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Ferritic–Martensitic steel Test Blanket Modules: Status and future needs for design criteria requirements and fabrication validation

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ABSTRACT

The Helium-Cooled Lithium-Lead and the Helium-Cooled Pebble Bed are the two breeding blankets concepts for the DEMO reactor which have been selected by EU to be tested in ITER in the framework of the Test Blanket Module projects. They both use a 9%CrWVTa Reduced Activation Ferritic–Martensitic steel, called EUROFER, as structural material and helium as coolant. This paper gives an overview of the status of the EUROFER qualification program and discusses the future needs for design criteria requirements and fabrication validation.

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1. Introduction

One of the missions of ITER is to test mock-ups of DEMO-relevant breeding blankets, the so-called Test Blanket Modules (TBM). Most TBMs proposed by the ITER parties make use of Reduced Activation Ferritic–Martensitic (RAFM) steel as the structural material. Europe is developing two types of TBMs, a Helium-Cooled Lithium-Lead (HCLL) TBM and a Helium-Cooled Pebble Bed ceramic/Be (HCPB) TBM, both using EUROFER as structural material and helium as coolant. The design of the TBMs is supported by detailed structural analyses and by an R&D program, including significant activities on the fabrication of the TBM steel box using diffusion bonding of plates with internal cooling channels and to the assembly of plates by various welding techniques.

The TBMs will be inserted in the ITER reactor. By consequence they must fulfil French regulations on pressure vessel equipments, possibly in its nuclear extension, as well as high standards of quality assurance required for reliable and safe ITER operation. For example, the TBMs have to follow, when applicable, the ITER structural design criteria for in-vessel components (SDC-IC). The SDC-IC needs however to be complemented by an extensive R&D qualification program to cover specific TBMs materials, fabrication and non destructive examination technologies. After a general review of the justification for the choice of the RAFM steel in the blanket program and TBM project, this paper gives an overview of the EU on-going effort for TBMs design and fabrication qualification.

2. RAFM steel as structural material for breeding blankets in fusion power reactors

One of the main technological requirements for the fabrication of blanket components is the development and qualification of structural materials able to withstand severe loading conditions together with 14 MeV neutrons, neutral and charged plasma particles, high surface heat flux and very strong magnetic fields. In the fusion-related R&D performed in the last decades, three major material families have shown to be able to eventually fulfil the requirements as reactor structural materials, namely RAFM steels (and their ODS versions), vanadium alloys and SiC_f/SiC composites [1–4].

RAFM steels have today the most complete technology data base and show the best performance and the best compatibility with breeding materials and coolants. For these reasons they are considered as structural materials for DEMO and first-generation PROTO_type fusion reactors [5,6]. Main advantages are listed in the following sub-sections.

2.1. Resistance to neutron irradiation

With regards to irradiation issues, the key parameter for the material choice is the expected neutron fluence, in particular in

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Table 1
Performance goals for fusion devices.

	ITER	DEMO	PROTO
Fusion power	0.5–1 GW	2–4 GW	3–4 GW
Neutron wall load	0.5–1 MW/m^2	2–3 MW/m^2	2–3 MW/m^2
Operational mode	Pulsed (300–1000s)	Quasi continuous	Continuous
Outlet coolant temperature	150 °C	500–550 °C	>550 °C
Integrated FW neutron fluence	0.3–1 MWy/m^2	3–8 MWy/m^2	10–15 MWy/m^2 (5 years lifetime)
dpa on the first wall	3–10 dpa	30–80 dpa	100–150 dpa (5 years lifetime)
He transmutation	48–160 appm (austenitic steel)	360–950 appm (martensitic steel)	1200–1800 appm (martensitic steel)
H transmutation	171–570 appm (austenitic steel)	1500–4000 appm (martensitic steel)	5000–7500 appm (martensitic steel)

the blanket first wall (FW) region. Performance goals for near-future and long-term fusion devices are summarized in Table 1. For the FW in a prototype fusion power plant, a reasonable target lies in the range of 10–15 MWy/m^2, i.e. about 100–150 dpa, almost twice the limit assumed for DEMO (max. 80 dpa).

With regard to material issues and compared to DEMO and next-generation fusion reactors, ITER is characterised by a strongly pulsed mode of operation, low neutron fluence and low temperature. It is therefore expected that the structural demands can be fulfilled by the use of the austenitic stainless steel of type 316LN-IG. This steel has however two main limitations for use in high neutron fluence, namely swelling and embrittlement due to high He and H production [7].

