Achievements of the Water Cooled Solid Breeder Test Blanket Module of Japan to the Milestones for Installation in ITER

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Abstract

As the primary candidate of ITER Test Blanket Module (TBM) to be tested under the leadership of Japan, Water Cooled Solid Breeder (WCSB) TBM is being developped. This paper shows the recent achievements toward the milestones of ITER Test Blanket Modules (TBMs) prior to the installation, which consists of design integration in ITER, module qualification and safety assessment. With respect to the design integration, targeting the detailed design final report in 2012, structure design of the WCSB TBM structure and the interfacing components (common frame and backside shielding) that are placed in a test port of ITER are presented. As for the module qualification, a real scale first wall mock-up fabricated by using Hot Isostatic Pressing (HIP) method by structural material of reduced activation martensitic ferritic steel, F82H, is presented. As for safety milestones, contents of the preliminary safety report in 2008 consists of source term identification, Failure Mode and Effect Analysis (FMEA) and identification of Postulated Initiating Events (PIEs), and safety analysis, are presented.

1. Introduction

Test Blanket Module examination project, in which breeding blankets are tested in genuine fusion reactor environment, is in proceed. Six TBMs will be tested in ITER simultaneously, under the leadership of different coutries. Water Cooled Solid Breeder (WCSB) TBM is being developped as the primary candidate of ITER Test Blanket Module (TBM) to be tested under the leadership of Japan.

To ensure the installation of reliable TBMs, it is necessary to show feasibility on the TBM milestones for installation in ITER. This paper summarizes the milestones and the achievements for the Japanese WCSB TBM toward the milestones.

2. Milestones of ITER TBMs prior to the Installation in ITER

FIG. 1 summarizes the milestones of the ITER and ITER TBMs. ITER is under construction toward the first plasma in 2016. Construction of ITER tokamak complex starts in 2009. Safety assessment by French authority begins in 2009.

Schedule of development of the ITER TBMs is defined according to the ITER schedule. Final target of development of the TBMs is installation of the TBMs in ITER, planned in 2015. Prior to that, some milestones of the ITER TBMs including milestones on design integration, module qualification and safety assessment should be achieved.

With respect to the design integration, it is necessary to show the consistency with ITER design on time with ITER design progress. According to the schedule of licensing to construct that begins in 2009, material composition definition for licensing was presented in 2007, and material characterization and fabrication process validation were presented in 2008. Auxiliary systems of the TBMs are under development, according to space requirement in advance to finalize the design of the ITER tokamak complex. Final target of the design work is the detailed design final report in 2012.

As for the module qualification, it is necessary to show fabrication capability and the integrity of prototypical size mockup in corresponding operation condition before the delivery of the TBM to ITER. For the qualification, some milestones are required. Japan party supposed the following milestones; fabrication of a small-scale mock-up in around 2010, thermal examination of the small-scale mock-up in around 2011, manufacture of a real-scale mock-up in around 2012 and thermal examination of the real-scale mock-up in around 2014. Japan party will carry out the real-scale mock-up examination according to the schedule of the small scale mock-up examination, so that the fabrication and the examination of the small scale mock-up may be omitted.
As for safety milestones, preliminary safety report of Japanese WCSB TBM was presented to the ITER organization in June, 2007, for description of TBM in ITER Preliminary Safety Report issued in Jan. 2008. To achieve the TBM examination in ITER, Japan party should present safety assessment report of the TBM to the French authority and the report should be authorized, which is supposed to be in around 2010 - 2012. According to the requirements in the licensing process, the report consists of source term identification, Failure Mode and Effect Analysis (FMEA) and identification of Postulated Initiating Events (PIEs), and safety analysis.

