

REPORT NO.

ITR-IEBH-2006-18 v1.0

TITLE

ITER Engineering Basis Handbook Vol. 2: Anatomy of the Plant

Chapter 6 - All the pieces of the puzzle

Section 18 - The ITER Test Blanket Module Program

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October 16th, 2026

About the ITER Basis Engineering Handbook

This handbook consists of two volumes which describe the ITER design from its inception up to the design, construction and assembly in 2025.

The handbook is not designed to be read as a continuous sequence of chapters. Instead, it is composed of focused, self-contained sections that address specific topics. Each chapter can be read and understood independently, allowing readers to engage with the material most relevant to their needs without requiring familiarity with preceding chapters. As a result, the reader will find certain overlapping content in chapters.

It is to be noted that at the time of writing, the design for some systems is still on-going. Therefore, the reader should consider that whilst there is significant value of this important point-in-time study, an update would be required as the Project progresses.

A broad Project overview is given in the first volume, to provide the reader with background information necessary to understand the context in the subsequent more-detailed chapters of the second volume, dedicated to the individual systems composing ITER.

For the overall table of contents of the Handbook and to access each one of the chapters, please refer to <https://www.iter.org/scientists/iter-technical-reports>.

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Volume 2

ANATOMY OF THE PLANT

Chapter 6

ALL THE PIECES OF THE PUZZLE

Section 18

THE ITER TEST BLANKET MODULE PROGRAM

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Chapter 6

ALL PIECES OF THE PUZZLE

6.18 The ITER Test Blanket Module (TBM) Program

6.18.1 Background and Overview

For its operations, ITER expects to use tritium from external sources but the next generation of DT fusion reactors (called “DEMO” in this document) will need to breed all the tritium it will consume, in order to reach the so-called “Tritium breeding self-sufficiency”. Tritium breeding is performed in the components surrounding the plasma, the tritium breeding blankets (TBB), which are subjected to very severe operating conditions and require the use of advanced materials and advanced technologies still in early development stages and not yet part of today’s industrial knowledge.

Therefore, in order to be ready to design a DEMO TBB, one of the main ITER missions is 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”.

This ITER mission was already identified in the ITER CDA phase in the late 1980s and specifically implemented in the EDA phase with the creation, by the Fusion Program Directors of the ITER Members (IMs), of the so-called ITER Test Blanket Working Group (TBWG) in 1994. TBWG’s main objectives were to coordinate the TBB-related activities performed by the IMs, define a TBB testing program for demonstrating the feasibility of various TBBs for DEMO, and address the interface between the ITER machine and TBB test objects [\[1\]](#).

During that time, all four IMs involved in the EDA (namely Europe, Japan, Russian Federation and USA) had a significant domestic R&D program for developing TBBs and had developed various TBB designs that were the basis for the assessment made by the TBWG in its initial years, as discussed in more detail in Section 6.18.2.

As mentioned in Section 6.18.2, during the EDA it was planned to have two ITER operational phases, the Basic Performance Phase (BPP) and the Enhanced Performance Phase (EPP). At that time, it was planned to install a TBB in ITER for the EPP (referred sometimes as “driver blanket”), working at low temperature with modest tritium breeding (i.e., a TBR of about 0.8) to partially cover the tritium fuel needs during the EPP. The characteristics of this ITER driver blanket and its development are briefly described in Section 6.18.3. It is important to note that the ITER driver blanket has never been discussed within the TBWG; it was mentioned for informational purposes only. The design responsibility for the ITER driver blanket rested directly with the ITER team due to its lack of DEMO-relevancy (since it was expected to use a low-temperature coolant system).

The TBWG assessed the TBB proposals coming from various IMs and, also, the development of the necessary ITER infrastructures to facilitate TBB testing. All the activities related to TBB testing performed by the ITER team and by the IMs formed the so-called “TBM Program” (even if this name started to be used only after 2005; in fact, previously the activities were called simply “breeding blanket testing”).

Since the beginning, it was clear that the TBM Program would test complete mock-ups of TBBs, which consist of the in-vessel part, referred to as Test Blanket Module (TBM) and its associated ancillary systems. These ancillary systems necessary to remotely operate a given TBB include cooling systems, tritium extraction systems, flowing liquid metal systems, instrumentation and control systems. Collectively, each TBM and its associated ancillary systems form a Test Blanket System (TBS).

Concerning the ITER infrastructure, the initial plan assumed that three or four equatorial ports would be available for the TBM program. The corresponding Port Cells area and other rooms within the Tokamak Complex were also allocated to the TBM Program in order to install all the TBS ancillary systems components. As detailed in Section 6.18.2, each port could host two TBSs. It was also considered that for performing relevant testing and getting relevant data for each TBB, the various TBSs shall be operated simultaneously and independently. The produced tritium shall be delivered to the ITER Tritium Plant (after being properly accounted for), while the extracted thermal power shall be delivered to the secondary ITER water cooling systems, called CCWS-1 (therefore, acting as a secondary cooling system for the TBSs coolant systems).

As described in Chapter 6.18.4, in 1998 the ITER Council required a size and cost reduction for the ITER design. The EDA was extended for three years without the participation of the US, leading to the production of the 2001 ITER design (called ITER-FEAT). A new TBWG (i.e., TBWG-2) was

nominated for proposing a revised testing program involving the three remaining IMs (i.e., EU, JA and RF).

Between 2002 and the signing of the ITER Agreement in 2006, the US rejoined the ITER project while three additional IMs joined, namely China, Korea, and, at a later stage, India. These IMs had a domestic R&D program for developing DEMO TBBs, leading to an increase in the number of TBBs assessed by the TBWG (as detailed in Section 6.18.5).

In 2009, shortly after the beginning of the ITER activities on the ITER Site of Cadarache, the TBWG was replaced by the TBM Program Committee (TBM-PC). Comprising official IMs and IO members, the TBM-PC managed the TBM Program, developed the associated TBM Research Plan and oversaw the TBM Program implementation in ITER. This included selecting the six Test Blanket Systems that could be tested in ITER (see Section 6.18.6).

In 2018, the TBM PC was replaced by the TBM Project Team (TBM-PT) formed by representatives of IO and of all the IMs and governed by a TBM-PT Steering Committee chaired by the IO-DG or delegate. The number of ports dedicated to the TBM Program has been decreased to two ports giving the possibility to test only four TBSs with the consequent need of further selecting the four TBSs to be tested (see Section 6.18.6).

Since 2018, the TBM-PT is the entity in charge of the implementation of the TBM Program, including its adaptation to the new 2024 ITER baseline (see Section 6.18.7).

The following sections describe the status and the major decisions taken in the evolution of the ITER TBM Program from the beginning in 1995 until 2024. It has to be noted that major decisions and choices on the TBB types to be tested have been taken individually by each IM based on domestic activities and preferences.

Some details of the large R&D program, including qualification aspects, performed by the IMs on the various families of potential TBBs since the 1990's and examples of the corresponding supporting R&D to the TBM Program are briefly described in Section 6.18.9.

6.18.2 The TBM Program during EDA (1995-1998)

This section has been written using the following reference: Design Description Document - Executive Summary of WBS 5.6 - Blanket Test Modules, ITER_D_22LGYQ - DDD5.6_TEXT (1998) [2].

During the ITER EDA, the TBM Program was discussed and assessed by the initial TBWG (TBWG-1) formed in 1995. It consisted of officially nominated representatives of the EU, JA, RF, US and ITER teams and was chaired by E. Proust from the EU. The TBWG-1 had two main objectives: (i) coordinating the development of TBM/TBS designs by the four IMs (at that time identified as "ITER

Parties”) and (ii) creating a coordinated test program within ITER, including details of the port availability for blanket testing and potential testing program during the BPP.

Since the beginning of the TBWG-1 work, it appeared evident from previous studies that a limited number of materials could be used to form a TBB, depending on the required functions, as follows:

- Li-based tritium breeders: (a) solid materials, namely Li-ceramics : Li_4SiO_4 , Li_2TiO_3 , Li_2ZrO_3 , LiO_2 , (b) liquid material, namely, natural lithium (7.5% ^6Li), eutectic Pb-16Li, molten salts (e.g., FLiBe, FLiNaBe).
- Neutron multiplier materials: beryllium (Be) and lead (Pb) and possible compounds.
- Structural materials: Ferritic/Martensitic steels (Reduced-Activation version), Vanadium alloys, SiC/SiC composites.
- Coolants (high temperature for high thermal efficiency): Pressurized water (as in PWR), helium, CO_2 and liquid metals (Lithium & Pb-16Li).

A TBB had to, therefore, be designed using a combination of the above materials. Best concepts are an optimal compromise among a series of constraints, such as temperature, pressure, loads levels, compatibility between materials under defined working conditions, safety, low activation/low radwaste characteristics, performances (e.g., TBR, thermal efficiency), technology availability and manufacturing processes for DEMO timescale, reliability. Because of the different status of the associated R&D and of different importance of the various criteria, the selected materials combinations by each IM can be quite different as discussed in the sub-sections below.

Objectives of the TBB Test Plan (TBM Program)

The principal objectives of the TBB test plan have been defined by the TBWG-1 as follows:

- Acquisition of experimental evidence of the possibility of obtaining a tritium breeding ratio sufficiently high to lead to tritium self-sufficiency in a DEMO reactor.
- Demonstration of the on-line tritium extraction and recovery system.
- Production of high-grade heat that is removed with a suitable coolant medium to demonstrate the feasibility of electricity generation in a future fusion power plant.
- Validation of Codes previously developed (out-of-pile, in fission reactors) to calculate temperatures, flow distributions, pressures, stresses in the material etc. These codes can be validated and improved by comparison with the tests in ITER.
- Confirmation and calibration of fission reactor test results obtained on the performance of the solid breeders, beryllium multiplier and insulator materials.
- Confirmation and calibration of heat transfer, hydraulics, thermo-mechanical structure, and safety test results obtained from blanket mockups in non-nuclear test facilities.

- Demonstration of the basic feasibility of the breeding blankets to show whether synergistic effects will cause failure not foreseen by the extrapolation from the earlier tests (out-of-pile, in fission reactors).

The most important restrictions for TBB testing are the magnitude of neutron flux, of neutron fluence, and of volumetric power density that in ITER is lower than the corresponding magnitude expected in a DEMO reactor. Therefore, for each selected blanket concept, various design versions of TBMs had to be developed using specific “engineering scaling” depending on the performance to be assessed, in order to achieve DEMO-relevant working conditions within the TBMs.

However, since the beginning, the behavior of irradiated TBB materials was not included in the TBM Program objectives due to the low neutron fluence on the FW expected in ITER even at the end-of-life, namely 0.3MWa/m^2 . In fact, for a DEMO TBB a minimal end-of-life neutron fluence $> 3\text{--}6\text{MWa/m}^2$ is envisaged, that is more than 10 times higher than what can be expected for a TBM. Therefore, ITER testing is not expected to give answers to long-term irradiation effects on blanket performances, failures and function (including on the behavior of materials and, in particular, structural materials as well as its impact on synergistic effects. Such effects were expected to be addressed in other facilities, e.g. fast-neutron fission reactors and/or fusion neutron sources.

It is important to note that these general objectives and limitations have only evolved little in the following years and, therefore, they will not be mentioned again in the following sections.

ITER Boundary Conditions During EDA

The TBM Program should not impact on the ITER operation plan and objectives. Therefore, it had to be developed using the boundary conditions defined by the ITER Project concerning both the available space and the operating conditions.

Geometrical Aspects

During EDA, it was expected to dedicate at least four equatorial ports to the TBB testing, three of which were dedicated to the TBM Program and the fourth one dedicated to the ITER driver blanket. The activities on the driver blanket were not addressed by the TBWG but covered directly by the ITER team (see Section 6.18.3).

A general approach was adopted to develop a common test port design to be used for all test ports that would be like the other ITER systems occupying the equatorial ports, such as the ICH, ECH, diagnostics, and remote handling. A common shield plug could also occupy an equatorial port when the designated port module is not available.

It was decided to use a super-assembly, consisting of a complete test blanket module, shielding, and structural support, to be installed as a pre-assembled and pre-tested module. This assembly would be completely supported by the vacuum vessel (VV) extension and would be independent

of the shielding blanket and backplate. The primary vacuum seal would be at the vacuum vessel extension port. The use of the super-assembly approach should ensure high reliability of the TBM maintenance requirements.

In the beginning, it was hoped that a TBM would occupy the entire volume of the test port. But analyses have shown the need for an isolation frame around the test module to provide a standardized interface with the ITER basic structure and a better shielding capability as well as neutronic and thermal isolation from the basic shielding blanket. Each IM would provide the test module dimensional data necessary to design the frame (height, width, and depth). Analysis made by the IMs shows that the frame thickness should be around 20 cm. This arrangement enables the whole Port Plug (TBM's, Frame, Shield, VV Plug and Piping) to be a self-contained unit that may be installed and removed as a single piece without remote handling operations inside the VV Port extension. This assembly can be completely assembled and tested prior to installation (see Figure 6.18.2-1).

It was concluded that for the TBM program, the three ports allocated offer adequate space for testing of up to six different types of breeding blanket, typically two TBSs per port. In fact, because of the space needed for the ancillary systems components in the Port Cell behind the port, it was concluded that, realistically, the installation of two TBSs per port was the maximum acceptable number. Moreover, the larger the number of TBMs per port the lower would be the tritium generation rate per TBM and the more challenging would be the achievement of different scientific objectives in the area of tritium recovery and processing. Therefore, this conclusion has been judged as the best compromise between the possibility of testing many different TBSs on one side and having a sufficient amount of generated tritium the other side.

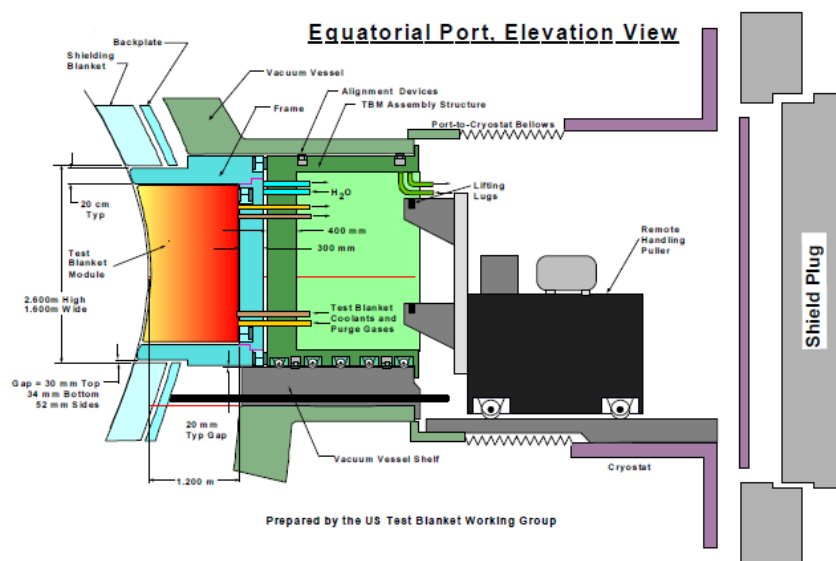


Fig. 6.18.2.1: Vertical view of the arrangement for a TBM port during the EDA.

Functional Aspects

During the EDA, the BPP was expected to last ten years and to reach a neutron fluence on the ITER FW of 0.3MWa/m^2 . The main expected operational data were the following: (i) fusion power of 1.5GW, (ii) pulse duration of 1000s, (iii) minimum pulse repetition time of 2200s, (iv) neutron wall loading on FW of 1MW/m^2 , (v) heat flux on FW of 0.5MW/m^2 , (vi) 50,000 pulses (BPP+EPP).

