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Progress and challenges of the ITER TBM Program from the IO perspective

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ABSTRACT

The paper describes the organization of the Test Blanket Module (TBM) program, its overall objective and schedule and the status of the technical activities within the ITER Organization-Central Team (IO-CT). The latter include the design integration of the Test Blanket Systems (TBSs) into the nuclear buildings, ensuring all interfaces with other ITER systems, the design of the common TBS components such as the TBM Frames, the Dummy TBMs, and the TBS maintenance tools and equipment in the TBM Port Cell as well as in the Hot Cell building, the design of the TBS connection pipes and the definition of the required maintenance operations and associated R&D. The paper also discusses the major challenges that the TBM Program will be facing in ITER such as the potential impact of the TBMs ferritic/martensitic structures on plasma operations, the approaches to tritium and contamination confinement, the required mitigation and recovery actions in case of accidents, and the assessment of the reliability aspects that could have an impact on ITER availability.

1. Introduction

A tritium Breeding Blanket (BB) ensuring tritium breeding self-sufficiency is a compulsory element for a demonstration power reactor (DEMO), the next-step after ITER. Therefore, although a BB is not required for ITER, since it will procure the tritium from external sources, among the ITER missions it is included that "ITER should test tritium breeding module concepts that would lead in a future reactor to tritium self-sufficiency, the extraction of high grade heat and electricity production".

Six mock-ups of different DEMO BBs, called Test Blanket Modules (TBMs), will be inserted and tested in ITER in three dedicated equatorial ports directly facing the plasma. Each TBM is connected with several ancillary systems, for cooling, tritium extraction, coolant purification, and instrumentation and control (I&C) to simulate a whole DEMO BB system. The TBMs and the associated systems form the Test Blanket Systems (TBSs). Their operations are the principal means by which ITER will provide the first experimental data on the global performance of the BBs that is a major challenge on the path to commercial fusion power. These activities correspond to the so-called "TBM Program". A successful ITER TBM Program represents an essential step for any fusion power development plan of all the seven ITER Members (IMs) [1,2].

The functional characteristics of the six TBSs are dictated by the operational conditions and requirements expected in a DEMO-BB system and, in this sense, they differ from the other ITER components that are designed taking into account ITER requirements only. However, they must be fully integrated in ITER; therefore they must be compatible with the systems and operational procedures of ITER and the ITER operating plan. Moreover, TBS operation must not endanger ITER performance, safety and availability.

Each TBS is functionally independent from the others. Three Vacuum Vessel (VV) equatorial ports and associated Port Cells (PC) are

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dedicated to the TBM Program. Two different TBSs will be tested in each of the three ports and, therefore, they will share the corresponding VV port and the PC area. The TBMs First Wall (FW) is acting as a plasma facing-component but it will be recessed of 120 mm compared to the ITER shield modules FW. This recess is necessary to avoid major heat loads transients on the TBM FW due to plasma instabilities which are expected in ITER but, in principle, should not to be present in a DEMO. In a TBM Port Plug (PP) the TBM Frame supports two TBM-Sets each of them formed by a TBM and the associated shield block. The availability of up to six Dummy TBMs is planned to replace the TBM-Sets in case of one (or more) of them is not available.

The following sections describe the major progress of the TBM Program focused on the activities made at the Central Team (CT) of the ITER Organization (IO), in particular on the TBS integration, on the required interfaces and on the design of some TBS common components. ITER is a French Nuclear Facility (INB-174). Particular emphasis is therefore given to the potential challenges that have to be faced for achieving safe and reliable TBS nuclear operations. All R&D and challenges related to the TBS components themselves are beyond the scope of this paper and can be found in [3–7].

2. TBM Program management and schedule

Following an ITER Council decision, the TBM Program has been implemented within the ITER Project since 2008 and it is governed by a specific high level advisory body, the TBM Program Committee [2]. The IO-CT is responsible for preparing the necessary infrastructures required for the installation of the TBSs including the procurement of TBM Frames, Dummy TBMs and standardized maintenance tools and equipment both in Port Cells (PCs) and Hot Cell Building (HCB). The IO-CT is also responsible of guaranteeing the TBS safety and reliability performance and of installing, commissioning and operating the TBSs. The IMs are in charge of the design, manufacturing and delivery of the TBSs to the ITER site.

The six TBSs will be procured by the five IMs mentioned in Table 1 with the remaining two IMs (RF and US) supporting the TBM Program by performing TBS-relevant R&D. The delivery of the TBSs and of the associated infrastructures is planned at the beginning of the ITER Assembly Phase-II in order to be ready to operate the TBSs during the ITER H-plasma phase. Table 1 lists the six selected TBMs for being operated in ITER and their main functional characteristics.