Because of their crystalline structure, Ferritic–Martensitic steels offer a much better resistance to irradiation swelling [8–10]. However, RAFM steels exhibit a sharp drop in strength at temperatures above 500 °C, and a shift of the ductile-to-brittle transition temperature (DBTT) to above room temperature when irradiated at temperatures less than 300–350 °C. Therefore, the temperature window of operation for RAFM materials is today considered to be in the range 300–550 °C [11–13]. In the future, an Oxide-Dispersion version of RAFM steel (ODS) could be developed in order to increase the maximum acceptable temperature [14].

2.2. Low-activation requirements

Because of neutron induced activation, structural materials are one of the major sources of radwaste in a fusion reactor and play a great role in the debate about a "clean" fusion energy. With regard to low-activation requirements, RAFM steels have proved to be more suitable than austenitic steels. The 8∼12% Ni content of austenitic steels is reduced to ppms in the case of RAFM steels which moreover lend themselves very well to substitution and adjustment of alloying elements contents to low-activation elements. Replacing Mo and Nb contents of conventional 9-Cr steels by W, V and Ta has proven to be feasible.

2.3. Mechanical and thermo-physical properties at high temperatures

To lower the thermo-mechanical stresses in the blanket structures, the selected structural materials should possess a combination of good mechanical strength, low coefficient of thermal expansion and high thermal conductivity at high temperatures (>500 °C). These properties are used to define a surface heat capability factor indicating the potential of the material to withstand high surface heat fluxes [12,13]. At 500 °C RAFM steels have a surface heat capability factor about 2.5 times higher than that of austenitic steels.

2.4. Compatibility with coolant and breeding/neutron multiplier materials

It is widely accepted that, for a viable breeding blanket concept, only a limited number of combinations of structural materials with coolant, breeding and neutron multiplier materials exists. Coolant/breeder compatibility issues include corrosion, chemical interactions, coolant system pressure and coolant/breeder temperature constraints.

RAFM steels are envisaged in blanket concepts using liquid metals (mainly PbLi) or ceramic/beryllium materials as breeder/multipliers materials and helium as coolant. The compatibility of RAFM steels with liquid metals has proved to be better than that of austenitic steels [15,16].

In summary, it is clear that the allowable maximum temperatures in a power plant and the choice of coolant, breeder, neutron multiplier and of the power conversion systems are critically dependent on the blanket and FW structural material performances. Hence, RAFM steels clearly offer the best compromise, in particular for DEMO and PROTO reactors.

3. Requirement to use RAFM steels as structural material for TBMs

Following the considerations given in the previous chapter, EUROFER has been selected by EU as the reference structural material for the two breeding blanket concepts envisaged for DEMO [17]. Besides the EU, all ITER Parties are considering blanket concepts based on the use of RAFM steels as structural material [18].

ITER provides the first facility to test blanket modules under a realistic fusion environment, namely a fusion neutron spectrum, a neutron flux in a large test volume, a volumetric heat source in structural and other blanket materials, a surface heat flux to the FW, a typical magnetic field strength and plasma disruptions and a reliable confinement of radioactive products allowing the production of relatively large amounts of tritium. It is, however, clear that the limited neutron fluence on TBMs in ITER requires a parallel qualification program in the International Fusion Materials Irradiation Facility (IFMIF) [19]. Even if fabrication/reliability and compatibility issues can also be addressed by out-of-reactor tests of small scale mock-ups or selected parts of the TBMs, testing of all the relevant aspects of an integrated system will only be possible in ITER.

The detailed objectives and strategy for TBM testing have already been discussed extensively by the different ITER Parties [17,18]. Common to all objectives is the strict requirement of "DEMO relevancy". Given the strong interaction between the blanket design and the structural materials it is not possible to envisage a different structural material for the TBMs without jeopardizing the technical objectives of the TBM testing in ITER.

4. TBMs design description

The HCLL and HCPB TBMs have the same design basic features of the corresponding blanket concepts for DEMO scaled to fit into a half of an ITER equatorial port. TBMs will be inserted in a water-cooled stainless steel frame required to limit the interactions between the module and the surrounding ITER environment and to provide a common interface for all TBMs. Due to recent studies about limitation of ITER magnetic field ripple, the orientation of TBMs would be vertical to allow the installation of a magnetic field correction coil in the port plug.