The testing of breeding blanket modules must not interfere with ITER operation, decrease ITER reliability and compromise safety of operation, or contradict ITER operational plans.

The testing program must use, as much as possible, available resources such as the ITER heat rejection system and isotope separation system, the ITER remote handling equipment and the ITER hot cell.

To be sure that TBMs are compatible with tokamak operation, the TBMs must be installed as early as possible before beginning the DT operation.

The TBM Program was developed only for BPP, the continuation during EPP was expected to be assessed at a later stage.

TBB Types Proposed by The Iter Members During EDA

Two main requirements were considered for the various TBM proposals before a TBM could be considered eligible for testing in ITER:

- TBM should use a sufficient level of DEMO-relevant technology to justify that the results of testing in ITER could not be achieved in other existing facilities prior to the tests in ITER.
- The proposed TBS should show, at least theoretically and based on existing knowledge, that they can be scaled to a DEMO blanket system, in order to maximize the benefits from testing in the fusion environment of ITER.

Each of the four IMs had made proposals for testing two TBMs in ITER. In particular:

EU: The selection of two TBBs to be tested in ITER was made after an extensive “breeding blanket selection” exercise among four potential TBB candidates, performed in 1996 with the participation of several experts from the various European Laboratories. Therefore, the EU proposed to test the two selected TBMs and associated ancillary systems, as follows:

- Water-cooled lithium lead (WCLL) TBM. The WCLL ITER test blanket module uses the eutectic Pb-16Li as the breeder/multiplier and pressurized-water (under PWR conditions, 15.5 MPa pressure, 325°C outlet temperature) as the coolant. The Pb-16Li coolant flows slowly (i.e., few mm/s) to extract the bred tritium outside the vacuum vessel.

- Helium-cooled pebble-bed ceramic/Be TBM. The He-cooled pebble-bed (HCPB) TBM uses a lithium-ceramic breeder material with beryllium as a neutron multiplier in pebbles form. The He-coolant is at about 8MPa with inlet/outlet temperatures of 250/450°C.

As planned for the corresponding DEMO BBs, both TBMs use reduced-activation ferritic/martensitic steel as structural material (grade EUROFER).

Japan: the following two TBM types were proposed.

- Water-cooled pebble-bed ceramic/Be TBM.
- Helium-cooled pebble-bed ceramic/Be TBM.

The two TBMs have layered and Breeder Out-of-Tube (BOT) configuration with Li₂O pebble-bed (with a backup of Li₂TiO₃) as breeder material; beryllium as multiplier material; reduced-activation ferritic/martensitic steel (grade F82H) as structural material; and either high pressure and high temperature water (15.5MPa, 280/320°C) or helium (8.5MPa, 360/480°C) as coolant.

Russian Federation: the following two TBM types were proposed:

- Helium-cooled pebble-bed ceramic/Be TBM. The TBM is based on the breeder-in-tubes (BIT) approach. It uses a lithium orthosilicate (Li₄SiO₄) ceramic breeder material in pebble form. The neutron multiplier may be either beryllium pebbles of about 1mm or porous beryllium with a porosity of 15-20%. Helium operates at 8MPa, with inlet/outlet temperatures of 300°C/480°C.
- Self-cooled Li/V-alloy TBM. It utilizes natural lithium as coolant and tritium breeder and a vanadium alloy (V-4%Cr-4%Ti) as structural material. Poloidal flow of lithium is adopted to provide for DEMO relevancy; thus, the full poloidal height of the port is required. Lithium inlet and outlet temperatures are designed to be 300°C and 600°C, respectively. The RF-DA collaborated with the US-DA in the design of the Li/V test module with the aim of manufacturing jointly at least one test module, testing it jointly in ITER, and sharing common auxiliary systems such as for heat rejection, tritium processing and Li chemistry control.

US: the following two TBM types were proposed:

- Helium-cooled pebble-bed ceramic TBM. The TBM utilizes He-coolant at, Li₂TiO₃ as the primary breeder material, beryllium as multiplier, and reduced low-activation ferritic/martensitic steel as structural material. For He-coolant, a static pressure of 8.5MPa, an inlet temperature ranging from 250 to 325°C, and an outlet temperature range of 375 to 450°C are selected (although higher coolant outlet-temperatures up to 600°C could be used for the SiC/SiC composite submodules).

- Self-cooled Li/V-alloy TBM. There were two vanadium/lithium TBM designs under consideration, which were representative of the DEMO blanket designs developed by the US-DA and RF-DA. The two TBMs differ in radial build configuration but possess similar tritium breeding and thermal hydraulic characteristics. The nominal lithium inlet and outlet temperatures are designed to be 300°C and 600°C, respectively, to demonstrate DEMO feasibility.

It has to be noted that all the IMs have a helium-cooled solid breeder blanket concept as one of their two blanket concepts selected for testing on ITER. It shows the general interest in this family of TBB concepts.

Most TBMs make use of low-activation ferritic/martensitic steels as structural material. Since these materials are ferromagnetic, their impact on the ITER plasma performance had to be checked.

TBB Testing Strategy Defined During EDA

When performing nuclear tests on blanket components and materials, two kinds of TBM design approaches can be considered depending on the addressed testing parameters: either act-alike or look-alike test modules.

Act-alike testing attempts to recreate key operating parameters governing processes being observed, such as the maximum temperature or temperature difference. For example, in a testing facility with lower heat fluxes, a TBM design would include thicker structures, and larger breeder and/or multiplier regions to increase the material temperatures to prototypical values.

Look-alike testing is based on reproducing the exact geometry of the prototypical blanket even if key operating parameters including the temperature might differ from prototypical conditions.

The number of TBM design versions corresponding to each of the above TBM types proposed by the various IMs was different. All IMs proposed act-alike TBMs (at least one), some IMs also proposed look-alike TBMs.

The value of testing look-alike TBMs is limited, because of the very different boundary conditions and lower power density. Even the local tritium production rate cannot be the same as in DEMO because of different materials present in the ITER shielding blanket which lead to a different neutron spectrum. The major interest in look-alike TBMs is to prove fabrication technology and sequence. It was, therefore, recommended to test in ITER only act-alike TBMs, which can have different design versions for testing different parameters.

These considerations introduced the idea of TBM “versioning” that will be kept also in future evolutions of the TBM Program. It means to have the possibility, for a given TBB concept, to have

different TBM design versions as a function of the evolving ITER operating conditions, of the specific testing objectives and of the implemented instrumentation.

Having more than one TBM version requires the definition of the timing for TBM exchange. There was a clear requirement that, apart from the case of an accident, such a replacement should not require an additional ITER shutdown. Therefore, scheduled ITER long-term maintenance (LTM) shutdowns should be used for this.

In order to account for the possibility that one of the TBMs is not available but still allowing the tests of the neighboring TBM, it was considered necessary to foresee a shield blanket having the same dimensions as the corresponding TBM, called “dummy TBM” (it might be necessary to use a ferromagnetic structure if the replaced TBM uses ferromagnetic material). Therefore, several dummy TBMs had to be available from day-1.

To improve the availability of each TBS, a spare component for each of the components forming the TBS (including the TBMs), identical to those installed in ITER, should be available for fast replacement in case of failure (if the failure was not due to a major design issue).

TBB Port Allocation During EDA

Due to the limited test port availability and the number of modules to be tested, it was concluded that, for testing early in the ITER test campaign, half port modules would be the most practical and useful choice. The liquid metal concepts required a full-height, half-width version; while some helium-cooled concepts preferred the half-height, full-width version. The remainder of the test blanket modules could accept both orientations. The initial intent was to allocate ports to blanket concepts from each IM, but due to the large number of proposed concepts and the limited port space, this was not possible. A tentative solution was to allocate the ports based on a generic concept to be filled with actual test modules and frames at commencement of ITER testing, as shown in Figure 6.18.2-2.

The decision to assign the TBMs to contiguous ports (numbers 19, 20, 1, and 2) is due to the desire to have a common location in the tokamak vault area to host all the components of the test blanket ancillary systems. Since only three ports were considered for TBMs (the fourth port being dedicated to the test of the ITER driver blanket), an additional virtual port was provisionally considered in case an additional port could be assigned to TBMs at a later stage. This proposal allowed us to assume to test two TBMs by each IM.

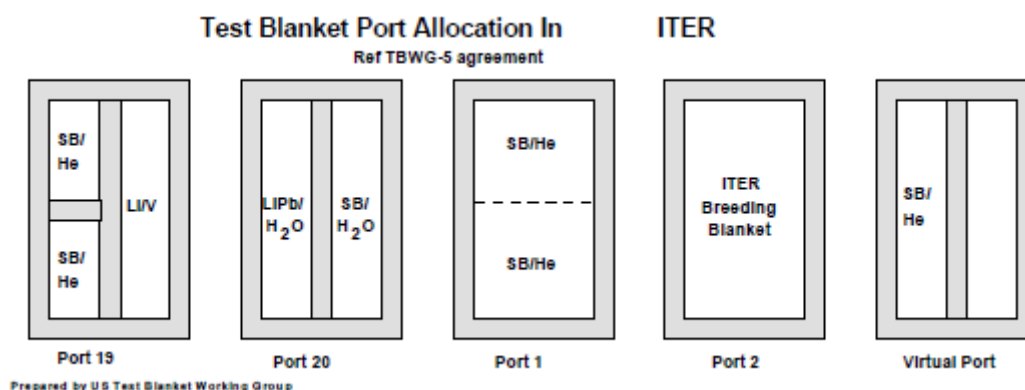


Fig. 6.18.2.2 : Schematic view of the TBM Port allocation during EDA.

Each TBM had to be relevant to the corresponding DEMO breeding blanket (in term of design, materials and operating parameters) and, in order to be operated, needed to be connected to several associated systems (e.g., primary and secondary cooling systems, tritium management and control systems, measurement systems) that have to be located behind the Test Ports and in other regions of the ITER buildings. Therefore, TBMs installation and operation implied the presence of several interfaces with the ITER basic machine and buildings whose feasibility had to be ensured by IO.

On the other hand, in order to be eligible for the testing in ITER, the TBM responsible teams had to demonstrate, at least in principle, that the TBM tests in ITER: (i) would not endanger the safety and performances of the ITER machine (i.e. “acceptability” of the tests), and (ii) would permit to obtain significant information on the corresponding DEMO blankets (i.e., usefulness of the tests).

6.18.3 The ITER Breeding Blanket (or “Driver Blanket”)

This section has been written using the following references: Y. Gohar, M. Billone, I. Danilov, W. Daenner, M. Ferrari, K. Ioki, T. Kuroda, D. Loesser, S. Majumdar, R. Mattas, K. Mohri, R. Parker, Y. Strebkov, H. Takatsu, “ITER breeding blanket design for the enhanced performance phase”, Fusion Engineering and Design 39–40 (1998) 601–608 [3]; M. Ferrari, A. Bianchi, G. Celentano, W. Daenner, M. Enoda, A. Gerber, Y. Gohar, W. Gulden, K. Ioki, T. Kuroda, A. Lopatkin, F. Lucca, X. Masson, R. Mattas, G. Mazzone, J. Mustoe, R. Parker, L. Petrizzi, A. Pizzuto, R. Plenteda, Y. Poitevin, R. Raffray, M. Roccella, N. Roux, F. Scaffidi-Argentina, J.-P. Simoneau, Y. Strebkov, F. Zacchia, ITER reference breeding blanket design, Fusion Engineering and Design 46 (1999) 177–183 [4].

Tritium breeding blanket development for fusion reactors in ITER was envisioned during the CDA and EDA phases. The goal was to install a breeding blanket during EPP as part of development effort supplemented with blanket testing located in 4 (or more) dedicated test ports. As part of the EDA interim design, blanket testing included four midplane ports reserved for TBMs, and a full breeding blanket could be installed for the EPP by replacing the FW/Shield if desired.

The use of a breeding blanket for the EPP was confirmed during the EDA detailed design (1996) as well as for the EDA final design (1998). The primary candidate design was assumed to be lithium ceramic with beryllium multiplier. The ITER breeding blanket (referred to also as “driver blanket”) would use the same cooling circuits as for the BPP, and should achieve a TBR > 0.8, allowing 1MWa/m^2 to be achieved over the EPP with 1.5 kg/year external tritium. This ITER breeding blanket concept had been further developed during EDA final design phase. Until that time, the ITER neutron wall load was maintained at 1MW/m^2 with a pulse length >1000s. However, these design parameters were reduced in the ITER EDA Extension Final Design (2001) with the goal of reducing the ITER device cost to 50% of the EDA final design. They have been further reduced in the current 2024 baseline scenario with a fluence < 0.1MWa/m^2 .

Due to its low operating temperature, the ITER breeding blanket is not DEMO-relevant and, therefore, was not included in the scope of the TBWG-1 and it was not part of the TBM Program. It is briefly mentioned in this document only for completeness as part of the ITER activities related to tritium production aspects.

As mentioned above, for compatibility reasons with the ITER design and the ability to satisfy the blanket functional requirements, a solid breeder blanket with beryllium neutron multiplier was selected. Lithium zirconate (Li_2ZrO_3) was the reference breeder material, and the lithium titanate (Li_2TiO_3) was the backup material based on the available data-base for solid breeders, in particular related to tritium release aspects at low temperature. The blanket uses Type 316LN austenitic steel as structural material and ^6Li enriched lithium. Beryllium pebbles are used for neutron multiplication to increase the tritium breeding ratio.

The TBR requirements for the ITER BB are 0.8 and 0.95 for 1MW year/m^2 and 3MW year/m^2 neutron fluences, respectively, assuming the same initial availability of tritium from Canadian reactors. The proposed design was able to satisfy these requirements. The final selection criteria for the reference breeder material were consequently mainly focused on other characteristics such as, for instance, mechanical properties at beginning-of-life (BOL) and end-of-life (EOL), swelling, stability under irradiation, fabrication routes and costs.

The ITER BB design was characterized using both neutron multiplier and breeder materials in the form of pebbles and by the adoption of internal radial-poloidal flat cooling plates (CP). These CPs also play an important role as stiffening elements of the blanket modular structure. The layout is based on a number of basic breeding cells (BC) toroidally arranged. Each BC is limited by two adjacent CPs, the volume in between is filled with Be pebbles surrounding a bundle of poloidal breeder rods arranged in two toroidal rows. Each breeder rod is composed of a steel cladding containing the breeder pebbles. The BC breeder rod bundle is maintained in position by means of two supporting elements connected at the poloidal end sections of the module. These elements also perform the function of distributors/collectors of the on-line helium gas purge used for removing the tritium from the breeder and beryllium pebbles to minimize the overall tritium inventory.

During the ITA, it was decided that the replacement of the ITER shielding blanket with the breeding blanket for the EPP was not a compulsory requirement anymore. The official statement was that “the replacement of the shielding blanket with a breeder blanket for the EPP should not be precluded” in case the decision of replacement was taken during the BPP. Therefore, the design development of the ITER breeding blanket and the associated R&D were put on stand-by (and never reactivated to this day).

6.18.4 The TBM Program During EDA Extension (1998-2001)

This section has been written using the following references: J.E. Vetter & ITER Test Blanket Working Group, ITER_D_2F76Y2, May 2001 [5]; A. R. Raffray, M. Akiba, V. Chuyanov, L. Giancarli, S. Malang, “Breeding blanket concepts for fusion and materials requirements”, Journal of Nuclear Materials 307–311 (2002) 21–30 [6]; V.A. Chuyanov & ITER Test Blanket Working Group, “ITER Test Blanket Working Group activities: a summary, recommendations and conclusions”, Fusion Engineering and Design 61-62 (2002) 273-281 [7].

