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Status of maturation of critical technologies and systems design: Breeding blanket

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ABSTRACT

The scope of the EUFOfusion Work Package Breeding Blanket is to develop a blanket concept for the EU DEMO reactor; this includes the blanket segments inside the Vacuum Vessel and the related Tritium Extraction/Removal Systems. In the Pre-Concept Design (PCD) Phase, two concepts have been selected as candidates; a solid and a liquid breeder blanket cooled with helium and water, respectively. The design of these two blanket systems has been adapted to the DEMO plant design developed in the PCD Phase and performances assessed. A large R&D programme has been implemented with the scope to evaluate different technologies for these blankets; including the development of breeders, tritium extraction and cooling technologies, and the manufacturing of the blanket system. A major milestone in the subsequent Concept Design Phase is the final selection of the blanket concept for DEMO.

1. Introduction

The presence of a fully developed breeding blanket (BB) System [1] is one of the key characteristics of DEMO; indeed, the plant not only has to guarantee the tritium self-sufficiency (i.e. to produce entirely the T that necessitates for the operation) but also use a high-temperature coolant to ensure a favourable heat conversion to generate a net electricity outcome. To achieve these goals, the BB System shall occupy more than 85% of the in-vessel surface/volume surrounding the plasma, collecting a similar percentage of the total power in its heat removal systems. For these reasons, the BB requires large and complex auxiliary systems to perform its functions, namely the Primary Heat Transfer System (PHTS) [2], the Power Conversion System (PCS) [3], and the Tritium Extraction and Removal (TER) System. In addition, safety characteristics and related safety systems are heavily impacted by the BB materials and technologies. Therefore, the selection of the type of blanket is a strategic choice that strongly constrains the whole DEMO plant design, its safety features and economic viability.

The major goal of the EUROfusion Work Package Breeding Blanket (WPBB) is to complete the design at the conceptual level of the BB systems (including TER) compatible with the DEMO requirements and interfaces [4]. The main objective for the design development of the BB concepts during the PCD Phase has been to strengthen the technical basis and resolve most of the main technical issues associated with the driver blanket concept candidates. Therefore, efforts have been dedicated to consolidating a design by 2020 and to the identification of the technical issues and R&D gaps for the next Concept Design (CD) Phase.

In contrast to past DEMO studies, the BB design activities during the PCD Phase were defined to follow a holistic design approach, where aspects of Systems Engineering, integration, industrialization and costs

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have been selected as design drivers. This design approach, which prioritizes mature technologies to maximize the overall plant Technological Readiness Level (TRL), had strong implications, for example in the way PHTS and PCS, as well as Remote Maintenance (RM) tools and Vacuum Vessel (VV), are understood and designed. For example, efforts for minimizing the pressure drops (i.e. the circulating power of the plant) or for improving the remote maintainability of the BB have been, therefore, the main design drivers during the PCD Phase, along with the maximization of the tritium breeding performance and ensuring the fulfilment of safety requirements.

Initially, four blanket concepts developed previously in Europe were reviewed [4], however in the latter stages of the programme, investigations were streamlined on the two concepts; namely, the Helium Cooled Pebble Bed (HCPB) and the Water Cooled Lead-Lithium (WCLL). These were judged more mature and promising as driver blankets for the DEMO power plant. Accordingly, the TBM programme has been aligned to this choice.

In the paper, Section 2 presents the design of the two reference blanket concepts as developed in the PCD Phase. Section 3 presents the R&D that is conducted to validate the design; this Section will present the following key technologies: development of breeders (solid and liquid), the tritium extraction technologies, the cooling technologies for the two coolants (helium and water) and the manufacturing of the blanket.

2. The blanket design for the EU DEMO

As aforementioned, a main requirement for the EU DEMO reactor is to produce all tritium necessary operating the plant, without relying on additional external sources apart from the several kilograms of tritium necessary to start reactor operations [5]. To achieve this, tritium should be produced so that the losses and trapping are compensated for; the blanket system should be designed so that approximately 5% more tritium can be produced in comparison to the amount burnt-up in the D-T reaction, therefore an effective Tritium Breeding Ratio, TBR, of ~1.05 is needed to meet this requirement. As the blankets are the only components to breed T in the reactor, the T self-sufficiency can only be achieved with an accurate nuclear design of this system. Additionally, breeder and neutron multiplier materials will be located in the proximity of the plasma and neutron absorption materials must be minimized in the breeding zone.

There are considerable design requirements placed on the BB system as a whole. The design of the blanket has to ensure effective cooling of all the parts subjected to surface and volumetric heat loads to cope with the temperature and design limits of the materials. The structures forming the blanket have to withstand the mechanic loads coming mainly from the coolant pressure, thermal stresses and electromagnetics loads. The intense neutronic flux requires a careful selection of structural materials able to operate for many years under irradiation without degrading their properties. In the near term perspective for the DEMO construction (next 20 years), the only possible structure material for the blanket construction is steel and, among steels, only ferritic-martensitic options have the potential to withstand the 14-MeV-neutron exposure for some years. In this class of steel, the Reduced Activation Ferritic-Martensitic (RAFM) steel, namely EUROFER-97 (9Cr-1WVTa), has been developed for more than 30 years within Europe and is considered the reference for the BB design [6].

Blanket structures and breeders will be exposed to severe neutron irradiation during operation and, after a certain operation time, they need to be substituted; for this reason, their lifetime is an important parameter for the total availability of the reactor. The replacement of blankets is a complex and time-consuming operation. The present DEMO requirements [7] foresee that a first blanket set has to be designed for a lifetime corresponding to neutron damages of 20 dpa (displacement per atom) that corresponds to about 2 full power years (FPY) for steel components exposed to an average neutron wall load of 1 MW/m^2. A second BB set should arrive at 50 dpa in 5 FPY; this means that one scheduled replacement of the whole blanket system is necessary for the life of the DEMO reactor (which is about 70 dpa in ~7 FPY).

Therefore, the DEMO plant should be fully designed to remotely maintain the BB through a dedicated and efficient RM system. A vertical replacement scheme through large upper ports is envisaged and, on this architecture, the design of the blanket was adapted during the PCD Phase [8]. According to this RM concept, each blanket sector (toroidal portion between two TF-coils) is vertically (i.e. poloidal direction) divided into 3 outboards (OB) and 2 inboards (IB) segments; for a 16-TF-coil-reactor this means 80 individual segments that should be replaced (see Fig. 1). Each segment has pipe connections for the inlet and the outlet of the coolant and tritium carrier (see Fig. 2 for the HCPB and Fig. 4 for the WCLL).

Driven by these external constraints, a blanket segment requires a robust Back Supporting Structure (BSS) that supports the Breeder Zone (BZ), containing the breeder and multiplier materials, and the First Wall (FW), facing directly the plasma. This BSS is then connected to the VV using an attachment system that allows replacement from the upper port. In addition, the BSS includes the main manifold system that feeds the BZ and the FW and connects the PHTS outside the vacuum vessel. In the current architecture, the BB is based on a Single Module Segment (SMS). This has been chosen against the former Multi-Module Segment (MMS) due to: (1) the need to increase the segments' cross-section to strengthen them against EM loads during disruption events, this has been also necessary after the reduction of the radial thickness from 1.3 m to 1.0 m of the latest DEMO baseline in 2017, and (2) to improve the reliability and availability of the plant, as the MMS architecture results in many more pipe service connections.

Even though the two investigated driver blanket concepts (see Sections 2.1 and 2.2) use different breeders and coolants, they share the same basic architecture that foreseen a strict separation between the BZ occupied by the breeder, multiplier and a tritium carrier, and the coolant channels. This corresponds to a separation of functions of the two independent loops: tritium transport and blanket cooling. The coolant (helium or water) flows capillary in small channels; it removes the neutron, ion and photon heat and maintains the required operational temperatures in the materials. The BZ is connected to the tritium extraction circuits; this allows the tritium to remain concentrated in a dedicated circuit and not to be diluted in the coolant. The T carrier (helium or PbLi) does not contribute substantially to the heat removal as its mass flow is low. The blanket is then a "two-chamber system" that geometrically recalls a heat exchanger. The resulting large interface surface between the coolant and the BZ chamber (evaluated of about 12,000–16000 m^2) causes some of the major issues in the current blanket design. Indeed, the large number of welds, necessary to manufacture this component, causes issues in terms of overall reliability [9]. On the other side, the large surfaces induce the necessity to strictly control (using barriers) the potential permeation of T from the BZ to the coolant chambers jeopardizing the T confinement function.

2.1. The helium-cooled pebble bed (HCPB)

The HCPB breeding blanket concept adopts a solid breeder and high-pressure helium as a coolant. The breeder fills the blanket box and tritium is extracted from it with a purge gas and transported from the reactor. The solid breeder is a ceramic lithiated compound; to increase the neutronic performance, it is traditionally combined with beryllium (again as solid) in the function of a neutron multiplier. With this combination, it is possible to reach very high neutronic performances. To maximise this result and exclude safety issues like the reaction of beryllium with water in accidental conditions, helium was always preferred as a coolant in EU concepts. In addition, helium can be adapted in very large temperature windows opening the possibility to increase the temperatures and the thermal-hydraulic efficiency of the concept. To achieve this, materials that can cope with higher

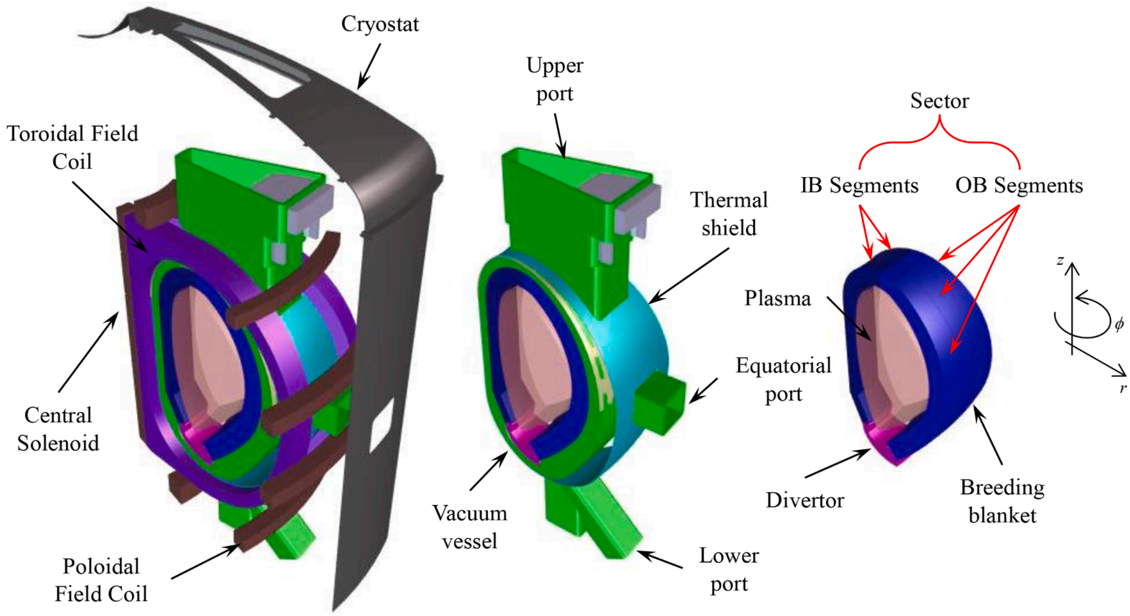

Fig. 1. EU DEMO baseline configuration.

temperatures still have to be developed and validated for fusion use; in the case of EUROFER, the thermal window is limited to a range of about 300 and 550°C.

The DEMO HCPB design developed on concepts from previous studies (see Dalle Donne [10] and Hermsmeyer [11] for the concepts of "sandwich" breeder zone and "beer box" reinforcement, respectively), and underwent a major revision in 2018. The design produced at the end of the PCD Phase adopts an innovative configuration, the so-called "fuel-breeder pin" [12]; this configuration includes a new strategy for the helium flow, using an advanced ceramic breeder and new material for the neutron multiplier, namely hexagonal blocks of $TiBe_{12}$ (see Fig. 2). The box structure is entirely EUROFER; a 2mm-layer of W coats the plasma side of the First Wall (FW). The coolant and purge gas pipework is connected to the segments by segment chimneys (Fig. 2-a); in total 2 pipes (inlet/outlet) for the helium coolant and 2 pipes for the purge system for each blanket segment. The internals are shown in the cross-sections A-A and B-B of Fig. 2-a and b. The BZ volume is formed by the FW and the BZ backplate and is filled by a radial arrangement of pressure tubes connecting the FW with the BZ backplate. These pressure tubes therefore also act as radial stiffeners and are key structural supports against an in-box Loss of Coolant Accident (LOCA). The fuel-breeder pins are then inserted into the pressure tubes and connected to the BZ backplate.

A fuel-breeder pin (Fig. 2-c and d) is a system of 2 concentric cylinders. The resulting volume in the pin cladding is filled with a ceramic breeder (CB) material, which is a mixture of Li_4SiO_4 + 35% mol Li_2TiO_3 (at 60% ^{6}Li enrichment) in a pebble bed form. The $TiBe_{12}$ is inserted around its corresponding pressure tube. Tritium is produced in both CB and $TiBe_{12}$ and it is extracted and transported out of the segments using a purge gas (He + 200 Pa H_2). He at 8 MPa is used as a coolant due to its neutronic and chemical inertness. The coolant temperature window is set then to 300 to 520 °C.

In particular, the introduction of beryllide structures implements features from the lessons learned during the first years of the PCD Phase [13]. The adoption of a radial flow in the BZ in the pins has drastically reduced the plant circulating power to ≈90 MW. With 16 helium blowers in the whole HCPB BB PHTS, each blower provides about 5.625 MW circulating power, for which a high TRL blower is available [14]. The pin arrangement allows better thermal management, permitting a higher outlet coolant temperature to 520 °C, a key advantage for the BOP. The filling of functional materials is another key advantage in this design, as well as the improved TBR performance (up to 1.20) [12].