The design of the TBMs consists of a EUROFER box of ~1655 (poloidal) × 484 (toroidal) × 575 (radial) (in mm) overall dimensions. The box consists of an U-shaped plate (First Wall and Side Walls – FW & SW) closed by cover plates and on its back by successive plates (Back Plates – BP) that act as coolant manifolds for the He flow distribution. The box is stiffened by an internal grid of plates (Stiffening Plates – SPs) in order to withstand the internal pressure of 8 MPa in case of an accidental in box leak. The grid defines an array of internal cells for the breeder units (BUs). In the case of HCLL, the liquid eutectic Pb-15.7Li (PbLi) slowly flows inside these BUs around 3 parallel horizontal cooling plates (CPs). The CPs are connected to a BU backplate ensuring the insert rigidity. Fig. 1 illustrates the HCLL TBM concept. The HCPB-concept presented in Fig. 2 shows the TBM in a horizontal arrangement (FZK Ref. design 1.1, with 3 × 6 BU cells) which can also be adapted to vertical arrangement (e.g. 8 × 2 BU cells). The breeding unit consists of a BU back plate, two ceramic pebble beds (PB), each one surrounded by two cooling plates and the beryllium PB (see Fig. 2).

All subcomponents (FW/SW, SPs, CPs, covers) except BPs consist of plates cooled by He (8 MPa, $T_{\mathrm{in/out}}$ 300/500 °C) circulating inside square/rectangular channels. Typical dimensions of these plates are:

- FW/SW: Thk = 30 mm, channel section = 12.5 × 11 mm^2.
- SPs: Thk = 11 mm, channel section = 6 × 10 mm^2.
- CPs: Thk = 6 mm, channel section = 4 × 4.5 mm^2.

The TBM conceptual designs are supported by dimensioning analyses (e.g. thermal, thermal-hydraulic and mechanic) with the objective to fulfil criteria given by the SDC-IC code [20]. The rationale of the concepts, design process and R&D developments have been described in several papers, including references to related analyses [17,21–23].

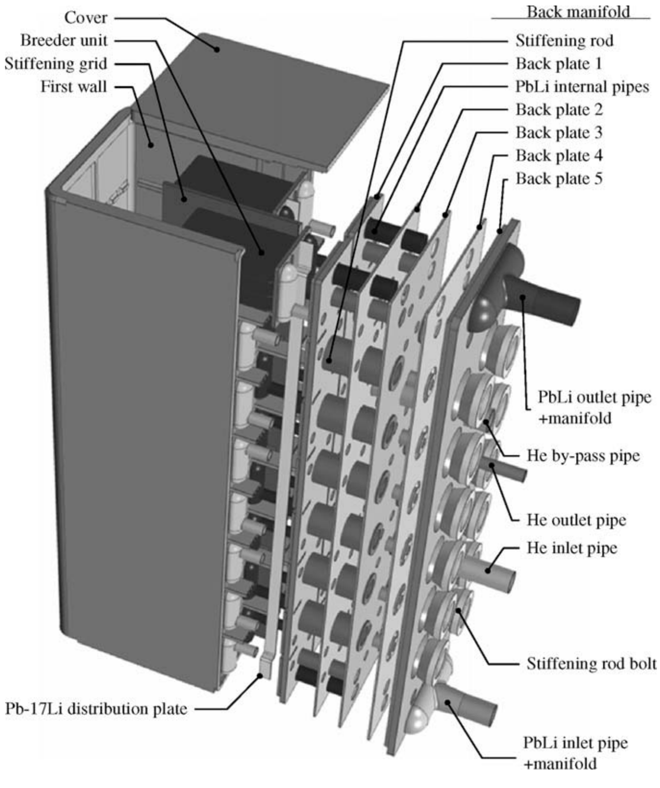

Fig. 1. Exploded view of the HCLL TBM.

5. Short overview of the envisaged manufacturing techniques

5.1. Subcomponents fabrication

The sub-components with internal cooling channels (FW/SW, SPs, CPs, covers) are obtained by diffusion bonding processes [24]. Grooved plates are used. Among the envisaged techniques, the three most promising are:

The "improved two-steps HIP" process: a first hot isostatic pressure (HIP) cycle at low pressure is used to seal the plates without significant deformation of the channels. A second high pressure HIP cycle is then applied to the structure with counter pressure inside channels to avoid collapse. This process has shown to require special attention with respect to fabrication procedure to avoid formation of oxides at the joints which degrade the impact toughness [25].

The "tubes forming + HIP" process uses thin tubes inserted between the grooved plates before HIPing of the whole assembly. During a HIP cycle, the thin tubes expand and conform to the rectangular grooves. Work is in progress to prevent failure of tubes during this phase.

The "weld + HIP" process consists of welding thin strips on the top of each groove and then adding a plate by HIP. Previous optimisations have resulted in the fabrication and the thermo-mechanical test of a CP test mock-up featuring straight internal channels [26,27]. The development of this process has been pursued focusing on welding procedures for bent channels and sensitivity to the positioning of the welded joint.