For each TBS, a specific procurement arrangement, called TBM Arrangement (TBMA), have been signed between IO and the concerned IM, in order to establish the formal framework of the TBM Program, including the IM commitment of delivering the TBS on due time, the IO commitment of integrating it in the ITER facility, and other important aspects such as intellectual property rights, rad-waste management and liability. Moreover, each TBMA specifies safety and Quality Assurance (QA) requirements, and establishes the TBS technical specifications and milestones, including the planned delivery date. A subsequent agreement is under preparation to cover the TBS testing, assembly & installation, commissioning, and non-nuclear operations.

3. TBM port plugs

The TBM PPs are the in-vessel component part of the TBSs. The IO-CT is responsible for the design and manufacture of the TBM Frames and of the Dummy TBMs. Various versions of each TBM type, equipped with different instrumentation, are planned to be tested in the different ITER operational phases with different testing objectives. Therefore, several TBMs replacements are scheduled. The adopted replacement strategy is to replace a whole TBM PP with a new one during the major shutdown periods of the machine, the so called “Long Term Maintenance” shutdowns. The refurbishment of the TBM PPs is made off-line in the HCB which implies that two frames need to be available for each port. As a consequence the design of the TBM PP has to be Remote-Handling (RH) compatible, which imposes significant constraints on the PP design. Each TBM PP is leak tested in the ITER Port Plug Test Facility before being installed in the VV.

3.1. TBM frame and dummy TBMs design

The TBM Frame has the function to neutronically and thermally insulate the two TBMs from each other and from their environment. The TBM Frame and the Dummy-TBMs designs are in the preliminary design phase [8]. The TBM Frame design is shown in Fig. 1. It is a water-cooled Stainless Steel (SS) structure with dimension of 1948 mm (toroidal) × 2400 mm (poloidal) × 3219 mm (radial). It comprises three parts: a front frame, a middle frame, and a rear frame with the “flange”. These three parts are welded together and the flange is bolted to the flange of VV equatorial port extension.

Dummy TBM has a plasma-facing surface of 462 mm (toroidal) × 1670 mm (poloidal), with 2339 mm radial length. Each Dummy TBM is manufactured with 40 mm thick SS plates welded together forming several boxes intended to contain the cooling water. Dummy TBMs are mounted and dismounted via a set of M27 bolts located on the rear side. This operation is performed in the HCB using RH equipment, once the whole TBM PP is removed from the port.

Both TBM Frame and Dummy TBMs are made of SS 316(N)-ITER Grade steel (as the ITER blanket modules) and cooled in parallel

Table 1
Main characteristics of the 6 Test Blanket Modules (TBMs) and of the key associated ancillary systems.

Port Plug	First TBM	Second TBM
Nb 16	Helium-Cooled Lithium Lead (HCLL) TBM, procured by EU [3] • Eurofer steel (structure), Pb-16Li (multiplier/breeder) • Coolant: helium at 8 MPa, 300/500 °C	Helium-Cooled Pebble-Bed (HCPB) TBM, procured by EU [3] • Eurofer steel (structure), be pebbles (multiplier); Li_4SiO_4 or Li_2TiO_3 pebbles (breeder) • Coolant: He at 8 MPa, 300/500 °C • Purge gas: helium at 0.4 MPa
Nb. 18	Water-Cooled Ceramic Breeder (WCCB) TBM, procured by Japan [4] • F82H steel (structure), be pebbles (multiplier), Li_2TiO_3 pebbles (breeder) • Coolant: H2O at 15.5 MPa, 280/325 °C; Purge gas: He at 0.1 MPa	Helium-Cooled Ceramic Reflector (HCCR) TBM, procured by Korea [5] • RAFM steel (structure), be-pebbles (multiplier), Li_4SiO_4 pebbles (breeder), Graphite pebbles (reflector) • Coolant: He at 8 MPa, 300/500 °C • Purge gas: He at 0.1 MPa
Nb. 02	Helium-Cooled Ceramic Breeder (HCCB) TBM, procured by China [6] • CLAM steel (structure), Be pebbles (multiplier), Li_4SiO_4 pebbles (breeder) • Coolant: helium at 8 MPa, 300/500 °C • Purge gas: He at 0.1 MPa	Lithium-Lead Ceramic Breeder (LLCB) TBM, procured by India [7] • RAFM steel (structure), Pb-16Li (multiplier), Pb-16Li & Li_2TiO_3 pebbles (breeders) • Coolants: He (8 MPa, 300/340 °C) & Pb-16Li (1.2 MPa, 300/480 °C) • Purge gas: helium at 0.1 MPa