Despite the achievements in PCD Phase with the HCPB pin design, critical issues remain to be addressed for the CD Phase. Some of them are shared with the present class of blanket design (the low BB reliability of the "two-chamber design", high manufacturing costs, or the risk of loss of structural integrity of the BB due to the DBTT shift in EUROFER). Other major issues are HCPB concept specific: (1) low TRL and still high associated costs for producing the $TiBe_{12}$ neutron multiplier and the breeder ceramic pebble beds, (2) potential high thermal stresses due to ~200 K difference between coolant inlet/outlet temperatures, (3) the low shielding capability of helium-cooled structures that requires accurate design provisions, (4) large diameters in the feeding helium coolant pipes, up to DN350 for the OB outlet coolant. To improve the reliability of HCPB BB, a proposal of HCPB equilizing the pressure between purge gas system and cooling system thus eliminating in-box LOCA welds is proposed and will be further studied in CD Phase. Corresponding studies on a high pressure HCPB TER are started, see below.

The TER system for the HCPB BB is a He-loop with the purpose to purge the HCPB BB BZ and consequently extracting tritium from the blankets. In addition, in the TER system, further processing in view of the removal of Q_2 and Q_2O from the He carrier gas is realized. The final tritium extraction/recovery shall be realized in the DEMO Tritium Plant (TP).

Following the recent assessment of the technologies for TER HCPB (see Section 3.3.1), the reference design resulting from the PCD Phase is based on two stages in series; first the adsorption of Q_2O on the Reactive Molecular Sieve Bed (RMSB) followed by the adsorption of Q_2 on the Cryogenic Molecular Sieve Bed (CMSB) at 77 K [15]. Tritium shall be recovered from the RMSB via catalytic isotope exchange (isotopic exchange between a purge gas H_2/D_2 and the adsorbed Q_2O on the RMSB) and from the CMSB during regeneration by heating-up of the beds. The extrapolation at the DEMO scale of the TER for the HCPB based on adsorption processes has been completed in PCD Phase with industrial support. The activities covered the pre-sizing of the TER equipment and the integration with the interfacing Tritium Plant system. The TER HCPB has been designed to process 10,000 Nm^3/h He gas at a pressure of 0.2 MPa, containing 200 Pa H_2 at the inlet in the breeding blanket and to recover the tritiated water and the elemental tritium from the He stream that is expected to be at concentrations in the range 10^{-4}–10^{-5} [16] (see Fig. 3).

Despite these achievements, further investigations are still planned

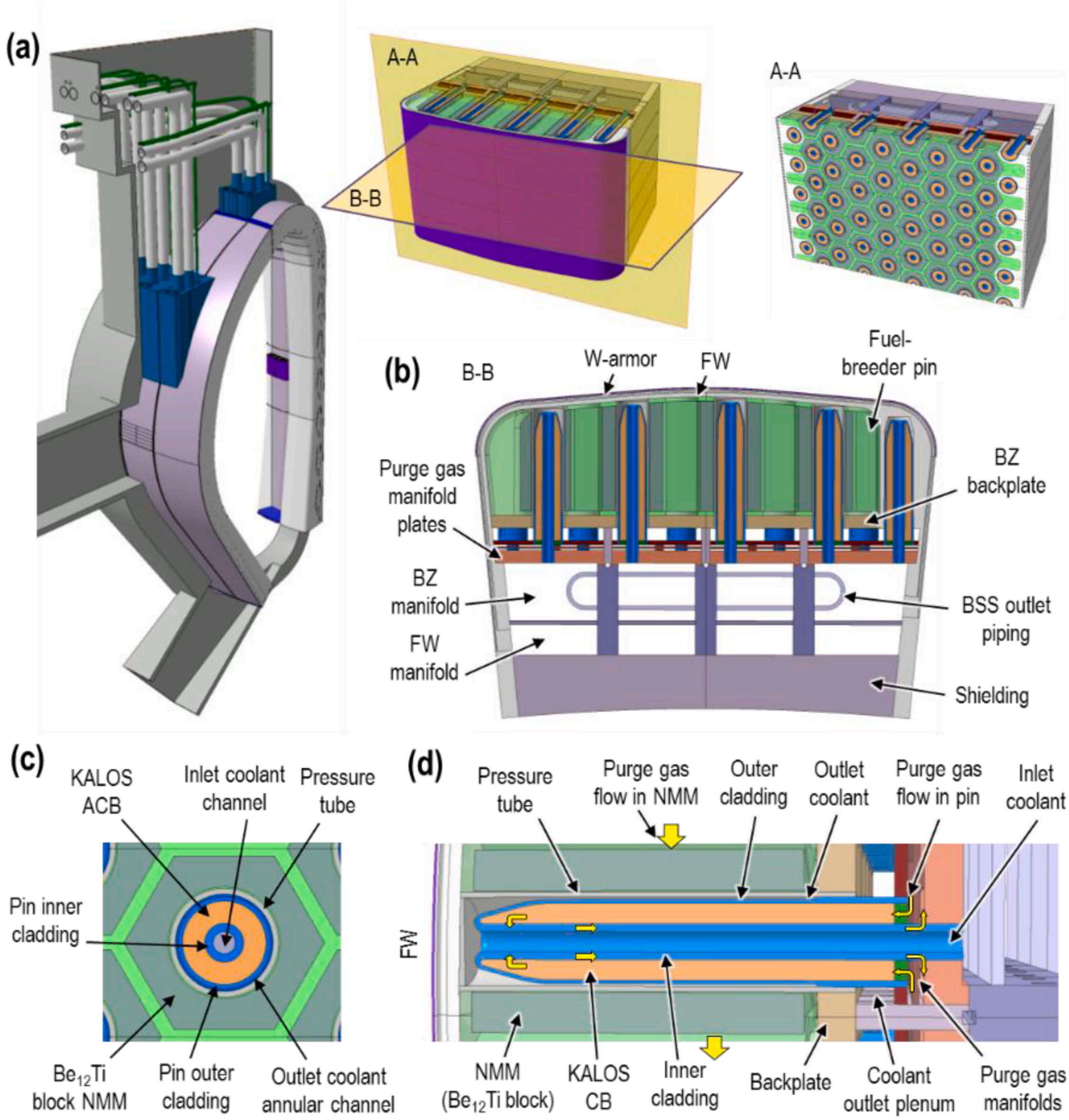

Fig. 2. Reference HCPB BB design for the EU DEMO.

in the CD Phase to improve the performance of this system. In particular, the Q_2 adsorption on the CMSB at 77 K has the following main drawbacks: large consumption of liquid nitrogen and large variations in the gas flow rate of tritium flow sent to the Tritium Plant, during the regeneration of the CMSB. Alternative solutions to the Q_2 adsorption at 77 K have been evaluated; in particular, it was found that hydrogen adsorption on getter beds, even at ambient temperature and wide ranges of operational pressure, can provide a good alternative.

Another design option under investigation is related to the distribution of tritium molecular species at the outlet of the BB; investigation showed that HTO in the present design is almost 20 times lower compared with HT form. However, there would be a real benefit of increasing the amount of steam in the purge gas up (adding H_2O in the purge gas composition) to the allowable limits that avoid intolerable corrosion of the BB components: this would minimize the HT tritium form and increase the HTO form reducing the tritium permeation in the cooling gas. In addition, the presence of steam in the purge gas allows a higher isotopic exchange rate compared with hydrogen [17].

The third option is related to the increase in the TER operational pressure equalising it to the level of the cooling gas; the large pressure difference inside the BB box is one of the main concerns related to the operational availability of the BB. The option of the HCPB TER operation at 8.0 MPa is under evaluation equalising the pressure in the two BB chambers and considerably reducing the mechanical requirements of the separating structures [18]. Each of these design options requires dedicated R&D that is described in Section 3.3.1.

2.2. The water-cooled lead lithium (WCLL)

The WCLL breeding blanket concept adopts a conventional cooling system (water at PWR conditions, 15.5 MPa, 295–328 °C) in combination with a liquid breeder, PbLi. More precisely, the lead-lithium eutectic alloy Pb15.7Li acts as neutron multiplier, tritium breeder and carrier medium. PbLi transports T produced within the BZ outside the VV, where it is extracted and routed to the fuel cycle. To maximize tritium production, the lithium present in the PbLi alloy will be enriched at 90% in ^{6}Li. The advantage of this concept is the high technological maturity of some basic technologies (e.g. components of the cooling systems) and the low costs of breeder and coolant. Despite this, some key technologies are still in a selection phase, including the T extraction

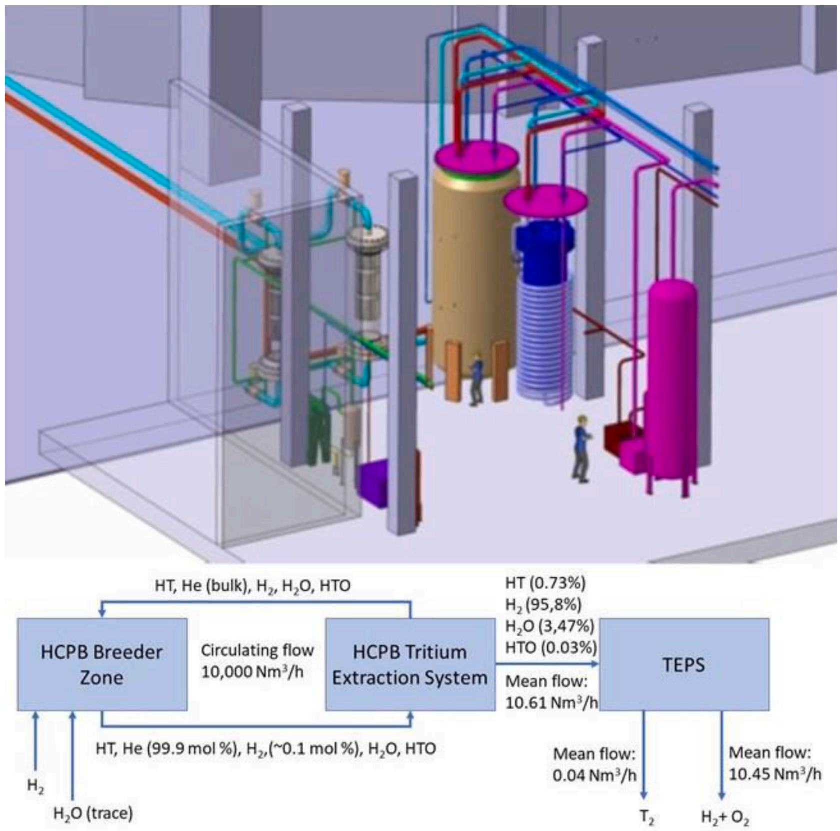

Fig. 3. Reference HCPB TER design for the EU DEMO.

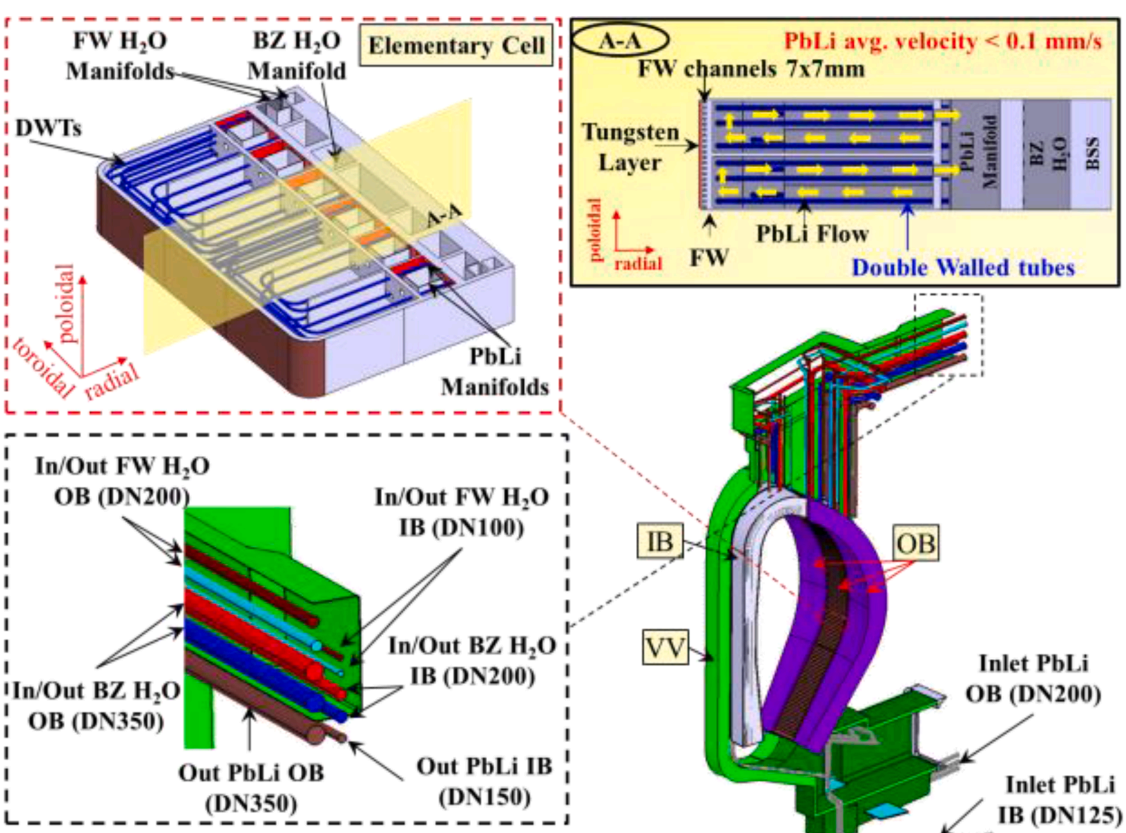

Fig. 4. WCLL BB. Detail of the elementary cell and integration in the sector architecture.

from the breeder, the water chemistry and the T purification from coolant water.

