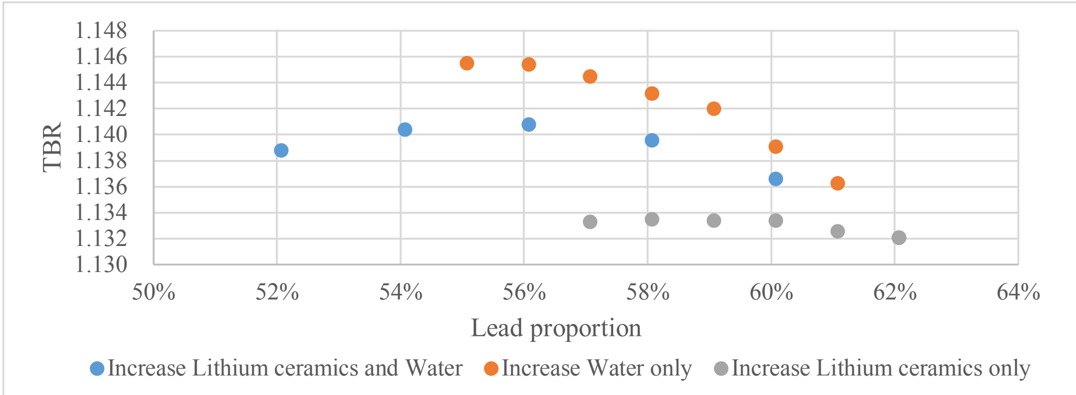

Fig. 3. TBR exploration of reducing the proportion of lead in BZ.

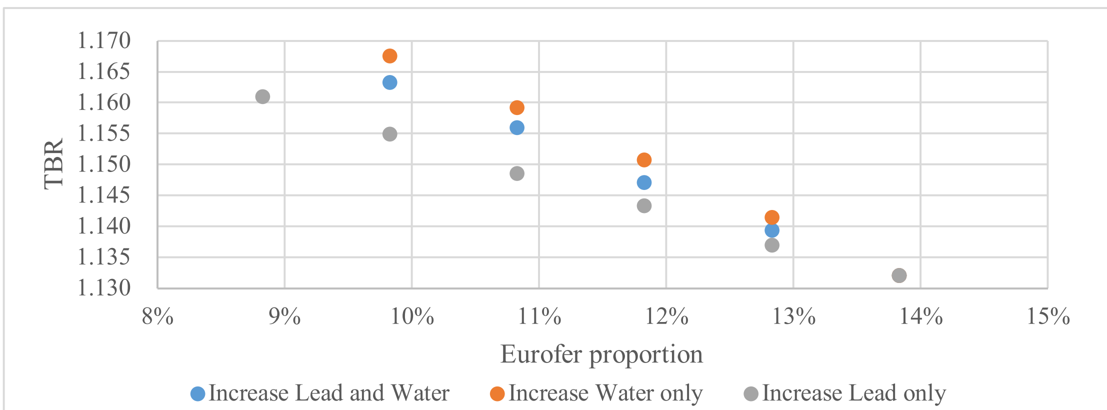

Fig. 4. TBR exploration of reducing the proportion of Eurofer in BZ.

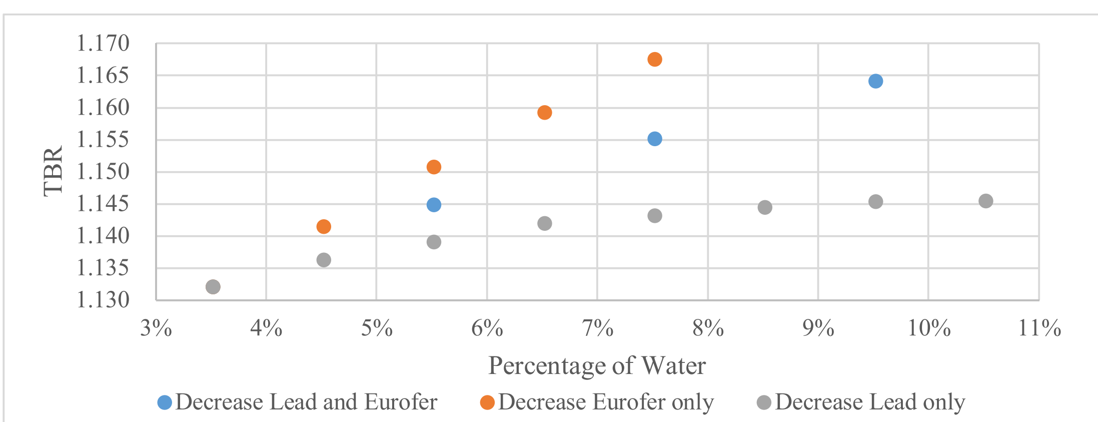

Fig. 5. TBR exploration of increasing the proportion of water in BZ.