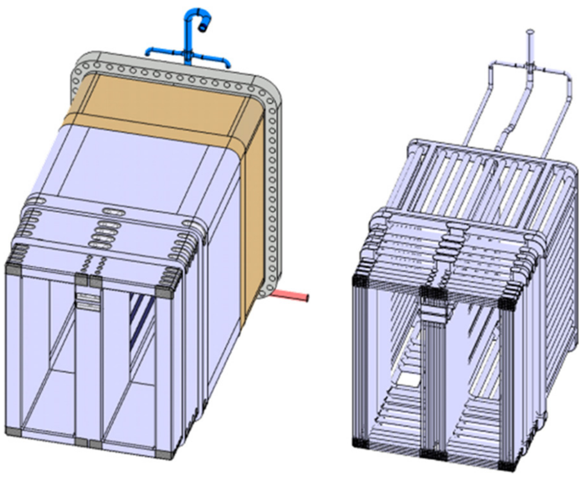

Fig. 1. A TBM Frame (left) and its cooling circuit (right).

by water at 4 MPa and 70 °C. The same coolant connections are planned for the TBM Shield of each TBM-Set since they have to be fully replaceable with the Dummy TBMs. The manufacturing route, including weld inspection accessibility, have been fully assessed and optimized by industrial experts.

3.2. *Main PP design and manufacturing challenges*

3.2.1. *Limitation of the contamination*

Each TBM PP will be regularly replaced and refurbished during ITER life time. The current maintenance scheme includes both hands-on operations and RH operations in HCB. In order to allow hands-on operation, the back side of the TBM PP must avoid any contamination during the refurbishment operation in the HCB red zone. To this aim, two types of cover plates have to be added at the back of the TBM PP, a two-layered open cover plate and a closed cover plate. The aim of the two-layered open cover plate is to protect the inner wall and the flange of the TBM Frame during the refurbishment operations in the HCB. The closed cover plate will be removed when the TBM PP is finally installed in the VV. The feasibility of these sequential operations needs to be experimentally validated.

3.2.2. *Improvement of the shielding performance*

In order to minimize the dose rate in the area behind the TBM PP, only narrow gaps are allowed between the various components. However, reducing these gaps increases the difficulty to assemble and replace the TBM PP. Therefore, a double dog-leg has been added between TBM Frame and neighboring components. Moreover, the gaps between TBM Frame and Dummy TBMs have been limited to 7–10 mm in order to minimize neutron streaming. The acceptability of these narrow gaps needs to be experimentally validated.

3.2.3. *Acceptability of the vacuum performance*

The back of the TBM-Sets (or Dummy TBMs) and the flanges are part of the VV boundaries, requiring a maximum acceptable leak rate of 10^{-10} Pa m^3/s (air equivalent). In order to provide leak tightness between TBM Frame and the TBM-Shield, a double metallic gasket sealing with leak detection system is implemented. This metallic gasket needs high compression to ensure the high vacuum sealing. The metallic gaskets are located within the TBM-Shield flanges in order to facilitate the remote-performance of the TBM-Sets refurbishment. To ensure tightness, M27 RH-compatible captive bolts are used with a 60 mm pitch. The leak tightness capacity of the metallic gasket in all possible ITER operational scenarios needs to be experimentally validated with full-scale mock-ups.

3.3. *Potential TBM impact on plasma performance*

The structures of the TBMs are made of Reduced-Activation Ferritic/Martensitic (RAFM) steels, which are ferromagnetic materials. The use of RAFM steels for the TBMs structures could generate some perturbation to the plasma confinement.

Recent experiments on DIII-D [9] with a mock-up pair of TBMs have shown that either external or internal correction coils, similar to those being designed for ITER, can correct the additional intrinsic TBM mock-up error fields at high performance with almost no degradation in performance.

To reduce the potential impact of the TBM magnetic perturbations, the recommended strategy is to minimize the TBM ferromagnetic mass (below 1.3 t), and take advantage of the initial ITER H/He-phase to better understand the possible TBM-induced disturbances and implement any appropriate countermeasure for the ITER operational phases that will follow.

4. Integration of the TBS ancillary systems in ITER and main interfaces

Each TBS includes one TBM and several ancillary systems, such as the cooling system, the Pb-16Li system, the tritium extraction system, and the measurement system. The corresponding components are located in various areas of the Tokamak and Tritium Buildings as shown in Fig. 2. All the TBSs ancillary systems are fully defined by the corresponding Process Flow Diagrams where are defined all the interfaces with other ITER systems and by the Piping and Instrumentation Diagrams that gives all the operating and control parameters.

