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Test blanket modules in ITER: An overview on proposed designs and required DEMO-relevant materials

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Abstract

Within the framework of the ITER Test Blanket Working Group, the ITER Parties have made several proposals for test blanket modules to be tested in ITER from the first day of H–H operation. This paper gives an overview of the proposed TBMs designs, of the ITER boundary conditions and of the expected TBM operating conditions. Operating conditions will vary throughout the various ITER phases, starting from the initial H–H phase where no neutrons and, therefore, no nuclear volume heating will be present, to the later D–T phase where pulses of up to 3000 s length may be expected. The paper is focused on the design requirements for the materials and subcomponents that will be used in the various TBMs, from the viewpoint of both the materials performance and the required R&D.

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1. Introduction

Within the framework of the ITER Test Blanket Working Group (TBWG), which includes representatives of the seven ITER Parties and of the ITER Team, the ITER Parties have made several proposals for Test Blanket Modules (TBMs) to be tested in ITER from the first day of H–H operation (day-one). It is recalled that the TBMs correspond to mock-ups of DEMO-relevant Tritium breeding blankets able to ensure DEMO Tritium breeding self-sufficiency. Although they are at different stages of development, all TBM proposals still need R&D before being eligible to participate in a coherent and coordinated TBM testing program in ITER [1,2].

The following sections describe the ITER boundary conditions, the proposed TBM designs, and the expected TBM working parameters, which should be similar to those of the corresponding DEMO blankets. In particular, the different structural

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materials, breeder and neutron-multiplier materials, and other functional materials used in the proposed TBMs are defined in term of expected performance and the main areas of required R&D are identified. The required time to manufacture the TBMs and conduct out-of-pile testing prior to installation in ITER has been estimated in order to establish the main R&D priorities and critical path activities.

2. TBMs test conditions and objectives

ITER operating conditions are very different from those expected for a DEMO reactor. Therefore, in order to achieve DEMO relevance for most working parameters, the TBMs have to make use of appropriate engineering scaling which may be a function of the specific testing objectives. Because of the lower neutron fluence in ITER (up to 3 dpa-Fe after 20 years of operation) compared to DEMO (more than 70 dpa-Fe in the blanket first wall), some important parameters, such as irradiation damage lifetime and reliability, cannot be tested in ITER.

2.1. Boundary conditions in ITER

ITER as an experimental machine will have a rather broad domain of operation around $Q = 10$, with fusion powers between 300 and 600 MW, depending on achievable confinement, density and maximum pressure. Three equatorial ports nb. 16, 18, and 2 (1.75 m wide × 2.2 m high) have been allocated for TBM testing. Up to now, only the first 10 years of ITER operations has been planned. They include 1 year of integration at the sub-system level and in-vessel component baking, 2.5 years of initial H–H operation, a brief D–D-phase and a long D–T phase. During the D–T phase the reference operating conditions for TBMs include an average surface heat flux on the first wall (FW) up to 0.27 MW/m^2 (with a peak at 0.5 MW/m^2), a neutron wall load up to 0.78 MW/m^2, and a pulse length of 400 s with a duty cycle of 22%. During the H–H phase, no neutrons will be present, however the peak heat flux on the FW could reach 0.3 MW/m^2 with an average of about 0.15 MW/m^2.

TBMs will be recessed by 50 mm from the nominal surface of the ITER shielding blanket FW in order to reduce plasma–wall interaction effects, with a maximum disruption energy load of 0.55 MJ/m^2 (1–10 ms) and they should have a 2 mm-Be protection layer on the FW. Inside each test port, the TBMs must be contained in a water-cooled steel frame, 20 cm-thick, which provides a standardized interface with the ITER structure, including thermal insulation of the machine (see Fig. 1). Therefore, in each port, the maximum available surface for testing is 1.35 m wide × 1.80 m high. Required gaps between the TBM and frame, and the separation wall (20 cm-thick) between TBMs in the same ports further reduce the size of such a surface.