The main difficulty in the qualification of joining technologies is to insure joint impact toughness close to that of the base material. This has been achieved on laboratory plain specimens [24] but needs also to be obtained on more relevant mock-ups. After optimisation, the reference joining processes will be qualified with testing of medium-scale mock-ups (1/4–1/3 TBM size) and finally on full-size prototypes.

5.2. TBM Box assembly

The TBM box will be manufactured by welding together the different plate sub-components. Laser and TIG welding processes have been developed and optimised over flat and T-shape samples relevant for welds between horizontal and vertical SGs [28]. Laser welding appears to be the preferred process and TIG is the back-up. The distortion level obtained with the laser process is acceptable for the manufacturing stage. For the TIG process, sound welds are observed. For the YAG laser process, the welding procedure developed appears to give results in accordance with the quality level required. The heat affected zone (HAZ) and fusion zones (FZ) are larger for the TIG process than for laser. Due to high hardness levels in the FZ and carbide precipitation in HAZ (toughness considerations), code and standards require the application of post welding heat treatment (PWHT) processes or even pre- and post-heating processes regardless of the welding thickness. PWHT has to be further optimised and qualified in collaboration with materials experts, noting that several PWH treatments will be needed for the fabrication of the whole TBM. Concerning the design aspects, the distance between the end face of Horizontal SG and the first cooling channel face ought be set to a minimum of 5 mm for the laser process and 7 mm for the TIG process in order to avoid deformation or excessive stresses in the cooling channel. Acceptable design limits are under investigation by designers and should be confirmed before the fabrication of larger welds mock-ups.

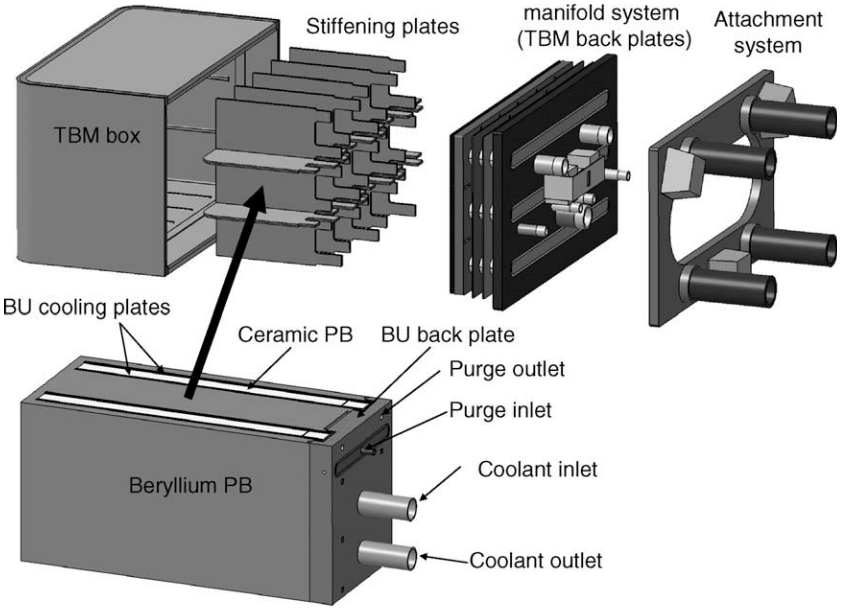

Fig. 2. Exploded view of the HCPB TBM in its horizontal arrangement.

For the FW/cover assembly, electron beam (EB) and hybrid MIG/laser joints processes were investigated. The HAZ and the weld distortions shall not affect the cooling channels. Further characterisation, including impact tests, are to be completed.

6. Needs for design criteria requirements and fabrication validation

The TBMs will be inserted in the ITER reactor and shall fulfil all ITER requirements in terms of code and standards (C&S). Even if the TBMs belong (like the ITER Shielding Blankets) to the non-safety-important class, they have to fulfil high standards of quality assurances required for reliable and safe ITER operation. For this reason, the TBMs, as with any other in-vessel component, have to follow the ITER SDC-IC when applicable. The base for the SDC-IC was the RCC-MR Edition 1985. The current SDC-IC does presently not cover the manufacturing and inspection methods as well as the full range of necessary data for the Eurofer [29].

For this reason a full review of the TBMs design and manufacturing is on-going in particular to identify missing information (design rules, categories of welds, material properties, etc.) in the present SDC-IC or even other existing industrial codes (RCC-MR Ed. 2002) or EU standards (EN). The following sections give the current status and objectives of this review.