The primary TBS Cooling Systems (CSs) extracts the heat produced in the TBMs and deliver it to a secondary circuit. For each TBM, the cooling pipes cross the TBM shield, the Port Interspace (PI), and the biological shield to reach the Ancillary Equipment Unit (AEU) where some components are located. The remaining components are located in other areas of the Tokamak and Tritium buildings using connection pipes passing through the PC shafts. All the six TBS CSs use the ITER Components Cooling Water System-1 (for nuclear components) as secondary circuit for releasing the produced thermal power within the TBMs and for the cooling of the major components. All CSs (He, water and Pb16-Li) are closed systems filled during commissioning. For the He-coolant systems, in order to compensate for the He-leaks during operation, the use of the main ITER Helium supply service is necessary. In the case of water and Pb16-Li, if an additional supply is needed it has to be supplied from external sources.

The TBS Tritium Extraction Systems (TESs) connect the tritium carrier fluids (either Helium or Pb-16Li) flowing in the TBMs to the corresponding components and equipment used in the Tritium extraction process. Some of these components are located in the AEU and the others in the Tritium building reached by mean of connection pipes crossing the Tokamak building gallery. These systems require the supply of liquid nitrogen from the existing ITER Nitrogen-supply services to be used in the Tritium extraction process.

Additional required ITER services for the various CSs and TESs equipment are compressed air services for operating the valves, demineralized water services, and helium services. Also electrical power supplies services are needed to operate the various TBS components.

All TBS equipment are operated, controlled, and monitored by adequate detectors including those specifically devoted to safety and investment protection. Moreover, in order to achieve the testing objectives described above, additional measurements are needed in the TBM PPs and in the TBM ancillary systems in order

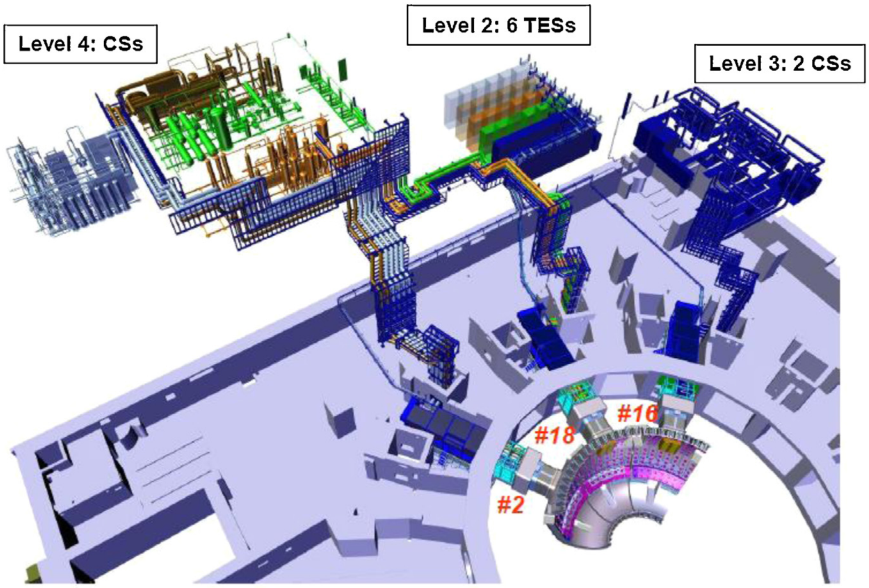

Fig. 2. Overall view of the 6 Test Blanket Systems located in various rooms of the Tokamak and Tritium buildings.

to be recorded for performing the appropriate on-line and off-line interpretations. The amount of associated cables for signals transmission has also been assessed.

The main required measurements, in all parts of the TBSs, range from measurements of neutron fluxes, temperatures, stresses, and pressures to tritium-concentration measurements. Appropriate sensors and measurement equipment are included in the various TBSs designs. Taking into account that about 100–200 analog signals can be processed in each cubicle, for each TBS two/three I&C cubicles for data acquisition and signal conditioning are foreseen; one more cubicle is needed for investment protection measurements and other redundant cubicles are required for safety control signals. These I&C cubicles are partially located in the Tokamak building and partially located in the Tritium building in areas with low radiation and magnetic fields. All these data have to be monitored to operate the TBSs. This monitoring will be performed by a team of up to two operators per TBS using the corresponding dedicated monitors that will be located in the ITER Control Room in the Control Building.

All TBSs equipment and piping have to be anchored to the floor and/or the wall via embedded plates in order to be able to withstand the various loads (e.g., gravity loads, seismic loads, thermal loads).