2.2. Testing objectives

TBMs need to be installed in the 3 test ports from the beginning of ITER operation. Important data can be obtained during the H–H phase, such as: (i) demonstration of the structural integrity of the TBM structures and attachment during disruption and vertical displacement events (VDE); (ii) assessment of the impact on ferritic/martensitic steel, used as a structure for most TBMs, on magnetic field

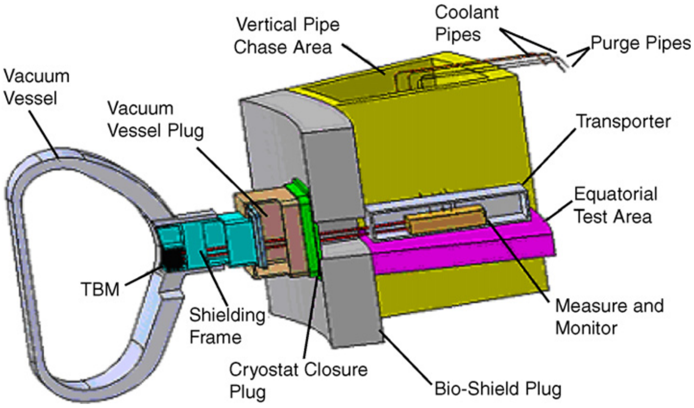

Fig. 1. Example of location of a TBM and associated system within the ITER vacuum vessel and building.

deformation in static conditions; (iii) verification of the need for Be-coating on the TBM FW. For TBMs using liquid metals, additional data can be obtained for the validation of the MHD pressure drop estimates and for T-control and management simulated with addition of H/D in the flowing liquid. In particular, the demonstration of the TBM integrity during the H–H phase is compulsory for obtaining TBM licencing for the D–T Phase.

During the D–T phase, the major overall testing objectives are: (i) validation of structural integrity predictions under combined and relevant thermal, mechanical and electromagnetic loads; (ii) validation of tritium breeding predictions; (iii) validation of tritium recovery process efficiency and T-inventories in blanket materials; (iv) validation of thermal predictions for strongly heterogeneous breeding blanket concepts with volumetric heat sources; and (v) demonstration of the integral performance of the blanket systems.

In order to achieve the expected testing objectives, appropriate instrumentation and measurement techniques need to be developed in the near future because most of the instrumentation currently available is not compatible with the expected severe TBM working conditions.

3. Proposed TBMs designs [1,2]

Starting from the different DEMO breeding blanket concepts defined by each Party, all able to achieve tritium breeding self-sufficiency and reasonable heat conversion efficiency, the following four main blanket families have been identified as candidates for installation as TBMs in ITER from the first day of operations: (i) liquid lithium–lead (LL) blankets, (ii) liquid lithium (Li) blankets, (iii) water-cooled ceramic/Be (WCCB) blankets, and (iv) He-cooled ceramic/Be (HCCB) blankets. Within each family, the proposed TBMs have many common features and R&D issues, and therefore offer the potential of possible common TBM tests in ITER.

In ITER, besides the low neutron fluence, the neutron flux and corresponding volumetric heat power density are also lower than that expected in a DEMO blanket. As a consequence, several TBMs have to be developed for each selected blanket concept during the first 10 years of operation, making use of ‘engineering scaling’ for testing specific DEMO ‘act-alike’ TBMs in order to address the different aspects of TBM performance. For instance, for thermo-mechanical tests, in order to reach similar thermal gradients despite the lower thermal loads in the TBMs compared to DEMO, wall thicknesses need to be adequately increased. On the contrary, for neutronics tests, materials fractions in TBMs have to be equal to those in DEMO. Of course, the design of ‘act-alike’ or ‘look-alike’ mock-ups needs a direct reference to a corresponding DEMO design and performance.

The following sections give an overview of the main features of the presently proposed TBMs, including some important design parameters as determined from the TBM operating conditions corresponding to the ITER reference D–T pulse [1,2]. In most cases, the TBMs have been designed assuming, a size of half a port, and can have a vertical ($57.5 \times 180\,\text{cm}^2$ max) or a horizontal ($135 \times 80\,\text{cm}^2$ max) orientation depending on the corresponding DEMO blanket characteristics. It must be noted that present TBM designs are still preliminary and could be modified in a near future in order to account for possible new R&D results and/or variation of the Parties TBM testing strategy. Moreover, this paper does not include TBM proposals from India since it has been written at the beginning of 2006, before the India participation to the TBWG.