Like the HCPB, the WCLL blanket has been extensively studied previously [19]. The DEMO concept resulting from the PCD Phase [20] presents a robust box segment with an internal grid of poloidal-radial and toroidal-radial stiffening plates, which assure the structural integrity of the component in particular against pressurization events (in-Box LOCA). The liquid PbLi fills the blanket box flowing between the poloidal-radial stiffening plates, actively cooled by bundles of Double-Walled Tubes (DWTs) that contain the coolant water.

The DWT technology (see also Section 3.6) has been adopted in the present design to mitigate the risk of tube break causing a reaction between water and PbLi; this reaction is one of the major safety issues of the WCLL design (Section 3.2.4). It was estimated [21] that even if the most pessimistic failure rate were assumed, the probability of a water/PbLi interaction event in the case of a DWT would be much lower than the one of a single wall tube with advantage in both safety and investment protection.

FW and DWTs are fed with water by two separate cooling circuits. PbLi and water are supplied to FW and BZ regions employing dedicated manifold systems, mainly consisting of a series of spinal collectors allowing continuous fluid distribution/collection along with the poloidal development of the segment. The design of a WCLL BB segment is made in a way that the segment can be thought as a poloidal stack of elementary cells. Water coolant pipes (4 pipes per segment) and PbLi outlet ones (1 pipe per segment) are integrated into the upper port, while the PbLi is routed to the BB through the lower port (1 pipe per segment). An overview of the WCLL BB, with the detail of the elementary cell, is depicted in Fig. 4.

One of the main achievements carried out during the PCD Phase in the WCLL BB design was the improvement of the neutronic figures of merit increasing the TBR value up to 1.15 maintaining good shielding performances [22]. Furthermore, it succeeded in increasing the FW average temperature, adopting a non-uniform poloidal channel distribution [23], without compromising both the BZ cooling capability [24] and the overall thermo-mechanic performances [25]. The optimization of the internal BB structures, with particular regards to the stiffening structures and the PbLi manifold, thanks to the extensive research made on Magneto-Hydrodynamics (MHD) phenomena occurring in the in-Vessel region [26].

Further design activities in the CD Phase should be focused on increasing the maturity level of inboard and outboard lateral blanket segments, as well as on the simplification of the BB layout to increase its reliability (reducing the number of welds) and its manufacturability. Further design specific issues for this concept remain to be addressed in the CD Phase; in particular, the drainage of the liquids (water and PbLi) before segment replacing operation if the remote systems cannot handle the entire weight of a full segment (about 160 t). Furthermore, the consequences on the design of helium formation in PbLi (nuclear reaction of Li with neutrons) with possible formation of gas plugs are still not clear.

The WCLL TER System is constituted of a PbLi loop connected to the BB BZ, a pumping system to recirculate PbLi, a Tritium Extraction Unit (TEU) that separates tritium from the PbLi flow and a circuit to transfer tritium from the TEU to the Fuel Cycle. The WCLL TER System is completed by several auxiliary systems to purify the PbLi flow from corrosion and activation products, control the PbLi chemistry, remove helium generated in the eutectic alloy, replenish ^{6}Li, heat and cool the PbLi flow, store the PbLi to empty the BB segments and shield the equipment due to PbLi activation. Challenges in the design are to protect the reactor systems from the activation products of PbLi and minimise the tritium permeation to the secondary containment.

Considering the design of the WCLL BB with a 16-sectors DEMO machine, the TER system is constituted of PbLi loops: 4 loops for the Outboard (OB) segments, where each loop is connected to 4 OB sectors; 2 loops for the Inboard (IB) segments, where each loop is connected to 8 IB sectors. PbLi IB and OB loops are connected to the WCLL BB, to the Tritium Plant and to the storage tank, which is used to store all PbLi. Fig. 5 shows the connections between the loops and the other systems. Each loop is a closed loop with forced circulation of the PbLi. In the PCD Phase, the preliminary conceptual design of this system and its major sub-systems and components were completed. The first conceptual design of the WCLL TER system was defined at the end of the PCD Phase and reported in [27]. It included a preliminary study on tokamak building integration, as well [28].

As the T extraction technologies are currently under investigation (see Section 3.3.2), namely the Gas-Liquid Contactor (GLC), Permeation Against Vacuum (PAV) and Liquid Vacuum Contactor (LVC), the TEU design is not yet finalized; large uncertainties remain in the parameters that affect the design (e.g. component dimensions) and performances. Nevertheless, the first system design for DEMO was completed with existing preliminary data for the PAV and GLC technologies. Also purification technologies (see Section 3.3.2) has been included in the design; they are necessary to remove the activated corrosion products, the activated products generated in PbLi (Po, Hg, etc.) and helium (also generated from PbLi). A preliminary design of the related components has been proposed. The storage tank (~1000 m^3) is placed to the lowest level of the circuit to permit complete gravity drainage of the liquid metal circuit.

The design of the WCLL TER needs to be finalized in the CD Phase with the selection of the more suitable technology. This is essential in particular for the TEU sub-system whose design will affect the overall size and performance of the TER. R&D results are still to be achieved for other subsystems, like the purification technologies or the modelling of the He-bubble solubility/transport in the PbLi, to properly design components (e.g. the BZ layout and the He removal system in the PbLi storage tank).

2.3. Alternative blanket concepts

Further additional BB concepts have been studied, some of which could be advanced blankets, designed to meet the requirements for a future commercial reactor, such as coolant conditions able to increase the thermal conversion efficiency of the machine. Among the possible candidates, 2 concepts have been extensively studied from the beginning of the PCD Phase: the Helium Cooled Lead Lithium (HCLL) and the Dual Coolant Lead Lithium (DCLL). A third one, the Single Coolant Molten Salt (SCMS), has been considered later.

The HCLL BB System is constituted of the following subsystems; the in-Vessel BB located inside the VV, the PbLi Loop, and the TER, located both outside the VV; PbLi Loop and TER designs are similar to the WCLL (see Section 2.2) sharing very similar requirements. The concept of the in-vessel HCLL BB consists of segments stiffened by actively cooled plates, between which the breeder flows slowly. The In-Vessel HCLL BB is based on the use of the Reduced Activation Ferritic/Martensitic (RAFM) steel EUROFER as a structural material, the eutectic PbLi enriched at 90% in ^{6}Li as a breeder, neutron multiplier and tritium carrier, and the Helium gas as a coolant at 8 MPa pressure with inlet/outlet temperature at 300 °C/500 °C set due to the thermal limits of the EUROFER of the structure, the eventuality for Helium to go out at higher temperature is a valuable option for thermodynamic efficiency and could be investigated considering advanced structural material. The detailed design of the HCLL and associated hydraulic, thermo-mechanical and neutronic analysis for justification of the requirements and design rules are available in [29].

The DCLL Breeding Blanket is a concept that tries to maximize the plant net efficiency by using the eutectic PbLi as the main coolant [30], which is also employed as tritium breeder, carrier and neutron multiplier. Helium at 8 MPa is used for cooling the FW and the supporting structures (EUROFER). Compared with other PbLi-BB concepts, the liquid metal in the DCLL flows at relatively high velocity (it has to extract most of the reactor power) leading to MHD issues [31]. For that

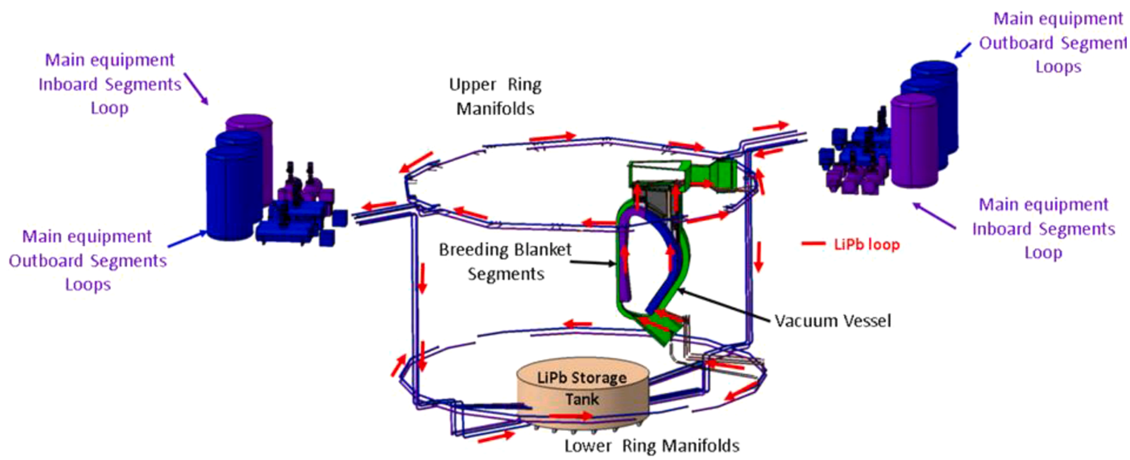

Fig. 5. WCLL TER general view [28]. The Outboard loops are in blue, the Inboard ones are in violet. At the bottom is the Storage Tank.

reason, specific ceramic components, i.e. the Flow Channel Inserts, are used to electrically isolate the blanket conducting walls from the liquid metal. Thus, together with the engineering design of the blanket, an ambitious work programme was developed to fabricate components made of alumina, with different arrangements and geometries, and supported by a complete characterization [32]. The EUROfusion program considered a version of DCLL working at the maximum operating temperature of the structural material (550 °C), to allow the use of conventional materials and technologies. It must be observed that the limitation to 550 °C means that the efficiency, which is the main advantage of this blanket technology, is also limited. Apart from the expected higher efficiency, another important advantage of this kind of blanket is the reduced tritium permeation and inventory, and a more simplified design of internals that increase reliability in the RAMI analysis. Considering that the DCLL was not selected as a possible driver blanket for DEMO, the activities have been re-oriented towards a more ambitious concept, where the DCLL could work at higher temperatures looking for larger plant efficiencies. A preliminary conceptual design has been presented in [33].

The SCMS Breeding Blanket is based on the use of Molten Salt (MS) as a breeder and coolant. This concept is at a preliminary concept design but shows several potential advantages: high coolant temperatures that lead to high thermal conversion efficiency, low-pressure drops under magnetic fields (MHD effects reduced due to low MS electrical conductivity), low operational pressure (requirements associated with Nuclear Pressure Equipment could be relaxed) and losses of heat are low too due to the weak thermal conductivity of MS. Several salts have been investigated, such as Fluorine and Chloride salts. The choice of salt is not yet fixed since many interfaces have to be involved to make a choice. FLiBe is a very good candidate regarding TBR requirement while its melting point temperature is high (460 °C) and N-alloy or coating on advanced ferritic-martensitic steel is needed to protect the structural material. FPbLi, ClPbLi and ClLiK are promising but neutron shielding must be developed to protect the VV and the TFC. Few data exist for FPbLi and ClPbLi salts. In addition, lead is used as a neutron multiplier. Thermal and thermal-hydraulic analyses have been conducted with FLiBe and ClLiK, with a particular focus on the second due to its low melting point temperature at 355 °C. In this case, the Fe-19Cr ODS (PM2000) structural material has been chosen with the proposed MS inlet temperature set at 480 °C and outlet at 580 °C. Detailed design, neutronic, thermal and structural analysis are promising and available in [34].

Studies on variants of the solid breeder blankets were also carried out in the PCD Phase to explore the standard HCPB design with different coolants (water or CO_2) or different neutron-multipliers (Pb) e.g. the Molten Lead Ceramic Breeder (MLCB) blanket that uses molten lead, lithium ceramic and pressurised helium. With virtually no tritium production in lead, there is no need to circulate the lead loop for extracting tritium (simplifying system). The neutronics, thermal-hydraulics and mechanical assessments to justify the MLCB concept have been successfully conducted by [35]. Furthermore, the absence of Beryllium (safety consideration for a water-reactive element) replaced by lead, led to an innovative alternative blanket concept that uses pressurised sub-cooled water as a coolant. This was investigated in the Water Cooled Lead Ceramic Breeder (WLCB) concept [36]. In addition, this concept has the advantage of combining the mature tritium extraction technology with that of a ceramic BB and the water cooling technology with that of a water-cooled blanket, which makes this concept very attractive in terms of technology readiness. Finally, supercritical CO_2 is steadily gaining interest as a secondary coolant to replace the traditional Rankine cycle across the nuclear and non-nuclear power plant industries. Its relative transparency to neutrons, more compact pipework, large industrial basis, abundance and low price makes CO_2 an attractive coolant option for fusion reactors. Based again on the HCPB pin configuration, the CO_2-Cooled Pebble Bed (CCPB) with $TiBe_{12}$ as neutron multiplier has been assessed by [37].

3. R&D on key blanket technologies

The qualification of the proposed designs required a large technology R&D programme to address critical feasibility issues, reduce uncertainties in design parameters and increase the TRL of the present technologies. This is necessary to justify the selection of the most appropriate technology and quantify the performances. The R&D programme developed in the PCD Phase focused on key technology for the present reference design of HCPB and WCLL, namely for breeders (solid and liquid), tritium extraction and manufacturing.

3.1. Solid breeder materials

Ceramic breeder and neutron multiplier materials are essential for self-sufficient tritium production in the HCPB concept. Traditional pebble bed configurations consist of interchanging layers of beryllium and Li_4SiO_4 pebbles. In the PCD Phase, several improvements in the design and new results in the material R&D lead to a new selection of the reference materials for the present DEMO concept, now based on an advanced ceramic breeder (ACB) in a pebble bed form and on new neutron multiplier, Ti beryllides ($TiBe_{12}$), in form of a hexagonal block.

ACB pebbles consist of lithium orthosilicate (LOS, Li_4SiO_4) with additions of lithium metatitanate (LMT, Li_2TiO_3) up to 35 mol%. The material has been extensively investigated with the primary objective to establish a well-controlled fabrication process, evaluate the material properties and build up a reliable database of the material properties [38]. A modified melt-based process for the pebble fabrication was established and advancements in the droplet generation process and optimized process parameters resulted in higher process stability and a yield of $\geq$ 90 wt%. The possibility of reprocessing ACB and their (simulated) re-enrichment with lithium was successfully studied considering the accumulation of impurities and the perpetuation of properties. During the CD Phase, an extensive process scale-up of the pebble production is foreseen aiming at an increased production rate of 5–10 kg/d to secure the supply and cover any needs for breeder blanket mock-ups and ITER TBMs. This larger facility will in principle also demonstrate the transferability to industrial-scale production.