5. TBS equipment classifications

Each TBS includes a variety of equipment that are associated with various classifications such as safety classification, ESP/ESPN classification (valid for, respectively Pressure Equipment and Nuclear Pressure Equipment), quality class classification, seismic classification, and tritium classification. It is stressed that most TBSs components are Protection Important Components (PIC). These classifications apply differently to different TBS equipment although the classification strategy has to be identical for the six TBSs since the six TBSs feature the same functions.

For instance, TBMs have to be considered nuclear pressure equipment but, since they have no safety function they are classified as non-PIC. However, since they require high reliability they are considered as quality class-one components. On the contrary, the TBM feeding pipes, since they are an extension of the vacuum vessel primary barrier for radio-isotope confinement, they are classified as Safety Important Class (SIC-1) components.

The classifications have a significant impact on the design, manufacturing and testing of each component. For instance, for equipment classified as ESPN, the design, manufacturing and testing have to be certified by an Agreed Notifying Body.

6. Maintenance aspects in the port cells and in the hot cell

This section is limited to the TBM program-based maintenance operations required to replace the TBM PPs [10]. The TBM PP is removed and reinstalled with the Cask & Plug Remote Handling System (CPRHS). The replacement process with the CPRHS is identical for all ITER equatorial port plugs. In order to perform these actions on a TBM PP, it is necessary to empty the corresponding PC. Therefore, it is necessary to have an appropriate arrangement of the TBM PCs and to develop feasible maintenance plans both for the TBM PCs and in the HCB, taking into account the ITER Plant Maintenance Policy.

6.1. TBM port cell maintenance plan

Each TBM PC hosts equipment of two TBSs and can be divided in two areas separated by the bioshield plug: the PI area and the AEU area. Within the PI area is installed the Pipe Forest (PF) which is formed by the feeding pipes of the two TBMs, by the supporting structure/frame and by the removable part of the bio-shield plug.

In order to replace each TBM PP with a new one, it is therefore necessary at first to take out the AEU, the bio-shield plug and the PF. The same operations in the reverse order will be made for the reinstallation. The AEU is maintained on-line in the HCB, the PF is replaced with a new one [10].

To operate the CPRHS two rails are installed on the PC floor. To facilitate integration and maintenance in the PC, the RH floor-mounted rails are used to support all the equipment in the TBM PC area. Fig. 3 shows the AEU, bioshield plug and PF with the floor mounted rails in the AEU area. The access to the slab of the AEU for workers is done using stairs. A Cask Transfer System will come underneath the AEU in order to move it. The rails are extended

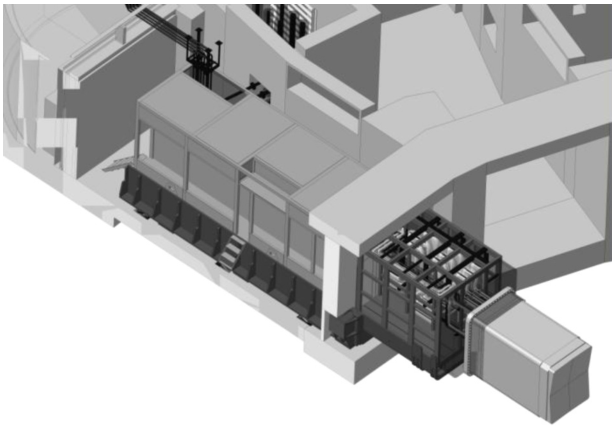

Fig. 3. AEU and PF supported by the floor mounted rails.

within the PF in order to sustain the PF weight and the loads induced by the CPRHS when handling the port plug.

The maintenance plan is based on successive disconnection and reconnection tasks in addition of removal and re-installation operations of the main components (AEU, bioshield plug and PF). It should take into account also all the preparation, verifications and control tasks related to protection of workers, the handling of material, compliance with all safety and health rules and requirements, installation of local enclosures/gloves-boxes very near to the concerned pipes or components to limit the spread of contamination, air local detritiation system, connection to the appropriate ventilation and breathing air system and so on.

All the operations have to be compliant with the applicable standards requirements with respect to the design, manufacturing, non-destructive control, installation and inspection. Moreover, since all the above maintenance operations are planned operations, an adequate demonstration of their feasibility is required including the use of large scale mock-ups.

6.2. *Required maintenance tools and equipment*

In order to perform the maintenance operations several tools and equipment will be required. The overall strategy is to use as much as possible tools that are already available from shelve, at least, for non-nuclear operations. In this way, the major required R&D on these tools will concern the upgrading of the tools to nuclear use (such as the addition of nuclear shielding to protect the electronics parts) and the adaptation of their design to RH usage.