and increasing the proportion of water, TBR is increased. This is because structural steel absorbs neutrons and water moderates them (Although water also absorbs neutrons, the moderation effect increasing reaction cross-section of ^{6}Li(n,α)T which improves TBR is more dominant).

TBR sensitivity study on FW material mix

For FW, material sensitivity is easier to carry out because it contains only coolant (pressure water) and structural steel (Eurofer). Four cases were tested, in which the proportion of water in FW decreased from 13.90% to 11.90%, 9.90% and 7.90% respectively.

As shown in Fig. 2, within a certain range, TBR increases by 0.003 ∼ 0.004 for every 2% decrease in water in the FW.

TBR sensitivity study on BZ material mix

Based on the material proportion of BZ Case 2 and the FW scheme with volume proportion of 11.9% water and 88.1% Eurofer, the TBR exploration of reducing the proportion of lead in BZ, the proportion of Eurofer and increasing the proportion of water was carried out in turn.

TBR exploration of reducing the proportion of lead in BZ are divided into three groups:

1. Reduce lead, increase the proportion of water and lithium ceramics;

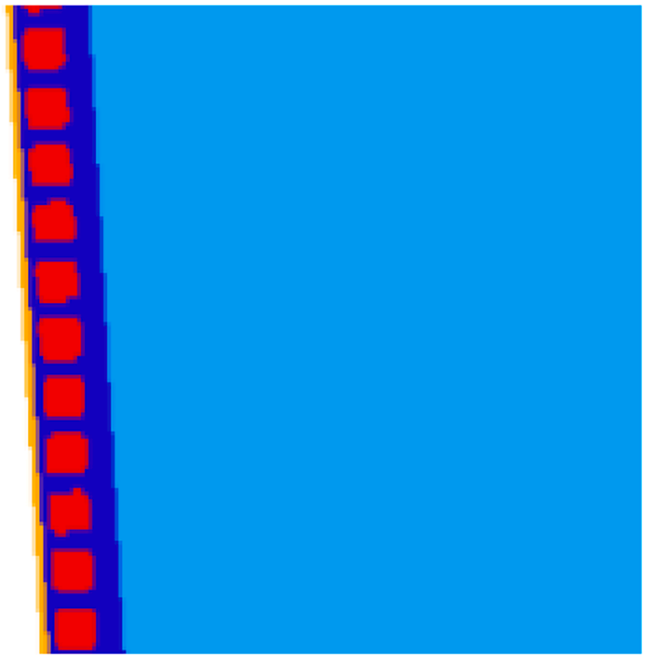

Fig. 6. Heterogeneous model of FW at the outboard mid-plane blanket region.

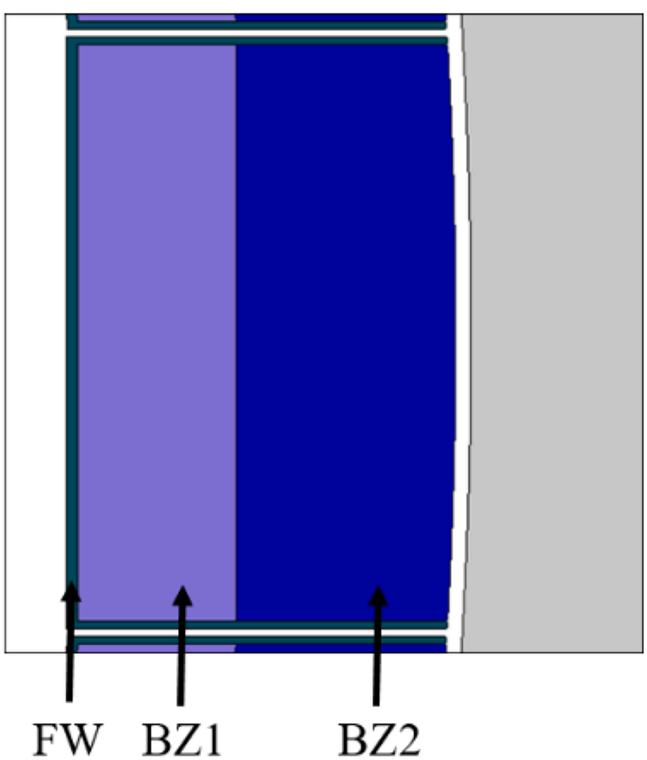

Fig. 7. Horizontal cut of the BZ structure in OB side.

