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First principles review of options for tritium breeder and neutron multiplier materials for breeding blankets in fusion reactors

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ABSTRACT

The current breeding blankets proposed in the different conceptual fusion power plants are based mainly on the use of Li_4SiO_4 and/or Li_2TiO_3 as tritium breeder and Be/$Be_{12}Ti$ as neutron multiplier or an eutectic $Li_{17}Pb_{83}$ for as a hybrid tritium and neutron multiplier. While these materials offer some tritium breeding capabilities, some recent studies show that the tritium self-sufficiency may not be ensured with these materials due to the strong reduction of blanket coverage after the integration of other in-vessel reactor systems (heating and current drive, limiters, large or double-null divertor systems, etc.). Also, some materials like Be raises several key feasibility concerns. The goal of this paper is to perform an update of the screening for tritium breeder and neutron multiplier materials and to assess the tritium breeding performance of the selected compounds in order to reveal new options. As for the neutron multiplier materials, a new subdivision between solid and liquid multipliers is proposed. For the selected compounds, detailed 3D heterogeneous neutronic analyses have been performed with MCNP5-1.60 assuming the architecture of the current EU DEMO Helium Cooled Pebble Bed (HCPB) as a benchmark breeding blanket. From the point of view of ceramic breeders, Li_8ZrO_6 has been found to outperform Li_4SiO_4 by more than 4% in terms of tritium breeding, having 6% higher melting point. From the point of view of solid neutron multipliers, $Be_{12}Cr$, $Be_{12}V$, $Be_{13}Zr$ and $Be_{13}Y$ show a similar performance as $Be_{12}Ti$, while $LaPb_3$, Zr_5Pb_4 and YPb_2 offer a solution for a Be-free blanket. As for liquid multipliers, Pb in combination with a ceramic breeder shows a very promising option. Moreover, Pb compounds like $Pb_{90}Mn_{10}$ and $Pb_{95}Ba_5$ offer similar performance as Pb with a lower melting point (290 °C). Due to the significant advantages of molten Pb as neutron multiplier, future work will be conducted to define a design of a helium cooled Molten Lead Ceramic Breeder blanket, as simple, cost effective blanket concept.

1. Introduction

A Fusion Power Plant (FPP) based on the fusion of deuterium (D) and tritium (T) to give He and a 14.1 MeV neutron ($D + T \rightarrow He + n$) necessitates of an *in-situ*, continuous production of T, due to the practical unavailability of such element in our environment. This is one of the basic functions of the so-called Breeding Blanket in a future FPP and in particular in the demonstration FPP (EU DEMO) [1], together with the extraction of thermal power and its contribution as neutron shield. This T breeding function is accomplished by irradiating a so-called breeder material with neutrons, which by means of $(n, x)T$ nuclear reaction will transmute elements of the material with production of T and some other byproducts. However, not all neutrons from the $D + T$ fusion are available for T generation, as some part of them is lost due to parasitic absorptions in the structural and non-functional materials of the blanket, or due to streaming and leaking through the blanket gaps and the blanket structure itself, respectively. Therefore, the breeding blanket necessitates of a so-called neutron multiplier to generate additional neutrons to compensate for these loses.

Since the 1980s, the former European Fusion Development Agreement (EFDA) and since 2014, the EUROfusion Consortium in the frame of the European Power Plant Physics and Technology (PPPT) program have directed several studies regarding different breeding blanket concepts, which are mainly divided on liquid or solid concepts depending on the aggregate state of the functional materials. The most remarkable due to their extension and coherence towards an integrated study of a power plant are the DEMO conceptual study in the 1990s (e.g. [2]) and the EFDA's Power Plant Conceptual Study [3]. In the former, four breeding blanket concepts were proposed: the Self Cooled Lithium Lead (SCLL), the Water Cooled Lithium Lead (WCLL) and two Helium Cooled Pebble Bed (HCPB) concepts, a Breeder In Tube (BIT) and a Breeder Out of Tube (BOT). While the SCLL and WCLL were based

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on the use of a liquid $Li_{17}Pb_{83}$ eutectic as combined mixture of breeder (Li) and multiplier (Pb), the HCPB-BOT was based on the use of (solid) pebbles of Li_4SiO_4 as T breeder and Be as neutron multiplier and the HCPB-BIT on pellets of $LiAlO_2$ or Li_2ZrO_3 as breeders and again Be as multiplier material. However, the study did not offer a clear rationale on the selection of these functional materials. Similarly, the PPCS study proposed again the WCLL, HCPB (only the BOT version) and SCLL and added two more concepts, the Helium Cooled Lithium Lead (HCLL) and the Dual Cooled Lithium Lead (DCLL), which in any case were also based on the use of LiPb and no further investigation was carried out on possible alternative functional materials. A second EU DEMO pre-conceptual study started in 2014 [4,5] have been newly proposed [6], proposing again the HCPB, HCLL, WCLL and DCLL based on similar functional materials as in PPCS, with the exception of a proposal for an advanced ceramic breeder material based on Li_4SiO_4 with additions of Li_2TiO_3 in order to improve its mechanical properties [52–54].

