# Neutronics Optimization of LiPb-He Dual-Cooled Fuel Breeding Blanket for the Fusion-Driven sub-critical System*

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**Abstract** The concept of the liquid $Li_{17}Pb_{83}$ and Helium gas dual-cooled Fuel Breeding Blanket (FBB) for the Fusion-Driven sub-critical System (FDS) is presented and analyzed. Taking self-sustaining tritium (TBR >1.05) and annual output of 100 kg or more fissile $^{239}Pu$ (FBR > 0.238) as objective parameters, and based on the three-dimensional Monte Carlo neutron-photon transport code MCNP/4A, a neutronics-optimizated calculation of different cases was carried out and the concept is proved feasible. In addition, the total breeding ratio ( BR = TBR + FBR ) is listed corresponding to different cases.

**Keywords:** neutronics, fusion - driven sub - exitical system, LiPb - He, dual - coded fuel, breeding blanket

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## 1 Introduction

The resource of fissile nuclear fuel, the safety problem of fission reactors and the disposal of long-lived radioactive wastes have restrained extensive utilization of nuclear fission energy. And the commercial fusion power still needs a quite long period to develop. As a medium step between the applications of fission and fusion, the Fusion-Driven sub-critical System, i.e. hybrid reactor, has been proposed. The necessary condition of the multi-function blanket for the fusion-fission hybrid reactor is still tritium-sustainable. Besides, the fuel breed blanket for the FDS needs an annual output of $^{239}Pu$ at least up to 100 kg or more [1~6].

Based on previous studies on plasma physics and high temperature gas-cooled reactor (HTGR) engineering technology [7], the concept of the liquid $Li_{17}Pb_{83}$ and pressurized helium gas dual-cooled system, along with its advantages, such as safety, feasibity and cost-effectiveness is presented. The neutronics optimization and analysis were carried out by taking tritium- breeding ratio (TBR) and fuel- breeding ratio (FBR) as objective parameters. Considering neutron leakage and tritium decay in the cycles, it is necessary to have a TBR >1.05 ~1.1. Based on the FEB [4] tokamak core design with operation availability being assumed to be 50%, the first wall loading is equal to 0.5 $MW/m^2$ on the same level of the ITER-FEAT design [8]. An annual output of 100 kg $^{239}Pu$ is the lowest requirement to the experimental blanket for FDS, i.e. FBR $\geq$ 0.238, when adopting natural uranium. The substantial concept

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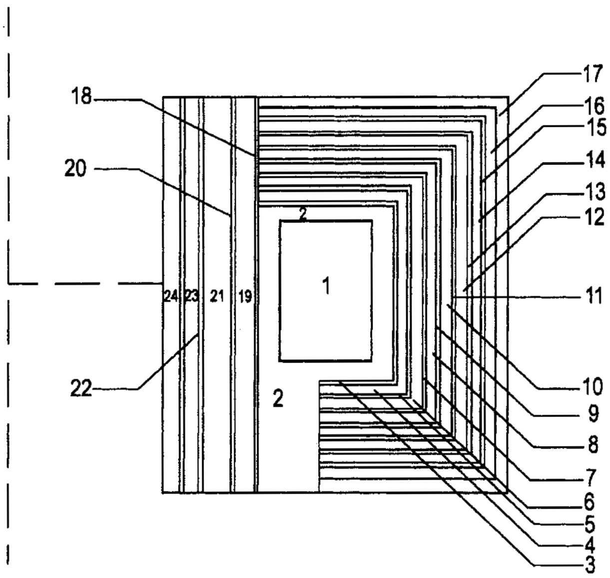