2. Reduce lead and increase the proportion of water;
3. Reduce lead and increase the proportion of lithium ceramics.

Please refer to Table A in the appendix for specific material proportions.

As shown in Fig. 3, if the scheme of only increasing the proportion of lithium ceramics is adopted, when the proportion of lead decreases from 62.07% to 60.07%, the increase in TBR tends to become moderate. If the scheme of only increasing the proportion of water, when the proportion of lead decreases from 62.07% to 56.07%, and the increase in TBR tends to become moderate. If the proportions of lithium ceramics and water were increased at the same time, when the proportion of lead decreased from 62.07% to 56.07%, TBR reached its peak. It is worth noting that when the proportion of lead is reduced, the effect of only increasing the proportion of water (moderating the neutrons) is the best, while the effect of increasing the proportion of lithium ceramics is not obvious.

TBR exploration of reducing the proportion of Eurofer in BZ are also divided into three groups:

1. Reduce Eurofer, increase the proportion of lead and water;
2. Reduce Eurofer and increase the proportion of water;
3. Reduce Eurofer and increase the proportion of lead.

Please refer to Table B in the appendix for specific material proportions.

As shown in Fig. 4, TBR increased when the proportion of Eurofer is reduced. This is because the structural steel plays the role of neutron absorption, which affects the tritium production of neutrons. Among them, the scheme of only increasing the proportion of water has the most obvious effect on the increase of TBR.

TBR exploration of increasing the proportion of water in BZ are also divided into three groups:

1. Increase water, reduce the proportion of lead and Eurofer;
2. Increase water and only reduce the proportion of Eurofer;
3. Increase water and only reduce the proportion of lead.

Please refer to Table C in the appendix for specific material proportions.

As shown in Fig. 5, if the scheme of only decreasing the proportion of lead is adopted, when the proportion of water increases from 3.52% to 9.52%, the increase in TBR tends to become moderate. Although increasing the proportion of water while reducing the proportion of Eurofer can increase the TBR. Eurofer, as a structural material, has very limited space to reduce.

According to Figs. 3–5, we can draw a conclusion: Under the current proportion of BZ Case 2 materials, appropriately reducing the proportion of lead and Eurofer, while increasing the proportion of water can increase TBR.

The effect of FW structure on TBR

Originating from the European DEMO design, the FW is in the shape of a rooftop, which is designed for shadowing the FW bending from charged particles. The new plasma physics study suggests that a rooftop shape may not be necessary, as the discrete limiters will prevent the charged particles from hitting the FW. Compared to a flat FW, a rooftop-shaped FW will leave less space in the breeder zone for tritium breeding. So, the rooftop-shape FW is replaced by a flat FW in this section. In addition, the neutronic performances can be significantly different if the FW is modelled with homogenous mixture or real heterogeneous structure. In order to investigate the influence of using homogenous mixture of FW, the outboard mid-plane blanket FW is then modelled with real heterogeneous structure, shown in Fig. 6.

In this blanket section, the TBR is 1.44E−02 for heterogeneous model and 1.40E−02 for homogenous model. It shows that an increase of TBR (about 2.9%) in this blanket section when heterogeneous model is used only in the outboard mid-plane blanket FW in WLCB.