Typical required tools are: (i) cutting and welding tools; (ii) beveling tools; (iii) pipe alignment clamps; (iv) non-destructive examination tools; (v) bolting tools; (vi) pallet system for moving large components; (vii) robotic arm to perform remote operations. The robotic arm is necessary to remotely perform all the required maintenance operations in the PI.

If the dose rate level does not preclude the access to workers, at least for a limited number of short-time interventions, the cutting and welding tools could be installed by the maintenance workers by hands and then further operated remotely. In the development of cutting equipment one target is to promote the process that will heat up as little as possible the pipes during the process in order to avoid the outgassing of Tritium trapped in steel walls during the TBS nuclear operations.

Whenever possible, it is advantageous to locally enclose the pipes and the tool in order to limit the spread of Tritium and dust contamination and to pump (with filters) these small closed volumes through “elephant trunk” type connection to the ITER Detritiation System.

6.3. *Main maintenance operation in hot cell building*

A wide variety of tools and equipment are required for the TBS maintenance operations in the HCB. Common tools and equipment shall be understood as standardized tools and equipment to be used for all 6 TBSs. The main operations envisaged in the HCB are the following:

(i) Refurbishment of the AEU components and preparation for re-use in the next ITER operation campaign. Several cutting/welding operations will be necessary.
(ii) Dismantling of the PFs and their export to the radwaste facility.
(iii) Refurbishment of the TBM PP with new TBM-sets prior to re-insertion in Vacuum Vessel (after leak-testing in the Port Plug Test Facility).
(iv) Separation of the TBMs from their associated shield. The TBM-shields will become operational rad-waste [11].
(v) The irradiated TBMs (or some parts) have to be sent to available IM facilities for Post-Irradiation Examination using appropriate nuclear transport casks. To comply with the IM’s requirements and handling capabilities, the TBMs might need to be cut in HCB before packaging and shipping [11].

6.4. *Estimated durations and ORE*

The definition of the various required on-line operations to replace a TBM PP, as described in Section 6.1, has allowed the evaluation of the required total time to perform these operations. It has been estimated that each of the two sequences, the de-installation and the reinstallation ones, will last about one month.

To be able to perform the maintenance operations in the PCs it is essential to reduce the Occupational Radiation Exposure (ORE) for workers down to acceptable level for the ITER Project and, in any case, to minimize its value (i.e., application of the ALARA principle).

A first way of reducing the ORE is to reduce the residence time for workers in the radiation areas. This reduction can be obtained by simplifying the required operations and by performing most of the operations remotely as discussed above. Another way consists of reducing the level of contamination by Tritium and activated dust; this reduction can be obtained by a proper management of the Tritium concentration in the PC (see Section 8) and by applying local enclosures in the maintenance areas. A third way is to reduce the radiation dose rate in the areas concerned by the maintenance operation.

In fact, several neutron shielding analyses have been performed in order to estimate the dose rate due to the activation of permanent components in the PF area and to reduce it by improving the TBM PP shielding capability. It has been shown [12] that the dose rate in the front part of the PF might exceed the project limit of 100 μS v/h, 12 days after shutdown (up to a factor 2) mainly because of the low shielding performance of the corresponding lower and upper ports. Therefore, a significant improvement of these shielding performances is on-going. In addition, the use of low-cobalt content materials would contribute to improve the situation.

In the AEU area, the dose-rate project limit is 10 μS v/h one day after shutdown. This limit is due to the fact that a worker could need to access this area protected by the bioshield during the Short Term Maintenance lasting 2–4 days. In this area the radiation level is mainly due to the activation of the AEU components in particular those containing Pb-16Li for which a specific shielding is needed.

7. TBS components testing

Each TBS is formed by about 70 to 100 major components, depending on the TBS type, that can divided in several families such as: (i) TBMs and TBM-Shields, (ii) circulators, compressors and pumps, (iii) pressure vessels, heat exchangers and heaters, (iv) piping, (v) valves, (vi) tritium process components, and (vii) instrumentation for TBS control and data acquisition.

An initial guideline for the acceptance testing and acceptance criteria for the various TBSs components families has been developed in [13]. A number of tests are required by ITER, being the nuclear operator, and being responsible to have the device available to execute the ITER Research Plan. They are complementary to the acceptance tests already required by the applicable codes & standards, and French regulations (depending on the component classifications).

The acceptance testing is a staged process. The completion of the TBS manufacturing, in accordance with the approved Manufacturing & Inspection Plan, will be followed by Factory Acceptance Testing, prior to TBS components are shipped. The site acceptance involves “Reception Inspection Tests”, on-site pre-installation and components test, and “Start-Up and Testing”. At each stage a partial or provisional acceptance of components and subassemblies shall be declared, allowing eventually the start of the commissioning.