**Fig.1** Schematic view of FDS-FBB-RT.

**Table 1.** Dimension and material compositions of the blanket

| Zone | Material and their volume fraction | Zone number | Thickness (cm) |
|---|---|---|---|
| Plasma source | Void | 1 | 200 |
| Scrape-off layer | Void | 2 | 15 |
| Wall | 316SS: 70% | 3, 5, 7, 9, 11, 13 | 1 |
| | He-gas: 30% | 15, 18, 20, 22 | |
| TB zone | $Li_{17}Pb_{83}$ ($^6Li$: 90%): 100% | 4, 6, 8, 10, 12, 14 | 58 (total) |
| FB zone | $UO_2$: 9%; Graphite: 45% | | |
| | SiC: 6%; He-gas: 40% | 21 ( inner TB zone ) | 40 (inner TB zone) |
| Beryllium layer | Be: 60%; He-gas: 40% | 19 | 10 |
| Reflector | Graphite: 90%; He-gas: 10% | 16, 23 | 10 (outer), 22 (inner) |
| Structural layer | 316SS: 70%; He-gas: 30% | 17, 24 | 10 (outer), 10 (inner) |

of the blanket and calculational model are depicted in section 2. The neutronic optimization and analysis are listed in section 3. In the final section 4, the overall conclusion is presented.