The choices for the functional materials in the EU were also in part influenced by the comprehensive studies previously performed in the US, especially during the Blanket Comparison Selection Study [7]. Here the most complete list to date of promising functional materials in different configurations of breeder, multiplier and coolants for solid and liquid breeding blankets can be found. However, it lacks from an *ab initio* search for those functional materials, especially for the neutron multipliers, where the options have been always very reduced. Broadening the choice of multipliers is then a central point of this paper.

Since those studies from the 1980s and 1990s our knowledge in material science and technology has been improved and global material databases have been developed and are readily accessible online. This, coupled with the exponential increase in computational power and the vastly improved level of detail of the in-vessel components of a FPP and DEMO, make possible to revise and complete the palette of options for breeder and neutron multiplier materials for breeding blankets. This paper aims at revising the search for neutron multiplier and breeder materials from first principles, setting first several fundamental requirements, scanning for appropriate chemical elements and investigating possible chemical compositions in each case, leading to a choice of suitable compounds. The choice is then verified with a 3D neutron transport code (MCNP5) by simulating the T breeding ratio in the current EU DEMO, utilizing a highly detailed geometrical model of the latest design HCPB breeding blanket.

2. Basic requirements for candidate functional elements

Despite the many elements and their possible combinations in different compounds that exists, any of them has to fulfill the following list of counter-acting requirements.

2.1. Safety (toxicity, reactivity, non-radioactivity)

The functional materials must present as low as possible toxicity, reactivity with air and water and the structural materials of the blanket. Also, the candidate materials should have a potentially low risk of releasing volatile or mobilizable products produced during their lifetime in the blanket (by means of e.g. irradiation, mechanical failure, etc.) that can be a safety concern.

In this regard, alkali and alkaline metals are on their own readily reactive at least with water. Their reactivity increases for higher period elements, which includes Li and Be, therefore they should be ideally used as compounds to reduce their reactivity. Elements heavier than Bi should be discarded under this requirement due to their natural radioactivity. The chemical toxicity of elemental Be (acute Be disease and carcinogen nature of this element) is a safety concern already raised during the BCSS [7] and care must be taken to minimize the inventory of such material while designing a blanket containing Be.

2.2. Low activation

One of the basic requirements in FPPs is that it is qualified as a low activation, i.e. the selection of materials that are to be under fusion environment meets a series of low activation characteristics, which include waste management, accident safety, maintenance and routine effluents, as defined in [12].

Of course, in order to obtain a qualified answer, a neutronic analysis of the reactor activation must be performed. However, a good indication whether an element will meet such criterion is by checking its waste and recycling classification. Although this classification is strongly dependent on the host country where the reactor is located [20], Fig. 1 shows as a model the usage limits of the elements depending on its quantity when placed in an in-vessel component and their incident neutron spectrum for near-surface burial following the US convention. Following this chart and for practical reasons, elements that can only be used in very small amounts (e.g. less than 1%) should not be considered, e.g. Al, Nb, Mo, Ag, Cd, Hf, Au, Bi, etc.

Although not appearing in the chart of Fig. 1, transuranic elements like U and Th are also excluded, as their use in a blanket would result in different high-level waste actinides (Pu, Am, Cm).

Especial attention must be paid to impurities that may be contained in the raw materials or that can be introduced during manufacturing

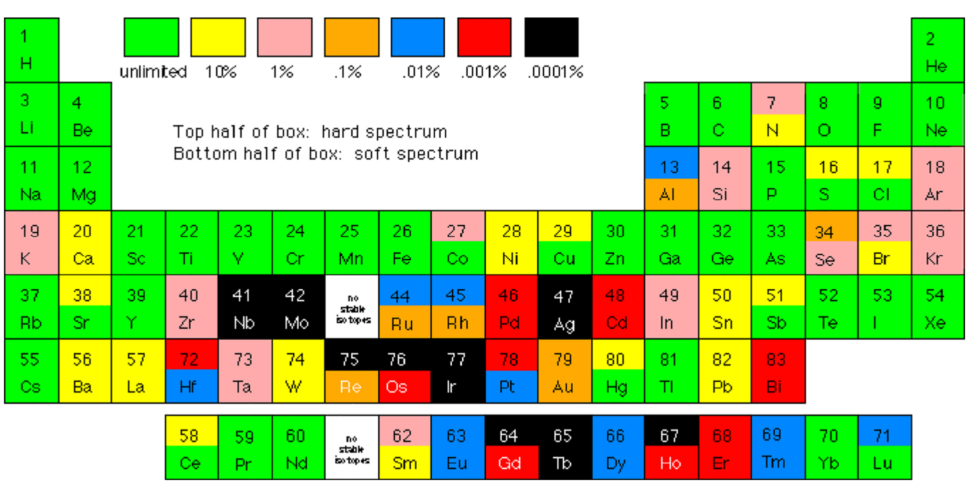

Fig. 1. Limits on the use of elements for near-surface burial after US methodology [12].