3.1. Liquid lithium–lead (LL) breeder TBMs

Within the LL blanket family, there are three TBM proposals, all consisting of a single box, vertical half-port size, and using the eutectic Pb–17Li and He at 8 MPa with $T_{\text{in}} = 300$ and T_{out} up to 500 °C.

- The EU design, the HCLL–TBM, uses He as coolant. The EU HCLL–TBM features a Eurofer steel box cooled by horizontal multi-pass rectangular cross section channels and closed by top and bottom cooled covers. In the rear, cooling is ensured by 4 steel plates also acting as distributing/collecting chambers for the He-coolant. Poloidal–radial and toroidal–radial He-cooled plates stiffen the TBM box in order to withstand accidental internal pressurization at the coolant pressure (loss of coolant inside the TBM). The corresponding stiffening grid forms 24 radial cells in which circulates the PbLi at few mm/s for external tritium extraction purposes. In each cell, five radial–toroidal cooling plates formed by internal double-U rectangular channels are inserted and welded to a common back plate. A single He circuit is envisaged, with He cooling at first the FW and then the breeder zone. The LiPb draining is performed by gravity from the TBM bottom in order to improve safety. Structure temperatures range between 350 °C and 550 °C. The LiPb/steel interface temperature is about 520 °C. The Li is enriched to 90% in ^{6}Li. In order to facilitate T-management and control, in anticipation of DEMO operation, the use of T-permeation barriers is envisaged.

- The US design, the DCLL–TBM, uses He only for cooling the FW and structures made of F82H steel, and uses the PbLi itself as second coolant at T_{in} of 460 °C and T_{out} up to 650 °C. The TBM box is stiffened by a vertical grid of He-cooled steel plate that also has the function of LiPb flow separator. The LiPb flows upwards in the front row and downwards in the back row at a velocity of about 10 cm/s. The steel structures are electrically and thermally insulated from the LiPb by means of SiC/SiC flow channel inserts (FCIs) that follow the contours of the channels formed by the grid leaving a gap of few mm. Maximum temperature in the steel structure is 550 °C while in the SiC/SiC it is about 600 °C. The Li is enriched to 90% in ^{6}Li.
- The China design has initially a single coolant (He) but can evolve to dual-coolant operations (DFLL, dual functional lithium–lead). DFLL–TBM system is designed to check and validate the technologies of both the HCLL and the DCLL concepts, using a similar basic structure and auxiliary systems. These two options will be assessed and tested earlier under out-of-tokamak conditions and in the EAST superconducting tokamak before a final decision can be made for testing in ITER. The DFLL–TBM consists of a CLAFM steel box, reinforced by two radial–poloidal and six toroidal–poloidal He-cooled stiffening plates that act as LiPb flow separator. The module box is formed by a U-shaped FW with radial/toroidal/radial He cooling channels. A multi-shell back plate that also acts as a helium gas collector and distribution system closes it in the rear. The He-coolant is delivered to the TBM through concentric pipes. The LiPb (1 MPa) flows in the poloidal direction with the inlet/outlet temperatures of 480/700 °C.

Concerning external circuits, the HCLL–TBM requires one He-coolant line connection with the Tokamak Cooling Water System (TCWS) vault. PbLi circuit components are located in the port cell, the recovered tritium is sent to the ITER Tritium system. DCLL and DFLL TBMs require one additional He-line connection with the TCWS vault corresponding to the He secondary circuit of the PbLi primary coolant (heat exchanger located in the port cell).

3.2. Molten lithium (Li) breeder TBMs

Within the family of blankets using molten lithium, there are two TBM proposals: a self-cooled version implying the use of V-alloy structures, and a He-cooled version implying the use of graphite as a neutron reflector.

