European DEMO breeding blanket design and development strategy in a roadmap to the realisation of fusion energy

L.V. Boccaccini\textsuperscript{a}, G. Aiello\textsuperscript{b}, A. Del Nevo\textsuperscript{c}, P. Norajitra\textsuperscript{a}, D. Rapisarda\textsuperscript{d}, C. Bachmann\textsuperscript{e}

\textsuperscript{a}Karlsruhe Institute of Technology (KIT), Germany
\textsuperscript{b}CEA, DEN, Saclay, DM2S, SERMA, F-91191 Gif-sur-Yvette, France
\textsuperscript{c}ENEA CR Brasimone, 40032 Camugnano, (BO), Italy
\textsuperscript{d}CIEMAT, Madrid, Spain
\textsuperscript{e}European Fusion Development Agreement (EFDA), Garching, Germany

Author’s e-mail: Lorenzo.boccaccini@kit.edu

Abstract. The objective of an EU DEMO able to deliver electrical energy in grid for 2050 is strongly dependent on the success of the Breeding Blanket development. The Blanket is the key component for the final production of electrical energy and for the production of T necessary for the self-sufficiency of the reactor. Four blanket concepts has been studied extensively in EU breeding blanket programme in the last 20 years; the selection of one of these for the DEMO Blanket system and its conceptual assessment is the ultimate goal of the Horizon 2020 programme in the Power Plant Physics and Technology in Europe. The present paper presents an overview of the EU Breeding Blanket development and discusses the open challenges to the development of an EU DEMO.

1. Introduction

The EU Fusion Roadmap [1] foresees the development and construction of a DEMO reactor (DEMO-2050 in the following of the paper) that will “deliver several 100s of MW of net electrical power starting from 2050”. The DEMO will be a “tokamak-class nuclear fusion power plant” capable “to breed the amount of tritium needed to close its fuel cycle.” In addition it “shall demonstrate all the technologies for the construction of a commercial FPP, including an adequate level of availability”. “DEMO shall, wherever possible and appropriate, utilise technology and benefit from the experience that has been developed by the ITER programme”. Furthermore, the Roadmap identifies as critical point the “implementation of the intrinsic safety features of fusion”.

The breeding blanket is a key component for the future DEMO reactor with the main functions to breed the tritium necessary to sustain the thermonuclear D-T reaction and to exhaust most of the energy generated in the reactor via high temperature coolant to allow for efficient electricity production. The Blanket and its related systems are also a central element to ensure the safety features. All the T necessary for the thermonuclear reaction is produced in Blanket and about 85% of the nuclear heat is collected within the blanket coolant system. Failures in the blanket systems have a major impact for severity and frequency of accidents.
In addition materials used in the blanket (coolant, structure and breeder) have the major potentiality to aggravating accidents due to chemical reactions (combustion, explosion, detonation). Materials in the blanket system constitute the greater source of radioactive wastes due to neutron transmutations and activation. The use of low reduction materials is the only way to maintain the target of recycling all the materials in a time of one century. As ITER has not a Breeding Blanket, operates at low coolant temperature and presents very low cumulative neutron fluence, the design of a Breeding Blanket can profit only limitedly from the ITER Shielding Blanket technology. More relevant for the BB development is the ITER Test Blanket programme that can give valuable information to the BB Project also if the TBM constitute only a small portion of the ITER machine.

2. The European Breeding Blanket Concepts

The most important and investigated blanket configurations that are today under discussion as candidate for the EU DEMO, have been developed in EU in the years from 1994 to 2004. Initially for the DEMONET configuration [2] and later in the framework the EU Power Plant Conceptual Study (PPCS) started in 2000 and concluded in 2004 [3]. While in the DEMONET study the focus was on a second step reactor (DEMO) after ITER, in the PPCS the focus was on possible fusion power plant (FPP) configurations that could achieve fully the requirements of a mature fusion technology in term of economical viability (cost of energy) and safety (not evacuation and not geological waste storage). Among the different FPPs proposed in those studies we find different kind of blanket systems based on solid and liquid breeders and different coolants (water, helium and PbLi); according to the above mentioned objectives of PPCS the systems and requirements were adapted and improved in order to explore the performance limits of the proposed concepts.