Concerning the material development, the addition of LMT to LOS results in a superior chemical and thermal long-term stability and a significant increase in the mechanical strength compared to the formerly pursued pure silicate material, thereby reducing the risk of powder formation and fragmentation. Further important properties of pebbles and pebble beds including thermomechanical and physical properties as well as compatibility issues were evaluated in dedicated experiments. The available data was recently issued in a new Material Property Handbook on Advanced Ceramic Breeders [39]. The experiments were accompanied by modelling the thermal and mechanical properties of pebble beds with the Discrete-Element-Method (DEM). It was found that a deviation of the pebble shape from perfect sphericity has a strong impact on the mechanical response of a pebble bed. A newly developed thermal DEM code, which was calibrated with experimental results, enables the simulation of the effective thermal conductivity of pebble beds including the dependence on the gas pressure, in particular taking the Smoluchowski effect into account [40]. Additionally, it is possible to analyse the temperature profile generated by neutronic heating [41] as shown in Fig. 6.

A decisive aspect for the tritium breeding materials is the availability and procurement of ^{6}Li enriched raw materials. In the present HCPB DEMO design, approximately 134 tons of 60% ^{6}Li enriched ACB pebbles are required corresponding to about 160 tons of 60 % ^{6}Li enriched lithium hydroxide monohydrate needed for the melt-based production of pebbles. A preliminary cost evaluation confirmed that the cost of the pebbles will be by far dominated by the lithium isotope separation cost. To ensure the availability of ^{6}Li it is high time to address the challenges of a lithium enrichment route for DEMO (see also 3.2.1).

The project decision (see Section 2.1) to substitute Be with $TiBe_{12}$ in 2018 as reference material for the HCPB was the consequence of a review of the results of tritium retention and analytical microstructural studies of beryllium pebbles obtained within the framework of the HIDOBE irradiation campaign; they show that a significant fraction of generated tritium in Be (up to 100% for material exposed to temperatures below 500 °C) is trapped within helium bubbles [42]. The total accumulated tritium in the inventory (estimated in the order of kg for DEMO) imposes severe safety issues and exceeds acceptable limits for the DEMO blanket. In addition, the production of large quantities of $TiBe_{12}$ pebbles is a laborious and costly process. It has therefore been proposed to use this material as a solid block. The usage of this advanced material with lower volumetric swelling, lower tritium retention, increased irradiation and chemical resistance as well as with higher melting temperature facilitates the switch from the pebble bed concept to a solid hexagonal block-based one.

The characterization of Beryllide has been in process for more than 20 years under different fabrication methods and manufacture shapes (also for small pebble productions). For this recent application in hexagonal rods, a new characterization for their applicability in the HCPB blanket of DEMO is required.

For the fabrication of titanium beryllide samples, vacuum hot pressing of a Be-Ti powder mixture on industrial equipment available at the Ulba Metallurgical Plant (UMP), Kazakhstan was explored and led to the successful fabrication of three full-size blocks (Æ144 × 150 mm^2) from titanium beryllide with density reaching 98.8% of the theoretical one demonstrating good replicability of this novel technology [43,44] (see Fig. 7).

To cope with concerns of block cracking with unpredictable increasing operational temperatures, the out-of-pile test started in the PCD Phase. More than 200 accelerated thermal cycles representing DEMO relevant ramp-ups and downs between 360 and 920 °C performed at the UMP ensured mechanical and chemical resistance of beryllide blocks with proper geometry [44]. Further real-size mock-up tests present major progress in the development of advanced multipliers, permitting a fast increase of the TRL for the complete HCPB tritium-breeding blanket. This approach paves the way for the fabrication of a full-scale prototypical mock-up and its qualification and functional testing under foreseen DEMO conditions for the HCPB blanket.

To qualify both functional materials for their next use in the ITER-TBM irradiation campaign, a dedicated neutron irradiation experiment is foreseen to be performed in the IVV-2M test reactor of the Institute of

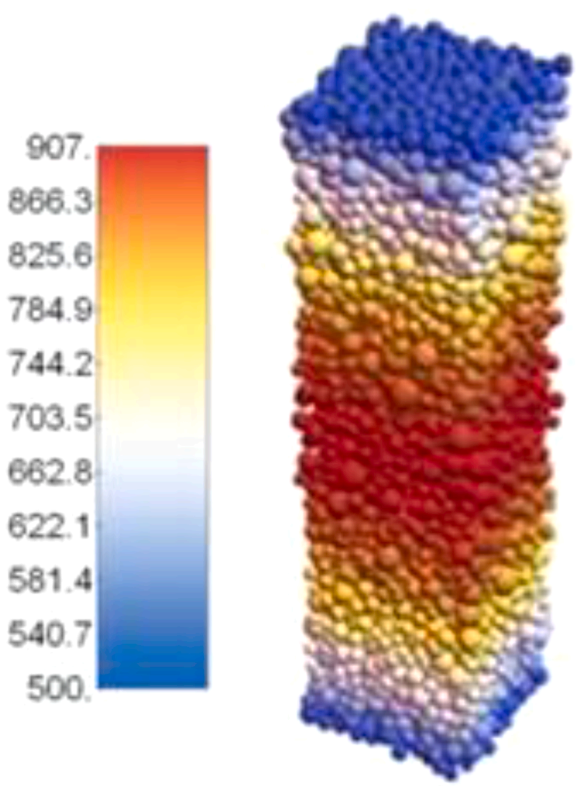

Fig. 6. Temperature distribution in the pebble bed at a helium purge gas pressure of 2 bar predicted for a distance of 50 mm from the First Wall, after [41].

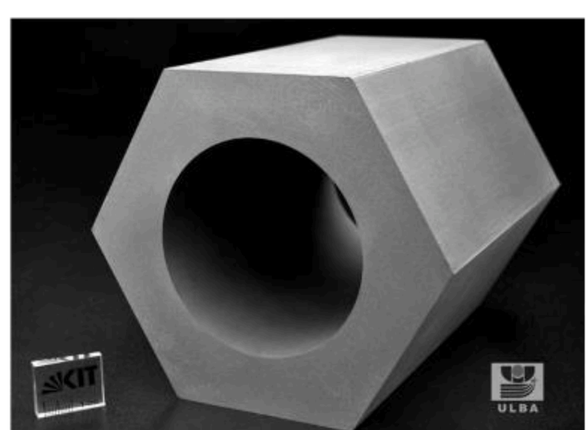

Fig. 7. Hexagonal $TiBe_{12}$ block after final machining.

Nuclear Materials (INM), Russian Federation. In this experiment, the maximum displacement damage can reach 3 dpa (equivalent in steel) that is the full irradiation level foreseen for the TBM.

For the ACB pebbles, it is essential to investigate the in-situ tritium release and determine the tritium residence time. Extensive post-irradiation examinations, planned at KIT, will analyse the development of the microstructure, the porosity and the mechanical properties, as well as compatibility issues and tritium release characteristics.

With these results, the material composition of ACB pebbles can be conclusively determined. For the beryllium-based neutron multiplier materials, the main objective is to characterize several productions of Beryllium pebbles (still planned for the initial ITER TBM operation) and beryllide specimens. These production methods are the extremely costly 1-mm beryllium pebbles produced by the rotating electrode method and the alternative less expensive pebbles obtained by the fluoride reduction method as by-products of beryllium extraction. The last ones need to be tested in particular for their irradiation resistance. Although significantly higher damage doses are expected for the DEMO BB and longer irradiations are later indispensable, this short-time neutron irradiation should be used for a fast screening of prospective beryllides (e.g. to confirm the selection of the titanium beryllide as reference material.

3.2. Liquid breeder PbLi

The PbLi is used at the eutectic composition to minimize the melting point (~235 °C); however, the composition, reported in the literature at this moment, presents scattering data between 15.8 and 17% at Li. Uncertainties in some other properties of the PbLi are known, which not only highly affect the performances of the blanket but also the design of the auxiliary systems. To fix design values, [45] collected all those properties, giving reference values to be used by the designers.

The use of PbLi as breeder material entails several issues: the chemical reactivity of PbLi with water and air; the control of impurities; the corrosion of steel due to the interaction with the PbLi; the consequent deposition of activated corrosion products; the tritium recovery from the liquid metal and the impact of the magnetic field on the flowing PbLi (magnetohydrodynamics phenomena). In addition, the production of the alloy with adequate nuclear standards is a challenge that presently is being studied, together with the enrichment in ^{6}Li. Dedicated experimental programs are being conducted to solve or alleviate all these issues, the main results will be presented in the next subsections.

3.2.1. PbLi production and characterization

The scaling-up of the PbLi production is fundamental for the realization of the WCLL BB, which needs around 10,400 t of the alloy. Most of the proposed methods are known to be suitable only for laboratory or semi-industrial scale, due to their low production rate (a few kg/y) and/or to technological limitations that make an effective scaling-up difficult. At present, three important parameters for the correct production of the eutectic alloy have been considered: the crucible material, the temperature and the protective atmosphere. Other important parameters are the geometry, the state of the starting materials (Pb and Li) and the operating time, which should be short to limit oxidation and loss of Li. Also, the PbLi chemical composition must be controlled and, in this context, the requirements for the PbLi chemistry have been fixed within the PCD Phase [46]:

One of the most critical impurities is Bi, which is usually present in commercial Pb. The presence of ^{209}Bi in the alloy causes the radioactive ^{210}Po production as a consequence of the Bi neutron activation. Even though Bi is produced during the irradiation due to the activation of Pb, the initial impurity content is crucial to reduce the level of this contamination.

Another important issue of the production process is the lithium enrichment, which is also the largest share of the cost for PbLi [47] as well as for solid breeders [38]. The most popular separation method is based on the isotope effect that arises during a chemical exchange of lithium between a lithium amalgam and an aqueous solution of lithium compounds. Among several chemical exchange methods, the Oak Ridge National Laboratory previously developed the COLEX (COLumn EXchange) separation method. A study performed by Giegerich et al. compared the available enrichment methods taking into account the scalability, the complexity and the status of the knowledge on each process [48]. The results of the study gave the highest rating to the COLEX. However, COLEX's main drawback is the high production of mercury as waste. An improved COLEX could be a viable and sustainable industrial method of lithium enrichment if these wastes could be reduced. The Karlsruhe Institute of Technology has set up a laboratory to optimize the exchange columns and the reflux sections, which are the two most important parts of this process. As shown in [48], several years of work are forecasted before being able to build a full-scale production plant.

3.2.2. PbLi purification

This PbLi purification deals with the control of helium, activation products and corrosion products generated during operation in the reactor. Three systems of the WCLL TER are conceived to purify PbLi: the Buffer Tank (for helium), the Activation Product Removal System and the Cold Trap (for corrosion products).

When tritium is formed, 2 g of ^{6}Li are burnt and 1.33 g of helium are released. With the current data, the production of helium in the BB will be above 500 g/day. Generated helium can remain solubilized in PbLi or coalesce to form a gas bubble if the concentration becomes higher than the solubility limit. The behaviour of helium mainly depends on PbLi mass flow rate, temperature, and pressure. In the PCD Phase, the nucleation of bubbles in the BB, firstly observed in the LIBRETTO experiments [49,50], was confirmed by Kordač et al. [51], where the authors demonstrated the importance of PbLi pressure and mass flow rate for the helium formation rate. The authors estimated a production rate of 10-40 ml/h for the WCLL BB, causing a reduction of the available PbLi volume of about 3–12%/year if helium will not be removed. The current approach for helium removal from PbLi takes advantage of the low helium solubility in PbLi and it is based on the reduction of PbLi velocity and pressure to lower the solubility limit, thus forcing helium to leave PbLi. Released helium would then be discharged from a dedicated line. Even though the main physical mechanisms leading to helium nucleation and removal from PbLi have been described, the system to practically remove helium from PbLi has to be designed and tested under different conditions and at different scales in the subsequent CD Phase. With the typical WCLL BB mass flow rates an efficiency higher than 90% has been estimated for a separator working at atmospheric pressure.

Under neutron irradiation, the composition of PbLi slowly changes in time while different species form as a consequence of the transmutation reactions caused by neutron irradiation. In the PCD Phase, the activation products and, among them, the main contributors to the environmental dose have been identified. The most harmful species identified are T, ^{210}Po and ^{203}Hg. A strategy to remove the activation products has been developed and is based on the evaporation of the activation products from PbLi, followed by filtration of the gas carrier. The activation products are relatively volatile and, therefore, will be removed by evaporation from the hot liquid PbLi. Similarly to what happens in the case of helium removal, the main mechanisms of activation product removal from PbLi have been analysed and understood. However, the system to practically remove volatile activation products from PbLi has to be designed and tested under different conditions in the CD Phase before being able to use it in the WCLL TER.

Finally, ferritic/martensitic steels are attacked by PbLi through homogeneous dissolution, at a rate depending mainly on temperature, PbLi velocity and impurity concentration [52]. Corrosion products are then transported by PbLi throughout the TER and the BB and can form plugs in cold points or near discontinuities. The current approach to PbLi purification from corrosion products has been identified during the PCD Phase and is based on the use of filtering devices, called cold traps. The principle of a cold trap is to cool down the breeder and thus decrease the solubility of dissolved elements. When the concentration of a particular element exceeds its solubility, it precipitates and can be separated using the gravity force, centrifugal force or can be filtered out. Although the purification principle is relatively simple, the design of a cold trap is not trivial as reliable experimental data or empirical correlation are lacking on the steel components solubility in PbLi (e.g. Cr and, especially, Fe) and the kinetics governing the precipitation phenomena. In the CD Phase, these uncertainties will have to be reduced, while experimentally assessing the performances of the removal system.