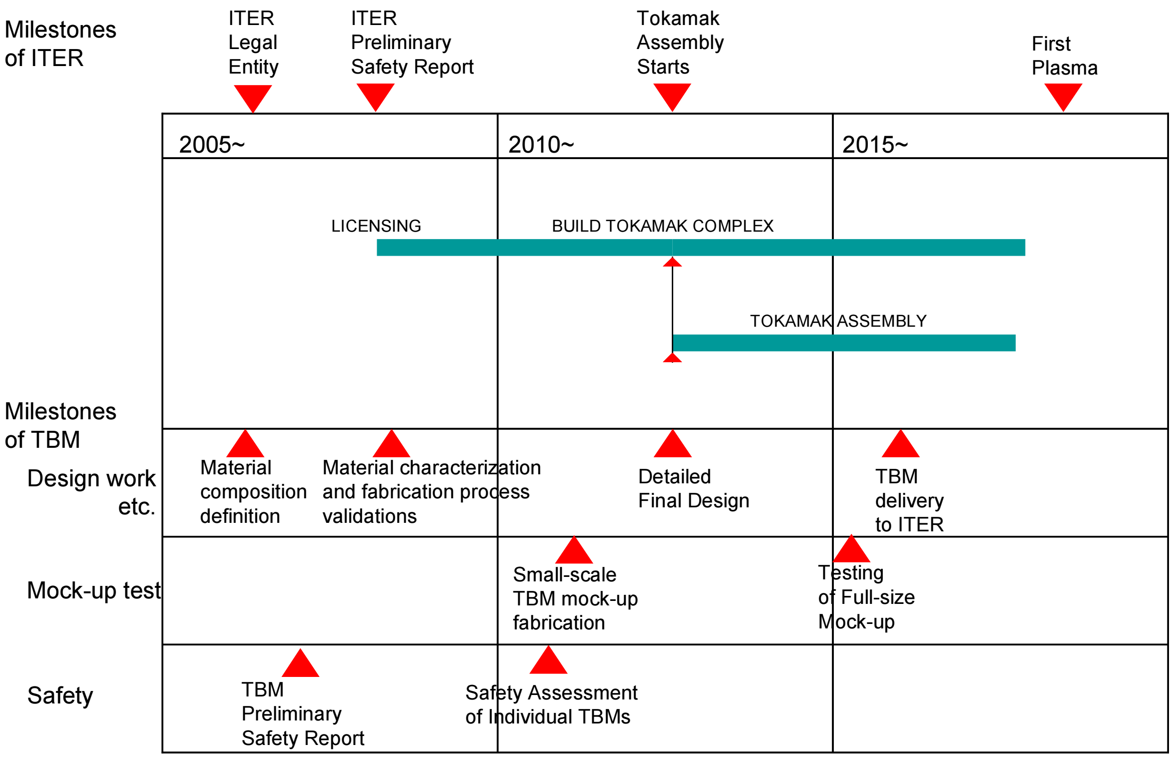


FIG. 1 Milestones of TBMs toward the installation in ITER

3. Progress of Structure Design of Interfacing Components

Toward the TBM final design report in 2012, structure design of the interfacing components between the WCSB TBM [1] and the ITER (common frame and backside shielding) has been developed. These interfacing components are placed in a test port of ITER, as shown in FIG. 2.
The structural materials of the TBM and the interfacing components are reduced activation martensitic ferritic steel F82H and SS316L, respectively. TBM is cooled with its own cooling

system and the interfacing components are cooled with ITER tokamak cooling water system. In the outer box structure of the TBM, pebbles of tritium breeder and neutron multiplier are packed forming layers. Between the layers, membrane panels with cooling pipes are settled and remove heat of the pebble beds by coolant water. At the first wall, beryllium armor tiles are laid.

In the structure design of the backside shielding, fabrication procedure and replacement procedure were also considered. By the developed structure design, consistency with ITER port structure and TBM interface structure was confirmed.

TBM has some own auxiliary systems, i.e., cooling system, tritium recovery system and diagnostics and control system. The design and layout of the auxiliary systems of the WCSB TBM are presented to the ITER organization to clarify the space requirement and interfacing conditions with ITER facilities.