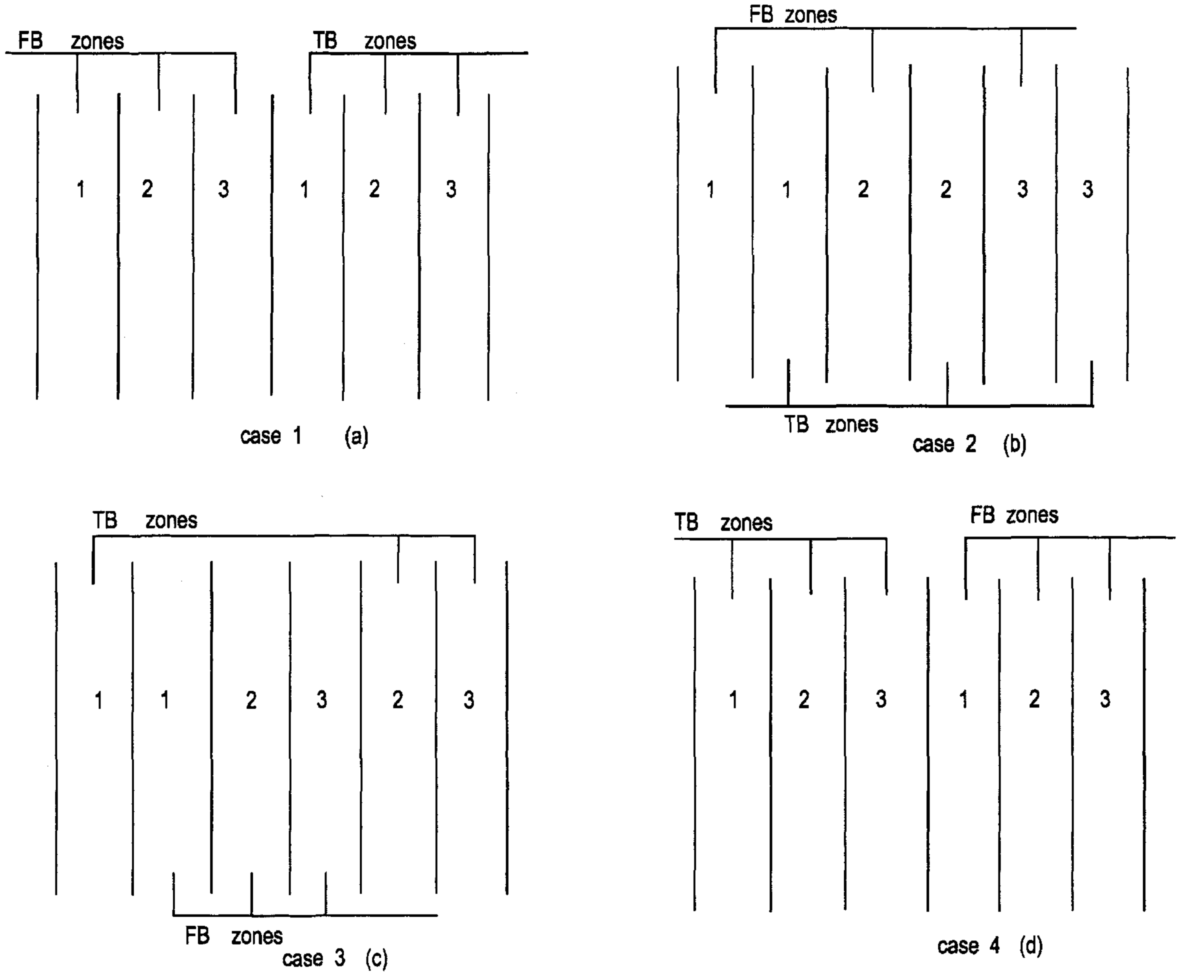


**Fig.2** The neutronics calculations of four different cases.

## 2 Blanket concept and calculational model

The proposed two-dimensional configuration of the dual-cooled fuel breed blanket is shown in Fig. 1. And the dimensions and material compositions of the blanket are presented in Table 1. The outer blanket consists of tritium-breeding (TB) zones for breeding tritium, fuel-breeding (FB) zones for producing plutonium-239, a graphite neutron reflector and stainless steel structure. The inner blanket is only used to breed tritium. In the dual-cooled system, not only liquid $Li_{17}Pb_{83}$ eutectic can serve as the tritium breeder but also Pb can multiply neutrons, and pressurized helium gas is used to cool the FB-zone, graphite reflector and structure so as to palliate the MHD of liquid $Li_{17}Pb_{83}$. In a form of dioxide, the uranium fuel of FB-zone is dispersed in graphite. As shown in Table 1, the volume fraction of fuel pebble, consisting of uranium dioxide from natural uranium or spent fuel oxide (in this paper,

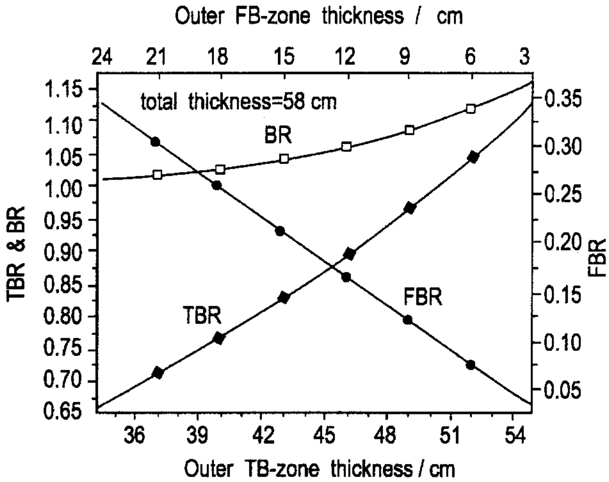


**Fig.3** Case 1.

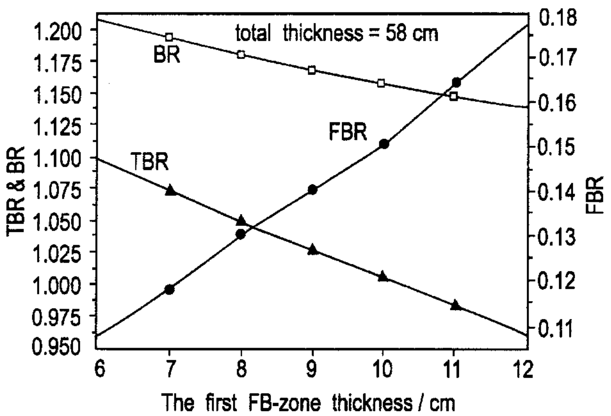


**Fig. 4** Case 2.

only natural uranium is taken into account), graphite and silicon carbide, is assumed according to the fuel technology level of HTGR. In the inner blanket, a Be layer and a graphite reflector are arranged to improve the multiplication of neutrons and breed more tritium. In the outer blanket, several TB-zones and FB-zones are convenient for pressurized helium gas to transfer heat and arrange their positions for the improvement of the multiplication of neutrons.