3.2.3. Coating technology

The possibility to realize a coating on EUROFER at the PbLi interface can mitigate several major risks and improve considerably the WCLL performances. The issues are related to several different critical topics. First of all, the corrosion of EUROFER under PbLi flow with interface temperatures of 300–550 °C in the BB and PbLi pipes; dissolved (and activated) corrosion products can be transported by the PbLi and can be set down in the colder parts of the blanket box and/or of the PbLi loop with blockage issues. The known issue in the fission of the LME (Liquid Metal Embrittlement) has to be considered. In addition, coatings are requested in the WCLL design with a tritium permeation reduction factor of at least 200. This can be an effective barrier to decrease the permeation of tritium from the breeder to cooling water, reducing the total inventory of T in the cooling system (at the moment is estimated at around 150 g) and the tritium released into the environment. The coating can electrically insulate the pipes to the liquid metal, avoiding large pressure drops in the flow due to MHD effects.

Three coating technologies based on α-Al_2O_3 were developed at laboratory scale and a preliminary scale-up of the technologies were performed, the present fabrication technologies are: PLD (Pulsed Laser Deposition) process developed by IIT (Italian Institute of Technology), ECX (Electrochemical) process developed by KIT, and ALD (Atomic Layer Deposition) process developed by IIT.

Corrosion compatibility tests carried out on ECX, PLD and ALD techniques have not shown corrosion attack in static PbLi at 550°C; the results have shown good corrosion stability [53]. The experimental results obtained suggest the possibility to use the ECXcoating in the PbLi loops pipes. Moreover, PLD coating has been demonstrated to be able to reduce the tritium permeation flux at least 10,000 under electron irradiation combined with thermal cycles and more than 250 under neutron irradiation. Within the FP8, samples coated by PLD and ECX were irradiated with neutrons in the LVR-15 reactor. The samples were exposed in the reactor to flowing PbLi in the temperature range 300–450 °C and irradiated by a neutron flux of 8.08•1012 n/(cm2s). The tritium permeation flux was measured during the tests, while metallographic and mechanical tests were carried out in the hot cell after the end of the irradiation [54].

PLD coating, characterized in the temperature range between 20 and 550 °C works also as an electrical insulator. The main limitation of the PLD process is intrinsic to the technique, it can only coat external surfaces. ALD technology is very promising in terms of capability to reduce tritium permeation flux and the possibility to be applied on complex geometry even at low temperature, however, further characterization is required.

To complete the preliminary characterization of coating performances, it is requested to analyze the corrosion resistance, permeability and mechanical properties of coatings irradiated with neutrons at relevant dpa for ITER TBM and DEMO BB.

In the CD Phase, the selected process (or processes) will be further developed in view of scaling to real geometries and components and to realizing and qualifying a demonstrator mock-up. The proposed program will continue for the whole conceptual phase. Preliminary results should be ready for the Blanket Selection, but the main results will be expected only at the end of the CD Phase.

3.2.4. PbLi/water interaction

A major safety issue of the WCLL breeding blanket is the interaction between PbLi and water caused by a water tube rupture in the breeding zone, the so-called “in-Box LOCA” (Loss of Coolant Accident) scenario. This issue has been investigated during the PCD Phase defining a strategy that has as the final objective to have a reliable and qualified system code for deterministic safety analysis and representative separate and integral test experimental data. This will permit the evaluation of the accidental consequences and choosing possible mitigating countermeasures, besides proposing design solutions to prevent damages to the blanket box structures.

After the implementation of the PbLi/water chemical reaction model in SIMMER codes, the validation activity has required to apply a standard code methodology [55] to experimental data, provided by the new LIFUS5/Mod3 facility [56]. Two campaigns were executed, enlarging the experimental database with reproducible and well-defined initial and boundary conditions [57], suitable for the validation of the modified version of SIMMER III and IV codes for fusion application. In parallel, the methodology set-up during FP8, based on a three-step process, was applied to the post-test analyses [58], comparing numerical results against experimental data and pointing out differences and similarities to analyse capabilities and deficiencies of the SIMMER codes. Moreover, the experiments constituted also a useful database for supporting the SIMMER/RELAP5 coupling calculation tool [59], which permitted to perform preliminary analysis on WCLL TBM and its ancillary systems, investigating the behaviour under an in-box LOCA postulated event [60, 61]. On the other hand, further investigation is required to overcome issues, which are still open, such as the evaluation and the reliable prediction of the WCLL in-box LOCA scenario at system level and the availability of integral test facility data. In the CD Phase the new designed LIFUS5/Mod4 Integral Test Facility (ITF) will be installed at ENEA CR Brasimone representative of the WCLL TBM operative conditions. The objective of the experimental campaign is to investigate the phenomenology, the behavior and the response of WCLL TBM under in-box LOCA at the system level. Moreover, the facility will be able to reproduce and assess the effectiveness of the safety functions and procedures implemented in such a scenario. This involves continuing the validation activity on the code coupling and the procedure for its application together with the validation of SIMMER codes against ITF experiments, implying the availability of a numerical tool with predictive capabilities that will be employed in the design and safety analysis activities of the WCLL BB of DEMO.

3.2.5. MHD code development and validation

The use of PbLi as a liquid breeder/coolant leads to strong magnetohydrodynamic (MHD) effects that need to be considered to assess the performance of the blanket. The main issue is the increased pressure drop compared to hydrodynamic flows caused by the electromagnetic Lorentz forces opposing the flow. The latter is induced when the liquid metal circulates in the strong plasma-confining magnetic field. Moreover, these forces affect the velocity distribution and often suppress turbulence with serious implications on heat and mass transfer. For reliable prediction of MHD phenomena under fusion-relevant conditions, asymptotic analyses and numerical simulations validated by complementary experimental campaigns are employed.

In recent years, experiments performed in the MEKKA laboratory at KIT and numerical analyses were conducted to investigate fundamental aspects of MHD flows and support the design of three liquid metal blanket concepts (HCLL, DCLL and WCLL) in the PCD Phase. Studies carried out included: flows in inclined rectangular ducts [62], the influence of contact resistance between fluid and wall, stability of laminar MHD flows and transition to turbulence, flows in non-uniform magnetic fields [63], and mixed convection heat transfer [64]. Specific analysis of MHD flows for WCLL blankets include magneto convection in WCLL-typical model geometries with internal obstacles (cooling pipes) [65,66], in geometries used in experimental campaigns [67], and for manifolds in a prototypical WCLL-TBM (see e.g. Fig. 9) [68].

An important outcome of studies for a HCLL TBM is that only properly designed manifolds will lead to a reasonably balanced flow partitioning among breeder units (BUs). Similar results are expected as well for future designs of PbLi manifolds in WCLL blankets. Likewise, the first numerical simulations of a WCLL TBM show that the overall MHD pressure drop is not really an issue but the initial design of the manifold suffers from the same drawbacks as the one studied for a HCLL TBM [68]. When the flow rate in the feeding channel decreases along the poloidal path, the pressure gradient (slope in Fig. 8) decreases. In the collecting part, the situation is reversed. Moreover, the electromagnetic coupling at common electrically conducting walls even leads to local flow reversals and pressure increase in neighbouring ducts where the flow rates are small (near the end of the feeding channel or the beginning of the collecting duct). Finally, it can be seen, that pressure heads driving PbLi into external BUs, e.g. BU1 and BU8 are much larger than near the centre, e.g. BU4-BU6, a fact that will result in flow imbalance among BUs. This will further be investigated in an upcoming mock-up experiment foreseen in the FP9 campaign. A possible remedy to balance the breeder flow across all BUs consists in adjusting the cross-sections of the feeding and collecting manifolds along the poloidal direction.

Recent progress in numerical modelling of MHD flows and the improved availability of high-performance computing allows simulations of flows in blanket-typical geometries close to fusion relevant parameters. Such simulations are complementary to experimental observations using scaled mock-ups as they provide insight into flow phenomena that are not observable from measurements of pressure or surface wall potential. For numerical simulations of PbLi flows in geometrically complex blanket structures, it would be desirable to use automatic grid generation. MHD peculiar issues such as very thin boundary layers, thin internal layers, stiff coupling between hydrodynamics and electrodynamics, and the tendency of perturbations to spread along magnetic field lines require new strategies for automatic grid generation that are lacking in tools dedicated to the simulation of hydrodynamic flows. Research in the CD Phase is foreseen on the generation of MHD-adapted grids for complex blanket geometries.

To judge the overall performance of entire blanket systems, flow details may be of minor importance in favour of a global view. For that reason, the use of systems codes represents a promising option for future development (see e.g. [69]). Finally, it should be mentioned that only a few MHD experiments using the breeder PbLi as liquid metal have been performed in the past. In 2021 the MaPLE facility, initially constructed and operated at UCLA (USA) and recently upgraded with EUROfusion contribution has been transferred to KIT. This facility will be available by 2022, as part of the CD Phase research program, for MHD experiments on forced and mixed convection heat transfer.

3.3. Development of T extraction processes

3.3.1. The T extraction from the purge gas in HCPB

In view of the design development of the TER HCPB (see Section 2.1), various processes with the potential for scale-up at the DEMO requirements have been evaluated and selected in PCD Phase. In the early stage of this evaluation, two extraction processes have been considered: the extraction process based on trapping/adsorption and the one based on membrane separation [70]. The present reference for the HCPB is based on a well-established cryogenic industrial process (by Linde AG) and works in batch modus switching the beds from absorption to regeneration. The membrane technology was extensively investigated as an attractive alternative based on a continuous process even if with lower TRL. The Q_2O and Q_2 separation based on membranes consist of a zeolite membrane cascade combined with a catalytic membrane reactor (PERMCAT). Following the experimental results, the selectivity of the membrane was found to be mainly mass-dependent [71] and therefore the separation between HT and He is impossible to be realized at the requirements of DEMO.

After the confirmation of the trapping/adsorption technology, the R&D shifted to explore the possibility to improve further the reference technology. The R&D is presently concentrated on the enhancement of the TER system in terms of energy consumption, reduction of the parasitic tritium permeation to the Cooling system and equalising the operational helium pressure between purge and cooling system overcoming the present limitations of the "two chambers" blanket design.

To overcome the main drawback of the reference TER HCPB technology, meaning the tritium adsorption on molecular sieve at 77 K, the alternative technology based on Getter Beds is under evaluation and development. The most recent investigations have been carried out on the Characterization of Non-Evaporable Getter (NEG) for NBI systems developed at SAES Getters [72]. During these investigations, specific experiments have been carried out to select a suitable getter elements configuration, and to characterize their pumping/adsorption

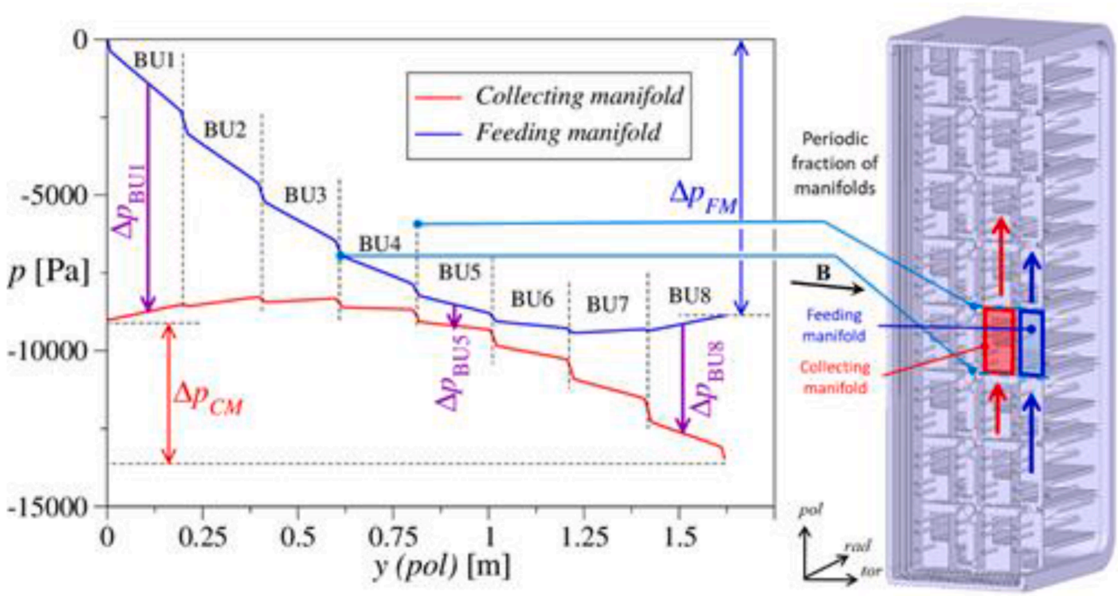

Fig. 8. Pressure distribution along the poloidal direction of the feeding and collecting manifolds of a WCLL TBM.

performances according to the requirements of the final applications. The main results of the experimental tests have led to the selection of NEG in form of disks of ZAO alloy (ZAO – Ti Zr V Al). The NEG performances are now under investigation at SAES and KIT in terms of pumping performances and embrittlement limits for H_2 and D_2. No embrittlement due to hydrogen and deuterium adsorption/desorption cycles is expected for loads below 1862 Pam^3/kg (1000 cycles tested for H_2 and 100 for D_2) and Getter disks can withstand without embrittlement single shot hydrogenation loads up to 1.33e+4 Pam^3/kg. Presently the production of the selected disks is undergoing at the industrial level aiming at upgrading the present *laboratory-scale* production capability.