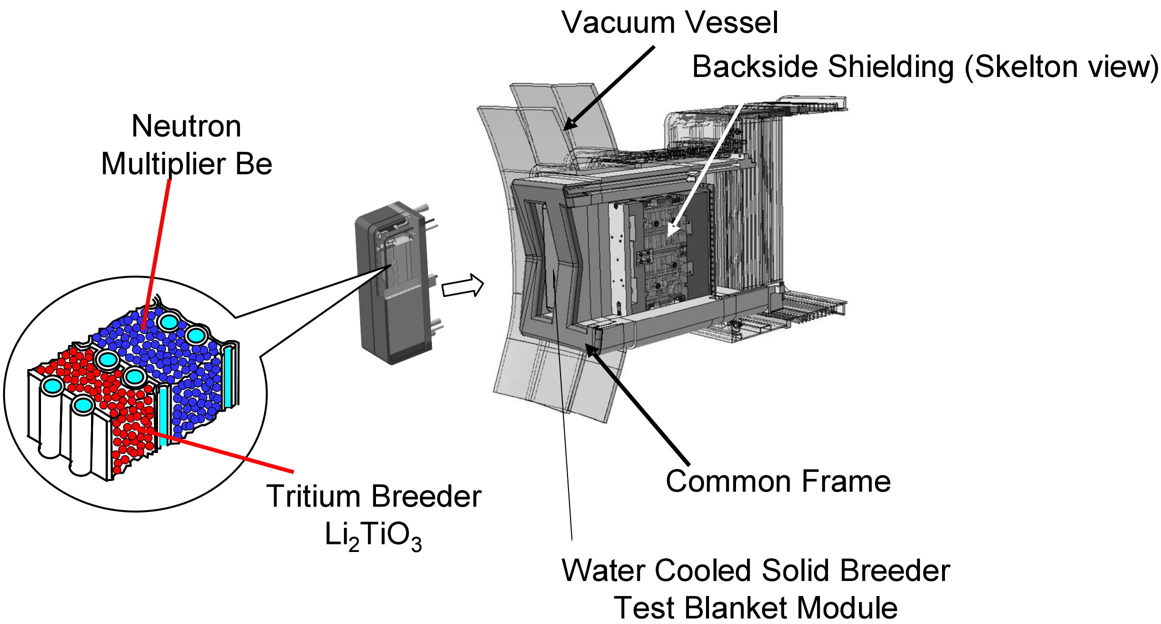
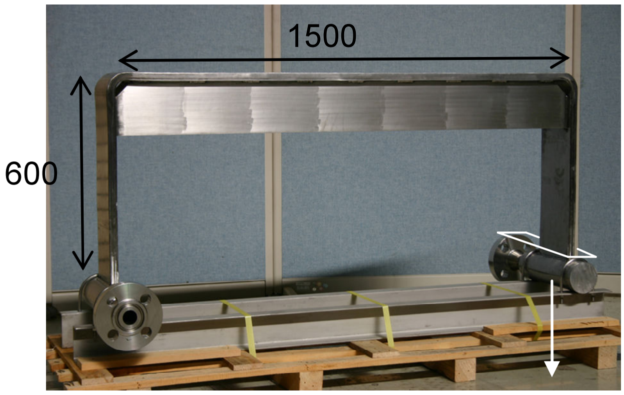


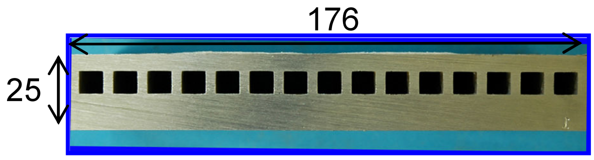
FIG. 2. Structure design of WCSB TBM structure and the interfacing components.

4. Achievement in Mock-up Testing

A real scale first wall mock-up was successfully fabricated by using Hot Isostatic Pressing (HIP) method by structural material of F82H. FIG. 3 shows appearance of fabricated mock-up and macro observation of the cross section of the first wall panel. Deformation of module structure after HIP was in the acceptable range from the view point of coolant flow distribution, heat removal capability and box fabrication. By the observation of HIP layer, it was confirmed that HIP joining process was successfully performed with no major pores along the HIP interface. High heat flux test with real cooling water condition of 15.5 MPa and 280^{o}C is planned using this mock-up. HIP Joining technology of first wall Be armor is also important technology because it directly affects the endurance of armor tiles and consequently ITER operation, which is also developed [2]. Other essential R&Ds for the WCSB TBM also showed steady progress on investigation of mechanical behavior of breeder pebble beds, development of advanced breeder/multiplier pebble, neutron measurement technology for TBM and purge gas tritium recovery technology [3].



Appearance of fabricated real scale TBM First Wall Mockup by F82H



Macro observation of Cross section of the first wall

FIG. 3. Real Scale Mockup of the WCSB TBM

5. Safety Assessments

Safety assessments including source term identification, Failure Mode and Effect Analysis (FMEA) and identification of Postulated Initiating Events (PIEs) [4], and safety analysis [5] are carried out.