In particular 4 concepts have been extensively investigated in these studies, namely the Helium Cooled Pebble Bed (HCPB), the Helium Cooled Lithium Lead (HCLL), the Water Cooled Lithium Lead (WCLL) and the Dual Coolant Lithium Lead (DCLL). All these blankets are considered suitable for a first generation of DEMO/ FPP and among them blanket concepts have been selected for the test in ITER in the Test Blanket Programme. They use ferritic-martensitic steel as structure materials; the development of these concepts led to the start in the 90-ties of a large EU programme for the development of a Reduced Activation grade well known as EUROFER [4].

The HCPB concept is based on the use of breeder (a ternary Li-ceramic like Li₄SiO₄ or Li₂TiO₃) and Beryllium in form a pebble bed; the concept is cooled with helium at 300-500°C and at a pressure of 8MPa. The extraction of the T from the ceramic breeder is done by a low pressure helium streaming; tritium is transported by the purging He outside the Vacuum Vessel and then removed to feed the reactor Fuel Cycle (see Fig.1a). This concept was developed in the DEMONET framework; later it was used in the PPCS as basis for the Model B [5]. The HCLL concept is based on the use of the PbLi eutectic (15.8 at.% Li) as breeder/multiplier in quasi-stationary conditions; the coolant is helium at the same conditions as in the HCPB (see Fig 1b). The PbLi is re-circulating slowly outside the Vacuum Vessel to allow the extraction of T and the chemical treatment of PbLi (removal of other products generated by nuclear transmutation and replacement of burned Li). This concept was developed in EU in the second part of the PPCS as basis for the so called Model AB [6]. Both HCPB and HCLL are blanket concepts selected for the test in ITER in the EU Test Blanket programme [7].
The WCLL concept is based on a PbLi as breeder like in the HCLL, but with water cooling at PWR conditions (Fig 1c). This concept has been studied extensively in the European Breeder Blanket programme before 2002, namely in the DEMONET programme and later in the PPCS where it was used as basis for model A [8]. Finally, the Dual Coolant Lithium Lead (DCLL) concept is characterised by the use of the liquid breeder PbLi as coolant together with helium; PbLi removes large part of the heat that is produced in the breeder, while helium flows in the steel structure keeping the temperatures at acceptable level for the material. This concept was developed in the DEMONET study for low PbLi temperatures (max outlet temperatures <500°C). The concept was used in the PPCS as basis for Model C [9] in a high temperature version (PbLi up to 700°C) derived from US ARIES studies.

All these concepts have been adapted for the DEMONET and PPCS reactor specifications; mainly for stationary or long pulse (>8 hour) plasma operation, neutron wall loads between 2.5 and 3.5 MW/m² and surface heating of about 500 kW/m². The analyses conducted in neutronics, thermo-hydraulics and structural analysis showed good potentiality of all these concepts to fulfil the requirements set in the mentioned studies. However the main limitation of these studies was the lack of a consistent plant integration work. Assumptions on performance of the different systems were not coherently checked and often were based on very optimistic judgment. The results for the blankets system design was very strong affected by a largely insufficient set of specifications.
3. **ITER Test Blanket programme**

Also if the blanket system is under study since several decades and different concepts have been proposed and investigated, in the first burning plasma device, ITER, this component will be absent. In fact ITER has been designed to use a relatively low amount of T in its entire lifetime (~20 kg) using the production in CANDU reactors. In ITER the Breeding blanket is replaced by a “Shielding Blanket” which main purpose is to remove the nuclear heat and shield effectively vacuum vessel and magnets from neutrons. Hence, the ITER shielding blanket design is almost irrelevant for a fusion reactor: a part the lack of breeding function, the materials adopted (e.g. AISI 316L as structural material) are able to withstand only low neutron fluences (less than 0.3 MWa/m$^2$) and the blanket outlet temperature (less than 150°C) is too low for an efficient electrical power production.

In ITER the breeding blanket will be tested only in form of Test Blanket Modules (TBM) in the framework of the international Test Blanket Programme. A TBM is a mock-up of a blanket concept with the dimension of less than a cubic meter and a surface exposed to the plasma of less than 1 square meter. Six of these TBMs will be inserted in three ITER Equatorial Ports that are adapted for this scope. The TBM programme in EU was developed starting from 1996 with a strong coupling between the breeder blanket design (in DEMONET and PPCS). The concept of “DEMO relevancy” for the test objects proposed for ITER was used as basis for the design; a complex test programme was elaborated in order to derive results that could be used for the DEMO breeding blanket development [10].