- Russian Federation (RF) has made a proposal for a SCLi TBM. It is a single box, made of V–4Cr–4Ti alloy, vertical half-port size. It uses porous Be as *n*-multiplier and the Li coolant at $T_{\text{in}} = 250$–350 °C and T_{out} up to 550 °C. The maximum temperature of the structural material is 600 °C. The Li is enriched to 90% in ^{6}Li. Its design is governed by the ITER safety requirement of limiting the Li volume to 35 L. The TBM is divided into two sub-modules in the toroidal direction having common liquid metal cooling and T-extraction subsystems. Each sub-module has Li channels poloidally oriented with the flow turn at the top. The containing structures are electrically insulated from Li by electro-insulating barriers, which allow reaching Li-velocities up to 0.5 m/s. The upward and downward flow parts of the channel are separated by porous Be-inserts. Behind the last Li duct, a further insert is added for shielding purposes; possible candidate materials are WC or TiC.
- Korea proposes to install a He-Cooled molten Li TBM (HCLi–TBM) using Eurofer structures and graphite neutron reflector. He-coolant has the same characteristics as in the other He systems. Molten Li is used as the tritium breeder and flows slowly for T-extraction purposes (few mm/s). Maximum temperature in the structure is 550 °C. Due to the low velocity of the molten Li, there are no serious MHD and material corrosion issues. Graphite is used as a reflector in order to minimize the neutron leakage from the TBM. Based on the neutronics analysis, the graphite reflector location is optimized with respect to the T-production: a thick graphite

region in the middle, with a thick Li-layer in the front and a thin Li-layer in the back. In DEMO, this blanket is expected to use natural Lithium. However, because of the low amount of Lithium allowed for safety reasons in ITER, in the HC–Li TBM the Li is enriched up to 90% in ^{6}Li in order to maximize the T-production.

For Li–TBMs, all Li systems are expected to be located in the VV port extension. He-coolant systems are in the TWCS vault.

3.3. Water-cooled ceramic breeder (WCCB) TBMs

For the WCCB blanket family, a TBM design is proposed by Japan. It has a 2 sub-module structure, vertical half-port size and uses water-coolant at PWR conditions ($T_{\text{in/out}}$ 280/325 °C), Be-multiplier and Li_2TiO_3 pebble beds. The two sub-modules have the same box structures and the same internal structures. The FW made of F82H has built-in rectangular cooling paths. As for internal structure, it has a multi-layer pebble-bed structure similar to that of the DEMO blanket. Breeder and neutron multiplier are in pebble form and are packed separately and divided into four layers by cooling panels. The cooling panel consists of F82H tubes, which have a inner diameter of 9 mm and a thickness of 1.5 mm, and thin plates connecting adjacent tubes. The inner box structure is welded to the first wall and to the back plate. The thickness of each layer and pitch between tubes in each cooling panel have been optimized in order to obtain similar levels of temperature and possibly similar stresses to those present in a DEMO blanket, according to the transient performance analyses of temperature evolution and tritium generation/release performance. Maximum temperatures are 900 °C in the ceramic, 600 °C in the Be, and 550 °C in the steel. In order to reduce T-permeation towards the water-coolant, the use of T-permeation barriers is envisaged. The WCCB TBM requires one water line connection to the TCWS vault, the tritium system being located in the port cell.

3.4. Helium-cooled ceramic breeder (HCCB) TBMs

All Parties are interested in developing HCCB blankets. At present, four Parties, China, EU, Japan and RF, have made independent TBM design proposals, while US and Korea propose to test submodules integrated in one of them. All proposed TBMs use ceramic breeder in pebble-bed form and He-coolant at 8 MPa with an inlet temperature of 300 °C and outlet up to 500 °C depending on operating conditions.

- The China design is a single CLAFM steel box, a quarter-port size, and uses Be and Li_4SiO_4 pebble-beds. The first wall is a U-shaped plate with toroidal coolant channels and beryllium protective coating, reinforced by He-cooled stiffening ribs to provide required strength in abnormal operation conditions. The internal space between the first wall module and back plate is used for breeding zone arrangement. The breeding zone contains a sequence of poloidal rows of circular coolant channels, of Li_4SiO_4 pebbles, and of Be pebbles. The Li_4SiO_4 pebbles are single-size pebbles (38% porosity) while Be is used as binary pebble-bed (20% porosity) with diameters of 0.5 and 1 mm. The TBM structure consists of the following main components: first wall, caps, grids, manifolds, attachments, cooling pipes, purge-gas pipes and sub-modules. The integral TBM consists of 9 sub-modules (cells). Each cell has an independent cooling circuit and purge-gas circuit. Li is enriched 80% in ^{6}Li.
- The EU design is a single Eurofer box containing 18 unit breeder cells, horizontal half-port size, uses Li_4SiO_4 or Li_2TiO_3 and Be pebble beds. Li is enriched 30% in ^{6}Li in case of use of Li_4SiO_4 breeder and 60% in the case of Li_2TiO_3breeder. Maximum temperatures are 900 °C in the ceramic, 600 °C in the Be, and 550 °C in the steel. Similar to the HCLL–TBM, the EU–HCCB–TBM is essentially a He-cooled box reinforced by a He-cooled steel grid and able to withstand the full pressure of the He-coolant in case of in-box LOCA and it features radial cooling with the high pressure manifolds integrated in the back plate structure. Breeder units are inserted in the grid and several cooling plates ensure heat-extraction from the breeder/multiplier. Ceramic and Be pebbles are purged by a low pressure He-stream for T-extraction that flows at first in the Be-beds and then through the ceramic-beds from the front region to the back manifolds.
- The Japan design has a 3 sub-module structure, horizontal half-port size, uses Li_2TiO_3 and Be pebble beds. Each sub-module has the same structure as a sub-module of the Japan WCCB TBM. Maximum temperatures in the various materials are also the same.