# 3 Neutronics calculation and analysis

According to the concept described above, a two-dimensional geometric model of the blanket is depicted in Fig. 1. The major and minor radii of tokamak are 400 cm and 100 cm, respectively. The elongation of plasma zone is $k$ =1.7. Furthermore, the neutron leakage of the divertor is taken into account by assuming that the cylindrical shell leakage port has a thickness of 100 cm. The code MCNP/4A [8] is used to calculate TBR, FBR and $P_d$ (power density). The previous studies have proved that in order to breed more tritium, $^6Li$ in $Li_{17}Pb_{83}$ must be enriched owing to the low density of lithium atom. In this paper, the enrichment degree of $^6Li$ is assumed to be 90%. The dimensions and material compositions of the inner blanket are fixed, and several different combinations of TB-zones and FB-zones in the outer blanket together with their sizes and positions are optimally arranged with a fixed total thickness of outer blanket. The neutronics calculations of four different cases (shown in Fig. 2) and the estimation of the $UO_2$ volume fraction effects in FB-zone on TBR, FBR and $P_d$ were carried out, and the results are listed as follow.

According to neutron wall loading and FBR with an operation availability of 50%, after the operation of a full-power-year, the calculated annual output of $^{239}Pu$ will be 840 kg/year when FBR is equal to unity, and FBR is ~ 0.238 when annually breeding is 100 kg $^{239}Pu$.

## 3.1 Case 1

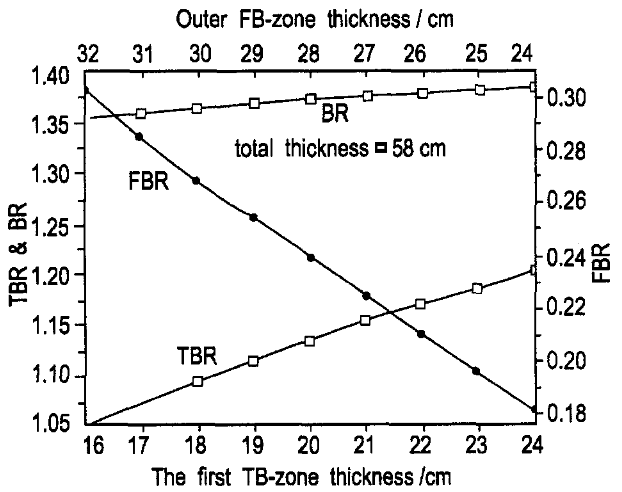


**Fig.5** The first condition of case 3.

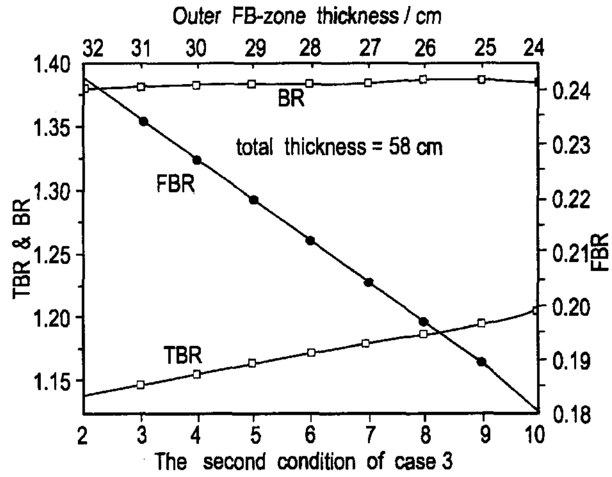


**Fig. 6** The second condition of case 3.

First, all FB-zones are arranged in the position of high neutron flux close to the plasma source (Fig. 2(a)). With varying the total thickness of FB-zones and TB-zones, a higher FBR is expected after tritium self-sustaining. The results that TBR increases and FBR decreases with the increased total thickness of TB-zones are presented in Fig. 3. At the same time, BR, namely the sum of TBR and FBR, also increases slightly. When TBR >1.05, FBR is dropped down to less than 0.05 and BR is only equal to ~1.16. At this moment, $P_d$ (W/cm$^3$) is 6.41, 5.48, 4.60, 1.06, 0.22 and 0.16 in turn in the three FB-zones and the three TB-zones. Then, it is shown that an increase in the total thickness of TB-zones won't imrove BR.