5.1. Source Term Identification

For the source term identification, i.e., nuclear heating, tritium breeding ratio (TBR), decay heat and induced activity have been estimated by nuclear analyses, including the two dimensional neutron and gamma ray transport analyses by DOT 3.5 [6], nuclear reaction analyses and decay heat analyses by APPLE-3 [7] and time evolutions of induced activities evaluation by ACT-4 [8]. According to the estimation, maximum nuclear heating of TBM is as 11.4 W/cm^3 in F82H at first wall, total decay heat of the TBM is 48.2 W/cm-height after 1 second and 0.38 W/cm-height after 1 year and the induced activity of the TBM is estimated to be about 2×10^{14} Bq/kg of 1 day after shutdown. Tritium production of the TBM is estimated to be 5.0×10^{13} Bq/fusion power days (FPD) (0.134 g-T/FPD).
As the tritium is produced in the TBM and recovered in the TRS, the produced tritium is distributed in these components. Tritium inventory in purge gas is estimated by multiplying tritium concentration and volume of purge gas as 9.62×10^{11} B q/m^3 × 0.34 m^3 = 3.3×10^{11} Bq = 1 mg. Tritium inventory in the breeder pebble beds is estimated to be 1.37×10^{12} Bq for 37 kg Li_2TiO_3 pebbles, by the Nishikawa's tritium transport model [9].
A part of the generated tritium is considered to permeate into water coolant. Tritium permeation rate is estimated using Doyle's transport formulas [10] and Serra's method [11] and the maximum amount of tritium permeated into coolant after 10 years ITER operation is estimated as 8.1×10^{14} Bq (2.2 g-T). It is noted that this esitimation is very conservative and

these values are thought to be more than tenth larger than the real situation.
Activated corrosion product (ACP) generation is evaluated from the result of F82H corrosion experiment [12]. Total amount of ACP is estimated to be 0.0235kg, which is corresponding to 9.64×10^{11} Bq. It is noted that this estimation is conservative and these values are larger than the real situation.

5.2 FMEA and PIEs

To clarify the potential accident scenarios, Failure Mode Effect Analysis (FMEA) has been carried out for the WCSB TBM. According to the results of the FMEA, the possible event sequences were identified for the purpose of the quantitative analysis of their hazards. From these possible event sequences, representative events were selected so that they could become envelope cases of all possible events. Such representative events are called Postulated Initiating Events (PIEs). The selected PIEs have been categorized into the following three groups;

(A) PIEs about release of radiological isotopes
In normal condition, Radiological Isotope (RI) inventories are contained by physical barriers. The PIEs of this group are caused by rupture of the barriers. Exposure of the public due to the release of RI must be evaluated.

(B) PIEs about pressurization
The PIEs of this group are caused by rupture of a pressure boundary, e.g., pipes of cooling systems. Maximum pressures of the pressurized compartments must be evaluated.

(C) PIEs about heatup of the TBM
The PIEs of this group are caused by degradation of cooling or excessive heat load unexpected by the design. The maximum temperature of components and the soundness of the boundaries must be evaluated.

Safety evaluation of the WCSB TBM has been carried out on each PIE group.

5.2.1 Evaluation of PIEs about Release of Radiological Isotopes (A)

PIEs in group (A) are categorized into the following subgroups by each RI inventory;

(A1) Release of RI from the Vacuum Vessel (VV)
Tritium of 1 kg and radioactive dust (Be, C and W) of several hundreds kg.

(A2) Release of RI from the purge gas.
Tritium of 3.3×10^{11} Bq = 1 mg.

(A3) Release of RI from the cooling system
Tritium of 9.8×10^{14} Bq = 3 g (after 140 FPD operation) and Activated Corrosion Products (ACP) of 0.0235 kg, 9.64×10^{11} Bq (after 140 FPD operation).

FIG.4 shows the RI inventories and possible releasing paths of the RI inventories.

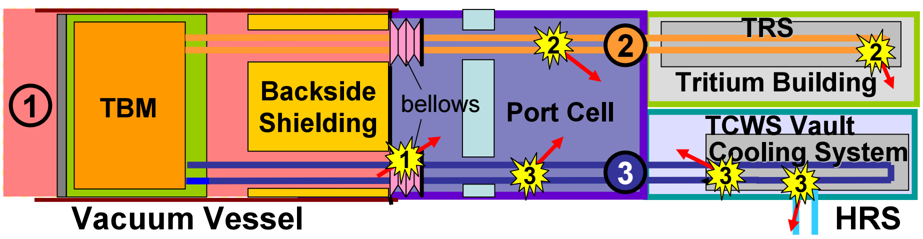


FIG. 4. PIEs about Release of Radiological Isotopes.

The PIE sub-group (A1) PIEs about release of RI from the VV, consists of only one PIE, release of RI inventory in the VV into port cell. The PIE is caused by rupture of the bellows at the backside shielding for a TBM-related pipe penetrating through the VV boundary. This PIE is equivalent to an ITER PIE, which is evaluated in the ITER safety assessment [13]. The result of the assessment is referred and it is confirmed that the total amount of released RI is below the release guideline of ITER project.
For the PIE sub-groups (A2) release of RI in the purge gas and (A3) release of RI in the cooling system, total amount of the RI inventory was so small that the estimated release amounts of RI were below the release guide line (5 g tritium and 50 g activated dust), even in the case of the release of the whole RI.