8. Tritium management

In DEMO, in order to achieve a Tritium breeding self-sufficiency most of the Tritium produced in the blanket needs to be recovered and reinjected into the plasma with only small fractional losses. The same requirement is applicable to the TBSs since they have to demonstrate this capability of recovering most of the produced Tritium. The difference between the produced tritium in each TBM and the recovered tritium is identified as “tritium losses” by the corresponding TBS. These tritium losses need to be quantified both from the programmatic point of view (i.e., need of demonstrating the tritium breeding self-sufficiency for DEMO) and for safety point of view (i.e., need to guarantee that all losses are fully managed and controlled).

Tritium losses can occur in all the locations where TBS components are present. The most important tritium losses are coming from the Pb-16Li systems because of potential high tritium permeation rates from Pb-16Li pipes and components. Therefore, the Pb-16Li systems are addressed as the worst envelope case. Since Pb-16Li systems are entirely located in the corresponding PCs, the most significant airborne tritium-concentration is expected in these locations and, therefore, only PCs are discussed here in more details. Conservatively assuming continuous back-to-back pulsed operations 24 h per day, and a conservative tritium permeation model, it has been estimated that about 2.8 mg/day of tritium could permeate from the Pb-16Li loop to the PC [14].

Each TBM PC is connected to the Detritiation System (DS) that, in order to maintain a pressure difference between PC and the adjacent gallery, allows clean air to be drawn in from the gallery, then it extracts Tritium-contaminated air back out of the PC and effectively reduces the tritium concentration. Since most of the extracted tritium (~99%) will be recovered there is no problem with regards to the tritium release in the environment. However, the PC area requires human access for performing maintenance operations as described in Section 6.1. As shown in [14], even considering the presence of DS, during operation the tritium concentration will be significantly higher than the regulatory maximum allowable value of 1 DAC, the Derived Air Concentration (for Tritium 1 DAC corresponds to 3.4×10^5 Bq/m^3 of air). It has been found that the use of a PC Local Air Cooler (LAC) allows to have optimal air circulation in the PC and, therefore, a quite uniform tritium concentration in the whole PC volume.

It has been shown [14] that it is possible to reduce the T-concentration below 1 DAC in relatively short time if, more realistically, only 10% of the estimated maximum tritium permeation is considered. This reduction is considered achievable by improving the permeation model and using appropriate Pb-16Li loop operating parameters. Using appropriate ventilation parameters and the presence of an additional LAC, the calculated required time to reach 1 DAC within the AEU region and PI area is 9 h and 10 h, respectively, that is well below the project requirement of accessing the AEU area 24 h after shutdown. However, this assessment has not taken into account the Tritium outgassing both from the concrete and the epoxy coating that is expected to cover the PC walls. If outgassing is taken into account, it could take much longer to reduce the Tritium-concentration down to 1 DAC. An experimental demonstration is needed.

9. Safety and investment protection aspects

An important aspect related with both safety and investment protection is the strategy to be applied to each TBS to avoid major safety concerns and to protect the investment (both of the TBS itself and of other ITER components). In particular, it is necessary to determine which actions have to be performed to mitigate the consequences of the most severe accidental events such as loss-of-coolant or loss-of-flow events. Current studies address the definition of the number and type of measurements for detecting such events and the actions required to other ITER systems via the Safety Control System and to the Interlock Control System. Several Safety Functions have therefore been identified and implemented in the TBS design. In several cases, the required actions lead to the request of triggering the plasma shutdown in order to avoid the failure of the TBM structures.

Since most TBS equipment and associated infrastructures are PIC, all the associated activities are Protection Important Activities. In fact, several safety analyses have been performed for each TBS and collected in specific TBS Preliminary Safety Reports. These reports demonstrate that all general safety requirements are fulfilled. With the beginning of the preliminary design phase, it has been possible to give more detailed safety requirements leading to the establishment by IO-CT of a “Defined Requirements” document that will be used in the future to demonstrate to the French Safety Authority the acceptability from the safety point of view of the TBSs designs. The implementation of these “Defined Requirements” on all the TBS PICs will be strictly monitored by IO-CT.

10. Quality and reliability

QA procedure and Quality Plan (QP) have been prepared by the IMs in agreement with IO-CT. It is recalled that the QP includes the following information: (i) the specific allocation of resources, duties, responsibilities and authority; (ii) details of all suppliers/subcontractors and how interfaces are managed; (iii) the specific procedures, methods and work instructions to be applied; (iv) the specific methods of communication, both formal and informal, to be established between working groups; and (v) any access restrictions to supplier facilities for IO-CT representatives.