One of the possibilities to mitigate the tritium permeation from the purge gas in the cooling gas is to increase the HTO content in the purge gas. Therefore, thorough investigations of the tritium recovery from the RMSB system, through the isotopic exchange between the tritiated water and a H_2/D_2 gas stream, have been carried out. The RMSB consists of several sections and during the tritium recovery process, regeneration of the RMSB, the water is desorbed and adsorbed on the following section enhancing the isotopic exchange process [73]. One of the main parameters of the regeneration process, with impact on the DEMO Tritium Plant where tritium is finally enriched, is the flow rate of the H_2/D_2 swamping stream. To minimize the flow rate of this stream, the impact of operating temperature and its evolution over the full regeneration of the RMSB has been investigated. As a general remark, as far as swamping gas flow rate for isotopic exchange is concerned, it was observed that the required flow rate is up to 7 Nm^3/h for a 10 h isotopic exchange period of time and respectively up to 3.5 Nm^3/h for 20 h isotopic exchange period of time. These values are conservative and are based on an isotopic exchange between HTO and H_2 at 80 °C. The higher temperature regeneration favours the isotopic exchange, due to the lower value of the equilibrium constant which means that the concentrations in the vapour phase and the liquid phase are closer. Nevertheless, the impact of the regeneration temperature on the swamping gas flow rate was found in the range of a maximum of 15% for the cases of temperature variation between 600 and 800 °C [74];

3.3.2. The T extraction from PbLi in WCLL

As already mentioned in Section 2.2, two technologies are currently under evaluation for the reference extraction process of T from PbLi, namely PAV and GLC; a third one (LVC) is a possible backup solution [75,76]. In the PAV a membrane separates PbLi from a vacuum; the membrane is made with a tritium permeable material, such as vanadium or niobium, thus allowing the diffusion of tritium from PbLi to vacuum as a consequence of the concentration gradient. In the GLC a flow of helium (or helium plus a small percentage of hydrogen to increase the extraction efficiency) is put in direct contact with PbLi in counter-current and tritium is removed by stripping. Packed columns are used to provide a large interfacial surface between the PbLi and the gas flow.

The PAV technology has several potential advantages over the GLC, including ease to operate as PbLi simply flows into some channels (no need to put two very different media in direct contact) and extraction occurs by concentration gradient; in addition, the outlet from PAV is a pure tritium flow and can be directly transferred to the tritium processing plant. Instead, tritium extracted by GLCs is mixed with helium; then, if protium is added to helium to enhance the tritium removal, different hydrogen molecular forms (H_2, T_2, HT) appear. Hence, the use of PAV avoids a processing step, simplifies the system and reduces the need for additional components, also minimizing the tritium residence time in the system [77]. However, GLC columns are easier to be manufactured, thanks to their widely used technology in many industrial processes. The technology has already been tested in PbLi, proving to be capable of extracting hydrogen isotopes from the alloy (but also confirming the many difficulties in operating a component where helium and PbLi have to flow in counter-current). A further issue for PAV is the large uncertainties in tritium transport parameters for the material used for the membrane [78].

Design and manufacturing of the first PAV mock-up with vanadium membrane were performed at CIEMAT for testing in the CLIPPER facility [79]. A different mock-up with niobium membrane is being designed and manufactured at ENEA Brasimone Research Centre to be tested in the TRIEX-II facility [80]. The results of the two manufacturing are promising. One of the main concerns for PAV is that the welding of vanadium and niobium is difficult due to oxidation tendencies, therefore successful results of the tests would constitute a milestone for the extraction technology. Aside from the other differences, a major parameter to be considered to select the more convenient technology for tritium extraction is the requirement for additional secondary systems. The secondary side of a PAV is a vacuum system, where the biggest challenge is the design of the vacuum pumps due to the high pumping speed that PAV demands to maintain an 80% efficiency [81].

The alternative LVC process is still under assessment, where PbLi is exposed directly to a vacuum without a permeation membrane. LVCs are high-efficiency and promising methods to extract tritium from liquid lead-lithium alloy. A possible configuration (investigated during the PCD Phase [82]) is in the “Vacuum Sieve Tray” (VST); here, the lead-lithium flows from an upper chamber to a bottom vacuumed one; these chambers are separated by a tray equipped with nozzles of the diameter of the order of the millimetre, which allows the alloy to form an unstable liquid jet of droplets. The high efficiency is due to a continuous evolution of droplets. Studies at Kyoto University [83] have shown that during their fall, droplets undergo internal oscillations, and pass from a prolate form to an oblate one, with a frequency of about 200 Hz for 1 mm diameter. These oscillations greatly amplify the mass transport of hydrogen isotopes. The investigation of general principles of LVC systems will be continued in the CD Phase with the possibility to test the most promising ones.

As shown in this Section, a large R&D is ongoing in the CD Phase to produce relevant information for the selection of reference technology for the design of WCLL TER; a down selection is required to complete the design of the WCLL systems.

3.4. Helium cooling technology

Even though the limiter/protection strategy adopted in the DEMO design [84] aims to reduce the values of the heat flux peak at the standard blanket FW, the FW has to withstand stationary peak loads at least up to ~1 MW/m^2. Initial studies conducted in the PCD Phase [85] have demonstrated the possibility to design helium-cooled first wall channels under this requirement for the HCPB Blanket design with reasonable pressure drops; this is possible adding heat transfer enhancing structures (e.g. ribs in the mm range) at the internal channel surface below the plasma-facing wall. Combined experimental and numerical works allowed the selection of the most suitable geometry for ribs, namely upstream pointing V ribs, which yield a very favourable ratio of removed heat per invested pumping power (Thermal Performance Number). The performance in terms of heat transfer augmentation is reported in [86].

For numerical simulations, scale resolving Computational Fluid Dynamic like Detached Eddy Simulations (DES) or Large Eddy Simulation (LES) provided an appropriate approach, while Reynolds Averaged Navier Stokes methods are significantly challenged by the complex rib-induced flows. Design analyses are therefore supported by experimental correlations for heat transfer and friction factor data.

Monolithic rib structured FW channels made of EUROFER were already fabricated with realistic lengths of 775 mm by the sink erosion. In the case of a FW fabricated in sandwich technology, the addition of ribs can be done by conventional machining in the accessible half-channels and is already practised for a FW prototypical mock-up in the CD Phase. In the CD Phase, the work will concentrate on the manufacturing and test of a first wall prototype in the HELOKA high-pressure helium loop to confirm the design previsions [87].

On the other side, the pin concept (see Section 2.1) has greatly reduced the pressure drop in the HCPB decreasing consequently the coolant velocity. The decrease in the helium velocity caused a reduction in the heat transfer coefficient. Increased surface roughness's are therefore proposed as a heat transfer augmentation technique for the pins. Therefore, DEMO relevant dedicated experimental campaigns are foreseen at the 8 MPa pressure high-temperature Helium Loop Karlsruhe (HELOKA) in KIT as validation and proof-of-concept test rigs for this pin design [88]. The engineering design and the manufacturing has been completed; the experimental campaign should be concluded in the early stages of the CD Phase.

3.5. Water cooling technology

The identification and optimization of the water coolant chemistry of the BB circuit was one important objective of the pre-conceptual phase design for DEMO. In the WPBB programme, this topic was intensively studied to understand the major differences from standard fission plants and to identify the specific requirements in a fusion environment [89].

In fact, distinctive elements like the presence of EUROFER, hard neutronic spectrum (14 MeV), high level of radiolysis, strong magnetic fields, and T presence in the cooling water challenge a fission-oriented solution. The recent outcomes from the fission industry highlighted: (a) the move towards using KOH instead of LiOH as an alkalising agent, (b) the progress made towards establishing the critical hydrogen concentration for suppression of water radiolysis products in fission reactor coolant circuits, (c) the advancements in the application of noble metal chemical addition for enhanced SCC mitigation, (d) the recent experience in the use of zinc injection in the hot functional testing phase for AP1000 and EPR reactors, and (e) the move towards online chemistry monitoring, analysis and trending systems.

Several studies were done in the PCD Phase. A preliminary estimation of the effect of the magnetic field on corrosion has been performed. Besides, the conditions employed were significantly different from those of the WCLL BB, this work has provided evidence of an influence of magnetic fields on EUROFER corrosion, suggesting that the occurrence of pitting may increase under certain field orientations. A flow cell is now being commissioned to work within a flow loop apparatus which will allow exposure of EUROFER to high-temperature water whilst in the high magnetic field.

The possible scenario in terms of Activated Corrosion Products (ACP) inventory, produced in the WCLL BB system under specific DEMO plant conditions, was formulated thanks to the support of the PACTITER code [90]. Corrosion tests were performed in parallel on EUROFER-97 and AISI316L to validate the ACP codes and to optimize the water chemistry for obtaining low corrosiveness, low impact in terms of ACP production, low neutronic consumption, simple chemistry control and suppression of radiolysis. From these studies, preliminary indications of optimized water chemistry were obtained. EUROFER-97 and AISI316L pipes showed a relative low corrosion rate, considering water solutions with different buffers (e.g. 1-11 ppm of LiOH, 500–750 ppm of NH_3). Based on the present experimental results, it can be assumed that the water chemistry to be used for the design of WCLL should have the following characteristics: pH between 6.8 and 7.4, dissolved oxygen ($<$ 10 ppb), conductivity (make-up water $<$0.1 μS cm-1 at 25 °C) and anion impurities as low as possible (each less than 25 ppb, combined less than 50 ppb).

Regarding the methods of radiolysis suppression, no specific experimental activities have been carried out. However, from literature studies, it was concluded that a hydrogen content not higher than 0.5 cc/kg guarantee the suppression of the phenomena of radiolysis [91].

In the framework of WPBB. a radiolysis model has been developed based on an existing water radiolysis code implemented within the FACSIMILE software package. It calculates the concentrations of oxidizing radiolysis products around the WCLL cooling circuit in the DEMO reactor, implementing data from the most recently available designs and assessments. This shows that micro-molar concentrations of O_2 and H_2O_2 can be produced in the breeder zone cooling pipes, though these fall by at least three orders of magnitude in the remainder of the circuit. The concentrations are significantly reduced by the addition of greater than 30 ppb H_2.

The selection of the suitable buffer is of course an interface issue between BB, BOP and TFV systems. From the side of WPBB, a preliminary recommendation of the buffer is oriented to LiOH and KOH. However, a final selection is still open due to the potential drawbacks of these solutions and should be completed by the end of 2023.

3.6. Blanket manufacturing

Several activities have been performed in the development of manufacturing technologies for the DEMO BB and in particular for the TBM in ITER that is already in a preliminary engineering phase; details can be found in reference [92].

In the PCD Phase, several technologies aiming at manufacturing sub-components including the presence of cooling channels such as the first wall, cooling plate, stiffening plate and side cap have been evaluated. They are based on machining (Electrical Discharge Machining), forming (bending), welding (Electron Beam Welding, Gas Tungsten Arc Welding (GTAW), Hot Isostatic Pressing (HIP) and Laser Beam Welding (LBW)) and additive manufacturing (e.g. Laser Power Bed Fusion) methods.

The proposed technologies will have to take into account during the next studies the actual size and associated constraints such as the tolerances achievable during the machining phases. Manufacturing technologies and associated preliminary procedures are developed and defined for the assembly by welding of these sub-components. Their assemblies with GTAW, EBW, LBW and HIP processes features several challenges. Numerous welds are needed to assembly the sub-components in the box. Cooling channels are embedded in the plates at ~5 mm from the welded joint. Damage or deformation of the cooling channels shall be avoided.

For the WCLL concept, a key task was the manufacturing of DWT (see Section 2.2); the use of this technology in the design has been engaged to reduce the probability of water leakage in the PbLi increasing the reliability of the concept. DWTs consist of two concentric EUROFER-97 tubes joined by a layer that has the function of mechanically separating the two steel tubes achieving at the same time a correct thermal conductivity. The two tubes are designed as redundant barriers regarding leakage of water inside the PbLi.

Design and industrial assessment of DWTs manufacturing sequence are performed on grade 91 steel tubes. Recent manufacturing delivered T91 DWTs including a pure iron layer at the interface between the inner and outer tubes joined together by diffusion bonding. The welded junction between the BP and the DWT has been assessed with different processes (see Fig. 9). The non-destructive controllability is also an issue that should be studied because the ability to control the three welds is not acquired. The next activities will consist of finalizing the design of this junction from a mechanical strength point of view and consolidating the welding procedure specification developed today. Investigations into the cost of manufacturing technologies have been initiated on full-size components and highlight the need mainly to reduce the price of EUROFER and to converge towards manufacturing techniques that consume less EUROFER.

For the joint technologies significant efforts to minimize the thermomechanical distortion have been made; the objective is to minimize the thermomechanical distortions during welding assembly of large components with the help of numerical simulations. We applied this approach to GTAW and laser welding processes. The numerical simulation aims at giving recommendations on the best welding sequence. Numerical welding simulation of large industrial components remains a challenge because the local scale of the welding process and the global scale of the component distortion are fully coupled, leading to very large numerical problems.