The effect of Lead-alloy on TBR

In order to avoid magnetohydrodynamic (MHD) effect of a liquid neutron multiplier, a high melting point lead alloy $LaPb_3$ (melting temperature 1160 °C) was used as solid neutron multiplier instead of liquid lead. Since lead alloy has less Pb atomic density hence less

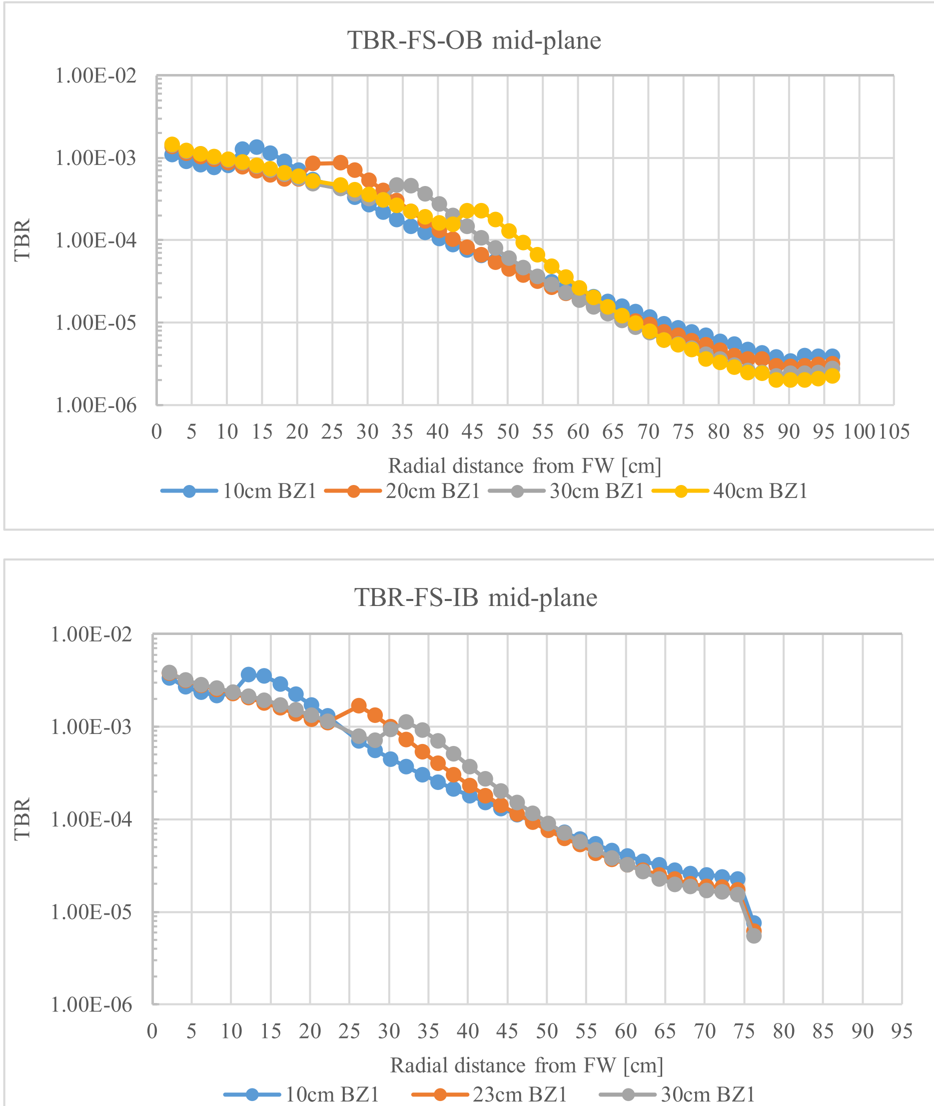

Fig. 8. Radial profile of TBR within different BZ1 radial thickness at outboard side (top) and inboard side (bottom).