During the EDA extension (1998-2001) the size of ITER was reduced leading to the so-called “ITER-FEAT” but the sector solid-angle increased (from 20° to 22.5°) because the number of ports was reduced from 20 to 18, and the port number where TBMs would be installed also changed. As shown in Section 6.18.2.5, the TBM Port numbers during EDA were 19, 20, 1, 2, while in ITER-FEAT three ports are now dedicated to TBM, namely ports 1, 2 and 18. In addition, the US left the ITER project.

The relevant operational parameters for the TBMs design/testing were set up as shown in Table 6.18.4-1.

Tab. 6.18.4.1 : Operational parameters for the TBMs in ITER-FEAT.

Parameter	Design (Peak) values for TBM	Typical values during testing of TBMs
Surface heat flux	0.25MW/m ²	0.1MW/m ²
Neutron wall load	0.78 (0.94 for 10s) MW/m ²	0.78MW/m ²
Pulse length	2000s	400s
Duty cycle	< 0.3	< 0.3 Typical case: 400/1800s
Number of burn pulses	30000 (Minimum)	
Average neutron fluence	0.5MWa/m ² (Target)	0.3MWa/m ² (Minimum)
Disruption heat load and its duration	For recessed surface: 0.5MJ/m ² during 1ms-10ms. (If not recessed: ~ 60MJ/m ² during 1ms- 1s)	

A second TBWG was created (TBWG-2, chaired by J. Vetter, EU) without the presence of US representatives. The IM Fusion Program Directors, at their meeting in Grenoble (F) in October 1999, endorsed a continuation of the TBWG with a revised charter, the scope of which was to develop a coordinated blanket test program and to address the interface between the machine and test objects including auxiliaries, facilities, machine operation, safety, reliability, and maintenance requirements.

The installation of the ITER driver blanket was no longer planned. Therefore, the corresponding testing in a specific port was no longer considered.

TBM Selection and Associated Port Allocation During EDA Extension

During the EDA extension, the importance of the TBM Program and its objectives were confirmed together with the allocation of three adjacent equatorial ports (i.e., Ports 1, 2, and 18). Its development was limited for the first ten years of operations, leaving at a later stage the decision

to continue or not TBM tests in the second ten years of ITER operation. To be sure that TBMs are compatible with tokamak operation, the test modules should be installed as early as possible before beginning the DT operation, namely on ITER day-1.

The ITER operational plan (Figure 6.18.4-1) had been discussed up to only for the first 10 years. It included 1 year of integration of the sub-system level, 2.5 years of initial operation in hydrogen, a brief DD operation and a long DT operation. DT operation would start with inductive operation pulses of up to 400s and 500MW fusion power, which would be followed by hybrid operation with longer pulses and, after some additional studies, by long non-inductive steady state pulses.

The DEMO Program of the three remaining IMs were discussed in detail. As conclusions, the three IMs confirmed the intention to test the same TBMs as proposed during the EDA (see 6.18.2).

The weight of a TBM (without a liquid) was limited to 2t. The weight of the integrated structure consisting of TBM/frame/shield plug to be taken by a transfer cask was limited to 40t. The ITER hot cell could be used to replace irradiated TBMs, but it was not designed neither for their repair nor for their post-irradiation studies. Post-irradiation studies could be performed in the IM-owner premises if the irradiated TBMs can be exported. Therefore, it was decided to implement in ITER Hot Cell the capability to export the TBMs.

The distribution of ports between different IMs and different types of blanket modules was done assuming that each module occupies one half of a port and considering two factors, namely the compatibility of different designs and the space orientation (vertical or horizontal) of the specific TBMs.

- The EU and JA ceramic He-cooled TBMs with horizontal orientation would use Port 1.
- The RF self-cooled Li/V alloy and He-cooled TBMs with vertical orientation would use Port 2.
- Port 18 would be used by the EU PbLi TBM and by JA ceramic water-cooled TBM with vertical orientation.

That allocation could be reconsidered if, at later stage, some problems emerge. In each port, the two TBMs were installed within a water-cooled steel frame as defined during the EDA.

TBM Testing Strategy During EDA Extension (ITER-FEAT)

During the EDA extension period, the activities of the TBWG focused on the required TBM testing and testing strategy to be adopted.

Different blanket concepts have partly different testing objectives. The number of TBM versions required to achieve all important objectives may also be different for individual concepts.

However, there were many common objectives requiring a synchronized sequence of tests such as:

- Transient electro-magnetic tests during the H-phase with measurement of magnetic fields, eddy currents, forces and moments acting on the TBMs during fast plasma transients to ensure the integrity of the TBMs.
- Neutronics and tritium production measurements during DD operations and the early DT operations to evaluate tritium breeding performance, validate codes and nuclear data.
- Thermal and mechanical testing during DT operations to investigate the thermal and mechanical behavior of TBMs designed to simulate as close as possible the temperature/stress conditions in a power reactor.
- Integrated tests during the high duty DT operations to evaluate the integrated behavior of TBMs and the required external systems for cooling and tritium extraction under a large variety of loads and operating conditions.

All IMs selected to test act-like TBMs. Going from one testing campaign to the next one might require a significant change of the TBM designs. Therefore, regular replacement periods for all TBMs have to be scheduled. As a rule, the TBMs could be changed once per year in accordance with the ITER operational schedule. Some TBMs could need additional replacements, to be synchronized among the IMs and with machine operation. Target replacement time should be less than one month for all three ports together.

The individual test programs had to be fitted into the overall program and synchronized with the other IMs. Detailed test objectives and corresponding duration were determined for all six TBMs. The TBM testing was planned to start on day-1 of ITER-FEAT operation and defined for the first 10 years. Typically, for each TBB, four TBM versions were designed with the integration of different instrumentation.

For example, for the HCPB TBB, the EU testing program foresaw a sequence of four TBM design versions. The first TBM (EM-TBM) would serve to investigate the consequences of electromagnetic transients and ferromagnetic effects. The second TBM (NT-TBM) would test blanket neutronics and tritium production. The third TBM (TM-TBM) would investigate the thermomechanical behavior of pebble beds, a key issue of the HCPB blanket concept. The fourth TBM (PI-TBM) would demonstrate the integral performance of a complete HCPB blanket system under different loading conditions.

For the WCLL-TBM it was planned to leave the same WCLL-TBM in place from its installation until the end of the BPP. The only exceptions were:

- long maintenance periods in which the TBM might be removed from the vacuum vessel if required;
- insertion for a limited duration of a specifically instrumented TBM for neutronic measurements;
- possible TBM failure when the TBM would need to be removed and replaced, and
- in case a newly developed preferred technology had to be tested.

Spare equipment for the TBMs and associated ancillary circuits would be ready to ensure easy and quick replacement if required. If a failure in a TBM is due to a design problem, the risk of a delay of its remaining test program is accepted.

The Russian Federation TBM program planned to test some DEMOs 'act-alike' TBMs for both He-cooled ceramic TBB and Li/V TBB. Some of the TBMs were a diagnostic type for measuring ITER magnetic field topography inside the TBM, for neutronics testing, and for transient electromagnetic tests during H operations. These tests could be relatively easily combined into a coordinated cross-IM TBM program. In DT operations, different TBMs would be used to test the first wall and the breeding zone at power reactor relevant temperatures. Among tests specific for the Li/V TBB test program were the demonstration of electro-insulating coating performance under the combined effect of neutron irradiation, high magnetic field, temperature gradients and liquid metal dynamic flow, and demonstrations of the engineering technique for self-healing of electro-insulating coatings, and for on-line removal of impurities from Li. These tests could start at the very beginning of ITER operation, since they primarily require just the relevant magnetic field.

For Japan, both He-cooled and water-cooled ceramic TBMs were submitted to the same testing sequence. The Japanese TBM program was dedicated mainly for investigating blanket characteristics under 14MeV neutron irradiation, under huge electromagnetic field and with their synergetic effects including high surface heat flux to the module first wall, and finally for demonstrating the blanket performance to be applied to a DEMO reactor. It was in many respects similar to the other IMs programs. In addition, it foresaw also the demonstration of high-grade heat extraction and electricity generation by TBMs.

As general consideration for the whole TBM Program in ITER-FEAT, irradiation effects on materials properties and blanket performance were the most critical issues for the testing. Some changes in thermo-physical properties of non-metals, e.g. thermal conductivity, occur below a neutron fluence of 0.1MWa/m^2 . Several important effects become apparent in the fluence range of $0.1\text{--}1\text{MWa/m}^2$. These effects include solid breeder sintering/radiation cracking and possible onset of breeder/multiplier swelling. They might be investigated by ITER tests. But most of the irradiation effects, especially on structural material characteristics including DBTT change, helium embrittlement and swelling, will appear only in the fluence range of $1\text{--}3\text{MWa/m}^2$ or higher.

Therefore, these irradiation effects on structural materials would need to be evaluated separately from ITER TBM test program.

The common Test Program proposed during the EDA extension is shown in Figure 6.18.4-1. The need for a synchronized replacement between the TBMs in the same port was recognized but considered to be addressed at a later stage.

First plasma														
Operational year	-1	1	2	3	4	5	6	7	8	9	10	11	12	Second 10 years
ITER Master Schedule		H-H			D-D	Low Duty DT			High Duty D-T			Upgrade	High performance	
N of burn pulses/year					1	750	1000	1500	2500	3000	3000			
EU HCPB EM-TBM		Electro Magnetic tests												
EU HCPB NT-TBM					Neutron tests									
EU HCPB TM-TBM								Therm/mech. tests						
EU HCPB PL-TBM									Integratged Tests					Integratged Testing
EU WCLL TBM Ref Design		EM, MGD, H-Permeation .				T control, Stress validation, LM circ.			T permeation					Integratged Testing
EU WCLL TBM - NT inst					NT									
JAPAN TBM W1		EM, Ferritic steel,												
JAPAN TBM W-2					NT+ Tritium extr									
JAPAN TBM W#								High grade heat. Cont.Tr. Extraction. Electricity						Integratged Testing
JAPAN TBM H-1		EM, Ferr. steel, Ov. Test												
JAPAN TBM H-2					NT+Tritium extr									
JAPAN TBM H-3								High grade heat . Continuous tritium extraction.						Integratged Testing
RF He TBM 0		EM and functional tests												
RF He TBM 1							Low T BZ		HighT Breeding zone tests					
RF He TBM 2							Low T FW				High T FW			
RF He TBM 3														Integratged Testing
RF Li TBM-0		EM, MHD , Insulation coating testing												
Rf Li TBM-1						NT								
RF Li TBM-2							Functional tests							
RF Li TBM-3									Performance testing					Integratged Testing

Fig. 6.18.4.1 : ITER-FEAT operational plan and coordinated schedule for TBMs testing.

6.18.5 The Activities of the Test Blanket Working Group after 2002 (TBWG-3)

This section has been written using the following references: L. Giancarli, V. Chuyanov, M. Abdou, M. Akiba, B.C. Hong, R. Lässer, C. Pan, Y. Strebkov, "Objectives and Progress of the ITER Test Blanket Working Group Activities", 20. IAEA fusion energy conference, Vilamoura (Portugal), 1-6 Nov 2004, IAEA-CN-116; IT/P3-20 [8]; L. Giancarli & ITER Test Blanket Working Group, "Report from the re-established Test Blanket Working Group (TBWG) for the Period of the ITER Transitional Arrangements (ITA)", ITER_D_4B7TS8, September 2005 [9]; L. Giancarli, V. Chuyanov, M. Abdou, M. Akiba, B.G. Hong, R. Lässer, C. Pan, Y. Strebkov & TBWG, "Breeding Blanket Modules testing in ITER: An international program on the way to DEMO", Fusion Engineering and Design 81 (2006) 393–405 [10]; L. Giancarli, V. Chuyanov, M. Abdou, M. Akiba, B.G. Hong, R. Lässer, C. Pan, Y. Strebkov & TBWG, "Test blanket modules in ITER: An overview on proposed designs and required DEMO-relevant materials", Journal of Nuclear Materials 367–370 (2007) 1271–1280 [11].

After the end of the EDA extension, ITER activities entered in the period of the ITER Transitional Arrangements (ITA), during which the activities were mainly focused on the negotiation on the ITER site. In the meantime, other countries joined ITER as ITER Members (including the return of US, and two additional new ones, China and South Korea). The ITER-FEAT parameters were confirmed.

In October 2003, it was decided to restart the activities of TBWG with an enlarged official membership (TBWG-3). New Terms of Reference were defined, L. Giancarli (EU) was nominated as Chair and the membership was revised including now representatives of the ITER Team and of the six ITER Members (China, EU, Japan, Russian Federation, South Korea, and US). The main objective of the TBWG was confirmed, aiming:

- to provide the Design Description Document (DDD) of the TBMs and their associated ancillary systems proposed by the various IMs including the description of the interfaces with the ITER machine;
- to promote co-operation among parties on the associated R&D programs;
- to verify the integration of TBM testing in ITER site including safety and environmental evaluations;
- to develop and propose coordinated TBMs test programs considering the new ITER operation planning.

Selection of TBM and Associated Ancillary Systems During ITA

Based on the evolution of the IMs DEMO studies and on the presentations of the activities made by the new-entry IMs, a revision of the TBSs proposals was made.

Among the evolutions, there was the decision made by EU to modify the coolant for the TBB using Pb-16Li, from water (WCCL-TBS) to helium (HCCL-TBS). The reason was potential cost savings in the development of the TBS cooling system that serves now the two EU TBSs.

All ITER Members were still interested in developing Helium-Cooled Ceramic Breeder (HCCB) blankets. The proposals were either to test independent TBMs based on different blanket concepts (by China, EU, Japan and RF) or to collaborate with other parties on a common TBM concept (by US and Korea). This line of blankets requires beryllium as a neutron multiplier and uses Ferritic/Martensitic Steel (FMS) for structures. Depending on the IMs domestic experience, the ceramic breeder could be either Li_2TiO_3 , or Li_4SiO_4 , or Li_2O and is used in a pebble-bed form.

The other selected breeding blankets differ from IM to IM. Namely:

- Japan selected a pressurized Water-Cooled Ceramic Breeder (WCCB) blanket as the reference design during EDA extension, which is a water-cooled version of the corresponding HCCB blanket with Reduced-Activation Ferritic/Martensitic (RAFM) steel as structural material [\[12\]](#).
- EU selected a Helium-Cooled Lithium-Lead (HCLL) blanket, using lead-lithium as breeder and neutron multiplier, and RAFM steel structures.
- China performed comparative studies between a HCLL blanket and a dual coolant version of it that uses helium to cool the RAFM steel structures while PbLi operated as a self-cooled breeder zone.

- US selected a Dual-Coolant Lithium-Lead (DCLL) blanket.
- RF selected a self-cooled lithium blanket using Be as a neutron multiplier and a vanadium-alloy for structures.
- South Korea selected a Helium-Cooled Lithium (HCLi) blanket using RAFM steel structures.

Within the HCCB blanket family, China, EU, Japan, and RF made four independent TBM design proposals, while US and Korea proposed to test submodules integrated to one TBM. All TBMs use ceramic breeders in a pebble-bed form, RAFM steel structures and He coolant at 8MPa with inlet temperature of 300°C and outlet up to 500°C depending on operating conditions. Specific features were the following: (i) the China design was a single box, 1/4 port size, and uses Be and Li_4SiO_4 pebble-beds; (ii) the EU design is a single box housing 18 breeder unit cells, 1/2 port size (horizontal), uses Li_4SiO_4 or Li_2TiO_3 and Be pebble beds; (iii) US proposed either to test a 1/4 port-size sub-module or to test 3 breeder unit cells inserted into the EU TBM; (iv) the Japan design had a three-submodule structure with a total of 1/2 port size (horizontal), using Li_2TiO_3 and Be pebble beds; (v) the RF design has a 2 sub-modules structure with a total of 1/2 port size (vertical) and uses Li_4SiO_4 pebble beds and porous Be-blocks; (iv) Korea proposed to test sub-modules to be integrated into existing TBMs, using Li_4SiO_4 and Be pebble beds while in the rear part of the blanket, a graphite pebble bed (or block) acting as a neutron reflector to reduce the required amount of Be.