Based on the collaboration with industrial experts, manufacturing

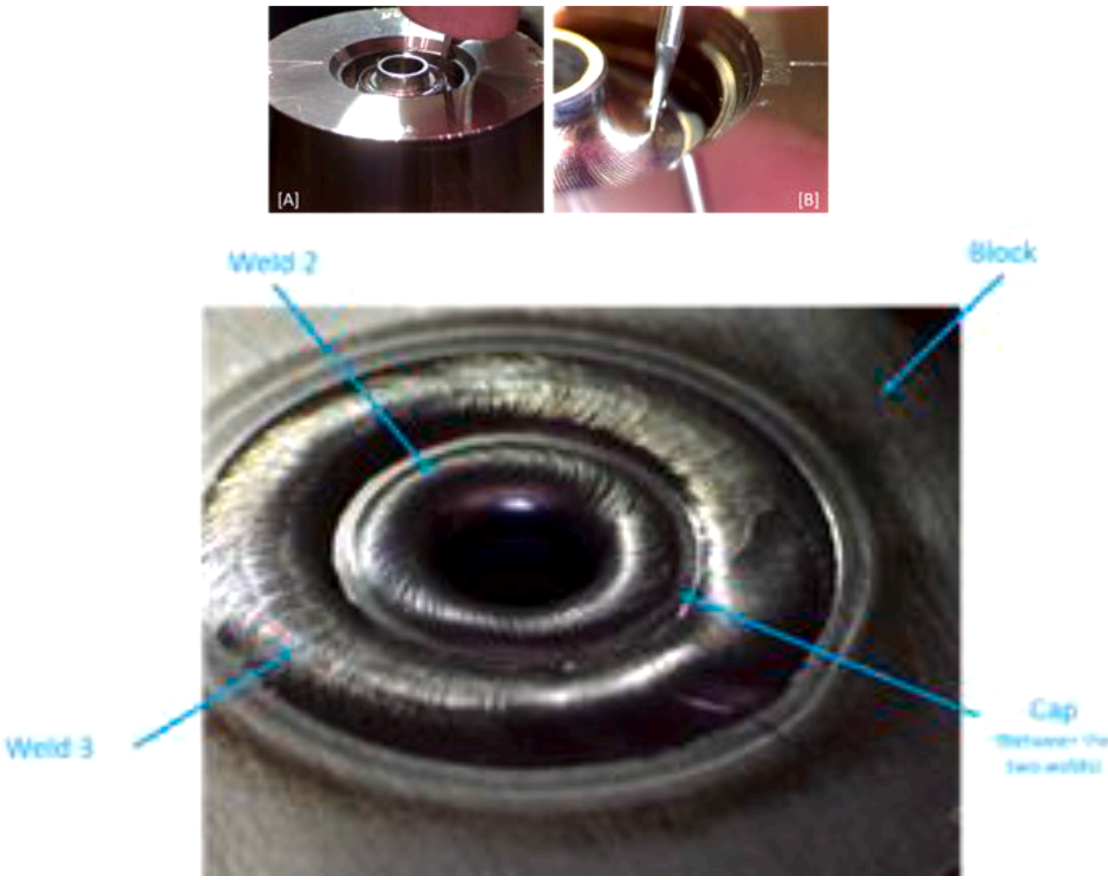

Fig. 9. Welding junction between DWT and BP.

routes for HCLL and WCLL were evaluated and defined including the phases of machining, welding, heat treatment, non-destructive test and mounting scenarios for the manufacturing of very large components such as the breeding module and the back supporting structure component, a total developed length of 16m for the outboard. This first analysis on the technologies and methodologies implemented and the identification of their limits on large components constitute a database that will have to be updated according to the evolution of the design and can be transferred to the other components. The development of these matrices is an important point for the next phase of study since it will facilitate interaction with the designer to integrate the constraints linked to manufacturing and have a global vision on the manufacturing of components to be produced.

Apart from the more conventional fabrication technologies, advanced manufacturing routes have been investigated as well, motivated by cost-reduction intentions and the demanding functional requirements (dimensions, complex 3D-shape of First Wall, reduction of welds and Heat Transfer Enhancement structures inside of the channels). It has been identified in [93] that Additive Manufacturing (AM) provides goal-oriented solution options.

Laser Power Bed Fusion (LPBF) has been investigated where promising material properties could be demonstrated for EUROFER components [94,95]. The process configuration was demonstrated as suitable for thin-walled high complex Breeding Blanket internal components. The option to produce hybrid components (LPBF + conventionally fabricated segments assembled by welding) [96] has been demonstrated to overcome size limits in powder bed based Additive Manufacturing.

The Direct Energy Deposition AM process of Cold Spray (CS) was addressed in combination with well-established processes, e.g. cold forming, machining, welding and HIP. A dedicated process chain has been created and TRL 3 (proof of concept) has been demonstrated at the end of the PCD Phase in a small-scale planar demonstration part with a First Wall relevant cooling channel configuration adapted for the HCPB blanket (see Fig. 10). The manufacturing sequence aims at the minimization of fusion welds and enables the realization of a very low proportion of AM-deposited material in the final product. The CS deposited layer only serves during production as support for a HIP step to join the conventionally fabricated external and internal shells where the HIP joint finally provides the load-carrying structure in the component [95]. Future work in the CD Phase is envisaged for increasing the TRL level steadily and to upscale towards First Wall relevant sizes and geometries taking into account the integral production scope and equipment (e.g. procurement options of full-scale semi-finished sells, industrial equipment such as HIP facilities or forming press machinery, etc.).

For the protection of the first wall (FW) against the plasma, it is envisaged to use W-coatings, due to the materials advantageous thermophysical properties and low sputtering yield. W has, however, a significantly smaller coefficient of thermal expansion (CTE) of 4.4×10^{-6} 1/K compared to the substrate material, a reduced activation ferritic martensitic (RAFM) steel like EUROFER, with a CTE of about 12.5×10^{-6} 1/K. When joining these two materials directly together, this difference in CTE will lead to thermal stresses and thus to failure of the joint. Implementing a functionally graded (FG)-layer in-between the substrate and the coating, on the other hand, compensates for this difference [97]. In the PCD Phase the manufacturing technology based on vacuum plasma spraying (VPS) was selected; this process is suitable to coat large areas, e.g. 2 m^2 of future FW, and with the desired coating thickness of 2 mm with reasonable effort, compared to for instance magnetron sputtering, sintering or electrodeposition. Several mock-ups with a coating area up to 270 × 65 mm were produced and successfully tested under thermal fatigue cycles (up to 1000 cycles) between 350 and 500 °C and heat fluxes up to 0.7 MW/m^2 in the HELOKA facility [98]. For the CD

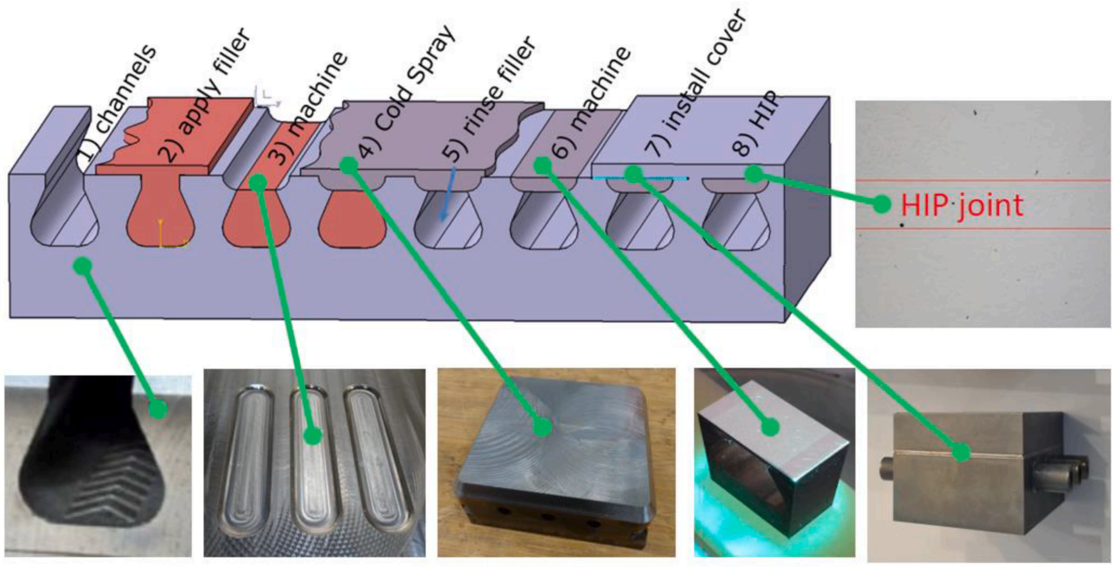

Fig. 10. Proof of concept demonstrator for Cold Spray based production sequence.

Phase, it is foreseen to transfer the coating process on the industrial level, to achieve a reproducible production on large components and in reasonable production times. The industrially produced layer systems will also be examined in terms of microstructural and thermomechanical properties, for better understanding and prediction of the layer system behaviour.

For the breeding module, a detailed analysis has been namely carried out on the assembly of subcomponents and it is reported in [99]. A list of all weld joints has been drawn up and a classification with regard to RCC MRx code has been proposed. The development of technologies and specific manufacturing procedure have to be associated with a dedicated contribution to the writing of manufacturing sections of the next code for DEMO.

Presently the Codes and Standards intended to be applied for Breeding Blankets do not include AM and the experiments are performed on prototypic level. The implementation of such new technologies is a challenge requiring to address the integral production chain: in case of AM with deposition of metal powder the integral powder production history shall be considered. The parameters applied for generation of the parts and all thermal post treatments (e.g. Hot Isostatic Pressing) need to be precisely specified and reproducibility demonstrated. However, presently a major issue remains the quantification of material properties and comparison to conventionally fabricated products. Promising properties have been already demonstrated in terms of tensile-, Charpy- macro- and microstructure-tests. But the qualification of the long-term and high temperature behavior of the material (creep and fatigue) is still in the initial phase. Especially potential degradation under irradiation as in a fusion in-vessel environment shall be addressed before the potential in terms of realization of complex geometries with internal channel structures can be exploited.

4. Conclusions

In the PCD Phase, two blanket designs have been completed and proposed for the two candidate driver blankets for DEMO. Both designs offer a possible solution for the DEMO blanket, but both still have issues that need to be addressed. The HCPB design shows excellent neutronic performance characteristics and a reliable tritium extraction system thanks to advanced breeder materials, but the design is laborious and costly, with the use of materials like beryllium and helium and with a cooling technology that still has to prove the appropriate TRL. The WCLL offers a concept based on a proven water cooling technology and the key material, PbLi, is largely available. Nevertheless, several issues are still present in the PbLi related technologies including no selected tritium extraction technology and no conclusive experimental data required before proceeding to a reliable design of the TER. Also, the chemical composition of cooling water that accounts for the fusion conditions is still to be completed before important systems like the CVCS or the Coolant Purification System can be designed.

In the first part of the CD Phase, the selection of the driver blanket will be achieved. To reach this goal the design of the two concurrent blanket system options should be completed; technologies should be selected, performance assessed and the plant integration investigated. At the same time, it will be assessed the possibility to use of the DEMO plant for testing advanced blankets (see [100] for this strategy); in this case the not-selected driver blanket or a more advanced blanket concept as described in Section 2.3 could be chosen for these test campaigns.

In Section 3 the development of the critical technologies has been presented and the programme for the CDP illustrated. The R&D was conducted in the PCD to address the aforementioned critical issues and other risks identified. The two concepts will then be evaluated and a down-selection made for the DEMO plant. In the second part of the CD Phase, the complete DEMO plant conceptual design with the selected BB will be completed and qualified before proceeding to the Engineering Design Phase.

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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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References