The conceptual design of the TBM includes neutronic, thermo-hydraulic and structural analyses assessed under code and standard. The design is in advance status as well the related licensing procedures that will be example and precedent for the future licensing of a blanket in a fusion reactor. Material development, characterisation and procurement of structural material (EUROFER), ceramic breeder pebbles (Li$_4$SiO$_4$ and Li$_2$TiO$_3$), beryllium (or Be-alloy) pebbles, PbLi eutectic, coatings (PbLi corrosion protection, T-permeation) done in the TBM programme are relevant for DEMO. In particular also manufacturing technologies, like manufacturing of plates with cooling channels and welding processes with EUROFER, are also relevant for the DEMO development. The cooling of TBM structures is relevant for DEMO reproducing the reactor conditions (300-500°C at 8 MPa); the helium loop itself is not. The same for the T-auxiliary systems; their design is mostly dictated by ITER and test specific requirements, but some processes can be find application in the DEMO T extraction system. All the experimental programme and modelling tools defined in TBM are aimed to interpret ITER data and to extrapolate them to DEMO; this in R&D field of neutronics, thermo-hydraulic, pebble bed thermo-mechanics, MHD, T transport, corrosion. Safety studies of accidents related to the TBM operation are ITER specific, but with interesting topics like interaction of water with Be or PbLi.

4. **Challenges for a Breeding Blanket for DEMO**

Although DEMO-2050 is not expected to be a fully optimised machine and able to reach all the performances requested for a commercial fusion reactor, the gap between ITER and DEMO-2050 will be significant. The blanket system in DEMO-2050 will experience high neutron fluence with damages in the materials in term of dpa and helium production; blankets will have shorter lifetime in comparison to the plant forcing to replace them during the plant operation like fuel elements in the nuclear technology. This calls for a class of structural materials not foreseen in ITER, in particular ferritic martensitic steels able to ensure an adequate life time of the blanket reducing the impact of replacement time and hence
increasing the plant availability. At the moment it is requested that blanket components shall be able to withstand cumulative damages of 20 up to 50 dpa; this means at least a complete replacement of the whole blanket system in the life of the DEMO-2050.

The system of blanket replacement dictates strongly the geometry and dimension of the blanket elements inside the vacuum vessel. Studies performed in the past years [11] are suggesting the use of a vertical maintenance system. This implies that blankets are organised in large vertical elements (called segments); in the reference scheme there are 5 segments per sector where the sector is the toroidal portion between two adjacent TF-coils (see Figure 2). Each segment is formed by several modules (6 in the figure) that are attached to a common back supporting structure; this structure contains the common manifold system for the coolant and allows the replacement of the segment as an unique units.

The need to ensure T self-sufficiency requires the integration in the blanket design of breeder (Li or Li compounds) and neutron multiplier (Be or Pb) materials, and to provide efficient systems to extract the T produced. Hence one of the primary design targets is to achieve a calculated tritium breeding ratio (TBR) that is compatible to criteria of T self-sufficiency of the reactor. Calculated values of TBR should be greater than the theoretical value of 1 of a certain margin to take into account several uncertainties that affect the calculations (e.g. nuclear data and modelling), the design elements (e.g. loss of blanket coverage due to inclusion of diagnostic or heating systems) and the amount of T that should be bred in excess (e.g. to compensate T losses or to provide the start-up inventory for a new power plant). In the specifications used in the EU design it has been always required a calculated TBR in 3D Montecarlo analyses greater than 1.10. This task is critical as the neutron balance (in spite of neutron multiplication accomplished by Be or Pb) is strongly degraded by neutron absorbers like structural or functional materials (e.g. EUROFER and W PFC-layers). The necessity to reduce the amount of structural material in the breeding zone (under 15% in many designs) is in contrast to other design criteria like structural strength against high pressure coolants.

The requirement of electricity production poses additional challenges to the blanket design and materials. At the contrary to ITER, a DEMO blanket has to operate at higher temperatures of the materials to allow maximum coolant temperatures >300°C that can ensure sufficient thermodynamic efficiency of the power generation cycles. This requires materials that are compatible in this range of temperatures and operating in a proper temperature window. In addition if a pulsed operation scenario (~2-hour-long-pulse) is selected, a complicated Balance of Plan is the consequence. Studies are ongoing but fatigue cycles for the structure could limit further the lifetime of the components.

A critical issue is also the thermo-hydraulic design of the first wall (FW) given the large uncertainties in the local surface heat load. Following the ITER design studies, it is now believed that the surface heating will be much higher than the 500 kW/m² assumed in the past. This, together with the large safety factors assumed due to uncertainties and protection
to possible off-normal conditions, is a major challenge to achieve of adequate coolant performance for integration in an electricity generation system.