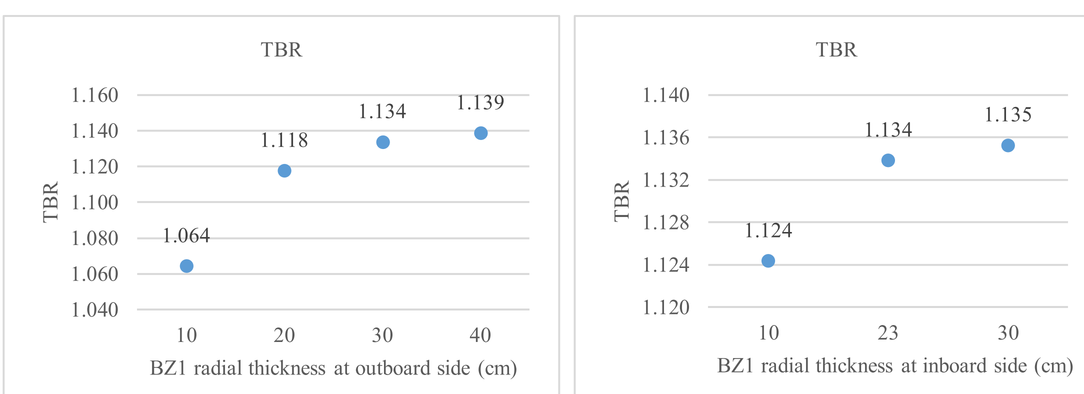

Fig. 9. TBR within different BZ1 radial thickness at outboard side (left) and inboard side (right).

effective than pure lead in neutron multiplying, the radial length of BZ at inboard side and outboard side was increased by 30 mm and 51 mm, respectively, while the radial length of back supporting structure (BSS) of inboard and outboard side were reduced. The thickness of FW is increased from 20 mm to 25 mm.

With the same material ratio, the TBR of $LaPb_3$ and pure lead as neutron multiplier are respectively 1.1464 and 1.1695. It shows when the neutron multiplier is replaced by $LaPb_3$, the TBR is reduced by about 2%.

Table A
Material proportion of reducing the proportion of lead in BZ.

Group 1	Lithium ceramics	Lead	Water	Eurofer
1	20.58%	62.07%	3.52%	13.83%
2	21.58%	60.07%	4.52%	13.83%
3	22.58%	58.07%	5.52%	13.83%
4	23.58%	56.07%	6.52%	13.83%
5	24.58%	54.07%	7.52%	13.83%
6	25.58%	52.07%	8.52%	13.83%
Group 2	Lithium ceramics	Lead	Water	Eurofer
1	20.58%	62.07%	3.52%	13.83%
2	20.58%	61.07%	4.52%	13.83%
3	20.58%	60.07%	5.52%	13.83%
4	20.58%	59.07%	6.52%	13.83%
5	20.58%	58.07%	7.52%	13.83%
6	20.58%	57.07%	8.52%	13.83%
7	20.58%	56.07%	9.52%	13.83%
8	20.58%	55.07%	10.52%	13.83%
Group 3	Lithium ceramics	Lead	Water	Eurofer
1	20.58%	62.07%	3.52%	13.83%
2	21.58%	61.07%	3.52%	13.83%
3	22.58%	60.07%	3.52%	13.83%
4	23.58%	59.07%	3.52%	13.83%
5	24.58%	58.07%	3.52%	13.83%
6	25.58%	57.07%	3.52%	13.83%

Table B
Material proportion of reducing the proportion of Eurofer in BZ.

Group 1	Lithium ceramics	Lead	Water	Eurofer
1	20.58%	62.07%	3.52%	13.83%
2	20.58%	62.57%	4.02%	12.83%
3	20.58%	63.07%	4.52%	11.83%
4	20.58%	63.57%	5.02%	10.83%
5	20.58%	64.07%	5.52%	9.83%
Group 2	Lithium ceramics	Lead	Water	Eurofer
1	20.58%	62.07%	3.52%	13.83%
2	20.58%	62.07%	4.52%	12.83%
3	20.58%	62.07%	5.52%	11.83%
4	20.58%	62.07%	6.52%	10.83%
5	20.58%	62.07%	7.52%	9.83%
Group 3	Lithium ceramics	Lead	Water	Eurofer
1	20.58%	62.07%	3.52%	13.83%
2	20.58%	63.07%	3.52%	12.83%
3	20.58%	64.07%	3.52%	11.83%
4	20.58%	65.07%	3.52%	10.83%
5	20.58%	66.07%	3.52%	9.83%
6	20.58%	67.07%	3.52%	8.83%

The effect of BZ structure on TBR

In this section, the thickness of FW is 25 mm. In the radial direction, the BZ is divided into two parts, namely BZ1 and BZ2. The BSS is replaced by BZ2. The BZ1 has the material composition of 19.00% lithium ceramics, 56.80% $LaPb_3$, 11.90% water and 12.30% Eurofer. And the BZ2 has the material composition of 19.0% lithium ceramics, 68.7% water and 12.3% Eurofer. Fig. 7 shows the horizontal cut of the blanket in OB side. Of course, this is a very simplified model, which is meant to provide quick feedback for a design concept. For a realistic design, the BSS structures and manifolds must be present for structural integrity.