[1] L. Romero, Fusion Energy and Power: Applications, Technologies and Challenges, Nova Science Publishers, 2015. Incorporated.
[2] I. Moscato, et al., Tokamak coolant systems and power conversion system options, Fusion Eng. Des. (2022), https://doi.org/10.1016/j.fusengdes.2022.113093. In this issue.
[3] L. Barucca, et al., Maturation of critical technologies for the DEMO balance of plant systems, Fusion Eng. Des. (2022), https://doi.org/10.1016/j.fusengdes.2022.113096. In this issue.
[4] L.V. Boccaccini, et al., Objectives and status of EUROfusion DEMO blanket studies, Fusion Eng. Des. 109-111 (2016) 1199–1206.
[5] U. Fischer, et al., Required, achievable and target TBR for the European DEMO, Fusion Eng. Des. 155 (2020), 111553.
[6] G. Pintsuk, et al., Materials for in-vessel components, Fusion Eng. Des. (2022), https://doi.org/10.1016/j.fusengdes.2021.112994. In this issue.
[7] G.A. Spagnuolo, et al., Systems engineering approach in support to the breeding blanket design, Fusion Eng. Des. 146 (2019) 31–35.
[8] O. Crofts, et al., EU DEMO Remote Maintenance System development during the Pre-Concept Design Phase, Fusion Eng. Des. (2022), https://doi.org/10.1016/j.fusengdes.2022.113121. In this issue.
[9] T. Pinna, et al., Approach in improving reliability of DEMO, Fusion Eng. Des. 161 (2020), 111937.
[10] M. D. Donne et al., European DEMO BOT solid breeder blanket, Technical report: KFK-5429, Kernforschungszentrum Karlsruhe, 1994, [Online]. Available: https://doi.org/10.5445/IR/270036526.
[11] S. Hermsmeyer, et al., Lay-out of the He-cooled solid breeder model B in the European power plant conceptual study, Fusion Eng. Des. 69 (2003) 281–287.
[12] F.A. Hernández, et al., Consolidated design of the HCPB breeding blanket for the pre-conceptual design phase of the EU DEMO and harmonization with the ITER HCPB TBM program, Fusion Eng. Des. 157 (2020), 111614.
[13] F.A. Hernández, et al., Advancements in the helium-cooled pebble bed breeding blanket for the EU DEMO: holistic design approach and lessons learned, Fusion Sci. Technol. 75 (5) (2019) 352–364.
[14] K. Kugeler, et al., Modular High-Temperature Gas-Cooled Reactor Power Plant, Springer, 2018.
[15] L. Frances et al., Private communication: preliminary conceptual design of HCPB TES (EFDA_D_2NS8K4), EUROfusion, 2018.
[16] A. Bender et al., Private communication: extrapolation at DEMO scale of the HCPB TER system based on cryogenic trapping (including tendering report) (EFDA_2N4MK6) EUROfusion, 2017.
[17] H. Kwast et al., EXOTIC: Development of ceramic tritium breeding materials for fusion reactor blankets The behaviour of tritium in: lithium aluminate, lithium oxide, lithium silicates, lithium zirconates, Technical report: ECN-C-95-123, ECN, Netherlands, 1995, [Online]. Available: https://www.osti.gov/etdeweb/servlets/purl/424800.
[18] I. Cristescu et al., Private communication: TER.HCPB-JUS-2-CD1-TER HCPB design description document (DDD) (EFDA_D_2PAJ4G), EUROfusion, 2020.
[19] L. Giancarli, et al., Development of the EU water-cooled Pb-17 Li blanket, Fusion Eng. Des. (1998) 639–644.
[20] A. Del Nevo, et al., Recent progress in developing a feasible and integrated conceptual design of the WCLL BB in EUROfusion project, Fusion Eng. Des. 146 (2019) 1805–1809.
[21] T. Pinna, et al., Preliminary study of DEMO disruptions due to component failures, Fusion Eng. Des. 136 (PartB) (2018) 1265–1268.
[22] F. Moro, et al., Nuclear analysis of the Water cooled lithium lead DEMO reactor, Fusion Eng. Des. 160 (2020), 111833.
[23] F. Edemetti, et al., Optimization of the first wall cooling system for the DEMO WCLL blanket, Fusion Eng. Des. 161 (2020), 111903.
[24] F. Edemetti, et al., Thermal-hydraulic analysis of the DEMO WCLL elementary cell: BZ tubes layout optimization, Fusion Eng. Des. 160 (2020), 111956.
[25] I. Catanzaro, et al., Structural assessment of the EU-DEMO WCLL central outboard blanket segment under normal and off-normal operating conditions, Fusion Eng. Des. 167 (2021), 112350.
[26] A. Tassone, et al., MHD pressure drop estimate for the WCLL in-magnet PbLi loop, Fusion Eng. Des. 160 (2020), 111830.
[27] M. Utili et al., TER.WCLL-JUS-2-CD1-TER WCLL design description document (DDD) (EFDA_D_2NBJS5), EUROfusion, 2020.
[28] R. Mozzillo, et al., Integration of LiPb loops for WCLL BB of European DEMO, Fusion Eng. Des. 167 (2021), 112379.
[29] J. Aubert, et al., Status of the EU DEMO HCLL breeding blanket design development, (in English), Fusion Eng. Des. 136 (2018) 1428–1432.
[30] D. Rapisarda, et al., Status of the engineering activities carried out on the European DCLL, Fusion Eng. Des. 124 (2017) 876–881.
[31] F.R. Urgorri, et al., Magnetohydrodynamic and thermal analysis of PbLi flows in poloidal channels with flow channel insert for the EU-DCLL blanket, Nucl. Fusion 58 (10) (2018), 106001.
[32] I. Fernández-Berceruelo, et al., Large-scale behavior of sandwich-like FCI components within the EU-DCLL operational conditions, Fusion Eng. Des. 136 (PartA) (2018) 633–638.
[33] I. Fernández-Berceruelo, et al., Alternatives for upgrading the EU DCLL breeding blanket from MMS to SMS, Fusion Eng. Des. 167 (2021), 112380.
[34] R. Boullon, et al., Molten salt breeding blanket: Investigations and proposals of pre-conceptual design options for testing in DEMO, Fusion Eng. Des. 171 (2021), 112707.
[35] G. Zhou, et al., Progress on the helium cooled molten lead ceramic breeder concept, as a near-term alternative blanket for EU DEMO, Fusion Eng. Des. 146 (2019) 1029–1034, https://doi.org/10.1016/j.fusengdes.2019.01.151.
[36] G. Zhou, et al., A water cooled lead ceramic breeder blanket for European DEMO, Fusion Eng. Des. 168 (2021), 112397, https://doi.org/10.1016/j.fusengdes.2021.112397.
[37] S. Wang, et al., First thermal-hydraulic analysis of a CO2 cooled pebble bed blanket for the EU DEMO, Fusion Eng. Des. 146 (2019) 2218–2221.
[38] O. Leys, et al., Current status and future perspectives of EU ceramic breeder development, Fusion Eng. Des. 164 (2021), 112171.
[39] J.M. Heuser et al., Private communication: material property handbook on advanced ceramic breeder (EFDA_D_2NVAS9), EUROfusion, 2019.
[40] M. Moscardini, et al., Discrete element method for effective thermal conductivity of packed pebbles accounting for the Smoluchowski effect, Fusion Eng. Des. (2018) 192–201.
[41] M. Moscardini, et al., Discrete element analysis of heat transfer in the breeder beds of the European solid breeder blanket concept, Fusion Sci. Technol. 75 (4) (2019) 283–298.
[42] N. Zimber, et al., Investigation of a high-dose irradiated beryllium microstructure, J. Nucl. Mater. 540 (2020), 152374.
[43] R. Gaisin, et al., Industrial-scale manufacturing experience of titanium beryllide block for DEMO blanket application, Fusion Eng. Des. 161 (2020), 111862.
[44] P. Vladimirov, et al., Development and characterization of advanced neutron multiplier materials, J. Nucl. Mater. 543 (2021), 152593.
[45] D Martelli, et al., Literature review of lead-lithium thermophysical properties, Fusion Eng. Des. 138 (2019) 183–195.
[46] A.I. Barrado, et al., Towards the development of technical specifications for the production of lithium–lead alloys for the ITER HCLL TMB, Fusion Eng. Des. 87 (7) (2012) 1297–1300.
[47] M. Utili et. al., Private communication: intermediate report on liquid breeder cost-relevant inputs and PbLi Loops (EFDA_D_2NDPQ3), EUROfusion, 2017.
[48] T. Giegerich, et al., Development of a viable route for lithium-6 supply of DEMO and future fusion power plants, Fusion Eng. Des. 149 (2019), 111339.
[49] R. Conrad, et al., LIBRETTO-3: Performance of tritium permeation barriers under irradiation at the HFR Petten, J. Nucl. Mater. 212-215 (no. ptB) (1994) 998–1002.
[50] R. Conrad, Irradiation experiments on liquid tritium breeding material Pb-17Li in the HFR Petten, Fusion Eng. Des. 14 (3-4) (1991) 289–297.
[51] M. Kordač, et al., Helium bubble formation in Pb-16Li within the breeding blanket, Fusion Eng. Des. 124 (2017) 700–704.
[52] G Benamati, et al., Mechanical and corrosion behaviour of EUROFER 97 steel exposed to Pb–17Li, J. Nucl. Mater. 307 (2002) 1391–1395.
[53] M. Utili, et al., Development of anti-permeation and corrosion barrier coatings for the WCLL breeding blanket of the European DEMO, Fusion Eng. Des. 170 (2021), 112453.
[54] R. Petráš, et al., Characterization of aluminum-based coatings after short term exposure during irradiation campaign in the LVR-15 fission reactor, Fusion Eng. Des. 170 (2021), 112521.
[55] M. Eboli, et al., Assessment of SIMMER-III code in predicting water cooled lithium lead breeding blanket "in-box-loss of coolant accident, Fusion Eng. Des. 163 (2021), 112127.
[56] M. Eboli, et al., Test series D experimental results for SIMMER code validation of WCLL BB in-box LOCA in LIFUS5/Mod3 facility, Fusion Eng. Des. 156 (2020), 111582.

[57] M. Eboli, et al., Experimental activities for in-box LOCA of WCLL BB in LIFUS5/Mod3 facility, Fusion Eng. Des. 146 (2019) 914–919, https://doi.org/10.1016/j.fusengdes.2019.01.113.

[58] S.Khani Moghanaki, et al., Post-test analysis of Series D experiments in LIFUS5/Mod3 facility for SIMMER code validation of WCLL-BB In-box LOCA, Fusion Eng. Des. 165 (2021), 112268, https://doi.org/10.1016/j.fusengdes.2021.112268.

[59] F. Galleni, et al., RELAP5/SIMMER-III code coupling development for PbLi-water interaction, Fusion Eng. Des. 153 (2020), 111504.

[60] F. Galleni, et al., Preliminary analysis of an in-box LOCA in the breeding unit of the WCLL TBM for the ITER reactor with SIMMER-IV code, Fusion Eng. Des. 169 (2021), 112472.

[61] M. Moscardini, et al., Thermo-hydraulic analysis of PbLi ancillary system of WCLL TBM undergoing in-box LOCA, Fusion Eng. Des. 168 (2021), 112614.

[62] V Klüber, et al., Numerical investigation of liquid metal flow in square channels under inclined magnetic fields for fusion relevant parameters, Magnetohydrodynamics 56 (2020) (0024-998X).

[63] L. Bühler, et al., Experimental investigation of liquid metal pipe flow in a strong non-uniform magnetic field, Magnetohydrodynamics 56 (2020) (0024-998X).

[64] S. Smolentsev, et al., Code-to-code comparison for a PbLi mixed-convection MHD flow, Fusion Sci. Technol. 76 (5) (2020) 653–669.

[65] L. Bühler, et al., MHD flow and heat transfer in model geometries for WCLL blankets, Fusion Eng. Des. 124 (2017) 919–923.

[66] A. Tassone, et al., MHD mixed convection flow in the WCLL: Heat transfer analysis and cooling system optimization, Fusion Eng. Des. 146 (2019) 809–813.

[67] C. Koehly, et al., Design of a test section to analyze magneto-convection effects in WCLL blankets, Fusion Sci. Technol. 75 (8) (2019) 1010–1015.

[68] C. Mistrangelo, et al., Magnetohydrodynamic velocity and pressure drop in manifolds of a WCLL TBM, Nucl. Fusion 61 (9) (2021), 096037.

[69] C. Courtessole, et al., MHD PbLi experiments in MaPLE loop at UCLA, Fusion Eng. Des. 109 (2016) 1016–1021.

[70] D. Demange, et al., Private communication: tritium Coupled Phenomena in HCPB: State of the art and rationale for the future work plan (F4E-2008-GRT-09, T29.2-D2), Fusionr Energy (2010).

[71] R. Antunes et al., Private communication: final commissioning of the new facility and first experimental results (2017) and experimental results concerning the permeation performances of the zeolite membrane (2018) (EFDA_D_2NZT2R), EUROfusion, 2019.

[72] G. A. Bongiorno et al., Private communication: characterization of NEG materials for NBI systems developed at SAES Getters (EFDA_D_2MMBDP), EUROfusion, 2015.

[73] I. Cristescu, et al., Developments on the tritium extraction and recovery system for HCPB, Fusion Eng. Des. 158 (2020), 111558.

[74] I. Cristescu et al., Private communication: report on DDD of reference HCPB TES for the review meeting 2019-2020 (EFDA_D_2PL9HG), EUROfusion, 2021.

[75] G.A. Spagnuolo, et al., Integration issues on tritium management of the European DEMO breeding blanket and ancillary systems, Fusion Eng. Des. 171 (2021), 112573.

[76] G.A. Spagnuolo, et al., Integrated design of breeding blanket and ancillary systems related to the use of helium or water as a coolant and impact on the overall plant design, Fusion Eng. Des. 173 (2021), 112933.

[77] D Demange, et al., Tritium extraction technologies and DEMO requirements, Fusion Eng. Des. 109 (2016) 912–916.

[78] M. Malo, et al., Experimental refutation of the deuterium permeability in vanadium, niobium and tantalum, Fusion Eng. Des. 146 (2019) 224–227.

[79] B. Garcinuño, et al., Design and fabrication of a Permeator against vacuum prototype for small scale testing at lead-lithium facility, Fusion Eng. Des. 124 (2017) 871–875.

[80] F Papa, et al., Engineering design of a permeator against vacuum mock-up with niobium membrane, Fusion Eng. Des. 166 (2021), 112313.

[81] B. Garcinuño et al., Private communication: report for TER technology assessment and selection in BB WCLL (EFDA_D_2NLLYR), EUROfusion, 2019.

[82] M. Mertens, et al., Model and simulation of a vacuum sieve tray for T extraction from liquid PbLi breeding blankets, Fusion Eng. Des. 112 (2016) 541–547.

[83] F. Okino, et al., Enhanced mass transfer of deuterium extracted from falling liquid Pb-17Li droplets, Fusion Sci. Technol. 64 (3) (2013) 543–548.

[84] F. Maviglia, et al., Integrated design strategy for EU-DEMO first wall protection from plasma transients, Fusion Eng. Des. (2022) this issue.

[85] F. Arbeiter, et al., Options for a high heat flux enabled helium cooled first wall for DEMO, Fusion Eng. Des. 119 (2017) 22–28.

[86] S. Ruck, et al., Thermal-hydraulic study on rib and dimple structures for cooling the First Wall of DEMO, Fusion Eng. Des. 146 (Part B) (2019) 2144–2148, https://doi.org/10.1016/j.fusengdes.2019.03.125. PagesISSN 0920-3796.

[87] F. Arbeiter et al., Private communication: BB.HCPB-JUS-2-CD1-R&D Helium cooling technology studies on high flux applications (EFDA_D_2PCE4Z), EUROfusion, 2021.

[88] G. Zhou, et al., Design of two experimental mock-ups as proof-of-concept and validation test rigs for the enhanced EU DEMO HCPB blanket, Fusion Sci. Technol. 75 (8) (2019) 1016–1023, https://doi.org/10.1080/15361055.2019.1629247.

[89] R. Torella et al., Private communication: BB.WCLL-JUS-2-CD1-R&D water chemistry for WCLL (EFDA_D_2P8FUN), EUROfusion, 2021.

[90] L. Di Pace, et al., Assessment of activated corrosion products for the DEMO WCLL, Fusion Eng. Des. 136 (2018) 1168–1172.

[91] C. Harrington et al., Private communication: industry report on corrosion and chemistry control for the WCLL system with investigation of corrosion mechanisms of Eurofer in aqueous solutions (EFDA_D_2PFFYT), EUROfusion, 2020.

[92] L. Forest, et al., Test blanket modules (ITER) and breeding blanket (DEMO): History of major fabrication technologies development of HCLL and HCPB and status, Fusion Eng. Des. 154 (2020), 111493.

[93] H. Neuberger, et al., Evaluation of conservative and innovative manufacturing routes for gas cooled test blanket module and breeding blanket first walls, Fusion Eng. Des. 146 (2019) 2140–2143.

[94] H. Neuberger, et al., Advances in additive manufacturing of fusion materials, Fusion Eng. Des. 167 (2021), 112309.

[95] S. Bonk, et al., Additive manufacturing technologies for EUROFER97 components, J. Nucl. Mater. 548 (2021), 152859.

[96] H. Neuberger, et al., Selective laser sintering as manufacturing process for the realization of complex nuclear fusion and high heat flux components, Fusion Sci. Technol. 72 (4) (2017) 667–672.

[97] D. Qu, et al., Numerical assessment of functionally graded tungsten/EUROFER coating system for first wall applications, Fusion Eng. Des. 98 (2015) 1389–1393.

[98] T. Emmerich, et al., Development progress of coating first wall components with functionally graded W/EUROFER layers on laboratory scale, Nucl. Fusion 60 (12) (2020), 126004.

[99] L. Forest et al., Private communication: "DEMO-JUS-1-CD1-R&D blanket manufacturing",(EFDA_ 2NUYQX), Eurofusion, 2020.

[100] G. Federici, et al., Overview of the DEMO staged design approach in Europe, Nucl. Fusion 59 (2019), 066013.