- The RF design has a 2 sub-module structure, vertical half-port size, uses Li_4SiO_4 pebbles and porous Be-blocks. Each module is made by He-cooled ferritic steel (RF–FS–9CrMoVNb) box, enclosing the breeding zone made of five T-breeding elements. Each element is a coil-pipe sintered in porous Beryllium briquettes. Each coil-pipe is an assembly of co-axial ferritic steel tubes. The inner tube is filled with ceramic pebbles and a purge gas ($He + 0.1\%H_2$ or Ne) for T-recovery is circulating through the ceramic pebbles. The He-coolant flows in the annulus between the coaxial tubes. Maximum temperatures are 600 °C in the ferritic steel, 650 ° in the Be, and 1000 °C in the ceramic pebbles.
- Contribution from Korea will be to test sub-modules integrated in existing TBMs. The objective is to minimize the required amount of Be. Be has a high multiplication efficiency and is regarded as one of the best neutron reflector materials. However, the natural resource of Be is very limited and hazardous to human beings as well. Therefore, the proposal is to reduce the amount of Be by replacing some of it with graphite as a reflector. As a breeder, Li_4SiO_4 with 97% of the theoretical density (TD) and 62% packing fraction is used, with a ^{6}Li enrichment of 40%. As for the Be-multiplier, a 95% TD and 80% packing fraction are used. Also the graphite is used in pebble-bed form in order to accommodate any possible geometrical changes during neutron irradiation. The packing fraction of the graphite is assumed to 85% in this design. The thick graphite reflector has an advantage in that it can play the role of a heat sink in the case of a loss of coolant accident.
- Contribution from US could be either to test a quarter-port size sub-module or to test unit breeder cells inserted in the EU–HCCB–TBM. In the latter case, the unit cell is to be inserted to address the issue of pebble-bed thermo-mechanical integrity. The proposed design incorporates features of an edge-on blanket configuration with an attempt to minimize the use of beryllium by increasing the breeder width as it moves toward the back of the blanket region. Specifically, an engineering scaling has been applied to reproduce prototypical ceramic breeder pebble-bed thermo-mechanical behavior. Since the ITER neutron wall load is much smaller than that of a DEMO reactor, the breeder unit dimension is adjusted to correctly duplicate the DEMO blanket temperature profiles.

For all HCCB–TBMs, the He-coolant system has to be located in the TCWS vault, therefore each TBM requires the connection of one coolant line (one inlet and one outlet pipe) between port cell and vault. Purge-gas system components are located in the port cell, while recovered Tritium is sent toward the ITER tritium plant in the tritium building.

4. Materials and R&D requirements

Starting from the proposed TBM designs, the next sections give an overview of the various materials that are expected to be used for TBM manufacturing and briefly address the main R&D issues which need to be solved before the TBM installation in ITER. The various materials used in each proposed TBM and the corresponding masses are summarized in Table 1.

4.1. Structural materials [3]

All TBMs use ferritic/martensitic steel as structural material, with the exception of the SCLi TBM that uses a V-alloy (V–4Cr–4Ti). Four different grades of ferritic/martensitic (F/M) steels are proposed: Eurofer, F82H, RF–FS(9CrMoVNb) and CLAFM, whose compositions are given in Table 2. The composition of the proposed V-alloy is also given in Table 2.