One of the major requirements to be fulfilled by each TBS is that “The operation of TBSs shall neither jeopardize the ITER operation, nor decrease ITER availability, nor compromise safety of operation”. It is, therefore essential to maximize the reliability of the TBS components whose failure could have a significant impact on the ITER availability. The consequence is the IO-CT requirement to classify the most significant components as Quality Class-1. A further IO-CT requirement is to perform the TBS RAMI (Reliability, Availability, Maintainability & Inspectability) analyses since the beginning of the preliminary design phase in order to identify the most critical components and to ultimately implement redundancy as the most extreme possible countermeasure.

Concerning the RAMI analyses one of the major difficulties is the fact that several TBS components, and in particular the TBMs, are first-of-a-kind components and that therefore incomplete information is available on the applicable failure rates. This situation could lead to the need of making very conservative assumptions which could lead to very severe requirements on the TBS design and manufacturing with a significant increase of cost and lead time.

11. Summary of the main challenges and conclusions

The major challenges for the TBM Program in the design and manufacturing phase from the IO-CT perspective have been identified and discussed. They can be summarized as follow: (i) the leak tightness of the PP sealing; (ii) the management of the radiation dose rate in the PC due to structures activation and to dust and tritium contamination; (iii) the demonstration of the feasibility of the maintenance operations, in particular in the port cells; (iv) the overall tritium management; (v) the interaction with Notified Bodies for some equipment using relatively new technologies, such as the TBMs; (vi) the impact of the TBM ferromagnetic structures on the plasma operations; (vii) the definition of appropriate failure rates able to achieve reliable RAMI results.

The conceptual designs of the six TBSs to be tested in ITER are now available and their integration in the ITER facility is on-going. For each TBS and associated infrastructures, the most important next step is the elaboration and the achievement of the preliminary design and the performance of all the associated analyses and feasibility assessments while addressing the identified challenges.

Disclaimer

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

References

[1] L.M. Giancarli, et al., Breeding blanket modules testing in ITER: an international program on the way to DEMO, Fusion Eng. Des. 81 (2006) 393–405.

[2] L.M. Giancarli, M. Abdou, D.J. Campbell, et al., Overview of the TBM Program, Fusion Eng. Des. 87 (2012) 395–402.

[3] Y. Poitevin, I. Ricapito, M. Zmitko, et al., Progresses and challenges in supporting activities toward a license to operate European TBM systems in ITER, Fusion Eng. Des. 89 (2014) 1113–1118.

[4] M. Enoeda, H. Tanigawa, et al., R&D status on water cooled ceramic breeder blanket technology, Fusion Eng. Des. 89 (2014) 1131–1136.

[5] S. Cho, M.-Y. Ahn, et al., Design and R&D progress of Korean HCCR TBM, Fusion Eng. Des. 89 (2014) 1137–1143.

[6] K.M. Feng, G.S. Zhang, G. Hu, Y.J. Chen, et al., New progress on design and R&D for solid breeder test blanket module in China, Fusion Eng. Des. 89 (2014) 1119–1125.

[7] P. Chaudhuri, et al., Progress in engineering design of Indian LLCB TBM set for testing in ITER, Fusion Eng. Des. 89 (2014) 1362–1369.

[8] B.Y. Kim, et al., Design and manufacture feasibility of ITER TBM frame and dummy TBMs, in: Proceeding of the ISFNT-12, Jeju Islands, Korea, 2015.

[9] M. J. Lanctot, J. A. Snipes, et al, A Path to Stable Low Torque Plasma Operation in ITER with Test Blanket Modules—post-deadline paper, IAEA FEC 2014, St. Petersburg. Submitted to Nuclear Fusion.

[10] R. Pascal, P. Cortes, et al., Main maintenance operations for Test Blanket Systems in ITER TBM Port Cells, Fusion Eng. Des. 88 (2013) 2417–2421.

[11] J. van der Laan, D. Canas, et al., Radwaste management aspects of the Test Blanket Systems in ITER, in: Proceeding of the ISFNT-12, Jeju Islands, Korea, 2015.

[12] R. Villari, B.-Y. Kim, et al., Nuclear analysis of ITER Test Blanket module port plug, Fusion Eng. Des. 98–99 (2015) 1668–1673.

[13] J. van der Laan, B. Cuquel, et al., Preparation of acceptance tests and criteria for the Test Blanket, Fusion Eng. Des. 98–99 (2015) 1889–1892.

[14] L.M. Giancarli, P. Cortes, et al., Tritium and heat management in ITER Test Blanket Systems port cell for maintenance operations, Fusion Eng. Des. 89 (2014) 2088–2092.