For all HCCB TBMs, the He-coolant systems were located in Level 4 of tokamak and tritium buildings (i.e., TCWS vault and annex); this implied that each TBM would require a connection of the coolant system (including inlet and outlet pipes) between port cell and vault. Purge-gas system components were mainly located in the port cell area, while the recovered tritium would be sent toward the ITER tritium plant in the tritium building.

Within the liquid lead-lithium blankets family, there were three TBM proposals, all consisting of a single box at 1/2 port size (vertical), and using He at 8MPa with $T_{in} = 300^\circ\text{C}$ and T_{out} up to 500°C. The EU design used only He as coolant (i.e., HCLL-TBS) while the US design used He-coolant for the structures and PbLi as breeder-zone coolant with T_{in} of 460°C and T_{out} up to 700°C (i.e., DCLL-TBS). The China design had initially a single coolant (He) but can evolve to dual-coolant operations (DFLL, dual functional lithium–lead [13]). HCLL-TBM requires one He-coolant system located in the TCWS vault. The PbLi circuit components were located in the port cell; the recovered tritium being sent to the ITER tritium system. The DCLL TBM required an additional He-coolant system in the TCWS vault to serve as He secondary circuit for the PbLi primary coolant (the associated heat exchanger located in the port cell).

For the WCCB blanket family, a TBM design was proposed by Japan. It had a two sub-module RAFM structure with a total 1/2 port size (vertical), using water coolant at PWR conditions and Be

and Li_2TiO_3 pebble beds. The WCCB TBM required one water coolant system located in the TCWS vault, with the tritium system being the same as that of HCCB TBMs.

Within the liquid Li-blanket family, RF proposed a self-cooled lithium (SCLi) TBM. It consisted of a single V-alloy box at 1/2 port size (vertical), using porous Be as n-multiplier and Li coolant at an inlet temperature of 250–350°C and an outlet temperature of up to 550°C. Korea proposed to install a He-cooled Li (HCLi) TBM using FMS structures and graphite neutron reflector. The He-coolant had the same characteristics as those in the other He-systems. For these TBMs, all Li systems were located in the VV port extension and port cell.

As general statement, it was considered that the initial TBMs for HH operations did not need to include all technology features required for the successive TBMs (e.g., the quality of ceramic pebbles does not need to be optimized). However, because it had to be used for safety validation, the main structural and functional features of the TBM had to be already present. It has to be stressed that for all proposed TBMs significant R&D had yet to be performed in order to ensure their installation on ITER day-1.

Proposed Approach, Port Allocation and Testing Plan During ITA

During the ITA, the IMs proposed several independent, DEMO-relevant, TBMs that could not all be tested simultaneously on day-1. Space limitation was not only due to the space available in the test ports but also to the limited space available in the port cells, in the vertical shafts, and in the TCWS vault. The situation would become even more difficult during DT operations because of the additional TBMs being proposed.

To facilitate the final selection and to define a fully coordinated test program, a strong collaboration among IMs was recommended by TBWG. This collaboration should go beyond mere space or time sharing and focus on technical convergence toward similar TBM design, and even whenever possible, common TBMs should be used. To promote collaboration between IMs, two working groups (WGs) were established within the TBWG activities to discuss potential similarities, one covering solid breeder blankets (based on lithium-ceramic breeder) and a second one covering liquid breeder blankets (based on liquid metals, namely natural lithium and on PbLi). The WGs were able to clarify the details of the various TBM design proposals and allowed to harmonize some TBMs operating parameters. However, it had not been possible to agree on common TBM designs.

As during the EDA extension, three ITER equatorial ports were made available for the TBM Program, however, they were identified then as ports 16, 18 and 2 because of some adjustments needed in the distribution of the equatorial ports for other components. Because of the increased number of IMs and consequently the number of proposed TBMs, the previous assumption of testing two TBMs per port was reassessed. It was concluded that the choice of installing two TBMs

per port is still the best one in terms of feasibility and integration while maximizing the number of TBSs that can be simultaneously tested.

Therefore, it was acknowledged the necessity to proceed with the selection of the six TBMs to be tested in ITER. With the support of the WGs mentioned above, several TBWG meetings were devoted to the comparison of the various proposals based on the technological readiness of the various proposed solutions and on the safety aspects when operating in ITER.

All proposed TBMs needed further R&Ds before proving their acceptability for installation in ITER at the beginning of H-H operations. It could be expected that not all the proposals would be validated and, therefore, it was recognized the importance of having some flexibility on the final choice of the TBM concepts to be installed in each port. On the other hand, to allow TBM systems integration in ITER, it was essential to know the number and the type of feeding pipe connections required in each TBM port. Therefore, the TBWG-3 have fixed this aspect which then became a constraint for future decision on TBMs test planning.

The ITER operational plan was defined then for the first 10 years. It included 1 year for sub-system commissioning and in-vessel components baking, 2.5 years of initial H-H operations, a brief DD operation and long DT operations.

A generic TBM testing plan was confirmed starting from ITER day-1 for electromagnetics and hydraulics tests, evolving to neutronics validation and finally tritium breeding, tritium management and thermal-mechanics tests (see Figure 6.18.5-1).

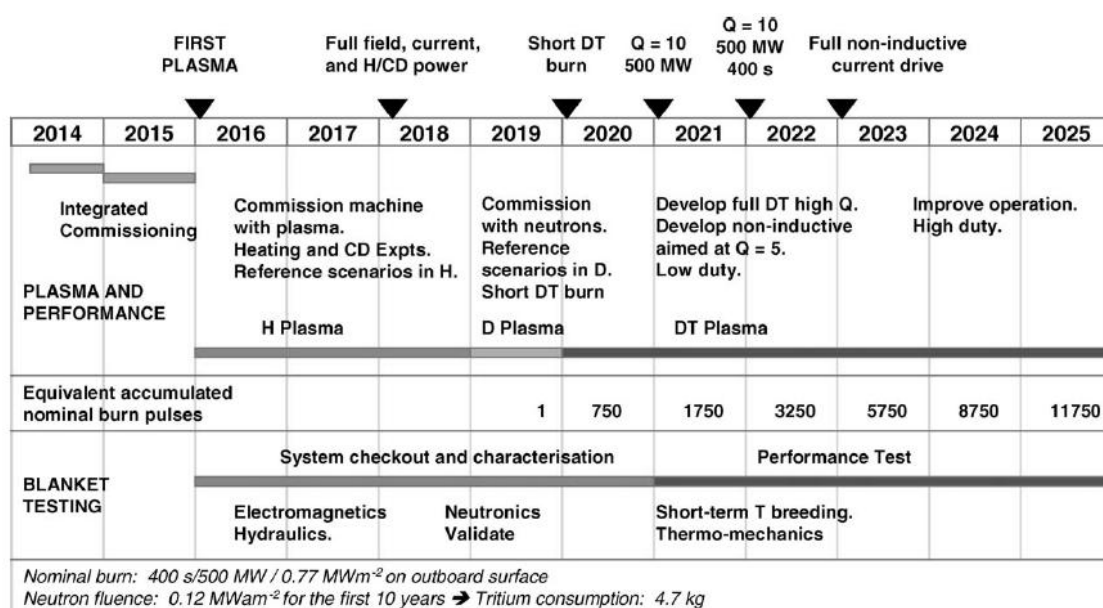


Fig. 6.18.5.1 : TBMs testing synchronized with the planned ITER operations during ITA.

TBM Program After the Signature of the ITER Agreement in 2006 and Creation of the ITER Central Team in Cadarache

The ITER Agreement has been officially signed in November 2006. Besides the six IMs present during the ITA, it was signed also by India that joined ITER in 2005. India joined also the TBWG activities in early 2006 with the consequent addition of other TBBs proposals.

The TBWG-3 continued to work until its last 19th meeting in March 2008. During the last two years most of the effort was made to assess the various IMs TBM proposals and to select the six TBMs that would be tested in ITER. To achieve this selection significant effort was made to promote collaboration between different IMs in order to agree on common TBMs, in particular in the case where several TBMs with similar characteristics were proposed. It is the case for the He-cooled ceramic breeder TBMs that was proposed by all the IMs.

To perform the selection, a high-level “ad-hoc working group” was created to review the TBWG reports, each Party’s TBM program commitment, and possible collaborations and sharing. The collaboration proposal was not particularly successful because the TBM-related activities, being based on domestic activities of TBBs for DEMO and next steps fusion reactors, were subjected to Intellectual Property Rights. Therefore, differently from the activities on all the other ITER systems, only limited information could be openly shared among the various IMs. To note that this difficulty of collaboration among the IMs has been an issue since the beginning of the ITER TBM Program and it is still an issue today.

Therefore, in most cases, each IM preferred to make internal domestic selection, mostly based on financial aspects, and reduce the number of TBM proposals. The objective was to find an agreement to test six TBMs. Since it was requested by the IO to have a commitment on final design and procurement of whole TBSs by the IMs proposing the tests, the domestic budget availability became an important factor for the decision. In this regard, EU could commit to the procurement of the two TBSs, Japan, China and India of one TBS, US and Korea jointly of one TBS, RF preferred not to commit.

The ITER Council officially supported the undertaking of the TBM Program under the framework of the ITER Agreement in the IC-2 meeting of June 2008 and requested the IO implement the TBM Program in ITER.

The IO implementation was based on the conclusions reached by TBWG. It was confirmed that up to six concepts of various tritium breeding blanket systems (TBSs) will be tested simultaneously [14], [15]. The TBMs will be installed in three dedicated equatorial ports of ITER (ports #2, #18, and #16). The TBMs will be inserted in a 20cm-thick water-cooled steel frame that serves as the unique interface with the vacuum vessel port extension.

In 2008, provisionally, the following six independent TBSs were proposed by the TBWG to be installed in ITER:

In Equatorial Port 16:

- The Helium Cooled Lithium Lead (HCLL) TBM, proposed and developed by EU. The HCLL TBM uses the liquid metal PbLi as tritium breeder and neutron multiplier and helium as coolant.
- The Helium Cooled Pebble Bed (HCPB) TBM, proposed and developed by EU- The HCPB TBM uses lithium ceramic as tritium breeder, beryllium as neutron multiplier, and helium as coolant.

In Equatorial Port 18:

- The Water-Cooled Solid Breeder (WCSB) TBM, proposed and developed by Japan- The WCSB TBM uses a lithium ceramic as tritium breeder, beryllium as neutron multiplier, and pressurized water as coolant [16].
- The Dual Coolant Lithium Lead (DCLL) TBM, proposed and developed jointly by US and Korea- The DCLL TBM uses the liquid metal PbLi as tritium breeder, neutron multiplier and as coolant for the breeder region. Helium is used to cool the structures. A Helium-Cooled Ceramic Breeder (HCCB) TBM was also under consideration, in parallel, by US and KO.

In Equatorial Port 2:

- The Helium Cooled Solid Breeder (HCSB) TBM, proposed and developed by China. The HCSB TBM uses a lithium ceramic as tritium breeder, beryllium as neutron multiplier, and helium as coolant.
- The Lithium Lead Ceramic Breeder (LLCB) TBM, proposed and developed by India- The LLCB TBM uses the liquid metal PbLi as tritium breeder, neutron multiplier and also as coolant for the breeder region. Helium is used to cool the structures, and a lithium ceramic is used as an additional breeder. RF supported India proposal on LLCB TBM and since 2010 participated in R&D on this blanket according to program of cooperation between governmental bodies and leading institutes of both countries.

It was decided to standardize the TBM Frame for all the three ports, using vertical TBMs, because, while solid breeder TBMs can accommodate both configurations, the liquid breeder TBMs benefit significantly from vertical TBMs.

For all the TBMs, the structural material was Reduced-Activation Ferritic/Martensitic (RAFM) steel, which is a ferromagnetic material.

Following the 2008 IC-2 decision, the TBM Program was then undertaken under the framework of the ITER Agreement and was technically fully integrated in ITER and in its corresponding research plan. However, the specificity of the TBM Program required a particular organization during both ITER construction and operation. The TBM Program responsibilities were defined as follows:

- The IO would be responsible for hosting and operating the six TBSs in the ITER facility by ensuring that adequate space and handling facilities (including hot cell) are allocated to the TBM Program. It is responsible for defining TBS acceptance criteria, of performing replacement and maintenance of the TBSs, dismantling, storing irradiated components until shipping, of designing and procuring port frames and dummy TBMs, and of checking TBSs reliability and safety.
- The IMs would bear the associated cost for TBS design (including associated R&D and manufacturing validation), TBS procurement, and TBS shipping to ITER site. They would be also responsible for defining the objective and planning of the TBS testing, shipping the irradiated TBMs from the ITER site to some appropriate domestic facilities and performing any required post-irradiation examinations. To be noted that TBSs would remain the property of the originating IM throughout the whole TBS lifetime (manufacturing, operation, dismantling and radwaste disposal).

6.18.6 The ITER TBM Program Committee (2009-2017)

In November 2008, the IC-3 officially established the ITER TBM Program [\[17\]](#), including the creation of the TBM Program Committee (TBM-PC) that was expected to discuss and approve all TBM-related technical and organizational activities, including TBS selection, TBM Program plan and milestones, TBM partnerships and to propose recovery plans in case of delays. The TBM-PC was formally established as an Advisory Committee to the IC on the TBM Program, with reporting at each IC meeting and, therefore, met twice a year, few weeks in advance of each IC meeting. The TBM-PC was composed of one member and up to three experts per each IM. Concerning the Chair, the rule was to nominate a Chair for two years, coming from an IM, on rotating basis. The first meeting of the TBM-PC took place in March 2009, chaired by Prof. S. Konishi (JA).

The IC-3 document included the definition of the responsibilities of the key actors to be implemented within the TBM-PC, namely: (i) the roles of the ITER Organization; (ii) the roles of the ITER Members; (iii) the TBM Program Structure; (iv) the roles of the Port Masters (PM); (v) the roles of the TBM Leaders (TL); (vi) the roles of a TBM Partner (TP); (vii) the arrangement between IO and PM; (viii) the arrangement between PM and TL; and (ix) the arrangement between TL and TBM Partners. It also included the following proposal for preliminary TBM port allocation to be further discussed and reviewed by the TBM-PC:

- Port 16: PM (EU), HCLL TBM (TL: EU) and HCPB (TL: EU)
- Port 18: PM (JA), WCCB TBM (TL: JA) and HCCB (TL: KO, decision to be confirmed)
- Port 2: PM (CN), HCCB (TL: CN) with alternative option for DFLL (TL: CN), and LLCB (TL: IN)

During the TBM-PC-01 the following proposals were made:

- CN proposed to be TL for the HCCB TBM (without alternative).
- KO withdrew their proposal to be TL (since no commitment was yet possible). As a result, one location in Port 18 could not have an assigned TBM Leader. However, both US and KO requested that the possibility to be a TBM Leader in the future (perhaps in the following 2-3 years) should not be precluded, which means that all interfaces for Port#18 should be defined as for all the other TBMs.
- It was therefore agreed that, until the ITER master schedule and other TBM schedule factors require a full commitment, the US will act as the “Interfaces Coordinator” for this half port, with the support of KO, on the basis of the needs for the Dual Coolant Lithium Lead (DCLL) concept that the US had previously developed (and that was expected to be the most demanding TBS in term of interfaces).