Significant R&D programs for F/M steels are under way in several countries. Most of the selected grades are being developed for fusion application with the specific objective of reducing their long-term induced activation (>100 y) and therefore avoiding long-term nuclear waste disposal.

For these F/M steels most physical properties before irradiation are already well known and have been used in performing the TBM designs. For instance, the working temperature window is about 300–550 °C.

Properties after irradiation are being studied in fission reactor experiments, and the most critical one appears to be the ductile-to-brittle transition temperature (DBTT) at high doses. The additional effects of 14 MeV neutrons (leading to larger He-production compared to fission spectra) cannot be studied in existing facilities.

Other R&D areas include design code qualification, tritium-related properties (e.g., solubility, permeability) needed for T-control and management,

Table 1
Materials masses in a half-port size TBM[a]

TBM type	Structural material		Breeder(s)		Multiplier		Coolant		Functional material(s)	
	Name	Mass (kg)	Name(s)	Mass (kg)	Name	Mass (kg)	Name	Mass (kg)	Name(s)	Mass (kg)
China HCSB	Eurofer	1326	Li_4SiO_4	51	Be pebbles	106	He	0.2 (8 MPa)	None	–
EU HCSB	Eurofer	1920	Li_4SiO_4 or Li_2TiO_3	97	Be pebbles	396	He	~0.6 (8 MPa)	None	–
Japan HCSB	F82H	1961	Li_2TiO_3 or others	104	Be or $Be_{12}Ti$ pebbles	305	He	0.5 (8 MPa)	None	–
Korea HCSB	Eurofer	833.8	Li_4SiO_4	85.3	Be pebbles	126.7	He	0.095 (8 MPa)	Graphite pebbles (n reflector)	305.3
RF HCSB (for one submodule)	FS (9Cr MoVNb)	524 × 2	Li_4SiO_4	35.5 × 2	Be (porous blocks)	310 × 2	He	(8 MPa)	None	–
US HCSB (for 3 unit cells)	F82 H or Eurofer	144	Li_4SiO_4 or Li_2TiO_3	38.5	Be pebbles	22	He	(8 MPa)	None	–
Japan WCSB	F82H	2041	Li_2TiO_3 or others	91	Be or $Be_{12}Ti$ pebbles	430	H_2O	38 (15.5 MPa)	Al_2O_3 (T-permeation barrier)	TBD
China DFLL	CLAFM	1193	Pb–17Li (also as partial coolant)	2196	as the breeder		He	0.76 (8 MPa)	SiC/SiC (flow channel insert)	105
EU HCLL	Eurofer	1784	Pb–17Li	2863	as the breeder		He	0.95	Al_2O_3 (T-permeation barrier)	<5
US DCLL	F82H	763	Pb–17Li (also as partial coolant)	1824	as the breeder		He	1.05 (8 MPa)	SiC/SiC (flow channel insert)	49
Korea HCML	Eurofer	802	Li	13.9	as the breeder		He	0.283 (8 MPa)	Graphite pebbles (n reflector)	333.7
RF SCLi	V–4Cr–4Ti	315	Li (also as coolant)	11	Be (porous blocks)	20			(1) Er_2O_3 or AlN (insulating coating) (2) WC inserts	<1150

[a] All TBMs FW are expected to be covered by a Be protection layer (thk. 2 mm, TBD).

Table 2
Structural materials composition (without impurities)

Name	Elements and fraction wt%
Eurofer	Fe (bal), Cr (9.40), C (0.11), Mn (0.50), Si (0.05), W (1.0), V (0.25), Ta (0.08), N (0.03), B (0.005)
F82H	Fe (bal), Cr (8.0), C (0.10), Mn (0.50), Si (0.20), W (2.0), V (0.2), Ta (0.04), N (<0.01), B (0.003)
RF–FS (9CrMoVNb)	Fe (bal), Cr (8.6–10), C (0.12), Mn (0.3–0.6), Si (0.17–0.34), Ni (<0.5), Mo (0.6–0.8), V (0.1–0.2), S (<0.025), P (<0.03)
CLAFM (China)	Fe (bal), Cr(9), Mn (0.45), C(0.1), W(1.5) ,Ta(0.15), V(0.2)
V–4Cr–4Ti (RF)	V (bal), Ti (4), Cr (4), Si (4.0E–2), Al (2.0E–2), Mo (2.0E–2), O (1.5E–2), Fe (1.2E–2)

compatibility with breeder materials and coolants, compatibility with coating fabrication process, and modeling of irradiation effects.