### 3.2 Case 2

The results of the first case are far from our expectation. In the second case (Fig. 2(b)), the TB-zone and FB-zone are alternately arranged and the three TB-zones are fixed to 15 cm, 15 cm and 10 cm in turn, respectively. Only sizes of FB-zones are variable. TBR, FBR as functions of thickness of the first FB-zone are shown in Fig. 4, apparently, increasing the thickness of the first FB-zone will enhance the total FBR but lower TBR because the absorption section of uranium moderates the neutron flux. In addition, BR drops down to ~1.19 while TBR ~1.07 and FBR ~ 0.12. And the power density $P_d$ (W/cm$^3$) is 5.41, 1.61, 0.82, 0.39, 0.18 and 0.18 in turn in all FB and TB zones from inner to outer blanket.

### 3.3 Case 3

In order to achieve tritium self-sustaining easily, the closest position to the plasma source is one TB-zone and three FB-zones between the first TB-zone and the other two TB-zones. In this case (Fig. 2(c)), two different conditions, i.e. case 3-1 and case 3-2, (see Figs. 5 and 6) are taken into account.

First, in the case 3-1 (Fig. 5), the outer two TB-zones are fixed to 5 cm and 5 cm respectively, and

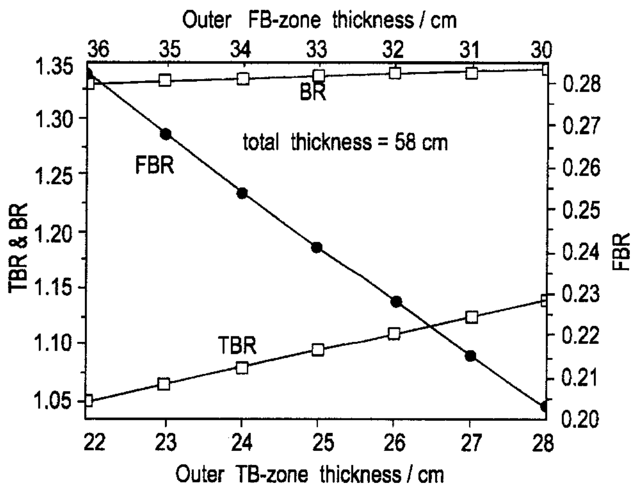


**Fig.7** Case 4.

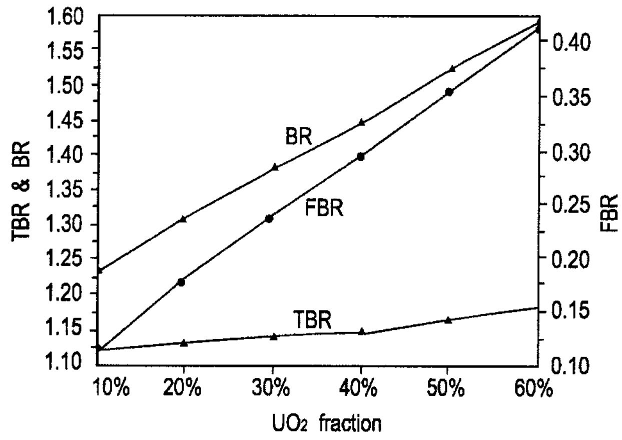


**Fig.8** Effect of $UO_2$ fraction.

**Table 2.** Results of 60% $UO_2$ in FB zones

| | Case 1 | Case 2 | Case 3-1 | Case 3-2 | Case 4 |
|---|---|---|---|---|---|
| TBR | 1.217 | 1.180 | 1.114 | 1.130 | 1.100 |
| FBR | 0.125 | 0.409 | 0.378 | 0.355 | 0.346 |
| BR | 1.342 | 1.588 | 1.492 | 1.486 | 1.445 |
| $P_w$ ($W/cm^3$) | 30.661 | 27.103 | 1.707 | 1.655 | 2.136 |