6.1. TBM design and structural material properties

Based on the large Eurofer database developed by the EU over the last decade, a SDC-IC Appendix has been developed summarizing the main properties data for designers. A review of this Eurofer material Appendix has been performed by Industry to identify future R&D needs, with the following main conclusions:

- In general, the justification of engineering curves for Eurofer material properties have to be reinforced with a more extensive use of the complete available Eurofer data base. In particular the quantity of data points has to be increased for a strict application of the SDC-IC design rules.
- In the case of the negligible thermal creep curves, data have to be completed to allow the correct application of the corresponding tests, and thus the choice of “low” or “high” temperatures rules.
- Properties under irradiation need to be completed. If the current lack of data does not always prevent the use of the design rules (for some data type, it can be recommended to use unirradiated conditions values), some analysis methods can be discarded, such as elasto-plastic analysis.
- Two main issues can explain the current lack of data related to the welded joints: (i) a difficult selection process, which follows an iterative procedure between design and material characterization; (ii) the impossibility to cut standard samples in very narrow regions for some components. To overcome these difficulties, advices from industry on the way to deal with the characterisation of very many weld configurations are requested. In addition, the strategy of ‘design by experiment’ foreseen by design codes to qualify full components should be further assessed, in particular for components such as CPs or SPs.
- Rules for the description of the combined effects of creep and fatigue do not exist and must be developed.

6.2. TBM fabrication

Due to the unique features of TBMs, the multi-code approach is the only applicable method for welded joints design. The codes used for this approach are RCC-MR, SDC/IC and ASME. The studies to be performed in this on-going activity include: (i) welds type identification according to their cross-section and to the role played in the TBM (structural, tightness, etc...), (ii) weld access identification and evaluation of the consequences on applicable welding processes and on welding and manufacturing sequences, (iii) identification of critical welding points (e.g. triple point) and recommendations for improvement of the design, (iv) identification of minimum distances between welds to verify compliance with related rules, (v) identification of welding procedures to be developed and qualified and (vi) identification of weld-design efficiency coefficients.

It has already been identified that the SDC-IC Appendix A for Eurofer does not give yet information about the interaction between the different welding processes. There might be negative influences combining HIP with EB (FW to caps), HIP with TIG (SG to back plates), EB with TIG (caps to back plates) or HIP + EB + TIG (SG to border of FW and caps). Only few of the envisaged TBM welding configurations are covered by existing code rules. As a consequence, the development of welding techniques has to be accompanied by the production of data for joint codification.

6.3. TBM non-destructive examination (NDE) and defect repairs

The choice of examination methods is driven by rules explained in RCC-MR chapter 4000 of subsection B, in ASME VIII – Division 2 section I and III, and in ASME III. EUROFER is not included in RCC-MR, but as it is derived from 9-Chromium steel, one can consider, when referencing to RCC-MR non destructive examination methods, the rules related to low-alloy steels. An objective of the ongoing analysis is to review non-destructive examination choices, knowing that the suggested methods depend mainly on the type of welded joints, welded assembly category and material to be re-welded.

Some preliminary comments have been issued. For ultrasonic NDE, the wave reflection at layer surfaces has to be proven and for radiographic NDE it has to be evaluated that possible tungsten enclosures of weld could be found with adequate accuracy. Other NDE methods, such as liquid penetration or magnetic powder, cannot be allowed for a use in vacuum environment.

7. Conclusion

Breeding blanket structural materials for fusion reactor applications are subject to severe constraints in terms of operating conditions and development needs. RAFM steels offer the best compromise among the limited number of potential candidates. EUROFER has been selected by EU as reference structural material and will be used to fabricate the TBMs that will be tested in ITER. In order to obtain sufficient and relevant data for breeding blankets design from the TBM testing in ITER it is mandatory to use of the same structural material.

In recent years promising manufacturing techniques for EUROFER components have been developed in the framework of the EU R&D program and a large database has been produced. Nevertheless, a significant effort is still required in order to apply the developed fabrication techniques to large scale components and to integrate them in industrial manufacturing processes as required already for TBMs.

Moreover, a large validation program is required in order to define an appropriate and complete set of design and manufacturing criteria for EUROFER to be applied to TBMs. A multi-code approach (e.g. SDC-IC, RCC-MR, ASME) has to be followed, with code cases to complete missing information on criteria, material data and appropriate manufacturing (e.g. welds) and inspections rules and methods. In parallel, the strategy of ‘design by experiment’ should be further assessed.

In order to satisfy all these requirements and be able to deliver a licensed TBM to be installed in ITER on time for the first H–H plasma operations, it is necessary to increase the existing EU effort through an aggressive supplementary R&D program specifically devoted to these subjects.

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