It was noted that in each port cell there are common aspects between the two TBSs. They include the TBM port plug hosting the two TBMs (see Figure 6.18.6-1). Other examples are the Pipe Forest (PF) in the vacuum vessel/bio-shield interspace, the bio-shield plug, the Ancillary Equipment Unit (AEU), the pipe bundle through the corresponding shaft, and the location of the cooling circuit and tritium circuit components [18]. Moreover, common aspects encompass replacement/maintenance operations and remote handling strategy, operation and treatment in the hot cell facility, and of course installation and replacement strategy. To efficiently run these common activities, the IO has created three Port Management Groups: PMG-2, PMG-16 and PMG-18, respectively for the ITER equatorial ports 2, 16 and 18.

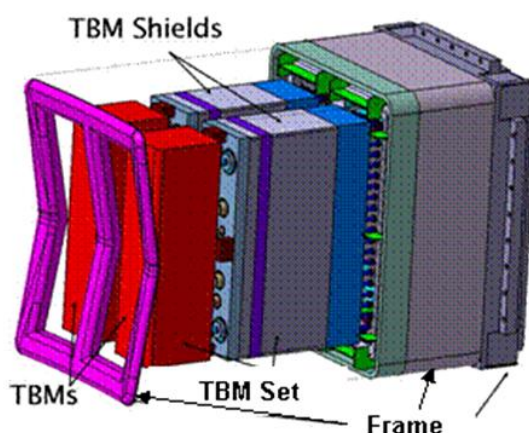


Fig. 6.18.6.1 : Exploded view of a Port Plug including two TBM-Sets.

Cost and Commitment Aspects and TBM Testing Plan

TBM-PC, under request of the IC, started to discuss, for the first time, cost aspects of the TBM Program and IMs Commitment based on the estimations that were already mentioned in the IC-3 document. The TBM-PC confirmed such estimations of the necessary resources during the Construction Phase for buildings and equipment providing for the testing of six independent TBM concepts in which all key facilities and building areas were considered (including the control room space, high-pressure pipes connecting the port cell and TWCS area). They were the following:

- Six test port frames and shields + six dummy TBMs (cost of correction coils, if needed, is not included): ~26M€.
- AEU (hot cell) increased area: ~7M€.
- Equipment such as RH, pipes, inspection/cutting tools, etc: ~11M€.
- The total estimated cost is ~80M€, which includes a 50% contingency due to the uncertainties related to the fact that the corresponding designs are not yet available.

In 2010, the views of the IMs were the following: in general, six ITER Members (except the US) confirmed their agreement on the cost sharing based on the cost sharing of the Construction Phase. The U.S. remained committed to pay its 9.09% share of the added civil infrastructure costs to accommodate the ITER TBM Program. This commitment does not extend to the other common expenses (port frames, RH equipment, correction coils, human resources) mentioned in the Annex of the IC-3 decision document. The TBM-PC identifies the US position as the remaining issue. At that time, it was concluded that the current US position should not disturb the entire TBM Program so it can continue as planned since potential solutions could be found in the agreements on the overall ITER budget. The discussion on the details was left to a later stage.

In the operation of the TBSs, the successful operation of the Tokamak and accompanying physics experiments was essential, so that the TBM program needed to be flexible enough to adjust, if necessary, to the needs of the rest of the ITER project [\[19\]](#), [\[20\]](#), [\[21\]](#). This included start-up and shutdown and the adjustment to different un-scheduled down times. The TBSs were expected to be installed in Assembly Phase 2, just after First Plasma.

The TBM testing program was expected to run from H/He operations, throughout the D-D, DT1 and the initial DT2 operations, assuming a TBM replacement about every two years (see Figure 6.18.6-2).

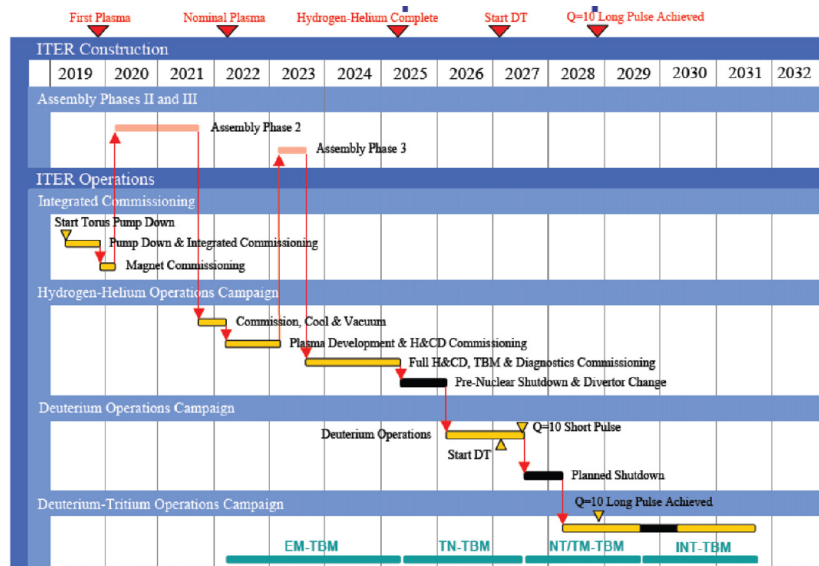


Fig. 6.18.6.2 : TBMs testing synchronized with the planned ITER operations in 2009.

Figure 6.18.6-2 shows the TBM testing plan involving the following four TBM versions for all the six TBSs:

- (i) the ElectroMagnetic TBM (EM-TBM), covering the validation of the assessment of the impact of ferromagnetic structures on plasma performance, the structural integrity of the TBM during disruptions, the collection of safety-relevant data for obtain authorization to proceed with the nuclear phase of ITER operation;
- (ii) the Thermal-Neutronic TBM (TN-TBM), mainly covering the verification of the operation and calibration of neutron sensors, the preliminary validation of the TBM neutronic responses and the MHD effects on the TBMs using liquid metal;
- (iii) the Neutronic-Tritium/Thermo-Mechanic TBM (NT/TMTBM), covering the validation of the TBM neutronic response by measuring the neutron flux and its energy distribution with all the neutron diagnostics developed for the TBM, the validation of the thermo- mechanical response of the TBM box, the preliminary validation of tritium control and recovery and the assessment of materials activation;
- (iv) the INTEgral TBM (INT-TBM), covering the validation of tritium control and recovery in the TBS, and the parametric analysis on the impact of the functional parameters (process fluids mass flows, heat transfers, and chemistry) on the global tritium system performance.

The TBM Arrangements (TBMA)

The TBM-PC in 2011 noted that there was no official commitment by ITER Members to deliver the planned TBSs. Therefore, it decided that a specific arrangement, called the TBM Arrangement (TBMA), will have to be signed between IO and each of the IM TBM Leaders, in order to establish

the formal framework of the TBM Program, including the IM commitment of delivering the TBS in 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 will specify the framework for the main governing, legal and administrative requirements related to the TBM Program, will define the management specifications, accepted sound project management practices, safety and QA requirements, and will establish the TBS technical specifications and milestones, including the delivery date.

In the framework of the TBM-PC and under the proposal of the IO, it was decided to prepare a generic TBMA to be used as template for each specific TBMA. The TBMA template is strongly based on the existing Procurement Arrangements used for the other ITER systems, but it includes the specificities of the TBM Program (namely, the fact that the IMs remain the owner of the TBSs). Each specific TBMA will have to be proposed by each IM TBM Leader to IO, and, after agreement, it will be signed soon after. It was expected to sign most of the TBMA in 2013 that will correspond to the official IMs commitment. After each TBMA signature, the corresponding TBS conceptual design review could take place to identify all possible technical issues still present and to define the action plan for solving them.

An Extraordinary Meeting of the ITER Council TBM Program Committee (TBM-PC-06_Extra, 3-4 April 2012), with the participation of the DG, was needed to reach the final agreement on the content of the Generic TBMA, formed by the Main Body, the Annex A on management specifications, the Annex B on technical specifications and the Annex C on milestones/schedule.

To ensure a timely delivery of the TBSs to the ITER site and to allow all the required IO monitoring activities, for each TBS, a TBMA had to be signed between the IO and the involved IM. These TBMA include, for example, milestones, procedures for quality control, procedures for data exchange, and, in addition, the applicable Intellectual Properties Rights (IPR) specifically for the TBM Program. In particular, it was established that the Intellectual Property acquired, developed or produced by the IMs during the design, development and manufacturing of the TBS is the property of the IMs. This specific IPR aspect makes it difficult to share technical information among the IMs and, therefore, limit the extent of potential collaborations.

Following the discussion on the TBMA and the urgency to sign them before 2013, in May 2012, KO officially proposed its intention to become a TBM Leader (TL) for the “Helium Cooled Ceramic Reflector” TBS (HCCR-TBS) using graphite pebbles as neutron reflector, since this TBS was the most advanced TBS design option in the KO domestic program. TBM-PC discussed the detailed contents of the HCCR-TBS concept, the plan of the KO TBM program and the technical features of the proposed TBM. The KO proposal was unanimously accepted, and KO was assigned to be a TL in port number 18 in replacement of the US proposal of DCLL-TBS. The proposal was endorsed by the IC.

The US also welcomed the KO proposal and dropped its position as the TBM Interface Coordinator when the above recommendation was endorsed by IC-10. The US continued to explore opportunities to collaborate with ITER Members with TBM responsibilities and reserved its right to become a TBM leader with its concept of dual coolant TBB type in the future. The TBM-PC accepted this request and noted that, since this concept involves liquid metal as a media of heat and tritium transfer, it needs an additional helium system to act as secondary system for the liquid metal system whose heat exchanger would be located in the port cell. The consequence would be the need of two He-coolant systems (one as primary coolant of the TBM structure and one as secondary loop, leading to four He-coolant pipes). TBM-PC agreed to consider leaving additional connection pipes to accommodate the dual-coolant type TBS in the future. The funding source for such accommodation is to be determined in future discussions.

The TBMA's were finally signed for the following TBBs, and the associated CDRs were performed immediately after [\[22\]](#), as shown in Table 6.18.6-1.

Tab. 6.18.6.1 : Selected TBSs for TBMA signature and CDR.

# Port	ITER Member	TBS	Signature of the TBMA	CDR date
16	Europe	TBS-1: Helium-Cooled Lithium Lead (HCLL)	September 2014	8-12 June 2015
16	Europe	TBS-2: Helium-Cooled Pebble Bed (HCPB)	September 2014	8-12 June 2015
18	Japan	TBS-3: Water-Cooled Ceramic Breeder (WCCB)	November 2014	2-6 February 2015
18	Korea	TBS-4: Helium-Cooled Ceramic Reflector (HCCR)	May 2014	2-6 February 2015
02	China	TBS-5: Helium-Cooled Ceramic Breeder (HCCB)	February 2014	22-25 July 2014
02	India	TBS-6: Lithium Lead Ceramic Breeder (LLCB)	March 2015	28 September – 1 st October 2015

To note that, in the signed TBMA's, the delivery dates, given in Annex C, for the TBS Ancillary Systems and the TBM-Sets were planned in 2023.

Following the recommendation of the TBM-PC, in June 2013, the IC endorsed the proposal on the transfer of responsibility for the design and procurement of the TBS Connection Pipes and the associated provision of financial resources from the IMs to the IO. The Test Blanket System (TBS) Connection Pipes (i.e. pipes connecting elements of the TBS in different rooms of the Tokamak Complex) need to be delivered several years earlier than the other TBS components: the Connection Pipes (CPs) for all the six TBSs have to be delivered simultaneously just after the completion of the nuclear buildings since they are captive to other ITER systems installed before the start of the ITER operation [23]. Therefore, the TBS CPs need special milestones and arrangements to ensure timely delivery. A Memorandum of Understanding (MoU) related to the Transfer of Responsibility for TBS CPs final design and procurement was signed between IO and each IMs.

It was also agreed to harmonize and standardize the TBS coolant systems CPs and the associated rational. At the CDR, to keep the maximum flexibility and not-preclude the future installation of dual-coolant concepts, there were six coolant pipes (3 inlet and 3 outlet) crossing the shaft for each port cell. Such rational had the following objectives: (i) to ensure the feasibility of the installation of the pipe supports by reducing the diameter of the pipes while keeping the pressure losses in each TBS coolant connection pipe below 0.1MPa; (ii) to simplify maintenance operations in reducing the number of required tools and to reduce time and risks for TBS maintenance; (iii) to reduce the number of pipes variants and to standardize pipe diameters in order to reduce the procurement cost.

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. Experiments performed on DIII-D [24] 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 was to minimize the TBM ferromagnetic mass to below 1.3t. It was left to the initial ITER H/He phase to verify these results and to detect the eventual TBM-induced disturbances during the initial ITER H/He phase and to implement, if needed, any appropriate countermeasure for the following ITER operational phases.

For each TBS, a Preliminary Safety Report was produced. A summary, covering the six TBSs was prepared and distributed to the ASN (Agence du Sureté Nucleaire = French Nuclear Safety Agency).

It was recalled that the IMs remain owners of the TBSs and, therefore, they are also responsible for the corresponding produced rad-waste and its management. A special working group was created to start the assessment of the produced radwaste and the cost implication for each IM.

The TBM Program after the Implementation of the ITER 2016 Baseline

Following the approval of the Conceptual Design (CD) for the six TBSs, their integration in the ITER building was performed (see Figure 6.18.6-3).

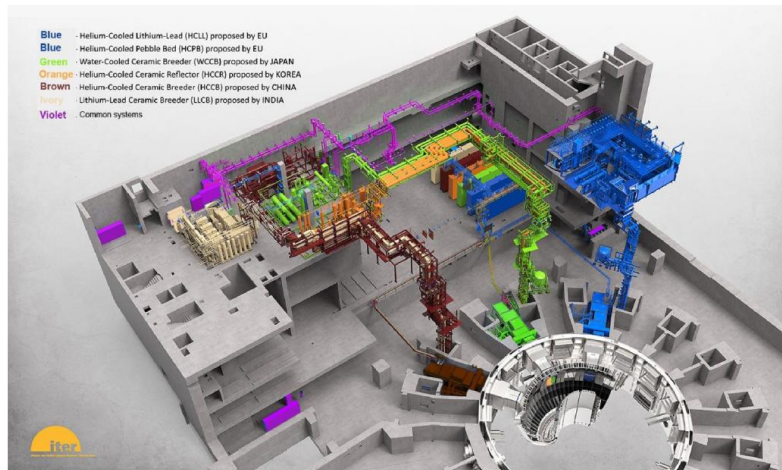


Fig. 6.18.6.3 : Overall view of the six Test Blanket Systems located in various rooms of the Tokamak and Tritium buildings.

The key activities of the ITER Research Plan from First Plasma to initial DT Operation was developed within the new framework of the “Staged Approach” including the possible scenarios and objectives for the Pre-Fusion Power Operation-1 &-2 and for the first Fusion Power Operation using DT. On this basis, the ITER 2016 baseline was approved.

The Pre-Fusion Power Operation-2 (PFPO-2) was then the last non-nuclear phase. Therefore, the TBSs were planned to be installed for operation in the PFPO-2 that was expected to last 21 months. Some concerns were expressed on the length of this phase that could be insufficient for performing all the TBS non-nuclear tests and operations required for the licensing for the following Nuclear Phase.