the thickness of the first TB-zone and the total sizes of three FB-zones are variable. When TBR ~1.05, FBR ~ 0.30 is shown in Fig. 5. If the thickness of the first TB-zone increases, TBR will continue to rise and FBR will be abated. In this condition, we have BR >1.35. Furthermore, the maximum $P_d$ of all TB-zones and FB-zones is ~2.24 $W/cm^3$ appearing in the first TB-zone.

Secondly, in the case 3-2, (Fig. 6) the thickness of the first TB-zone is fixed to 24 cm owing to the great effect of TBR caused by the first TB-zone. The sum thickness of the other two TB-zones and the total size of three FB-zones are changed. The calculated results are presented in Fig. 6. Because the first TB-zone is thicker, the total TBR will be larger, but FBR will be reduced and BR is around 1.37.

### 3.4 Case 4

In the final case (Fig. 2(d)), all the three TB-zones are arranged in a position close to the plasma zone, and outside them there are all the three FB-zones. The x-coordinates in Fig. 7 are the total thickness of TB-zones and the sum size of FB-zones, respectively. In this instance, when TBR is ~ 1.05 for self-sustaining, FBR is $\sim 0.282$ and the total BR is $\sim$1.33. The maximum $P_d$ in all breeding zone is only $\sim 2.13$ W/cm$^3$. The changing trend is still an ascending TBR and a descending FBR as stated above.

### 3.5 Effect of uranium dioxide fraction

The above-stated material compositions in FB-zones are assumed according to HTGR. We will vary them for calculation in order to study the effects of $UO_2$ fraction on FBR, TBR and total BR. By taking 60% as a $UO_2$ fraction with a porosity fraction of 40%, the calculations of different cases carried out were in accordance with our expectation. The results of BR and power density in Table 2 show that BR of the second case is increased furthest. Consequently, we will choose the second case to study the effects of $UO_2$ fraction. The change in FBR, TBR and total BR are shown in Fig. 8. And the corresponding maximum $P_d$ is also indicated. However, the dual-cooled system of the fuel breed blanket for FDS can easily cool all heats. In HTGR, where the uranium fuel with a thin coverage of graphite and silicon carbide, can palliate the risk of the reactors. Accordingly, the calculated $K_{eff}$ of the top FBR as an instance is $\sim$ 0.16 being far from critical threshold.

## 4 Conclusions

Taking TBR >1.05 and FBR >0.238 as the bottom limit, it is difficult for case 1 and case 2 to meet the requirement, but the other two cases won't be so. If we consider HTGR fuel compositions, in the former two cases, there are three or one FB-zone arranged in the closest position to plasma zone so as to breed more $^{239}$Pu fuel. Moreover, graphite in FB-zone can moderate neutrons to improve $^6$Li $(n, \alpha)$T reaction in TB-zone to breed tritium. However, actually if tritium is self-sustainable, FBR will not meet the previous expectation. In the second condition of case 3, because the thickness of the first TB-zone is fixed to 24 cm, it can not achieve FBR > 0.238 until the sum thickness of FB-zones rises up to 32 cm. By analysing the first condition of case 3 and case 4, tritium is easy to be self-sustainable because the TB-zone is in the position close to the first wall to the benefit of breeding tritium. FBR of case 3 is higher than that of case 4 because the FB-zone of case 3 is nearer to the plasma source than case 4.

Apparently, increasing the $UO_2$ fraction of fuel zones will improve TBR and FBR. Besides, the total breeding ratio of the second case will be maximum when $UO_2$ fraction is up to 60%, and the corresponding $K_{\text{eff}}$ is only $\sim$ 0.163 far from the critical threshold.

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