For these F/M steels, little industrial production experience is available. Moreover, component assembly and joining technologies are not yet available. Experimental work on various techniques, such as HIP, laser welds and EB welds, is being performed at the laboratory level, but significant R&D is still required before reaching the industrial scale. The issue of performing the required heat treatment in an assembled component also has to be investigated.

Joints between martensitic and austenitic steels have to be developed in order to allow the transition between martensitic steel used for TBMs and austenitic steel that is expected to be used for the piping. The location of the transition region (inside or outside of the vacuum vessel) is not yet defined.

Similar R&D is required for V–4Cr–4Ti. Additional R&D concerns include oxygen embrittlement and feasibility of electrical insulating coatings that are required in the SCLi TBM for reducing MHD-induced pressure drop.

4.2. Breeder and multiplier materials

The eutectic Pb–17Li is used as breeder and multiplier in the LL TBMs. For this material, areas of R&D include compatibility with F/M steels and SiC/SiC, tritium solubility, MHD effects, and the tritium extraction process. Efficient purification processes for activated elements and for corrosion products need to be further developed. For these blanket concepts, the lithium has to be enriched in the range from 70% up to 90% ^{6}Li.

For molten lithium the main R&D areas are compatibility with F/M steel and insulating coatings, MHD effects, the tritium extraction process, and impurity control. Because of the high reactivity of molten Li with water and air, safety assessment is also an important area of investigation.

Ceramic breeders [4] are used in pebble-bed form in all CB TBMs because of better resistance to thermal loads. Li_4SiO_4 and Li_2TiO_3 are the two candidate ceramics that are under developments in various countries. Both ceramics show acceptable properties for use as a breeder in a DEMO blanket. The major issue that has still to be investigated is their behavior under long-term irradiation. Other R&D areas are the behavior and modeling of the pebble beds under thermal loads and under irradiation loads, the thermal conductivity of the bed, and pebble fabrication with appropriate dimensions. The effect of Li burn-up in DEMO has also to be fully assessed. For these materials typical required enrichments range from 30% to 60% of ^{6}Li. From the ceramic material point of view, the required R&D for HCCB and WCCB TBMs is very similar, with the major difference being the slightly different temperature distribution in the pebble beds.

All ceramic breeder TBM designs involve beryllium as a *n*-multiplier whose volume has to be about four times larger than the ceramic pebble volume. In most cases, Be is used in the form of pebble beds. The main R&D area for Be pebble beds are similar to those of ceramic pebbles, with the additional issues of Be-swelling under irradiation and the reduction of T-inventory. Production of Be pebbles is also under investigation. In the case of WCCB TBM, the comprehension of the Be/water reaction and its management are additional key R&D items. Both RF TBMs proposals, the HCCB–TBM and the SCLi TBM foresee the use of porous-blocks of beryllium. Thermal property characterization, the fabrication process, and behavior under irradiation are the main R&D areas that need to be addressed for this material.

4.3. Functional materials

In order to accomplish their missions of T-breeding self-sufficiency and high-grade heat recovery, some breeding blankets need to make use of specific materials that allow the blanket and associated systems to operate correctly and safely [5]. The most significant examples are listed below:

- DCLL blanket requires the use of SiC/SiC flow channel inserts in order to electrically and thermally insulate the flowing LiPb from the steel walls. Main areas of R&D include SiC/SiC fabrication and joining, SiC/SiC compatibility with flowing LiPb, and behavior under low-dose irradiation. Because of the low LiPb temperature, the availability of SiC/SiC FCIs is not compulsory for the TBM installed on day-one. In fact, surrogate FCIs using ferritic steel or refractory alloys clad with alumina insulators could potentially be used as a back-up solution.
- The presence of tritium permeation barriers could considerably facilitate T-management and control for most blankets. Their use would be particularly useful in the HCLL blanket because it features a high T-permeation rate from LiPb to the He-coolant. Significant R&D is going on, especially on alumina-based barriers. The fabrication process for martensitic steels and their behavior under irradiation are the main uncertainties to be addressed. In the TBM a T-permeation barrier would be desirable but not compulsory during the first H–H phase.
- The SCLi concept requires, even during the H–H phase, an electro-insulating material to be placed on the interface of Li/structure material to decrease induced currents and magneto-hydrodynamic pressure drop resulting from the interaction of these currents with tokamak magnetic fields. Some different concepts of self-healing electro-insulating coatings, based on CaO, AlN, Er_2O_3, Y_2O_3, or multi-layer structures are being considered. Main uncertainties are the compatibility with flowing molten Li, crack formation, and self-healing capability.
- A WC or TiC shield/reflector is used in the SCLi blanket to improve T-production. Other than their high shielding capability, very little data are available for these materials. Although not compulsory during the H–H phase, R&D is required to verify their compatibility with Li, and their thermal properties before and after irradiation.
- In the HCLi blanket, a very large amount of graphite pebbles is used as *n*-reflector in replacement of Be. Also in this case, very little data are available on graphite pebble characteristics and on their behavior under irradiation. Specific R&D should address areas such as thermal and thermo-mechanical properties of pebble beds, T-inventory and behavior under irradiation.

4.4. R&D schedule

To provide relevant information for DEMO breeding blankets, ITER TBMs and associated systems have to use similar design, functionalities, materials and fabrication technologies as those expected in DEMO. The requirement of installing the TBMs at the beginning of ITER operation, dictated for TBM licensing purposes, implies that most TBM materials and fabrication technologies have to be available in a relatively short term.

Several steps need to be performed prior to TBM installation in ITER. The most important are: (i) selection of materials grade and fabrication routes; (ii) characterization of materials in fission reactor irradiations; (iii) confirmation tests for component performance and reliability; (iv) out-of-pile tests of mock-ups and associated systems up to the test of prototypical TBM systems; and (v) validation of remote handling equipment and procedures.

TBM installation in ITER is expected in 2016 after successful ITER acceptance tests [1]. TBM manufacturing should therefore start in 2012. Small-scale and medium-scale mock-up fabrication and testing should be completed before that date. It is expected that such experimental campaigns will last at least 3 years. As a consequence, only about two years (up to 2008) are available for finalizing the basic R&D on materials and on assembly techniques whose results have to be applied to the mock-up designs.

The initial TBMs tested in the H–H phase do not need to include all technology features required for the following TBMs. However, because they have to be used for TBM licensing, the main structural and functional features have to be present. Therefore, R&D concerning structural material characterization, design codes and assembly technology need to be completed and validated before the first installation in ITER. Partial validation is already required for previous small-scale and medium-scale mock-ups.

For all the other materials, the time scale appears to be more relaxed. For instance, the quality of ceramic pebbles or Be-pebbles does not need to be optimized for the initial TBMs. The same consideration applies to FCIs, permeation barriers and to the other functional materials. One exception is the electro-insulating coating on V-alloys. MHD effects are present from the beginning of the H–H phase, therefore coatings with acceptable performance need to be available in the short term.

5. Discussion and conclusions

The tests of DEMO-relevant TBMs in ITER will give essential information to accomplish breeding blanket development whose use is compulsory for DEMO.

Besides the need for checking TBM compatibility with ITER operations, TBM testing in the initial H–H phase is essential both to demonstrate structural integrity and safety-related performance of TBMs before starting the D–T operations and to validate remote operations on the TBM systems.

The preliminary TBM integration work in ITER has shown that blanket testing in ITER will be very complex and very lengthy. It is therefore required to make the most of the performance tests, if feasible, in dedicated out-of-pile facilities prior to the installation in ITER.

Significant R&D on structural materials has to be performed prior to TBM installation in ITER. It includes materials fabrication routes and irradiation resistance, out-of-pile tests of mock-ups and associated systems up to the scale of prototypical TBM systems, and remote handling equipment validation. Therefore, the requirement of installing TBMs at the beginning of ITER H–H operations fixes a tight time-schedule on the expected experimental campaigns prior to installation in ITER.

The TBM designs are performed taking into account the corresponding testing objectives. However, to obtain the expected data from the various tests, the available instrumentation is not satisfactory and, therefore, the development of appropriate instrumentation is an high priority activity.

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