The corresponding TBM-Program Master Schedule showed that the planned delivery dates for the six Test Blanket Systems (TBSs) were planned for the TBSs installation for Assembly Phase III (due date Dec-2029). As in the previous schedule, the TBS Connection Pipes system has to be delivered significantly earlier, before the First Plasma, with due dates spread between 2020 and 2022.

The Task Force on the TBM Program Safety Demonstration, created by the TBM-PC since 2014, completed the first review of the IM’s input documents, documented the gap analyses, and made a first round of improved inputs. A significant degree of harmonization in the TBS descriptions had already been achieved. Main topics addressed were the approaches for TBS nuclear analyses,

tritium transport modelling, and accident analyses, and their validations. Supporting benchmark activities were monitored. A benchmark on tritium modelling was launched.

The last meeting of the TBM-PC (TBM-PC-17) was in May 2017.

6.18.7 The ITER TBM Project Team (2018 – 2024)

Under the IO proposal, the IC replaced the TBM-PC with a new TBM Project Team organization in 2018 that corresponds to the present TBM Program organization. The TBM-PT is governed by a Steering Committee (SC) chaired by the DG (or delegate) with official representatives of the seven IMs. The SC has nominated a Project Team Leader and the seven IM TBM-PT Representatives.

Two major events occurred in the first two years of activities of the TBM-PT that significantly impacted the TBM Program.

First, the EU has decided to replace the HCLL-TBS with its water-cooled version, the WCLL TBS. The revised TBMA, officially confirming this change and the acceptance by the IO, was signed in May 2020. The WCLL-TBS CDR was performed on the 16-19 September 2020.

Secondly, under the IO proposal, the IC-23 (November 2018) has agreed to reduce the number of equatorial ports dedicated to the TBM Program from 3 to 2. The port #2 became an additional port dedicated to the Disruption Mitigation System (DMS). The implication was that only four TBSs can be simultaneously tested and, therefore, the process of selection of the four TBSs started.

Several months of discussions within the TBM-PT have occurred, mostly based on installation sequence strategy and on domestic budget availability. TBM-PT promoted the possibility of collaboration between IMs as one way of reducing the number of TBSs.

EU and KO started discussions and negotiations to perform a joint project on the He-cooled ceramic breeder blanket, based on the work done for the HCPB-TBS and for the HCCR-TBS. After months of negotiations, an Agreement was signed between EU and KO for the joint development of one TBS with a budget and effort sharing of 60(KO)/40(EU), technically based on the HCPB-TBS CD and with KO as TBM Leader. The common TBS design took the name of Helium-Cooled Ceramic Pebble (HCCP) TBS having the same operating conditions as the HCPB-TBS.

India decided to develop an He-cooled solid breeder TBS but, because of lack of budget, with the objective to deliver it a later stage.

The TBS Initial Configuration

This section has been written using the following reference: L.M. Giancarli, X. Bravo, S. Cho, M. Ferrari, T. Hayashi, B-Y. Kim, A. Leal-Pereira, J-P. Martins, M. Merola, R. Pascal, I. Schneiderova, Q. Sheng, A. Sircar, Y. Strebkov, J. van der Laan, A. Ying, “Overview of recent ITER TBM Program activities”, Fusion Engineering and Design 158 (2020) 111674 [25].

Following the considerations mentioned above, TBM-PT made the proposal to agree, at first, on four TBSs to be tested during a first set of ITER campaigns and then, to test other TBSs in replacement of the initial TBSs during a second set of ITER campaigns.

As conclusion (still valid today), it was decided to have a TBS “Initial Configuration”, operated during PFPO-2, FPO-1 and FPO-2, based on the following 4 TBSs:

Port #16:

- The WCLL-TBS, developed by EU. It includes the following sub-systems: the lithium-lead system, the water coolant system, the coolant purification system, the tritium extraction system, the tritium accountancy system, and the instrumentation and control systems (including the neutron activation system).
- The HCCP-TBS, jointly developed by EU and Korea. It includes the following sub-systems: the helium coolant system, the coolant purification system, the tritium extraction system, the tritium accountancy system, and the instrumentation and control systems (including the neutron activation system).

Port #18:

- The WCCB-TBS, developed by Japan. It includes the following sub-systems: the water coolant system, the tritium extraction system, the tritium accountancy system, and the instrumentation and control systems (including the neutron activation system).
- The HCCB-TBS, developed by China. It includes the following sub-systems: the helium coolant system, the coolant purification system, the tritium extraction system, the tritium accountancy system, and the instrumentation and control systems (including the neutron activation system).

It was agreed that after these testing campaigns, a TBS “Second Configuration” would be defined, with priority for the He-cooled ceramic breeder TBS proposed by India and for the dual-coolant proposed by US, to be tested from FPO-3 and beyond.

It was also decided that, because of the space limitation in the port cells shafts, the TBS coolant connection pipes design was limited to only two coolant systems for each port cell (each one with one inlet pipe and one outlet pipe). In the “Initial Configuration” there is one water-cooled TBS

and one He-cooled TBS in each TBM port cell. However, it is expected that in the “Second Configuration” there could be additional proposals of He-cooled TBSs or of dual-coolant type TBSs in replacement of one water-coolant TBSs.

Therefore, it was decided to design and procure the water-coolant pipes considering the possibility of being used for helium at a later stage (i.e., dual-function strategy that is accepted by regulations if envisaged since the beginning). This decision could allow to install in the “Second Configuration” an additional He-coolant TBS or even the dual-coolant TBS requiring the use of four He-coolant pipes (in this case, the DCLL-TBS would be alone in one port).

This proposal was endorsed by the TBM-PT-SC.

The view of the four TBSs of the “Initial Configuration” is given in Figure 6.18.7-1. For these four TBSs, a Preliminary Design Status Assessment (PDSA) was performed in early 2023 where all the available details were assessed with the identification of the missing items/analyses that would be required to perform the Preliminary Design Review.

The TBSs will be operated simultaneously from the ITER control room in synchronization with the ITER operations.

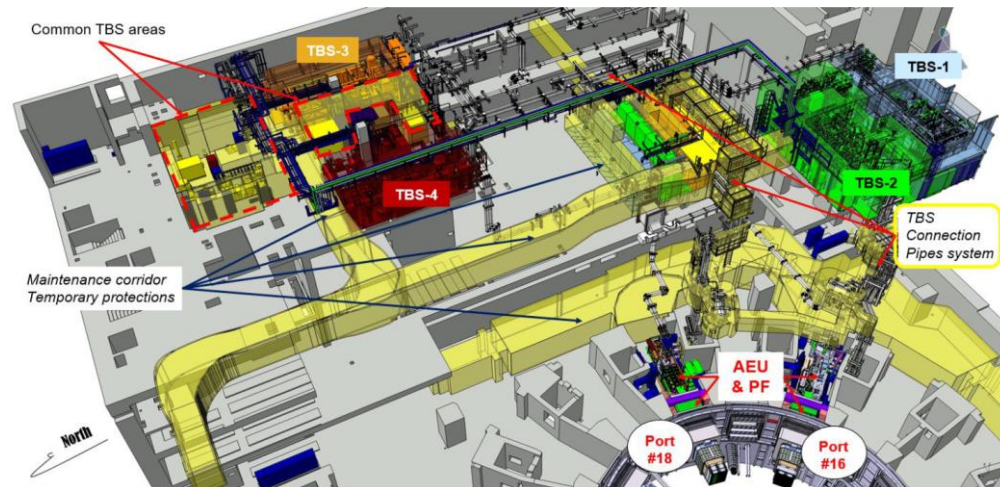


Fig. 6.18.7.1 : Overall view of the four Test Blanket Systems of the TBS Initial Configuration.

Testing Plan for the TBS Initial Configuration

The testing of the four TBSs of the “Initial Configuration” is expected to start at the beginning of the PFPO-2 using the PFPO-2-TBMs (see Figure 6.18.7-2) that are similar with the previous EM-TBMs. The name was changed in order to stress that each TBM design version is strictly related to the operation conditions of the specific ITER phase.

In the following phases, the TBMs are expected to be replaced during each Long-Term Maintenance (LTM) shutdown with new TBM versions called FPO-1 TBMs and FPO-2 TBMs.

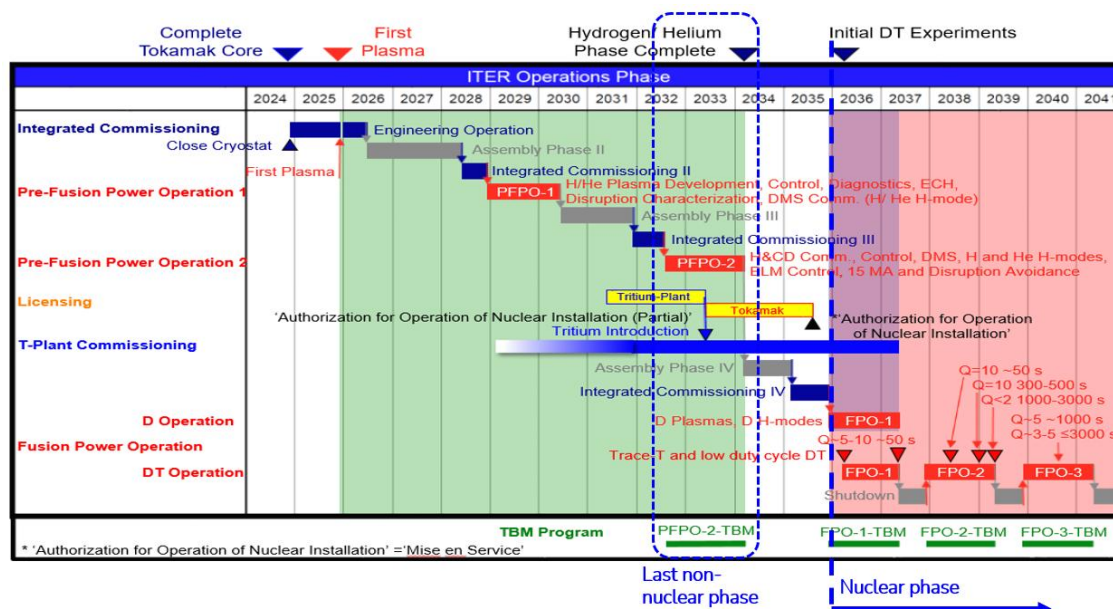


Fig. 6.18.7.2 : TBMs testing synchronized with the planned ITER operations during the ITER Staged Approach.

For FPO-3 and beyond, the testing of the TBSs of the “Second Configuration” could be performed. It was assessed that, for a typical LTM duration of 8 months, it is only possible to replace the TBM types but not the associated ancillary systems components. Therefore, any new TBM should be compatible with the existing ancillary systems. To replace a whole TBS, as it would be needed for installing a DCLL-TBS, a significantly longer LTM shutdown duration would be needed.

6.18.8 Examples of R&D Activities Performed by the IMs for Accompanying the TBM Program over the Years

Since the ITER CDA phase, many R&D activities on TBBs have been performed worldwide. The activities cover the development of specific materials and associated performance, of specific components to be operated in relevant reactor conditions, and the construction of appropriate test facilities and experimental loops. The outcomes of these activities were initially devoted to the development of TBBs designs for DEMO reactors and then supporting the TBM Program since mid-1990 (see sections 6.18.2-7) until today.

The TBB-related R&D results have been used in support of the various proposals of TBSs made over the years by the various IMs and the corresponding references are listed within the main “overviews” documents referenced above.

It is not in the scope of this document to describe the various R&D achievements; however, this section gives a few examples of R&D topics addressed by the various IMs since the beginning of the TBM Program and a non-exhaustive collection of relevant references available in the literature where many more details can be found.

TBM Program R&D in China

For the CN HCCB TBM design, at first SWIP proposed its design with the size of 1/4 ITER equatorial port in 2003 and then proposed several designs from 2004 to 2014 with different number of sub-modules and different breeding zone layout [26], [27], [28]. Since the beginning of PD phase in 2015, the whole TBM design has been largely optimized considering fabrication feasibility and reduction of ferromagnetic structural material [29]. During the development of HCCB TBM, CN HCCB TBM team gained a lot of experience regarding interface control, material databases, design standards, design procedures, analysis guidelines, load specifications, etc., which are very important for all key components design.

Development of TBM fabrication [30] - For fabrication technology R&D of complicated TBM geometry, HIP was considered as the main integration process, and one 1/3 size trial was fabricated. However, as 100% NDT could not be performed with the structure, and it was difficult to guarantee its structural integrity, HIP technology was not authorized by French regulation and standard. Therefore, since the beginning of PD phase in 2015, further design optimization mainly focused on simplification of the structure, considering application of mature welding technologies (e.g., EB and LB welding). Mockups of several sub-assemblies were manufactured and finally one 1/2 size mockup was successfully fabricated. Within years of mockup fabrication experience, CN HCCB TBM team has gained a lot of lessons and feedback regarding welding and inspection procedures. In order to meet the requirements from IO and French regulations, CN HCCB TBM team is under consultation with one ANB company in France and trying to make further design improvements regarding fabrication and inspection feasibility.

Structural materials development [31], [32], [33] - The structural material of the CN HCCB TBM is CN-RAFM steel developed by China. Two CN-RAFM steels (CLF-1 and CLAM) have been developed from the beginning of the 21st century. The production capacity increased from several kilograms to 1 ton-scale during the first phase (2001~2014) and up to industrial scale production (i.e., 5t) was developed in a second phase (2014~2021). The engineering qualification of CN-RAFM steels is under way since 2021, and the development of the database for the structural material is in progress.

Tritium breeder material development [34] - The tritium breeder materials of the CN HCCB TBM are CN-Li₄SiO₄ ceramic pebbles developed by China. While tritium breeder materials have been studied and investigated since the 1980s based on the requirements of hybrid fusion-fission reactor (HFR), the development of a large-scale fabrication process for the Li₄SiO₄ pebbles began in the early 21st century and engineering qualification is on-going. Currently, an industrial-scale

production process with a production capacity of 1-ton per year has been achieved. In order to verify the stability of production and performance, the engineering qualification of the CN-Li₄SiO₄ pebbles is under way, including the batch production and testing.

Neutron multiplier material development [35] - The neutron multiplier materials of the CN HCCB TBM are Be pebbles developed by China. The beryllium pebbles were fabricated by the Rotating Electrode Process (REP) method. The beryllium pebbles have been developed since 2010. After numerous production process optimizations and production equipment upgrades, the production capacity of beryllium pebbles increased from a few hundred grams to industrial scale production (i.e., 2t). The engineering qualification of the CN-Be pebbles is under way to verify the stability of production and performance of beryllium pebbles.

Tritium permeation barrier coating development - Advanced tritium permeation barrier was developed by China. Al₂O₃ coatings with high PRF (Permeation Reduction Factor) were prepared by several different techniques, including wet chemical method and physical method. To further improve corrosion resistance and anti-irradiation property, composite coating, including Al₂O₃/Cr₂O₃ and ZrN/ZrO₂, was developed and studied [36]. To evaluate the hydrogen permeability of the coating or structural materials accurately, China developed gas driven permeation method and electrochemical hydrogen permeation testing method. The device could get hydrogen isotope permeation data under corrosion or ion irradiation environments.

TBM Program R&D in EU

Breeding blanket R&D has been performed in EU since the 1980's in the framework of DEMO studies and then in support of the TBM Program since the 1990's [37], [38], [39] until the present days.

Initially, the R&D was mainly addressing structural materials and functional materials and then pursued in concept and manufacturing validation including the manufacturing of many mock-ups and the construction of testing facilities.