5.2.2 Evaluation of PIEs about Pressurization (B)

The PIEs of group (B) are caused by a rupture of pressure boundary, e.g., pipes of cooling systems. In such cases, the maximum pressure in each pressurized compartment should be evaluated. As shown in FIG.5, PIEs in this group are categorized as follow;
(B1) Pressurization of the TBM box structure due to rupture of pipes in the TBM and ingress of coolant
(B2) Pressurization of VV due to rupture of pipes and ingress of coolant
(B3) Pressurization of port cell due to rupture of pipes and ingress of coolant
(B4) Pressurization of TCWS vault due to rupture of pipes and ingress of coolant

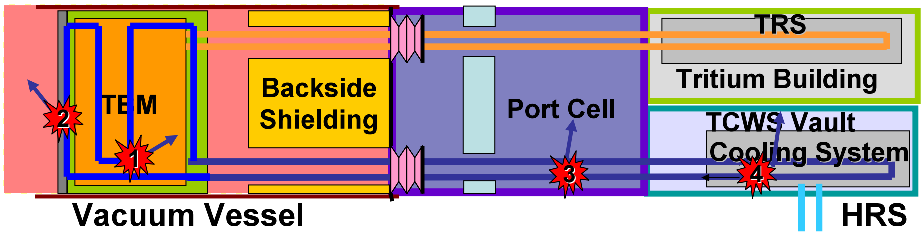


FIG. 5. PIEs about Pressurization.

For (B1) pressurization in the TBM, there is no sufficient pressure relief line. Therefore, once the TBM box structure is pressurized, the maximum pressure is predicted to reach nearly the normal operational pressure of the cooling system, 15 MPa. Therefore, the TBM is designed with the design pressure of 15 MPa so that plastic collapse of the TBM box structure can be avoided in the case of internal pressurization.
In cases (B2), (B3) and (B4), pressure relief system is planned in each compartment for the mitigation of over-pressurization. In these cases, the maximum pressure is needed to be evaluated, with consideration of the flow balance between the blow down through the rupture point of the cooling system and the flow through the pressure relief line to pressure boundaries, e.g., the suppression chamber and the ventilation system. For such evaluation, a one-dimensional simplified analysis was performed using TRAC-PF1 code [14]. According to the analysis, no severe overpressure is resulted in cases (B2), (B3) and (B4).

5.2.3 Evaluation of PIEs about Heat-up of the TBM (C)

The PIEs of this group are caused by degradation of cooling or excessive heat load unexpected by the design. PIEs in this group are considered as follow;
(C1) Loss of cooling of the TBM during plasma operation

Heat-up of the TBM due to loss of cooling during plasma operation is evaluated. After plasma termination, heat balance is to be evaluated between residual heat of the TBM by decay heat of induced activities and cooling by thermal radiation.

(C2) Ingress of coolant into the TBM during plasma operation

Rupture of a cooling channel in the TBM box structure is assumed. The cooling system is assumed to continue its operation. The discharged coolant in the TBM causes heat source by chemical reaction between beryllium pebbles (neutron multiplier) and the discharged water, in addition to the nuclear heating of the TBM during plasma operation.

(C3) Loss of off-site power after ingress of coolant into the TBM

Loss of off-site power, i.e., plasma disruption and loss of cooling, is assumed after the event sequence (C2). Heat balance with the decay heat, the chemical reaction between beryllium and water and the cooling by thermal radiation is to be evaluated.

Evaluation of the effect of heat-up events has been performed by using a one-dimensional thermal conduction calculation code. By concluding the results of the analyses, the following safety design strategy is clarified to be effective for the WCSB TBM.

(i) The WCSB TBM should be designed so that no cooling pipe rupture can be guaranteed after the loss of cooling and the heat-up of the TBM.

(ii) Cooling system of the TBM should be designed to continue operation even after the ingress of the coolant into the TBM.

6. Summary

The milestones and the achievements of the WCSB TBM are summarized. The milestones includes structural design work, qualification and safety assessments.

(1) Concerning the structural design work, proceeding of the TBM design work and the interfacing structures of the TBM are presented.

(2) Concerning the qualification, real-size mock-up fabrication is presented.

(3) Concerning the safety assessment, source term identification, FMEA and safety analyses are presented.

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