In order to find out the best radial thickness of BZ1, six cases have been tested. From case 1 to case 4, the radial thickness of BZ1 at inboard side are keep 23 cm, and the radial thickness of BZ1 at outboard side are 10 cm, 20 cm, 30 cm and 40 cm, respectively. In case 5 and case 6, the radial thickness of BZ1 at outboard side are keep 30 cm, and the radial thickness of BZ1 at inboard side are 10 cm, and 30 cm, respectively.

Fig. 8 shows the radial profile of TBR within different BZ1 radial thickness at outboard side and inboard side. It can be seen that at the boundary between BZ1 and BZ2, thanks to the neutron moderation of water, there is an increase of TBR.

Table C
Material proportion of increasing the proportion of water in BZ.

Group 1	Lithium ceramics	Lead	Water	Eurofer
1	20.58%	62.07%	3.52%	13.83%
2	20.58%	61.57%	5.52%	12.83%
3	20.58%	60.07%	7.52%	11.83%
4	20.58%	59.57%	9.52%	10.83%
Group 2	Lithium ceramics	Lead	Water	Eurofer
1	20.58%	62.07%	3.52%	13.83%
2	20.58%	62.07%	4.52%	12.83%
3	20.58%	62.07%	5.52%	11.83%
4	20.58%	62.07%	6.52%	10.83%
5	20.58%	62.07%	7.52%	9.83%
Group 3	Lithium ceramics	Lead	Water	Eurofer
1	20.58%	62.07%	3.52%	13.83%
2	20.58%	61.07%	4.52%	13.83%
3	20.58%	60.07%	5.52%	13.83%
4	20.58%	59.07%	6.52%	13.83%
5	20.58%	58.07%	7.52%	13.83%
6	20.58%	57.07%	8.52%	13.83%
7	20.58%	56.07%	9.52%	13.83%
8	20.58%	55.07%	10.52%	13.83%

Fig. 9 compares the total TBR within different BZ1 radial thickness at outboard side and inboard side. It can be seen from the results that TBR increases with the increase of radial thickness of BZ1. When the radial thickness of BZ1 at outboard side and inboard side reaches 30 cm and 23 cm, respectively, the increase in TBR tends to become moderate.

Conclusions

In this paper, TBR exploration of an innovative Water cooled Lead Ceramic Breeder (WLCB) blanket for the European DEMO is carried out base on Serpent-2. Lithium ceramics, Lead/ Lead-alloy, 15.5 MPa water and Eurofer are used as tritium breeder, neutron multiplier, coolant and structural material respectively.

Firstly, TBR parametric analysis was performed to roughly find out the influence of a single material on the TBR and screen out the combination that meets the requirements of tritium self-sufficiency.

Then the sensitivity of TBR to different materials was studied. For the FW, TBR increases by 0.003 ~ 0.004 for every 2% decrease in water within a certain range. For the current material proportion of BZ, TBR can be improved by increasing the proportion of water or decreasing the proportion of Eurofer. TBR can also be improved by appropriately reducing the proportion of lead, and the corresponding increase the proportion of water is better than the increase of the proportion lithium ceramics. Even though a solid neutron multiplier $LaPb_3$ avoids MHD effect, there is a decrease of TBR when $LaPb_3$ replaces pure Pb.

In terms of FW structure, compared to homogenous model an increase of TBR (about 2.9%) is achieved when heterogeneous model is used only in the outboard mid-plane blanket FW in WLCB.

When the BZ is divided into BZ1 and BZ2, the TBR increases with the increase of radial thickness of BZ1 in a certain range. When the radial thickness of BZ1 at outboard side and inboard side reaches 30 cm and 23 cm, respectively, the increase in TBR tends to become moderate.

The results presented here provide useful insights for the further design activities of WLCB.

CRediT authorship contribution statement

Yudong Lu: Conceptualization, Methodology, Writing - review & editing. **Minyou Ye:** Investigation, Supervision, Funding acquisition, Writing - review & editing. **Guangming Zhou:** Investigation, Conceptualization, Writing - review & editing, Supervision. **Francisco A. Hernández:** Investigation, Writing - review & editing, Supervision.

Jaakko Leppänen: Software. **Yuan Hu:** Software, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

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