In the framework of the EU TBM Program, for the structural materials the focus has been on the development of a low-activation ferritic/martensitic steel, in particular the EUROFER whose industrial production and characterisation have been on-going since the 1990's [40], [41], [42], [43]. Concerning breeder materials, the eutectic Pb-16Li is the leading material for liquid breeder, and the ceramic Li₄SiO₄ and Li₂TiO₃ are the most studied solid breeders. Several irradiation experiments on structural materials and on breeder materials have been performed over the last 30 years.

Moreover, experimental activities on PbLi/RAFM steels (mainly EUROFER97) compatibility have been carried out in different European labs while particular attention was given since the late 90s to the experimental and modelling study of the PbLi/water interaction.

More information on the EU activities at the time of the TBWG can be found in many papers available in the literature, for instance in the references [\[44\]](#), [\[45\]](#).

In the last two decades another important area of R&D has been the development of tritium processing technologies: worth to be mentioned are the permeation-based tritium concentrators in PbLi, tritium extraction technologies from PbLi (gas-liquid contactors and permeator against vacuum) and tritium concentrators in gas phase (e.g. ZrCo getter beds, zeolite adsorption beds). In this context, a relevant effort has been spent on the development and verification/validation of tritium transport simulation tools at TBS/TBB system level, based on the simulation EcosimPro platform.

TBM Program R&D in India

The main R&D activities performed in support of the LLCB-TBM design (most of these applicable also to the helium-cooled solid breeder TBM design) were the development of RAFM steels, the lithium ceramic (lithium meta-titanate and lithium ortho-silicate) pebble fabrication route, the compatibility between RAFM steel and lead–lithium eutectic (e.g., corrosion performance) including the construction of a PbLi loop, alumina coating experiments related to MHD insulation, tritium extraction efficiencies both from PbLi and helium.

The Indian TBM R&D program is focused on the development and characterization of TBM materials such as, IN-RAFM steel structural material, functional materials (Pb-16Li, Li_2TiO_3), development of liquid metal technologies, tritium technologies and manufacturing technologies for the TBM system. India has also commissioned a high-pressure (8.0 MPa), high-temperature (300–450°C) Experimental Helium Cooling (EHCL) system which is a prototypical facility for testing helium cooled tritium breeding blanket mock-ups and other components of fusion system such as divertors and lead lithium-helium heat exchangers.

More information on these activities in India can be found in the literature, for instance [\[46\]](#), [\[47\]](#), [\[48\]](#), [\[49\]](#), [\[50\]](#), [\[51\]](#).

TBM Program R&D in Japan

Breeding blanket R&D has been performed in Japan since the 1990s in the framework of DEMO studies until the present days and then used in support of the TBM Program covering several types of breeding blankets [\[52\]](#).

One of the primarily R&D is the development of a domestic RAFM steel, called F82H, with both out-of-pile and in-pile testing, partly in the framework of international collaboration [\[53\]](#).

Other R&D topics specifically for WCCB-TBM are out-pile and in-pile R&D, neutronics and tritium production tests with 14MeV Neutrons and tritium recovery system development. Out-pile R&D

consists of the development of blanket module fabrication and the development of thermo-mechanical and chemical compatibility design database of breeding region of the blanket. In-pile R&D consists of the development of irradiation technology for partial blanket mock-ups in fission reactor, the development of fabrication technology for breeder and multiplier pebbles, and irradiation tests of breeder and multiplier pebble beds.

More information on these activities in Japan can be found in the literature, for instance [\[54\]](#), [\[55\]](#), [\[56\]](#), [\[57\]](#), [\[58\]](#), [\[59\]](#).

TBM Program R&D in Korea

The ITER project began with the Conceptual Design Activities (CDA) phase in April 1988. The work was carried out jointly by physicists and engineers of the four IMs in order to be sure of building consensus and of aiming at the construction of a common device after the weak attempts during the INTOR studies to come to an agreement on the way ahead in fusion.

The main R&D activities carried out since mid-2000 in support of the Korean TBM Program covered:

- (i) structural materials and joining technology development including their DB establishment;
- (ii) functional materials like ceramic breeder material (i.e., Li_4SiO_4 and Li_2TiO_3) and graphite pebbles as a reflector material development, and their database establishment;
- (iii) safety analysis code development and verification & validation;
- (iv) high heat flux test facility and He loop construction for testing the fabricated TBM, its mock-ups, and prototype.

More information on these activities in Korea can be found in the literature, for instance [\[60\]](#), [\[61\]](#), [\[62\]](#), [\[63\]](#), [\[64\]](#).

TBM Program R&D in Russian Federation

Three blanket options were chosen in the RF for fusion DEMO reactor: self-cooled Li/V-alloy, HCCB and LLCB [\[65\]](#), [\[66\]](#). Design development of TBMs and R&D was conducted for all these options in the frame of ITER TBM activity [\[67\]](#), [\[68\]](#), [\[69\]](#).

Structural materials: V-4Cr-4Ti alloy for Li blanket and low activation Ferritic/Martensitic steel (FMS: Fe-12Cr-2W-V-Ta-B) for two other blanket options were developed and characterized, including tests in fission reactors [\[70\]](#).

Electro-insulating coatings/barriers were developed for Li/V and PbLi/FMS systems [\[71\]](#).

TBM mock-ups with modeling liquid metal were tested in a magnetic field to check MHD and HT codes [72].

Liquid metal technologies were developed for Li/V and PbLi/FMS systems.

Manufacturing, in-pile testing and post-irradiation examinations of tritium breeding zone models for HCCB TBM (Li_4SiO_4 pellets + porous beryllium and Li_4SiO_4 pebble + Be pebble-bed) were performed [73], [74], [75].

TBM Program R&D in USA

During 1995 and 1996, the US Home Team undertook significant research and development (R&D) on an advanced lithium/vanadium breeding blanket. The primary objective of this endeavor was to establish a robust database and validate the efficacy of the liquid lithium-vanadium advanced blanket design.

This project encompassed two principal activities as described in Ref. 72. The first activity involved a series of subtasks aimed at vanadium alloy development. These included determining the baseline mechanical properties of non-irradiated base metal and weld metal joints, assessing compatibility with liquid lithium, conducting material irradiation tests, and refining material manufacturing and joining methods. The second activity was centered on the development of a liquid lithium-vanadium advanced blanket with an insulator coating. This involved efforts to develop electrical insulation and conduct testing for liquid metal systems, study the magnetohydrodynamic pressure drop and heat transfer for self-cooled liquid metal systems, explore the chemistry of liquid lithium, and engage in the design, fabrication, and testing of ITER-relevant size mock-ups. The results of these US activities were considered in US and in RF for the development of a liquid lithium/vanadium alloy TBMs.

During the ITA phase, the US R&D focused on ceramic breeder materials and on support to the DCLL-TBS design [76], [77], [78]. In 2007, a detailed report was prepared to provide technical insights, execution plans, and cost estimates for the United States' involvement in the ITER TBM Program [79]. This initiative was prompted by a request from the Office of Fusion Energy Sciences within the US Department of Energy (DOE), aiming to assist the DOE in selecting a specific strategy. The report emphasized DCLL as the primary blanket concept chosen by the US TBM team for testing in ITER. The report outlined a series of R&D tasks that directly contributed to crucial design and fabrication decisions, addressed TBM safety issues and reliability risks, and were necessary to understand, operate, and analyze US TBM experiments in ITER. Despite the comprehensive execution plan, it was not implemented [80].

To study the multiple effects of liquid metal (PbLi) magnetohydrodynamic (LM MHD) flow with heat transfer, an out-of-pile MaPLE-U facility was constructed [81]. Initial experiments were conducted at UCLA, with subsequent experiments being carried out at KIT (Germany) [82].

6.18.9 The ITER Baseline 2024, the TBM Program Research Plan and Future Planned Activities

In 2023, the ITER Project started a deep revision of its operation plan and of the corresponding Research Plan that has led to the new ITER baseline 2024.

The ITER baseline 2024 (see Figure 6.18.9-1) consists of an initial phase, called “Start of Research Operation (SRO)”, lasting about two years, in which H-mode operation in Deuterium-Deuterium (DD) plasmas is planned. This phase is followed by a “DT-1” operation phase that includes the achievement of $Q = 10$ operation for 300–500 s in Deuterium-Tritium (DT) plasmas with a limited neutron fluence (about 1/100 of the present end-of-life Project Specification) and the demonstration of the integrated fusion engineering. Finally, a “DT-2” operation phase is planned with the target to achieve all the ITER Project Specification goals.

The phase DT-1 is divided into five campaigns FPO-1 to FPO-5, each of them lasting two years (16 months operations and 8 months of Long-Term Maintenance (LTM) shutdown). FPO-1 campaign includes both H and DD plasmas with addition of tritium traces towards the end. The FPO-2 campaign is largely made with DD plasma and some DT plasma pulses. In the FPO-3 campaign is mainly D-T plasma pulses with short length (~50 s) and aims to the achievement of $Q=10$ objective. FPO-4/FPO-5 aims to long DT-pulse up to ~300s.

Updated TBM Program Research Plan – Level 1 (TBM-RP/L1)

Within this 2024 baseline, the TBSs are planned to start the operation at the beginning of DT-1 with the initial objective of being able, for the first time, to simultaneously operate and control four TBSs and all the associated sub-systems from the centralized ITER control room.

The four TBSs of the “Initial Configuration” are expected to be installed just after SRO and start operation in FPO-1 and go on until FPO-4/FPO-5. As in the past, the TBS testing strategy is to test different design versions of the corresponding TBM concept, each of them adapted to the operational plan of ITER. This strategy implies that each TBM will have to be replaced several times requiring the removal and the re-installation of the TBS components present in the TBM PCs. The newly adopted TBM replacement strategy is to substitute a whole TBM PP with a new one during each LTM shutdown without reusing the TBM frames (as foreseen in the past).

In early 2024, an assessment has been completed [\[83\]](#) to determine if the objectives of the TBM Program can be achieved during DT-1, despite the low cumulative neutron fluence. It was concluded that to achieve most of the objectives, especially the ones related to tritium processing, and to have reliable measurements results, it is required to have some ITER operational days fully dedicated to the TBM Program with the following main characteristics:

- A Fusion Power of at least half of the maximum ($\sim 250\text{MW}$). It gives sufficient heat loads on the TBM first wall and first wall neutron-wall loading to achieve a sufficient tritium production rate.
- A pulse length with a flat top of at least 300s to achieve the thermal quasi-steady state in TBMs.
- A high repetition time, for instance having around 32 “back-to-back” pulses for 16h (a day with 2 shifts), to achieve a pseudo equilibrium among the various tritium-related characteristics (i.e., production, extraction, permeation and coolant tritium purification).

Other specific requirements (defined as TBM Program “Minimal Requirements (MRs)”) have also been made such as for instance: (i) to implement plasma pulses in HH and DD phases with flat top (FT) duration $\geq 450\text{s}$ and surface heat flux $\geq 0.20\text{MW/m}^2$; (ii) to have available in the TBM port cells additional ordinary load (OL) electrical power (few hundreds of KW), in order to be able to compensate the lack of neutron volumetric power within the two TBMs during the DT-1 campaigns; (iii) to have more than 20 long isolated pulses with DT plasma, relatively high fusion power & long pulse FT duration ($\text{FP} \geq 350\text{MW}$, $\text{FT} > 450\text{s}$); (iv) to have several isolated pulses with DT plasma with fusion power of 500 MW (even with relatively short FT duration $> 50\text{s}$).

These TBM Program requirements have been agreed and implemented in the ITER Research Plan – Level 1 endorsed by the IC in June 2024. Therefore, the Level 1 of the TBM Program Research Plan (TBM-RP/L1) has also been completed and integrated into the ITER Research Plan-Level 1 [84].

In the TBM-RP/L1, the main identified Top-Level Objectives (TLOs) during DT-1 are similar to the initial TBM Program objectives and have been confirmed to be the following:

- TLO-1: Validation of structural integrity theoretical predictions under combined and relevant thermal, mechanical and EM loads.
- TLO-2: Validation of tritium breeding predictions.
- TLO-3: Validation of tritium recovery process efficiency and T-inventories in the relevant TBS materials.
- TLO-4: Validation of TBM thermal-hydraulic predictions with volumetric heat sources.
- TLO-5: Validation of main technologies relevant for future fusion reactors.
- TLO-6: Demonstration of the integral performance of the TBS sub-systems, including the achievement of coolant thermo-hydraulic parameters compatible with those required for high-efficiency electricity production.

The achievement of these objectives during DT-1 would be considered very important for the next-step DEMO breeding blanket design and manufacturing.

Most of the TLOs can be achieved progressively in one or more FPOs. Starting with these TLOs, several lower-level objectives have been identified for each campaign, the so-called Campaign Testing Objectives (CTOs). The achievement of each CTO requires the availability of some MRs, the implementation of specific instruments, the implementation of some TBM/TBS design changes specific to each campaign and the performance of some Post-Irradiation Examinations (PIEs) in IMs premises on shipped TBM samples.

Some examples of CTOs with initial considerations on how they can be achieved are the following:

- Capability of TBMs to withstand disruptions. It is driven by plasma current and plasma performance perturbations. It is needed to integrate appropriate strain gauges and displacement sensors in the TBMs.
- Thermo-mechanical gradients in the specific TBM FW to check its structural load capacity; typical thermal response time constant of the TBM FW is 80-100s. Electrical heaters were added within the TBMs to compensate for the low volumetric heat produced by neutron for most DT-1 campaigns. Typically implemented measurements devices include thermocouples and strain gauges.
- Thermomechanical load capacity of the whole TBM-box; the corresponding time constant is of some hundreds of seconds. Electrical heaters are implemented. Typically implemented measurements devices include thermocouples and strain gauges.
- Capability of circulating the lithium-lead (melting point: 235°C) in high magnetic field. Typical devices are mass flowmeters and pressure drop detectors compatible with the LiPb.
- Capability to extract efficiently tritium from the lithium-ceramic pebbles and to verify pebble-beds performance (electrical heaters are implemented in order to reach sufficiently high temperatures, up to peak temperature of 800°C-900°C for the pebble-beds testing). Typical devices are thermocouples and devices measuring the tritium concentration (mainly ionization chambers) in various TES locations.
- Capability to extract efficiently tritium from flowing PbLi. This requires the use of PbLi flowmeters, thermocouple and tritium concentration sensors in PbLi and in gas (helium) phases.
- Demonstrate the tritium extraction efficiency of the TESs. The TBM/TBS design is driven by the tritium concentration reached in the purge gas; it is needed to reach quasi-equilibrium of the tritium concentrations in the various TBS components (time constant of some thousands of seconds). Specific devices need to be developed to measure tritium concentration in various TES locations.
- Estimate the tritium permeation into the coolant and the required tritium coolant purification system efficiency for the He-coolant based TBSs. As in the previous topic, it is needed to reach quasi-equilibrium of the Tritium concentrations in the TBS various components. Specific devices might need to be developed to measure tritium concentration compatible with high-temperature high-pressure environment.

It is stressed that the reduced neutron fluence in DT-1 compared to the previously expected value does not allow us to obtain significant data on the TBM materials behavior under neutron irradiation. However, as explained in the previous chapters, since the beginning the obtention of this data was not among the objectives of the TBM Program because of the low neutron fluence expected in ITER compared to DEMO anyway. It was always considered that these data should be obtained from other specific facilities that should be dedicated to test high-fluence irradiation effects on breeding blanket (such as “neutron source” facilities for material testing or “volumetric neutron source” facilities for blanket mock-ups testing).

Future Planned Activities

Based on the ITER Baseline 2024, the TBM-PT has revised the TBM Program schedule (see Figure 6.18.9-1). The delivery dates of the four TBSs are now planned for early 2036.