Finally, safety and licensing requirements for a nuclear power plant will impact the selection of blanket design solutions, material choice and adopted technologies. First of all the T production/consume in a 3-GW-fusion power is about half kg per day at full operation. Furthermore, safety considerations play an important role in the design; main issues are related to tritium control and inventory in the blanket as well as design features to mitigate possible main accident. E.g. great impact in the EU blanket design has the requirement to avoid explosion of the box in case of an in-vessel LOCA; in this case the high pressure coolant (He at 8 MPa or water at 15.5 MPa) bursts into the box that in operation is subjected to low pressure. The fulfilment of this requirement obliges to reinforce the box structure e.g. with a grid system that increase the steel amount in the blanket zone with negative consequences in the TBR.

5. The Breeder Blanket Development in the EU PPP&T Programme

With the start of the Power Plant Physics and Technology (PPP&T) studies in the EU Fusion Programme, the Breeding Blanket development has been reorganised to cope with the objectives of the Roadmap. The four blanket concepts described in Section 2 have been included in the development plan: main goal of the Breeding Blanket Project is to support the development of a integrated plant design for DEMO 2050 adapting these blanket concepts and the related technologies to the overall specifications. This work will help to explore the feasibility of blanket systems for this kind of reactor and at the end providing technical background for a selection of the more interesting configurations.

Figure 3 shows the CAD design of these blanket concepts at the end of the PPP&T work programme 2013; here equatorial modules are represented. The concepts have been adapted to the proposed vertical segmentation with poloidal division of the segment in modules. Important goals of the current design are the improvement of the performances: this include the neutron balance (higher TBR), the thermo-hydraulics lay-out (higher cooling capability and pumping performances) and the structural design. In parallel an effort is done among all the Projects to define the interfaces among the different systems and complete the list of the requirements for all the systems. After this phase it will be possible to proceed to the optimisation of the blanket design.

The implemented programme in the Breeding Blanket Project, foreseen the achievement of a consolidated conceptual design at the end of 2017 and a finalisation at mid 2020. This conceptual study will include also an assessment of manufacturing technology for the blanket structures. In parallel activities are foreseen for the design of PbLi loops of the liquid breeder blankets and of the Tritium system necessary to the extraction of T. A list of the topics included in the Project is presented in Table 1.

6. Conclusions

Although the EU breeding blanket programme has a long history of more than 30 years, the ambitious goal proposed by the Roadmap represents a significant challenge. Four blanket concepts belong to the EU options for the blanket systems, ranging from solid to liquid breeders, and with different coolants. The adaptation of these blanket concepts to an integrated DEMO design will be key task to the success of DEMO.
Table I: topics considered in the EU Breeding Blanket Programme 2014-2010

<table>
<thead>
<tr>
<th>Areas in the Breeding Blanket Project</th>
<th>HCPB Blanket</th>
<th>HCLL Blanket</th>
<th>WCLL Blanket</th>
<th>DCLL Blanket</th>
<th>PbLi Technology</th>
<th>Tritium Technology</th>
<th>Manufacturing Technology</th>
<th>FW/limiter design</th>
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<td>Design &amp; Integration</td>
<td>Design &amp; Integration</td>
<td>Design &amp; Integration</td>
<td>Design &amp; Integration</td>
<td>Design of PbLi Loop</td>
<td>Design of Tritium Auxiliary systems</td>
<td>Assessment of manufacturing technology suitable for the blanket concepts. Test of component in helium and water facilities</td>
<td>Definition of DEMO FW specifications Design of Limiter structures Enhancement of helium and water cooling technology for FW elements.</td>
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<td></td>
<td>Ceramic Breeder and Beryllium development</td>
<td></td>
<td>Water Cooling technology including corrosion</td>
<td>Flow insert technology</td>
<td>Magneto-Hydro-Dynamics Anti corrosion barriers development PbLi purification</td>
<td>Modelling of T transport Development of T extraction processes Control of T permeation and release</td>
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**FIG. 3.** Breeding Blanket Concept developed for the DEMO/PPPT-WP2012: a) the Helium Cooled Pebble Bed (HCPB), b) the Helium Cooled Lithium Lead (HCLL); c) the Water Cooled Lithium Lead (WCLL), and d) the Dual Coolant Lithium Lead (DCLL)
References


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