All the design activities concerning the TBSs of the “Initial Configuration” are in the preliminary design phase and will be completed on time for the TBSs Preliminary Design Reviews planned in 2026.

The TBM Research Plan – Level 2 (TBM-RP/L2) has been developed in 2025 starting from the TBM-RP/L1. The TBM-RP/L2 preliminary describes the way of obtaining the relevant experimental data in each FPOs, including the design of required instrumentation and sensors, their integration in the TBS designs and the associated modeling activities necessary to extrapolate the obtained results to DEMO [85].

TBS safety-related aspects will be further developed in the next few years in order to contribute to the preparation of the revised version of the ITER RPrS (Rapport Preliminaire de Sureté) planned in late 2027.

As described in previous chapter 6.18.8, significant R&D is on-going and will continue to be performed by the IMs to validate the TBS design choices, the manufacturing technologies, and the TBS operation plan, with the objective to be completed on time for the corresponding FDRs (planned in 2029).

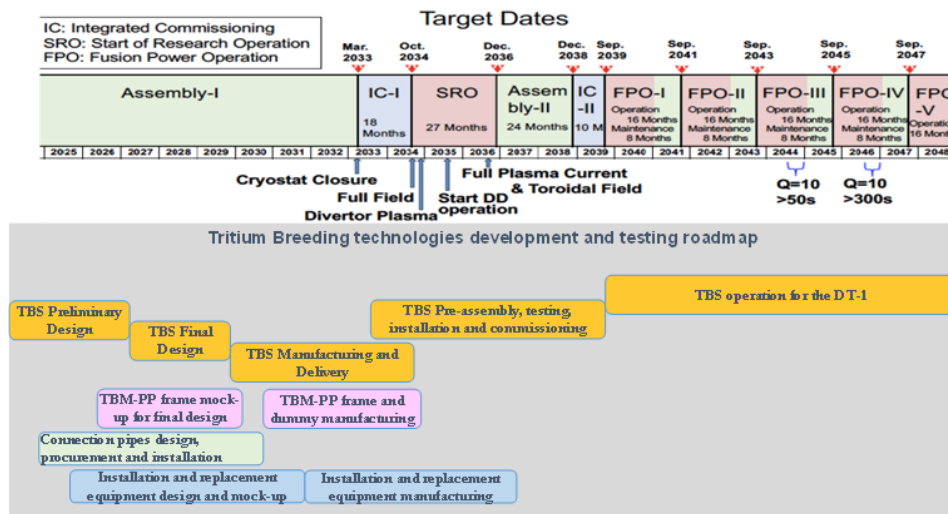


Fig. 6.18.9.1: TBM-PT development and testing roadmap in the ITER Baseline 2024.

Executive Summary – Main Impacting Events in the Evolution of the TBM Program and Associated Lesson Learned

The TBM Program holds a special place in the history of ITER. Although one of the main ITER's missions has always been to “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”, let's say it clearly: the initial design of ITER and its major evolutions have never been driven by this mission. Over the years, ITER did maintain a capacity for testing TBBs for future fusion reactors (e.g. DEMO); however, since these technologies are not needed in ITER, they are developed as part of an independent program (i.e., the TBM Program) that uses ITER as a testing facility, although being fully integrated in ITER.

Since the 90's and still today, the development of TBBs for future fusion reactors and of their test version for ITER, called TBS, has been conducted by the IMs in the framework of domestic R&D programs. Although international exchanges between IMs on these technologies' development have always been promoted within the ITER framework, including collaboration both on design and on R&D, these programs remained fundamentally domestic and independent, with very little exception.

Strategic decisions, like TBB technological choices or evolution, remained solely in the hands of the IMs. The role of ITER was rather to ensure their acceptability in terms of space, design features harmonization, integration in the ITER machine, maintenance, safety, reliability, and the feasibility of testing operations by preparing the required infrastructures, e.g. interfaces with other ITER systems, maintenance tools and equipment. Along the evolution of the ITER design and the progress of its construction, these infrastructures and the projected test conditions in ITER have evolved, necessitating to adapt the TBM Program.

The history of the TBM Program in ITER is, therefore, first the history of innovative R&D domestic programs – the TBB technologies for fusion reactors – but implemented in an evolving test facility: the ITER machine. So, it may be today difficult to distinguish which one, either the domestic TBB R&D program or the evolution of ITER, was the driver of the TBS design appearing today. In summary:

- Since the ITER EDA in the 90s, the concept of equatorial test port plug emerged for testing in ITER TBB technologies developed in domestic R&D programs. Since the beginning, the focus was then on partially integrated medium-size *technological* testing (by opposition to small-size material testing like in “material-testing reactors”). Despite the best effort to maximize the test volume in the port, it became clear that a 20cm thick water/steel frame surrounding the testing modules was needed to provide neutronic and thermal isolation from the basic shielding blanket. However, IMs still hesitated between half-port and quarter-port modules. Indeed, up to three equatorial ports were envisaged in ITER for testing up to eight module concepts. The constraint of integrating the associated ancillary systems was identified later but did not constitute a driver at that time. Among the eight concepts envisaged, four were helium-cooled Li-ceramic, one water-cooled Li-ceramic, one water-cooled lead-lithium and two self-cooled Li/V alloy. The predominance of helium-cooled concepts using RAFM steel structure has, therefore, existed since its origin. It is still predominant in the TBM Program today. The temperature range of the helium coolant was still quite heterogeneous among the four concepts. However, it was clear that IMs aimed to operate these concepts in a domain requiring relatively limited material R&D. In contrast, other concepts, like the two self-cooled Li/V-alloy ones, offered more long-term potential but required R&D and safety efforts that might be too challenging to be pursued within the context of the ITER project. Regardless of the concept, IMs identified that, despite the long pulses of 1000s expected in ITER and projected plasma heat flux up to 0.5MW/m^2 and neutron wall loading close to 1MW/m^2 , a design adaptation was needed to get materials temperatures closer to those expected in a later DEMO. This ‘act-like’ design approach is still in use today.
- The EDA extension did not result in fundamental changes to the TBB testing program. There was some reduction in the loading conditions (typical pulse duration of 400s, heat flux of 0.1MW/m^2 and neutron wall loading of 0.78MW/m^2), and the notion of progressive testing phases in ITER became clearer. The concept of TBM ‘versioning’ with ad-hoc instrumentation was further developed, with module replacement synchronized with ITER maintenance phases. There was no change fundamentally in the TBB test concepts proposed, although their number was reduced to six, which allowed to adopt a half-port configuration for all modules: three He-cooled Li-ceramic (two horizontal, one vertical), one self-cooled Li/V-alloy (vertical), two water-cooled (Li-ceramic and lead lithium, both vertical). The impossibility of repairing modules in the ITER facility became clear. A progressive testing strategy with act-like TBMs and ad-hoc instrumented-modules was further developed. IMs were clearly counting on the most loaded D-T phase of ITER

operation to reveal synergetic effects in TBB technologies. The overall fluence limitation on modules was well identified, and it was clear that most material effects visible from 0.1-1MW-a/m² would not be attainable in ITER.

- The period of the ITA and the arrival (or return) of new IMs reactivated discussions on the format and content of the TBM program. Two new TBM proposals emerged: (i) the DCLL-TBS proposed by the US (and later by CN) and (ii) the HCLL TBS (the helium-cooled version of the WCLL). For the He-cooled concepts, the coolant operating conditions had then converged to the range of 300-500°C. Some variants in Li-ceramic breeder materials and in design (e.g., graphite back reflector) still distinguished the various concepts. Generally, this was a time of active domestic R&D programs worldwide (see Section 6.18.9), which contributed to reactivate the “fluidity” of proposals in ITER. It was clearly identified that there were too many concepts overall for a test configuration in ITER that was now quite well established, namely (i) use of half port modules, (ii) use of act-like TBM versions with ad-hoc instrumentation synchronized with ITER long-term maintenance shutdowns. Attempts to consider sub-modules tested in other “host” modules failed. The TBWG and exchange platforms among domestic programs went as far as possible, and the convergence had to come from the official ITER framework under parallel finalization.
- The TBM Program was not part of the ITER negotiations for reasons explained in the introduction, but the newly established ITER Agreement and its structured ITER Central Team in Cadarache created the conditions for IMs to converge on an agreed TBM Program in ITER. These conditions were essentially budget, schedule and regulation related. The IMs willing to maintain TBS in ITER had now to commit by contract with a nuclear operator. The first consequence was that longer-term concepts like self-cooled Li/V alloy or DCLL were withdrawn or left as an option for a later phase. Only TBM concepts using RAFM steels and helium or water-coolants were kept. Still the He-cooled Li-ceramic concepts were predominant with three TBSs, while three other concepts were WCCB, HCLL and a new mixed version of Li-ceramic and lead-lithium breeders (LLCB). In the TBM-PC, the notion of time constraint, budget commitment, safety and standardization occupied most of the effort of IMs and IO. As a result, six TBM Arrangements (TBMA) were signed between five IMs and IO, including the applicable IPRs. During that phase, mainly because of the IPRs conditions, there was no example of common TBSs, despite several attempts of the IO to foster that solution. Only the withdrawal of one TBM test port for another ITER technical obligation (disruption mitigation system) finally convinced two IMs (i.e., EU and KO) to co-develop one He-cooled TBS. However, this was, and still is, an exception within the TBM Program.

The recent definition of the 2024 ITER baseline and its drastic fluence reduction in the first DT-1 phase (~1% of the EoL fluence) has not induced fundamental changes in the TBM Program for the following two main reasons:

- The foreseen scenarios for plasma pulses (fusion power vs. duration) are such that the experimental campaigns relevant to achieve the TBM Program objectives in the area of validation of the tritium processing technologies and modelling are still retained;
- The study of the effects of neutron fluence on the TBM materials is not part of the TBM Program objectives.

The port allocation, the basic design of TBMs and their ancillary systems remained unchanged. The possibility of testing different TBSs is still available in the DT-2 phase that is expected to fulfill all the previous ITER objectives (including the total neutron fluence on the first wall of 0.3MWa/m^2). The need for electrical heating in TBMs to compensate for the lack of heating power and short pulses in first operational campaigns was identified, and a series of back-to-back pulses in later operation phase was negotiated. Under these conditions, the main TBM Program objectives can still be fulfilled in DT-1, even if some uncertainties still exist today.

The TBM program has converged to a more stable configuration with some valuable lessons learned over the years. Key points include:

- After many years of discussions between the IO and the seven IMs, the TBSs test configuration in ITER (TBS architecture, TBM concepts, test sequence, maintenance constraints, etc.) is now stabilized and cannot fundamentally change anymore. It corresponds to the maximum information an experimental machine, like ITER, may offer to the TBM Program, still clearly essential for TBM development. The main aspects are the following:
 - Installation of two vertical TBMs per port with an associated specific water-cooled TBM-shield (called TBM-Sets), integrated in a 20cm-thick water-cooled steel frame. The frame and the two TBM-Sets form the TBM Port Plug (PP) that is a unique component from the point of view of installation and replacement, meaning that a replacement of a TBM implies the replacement of the whole TBM PP. It can be planned only during an ITER LTM shutdown.
 - Availability of two equatorial ports dedicated to the TBM Program. Definition of the four TBSs forming the TBS “Initial Configuration”. Installation of the TBSs in the installation phase for TBSs operation starting at the beginning of the DT-1 phase.
 - Harmonization of the TBS operating parameters, in particular for He-coolant and Water-coolant systems.
 - Use of “act-alike” TBMs during the various FPOs.
 - Limitation to 1.3 tons of RAFM steel in order to limit to an acceptable level the impact on the ITER magnetic configuration.
 - Identification of the Pipe Forest and of the Ancillary Equipment Unit as the two self-sustained components common for the two TBSs present in the same port, which

- need to be independently transferred to the Hot Cell to proceed to the TBM PP replacement.
- The irradiated TBMs have to be exported from Hot Cell to the owner IM premises for Post-Irradiation Examinations.
 - The complexity of the TBS integration in ITER strongly limits opportunities for changes to the TBS concepts during DT-1. Changes could become possible for DT-2 if a sufficiently long shutdown is available between the two phases.
 - One of the major added values of ITER to the TBB technology testing programs will be to provide real and full experience of integration in a tokamak reactor (e.g. nuclear and thermal loadings, tritium management, licensing, pressure equipment regulation, maintenance, operation, etc.).
 - Since its beginning, the TBM Program has generated a large amount of R&D and corresponding publications in the literature as shown in the few examples given in Section 6.18.8. Significant supporting R&D, that required for component operation validation, is already planned in the next few years. It is recognized that many R&D activities addressed by the TBM Program during the design and manufacturing phases are already given and will give significant information in support of the design of TBBs of the next step machine. This aspect is very important because these R&D results will be available in the next few years, i.e., much in advance of the data that will be produced by the TBSs operations as defined in the TBM-RP/L1.
 - Collaboration between IMs has never materialized under the form of TBS co-development, with the only recent exception of EU/KO for the HCCP TBS. The independence of domestic TBB programs still prevail over the commonality of the test facility and the established Intellectual Properties make full collaboration between IMs difficult, unless specific IP agreements are negotiated. Therefore, today's collaborative actions among IMs in the ITER TBM Program are mostly managed by the TBM-PT and by associated coordination working groups. The TBS integration in ITER is managed bilaterally by the IO as nuclear operator and each IM, even if leading to the common objectives described in the TBM-RP/L1.

In conclusion, the ITER TBM Program is unanimously considered a unique opportunity and an essential step towards the definition of TBB for DEMO. The identified TBB test limitations, particularly the impact on materials properties of neutron fluence relevant for next step reactors (e.g., DEMO) call for domestic or collaborative explorations of complementary programs. These should include dedicated neutron source facilities for materials testing and volumetric neutron source (VNS) facilities allowing DEMO-relevant neutron fluence.

Glossary

BPP	Basic Performance Phase
CDA	Conceptual Design Activities
DCLL	Dual-Coolant Lithium Lead
DEMO	Next D-T fusion reactor after ITER
DFLL	Dual Functional Lithium Lead
DRP	Design Review gates (Preliminary)
DRF	Design Review gates (Final)
DT-1	Deuterium-Tritium phase 1
DT-2	Deuterium-Tritium phase 2
EDA	Engineering Design Activity
EPP	Enhanced Performance Phase
FPO	Fusion Power Operation (campaign)
HCCB	Helium-Cooled Ceramic Breeder
HCCP	Helium-Cooled Ceramic Pebble
HCCR	Helium-Cooled Ceramic Reflector
HCLL	Helium-Cooled Lithium Lead
HCPB	Helium-Cooled Pebble Bed
IMs	ITER Members (identified as ITER Parties before the signature of the ITER Agreement)
IPR	Intellectual Property Right
ITA	ITER Transitional Arrangements
LTM	Long-Term Maintenance
LLCB	Lithium Lead Ceramic Breeder
PbLi or Pb-16	Lithium-lead eutectic (it is usually mentioned as Pb-16Li- before 2010, in the literature it was identified as 17Li-83Pb)
RAFM	Reduced-Activation Ferritic/Martensitic (steel)
PP	Port Plug
SCLi	Self-Cooled liquid Lithium
TBB	Tritium Breeding Blanket
TBM	Test Blanket Module
TBM-PC	TBM Program Committee
TBMA	TBM Arrangement (similar to the ITER Procuring Arrangements but with additional aspects specific for the TBM Program)
TBM-PT	TBM Project Team
TBM-RP/L1	TBM (Program) Research Plan/Level1
TBS	Test Blanket System
TBWG	Test Blanket Working Group
WCCB	Water-Cooled Ceramic Breeder
WCLL	Water-Cooled Lithium Lead

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