

Design and Manufacturing Feasibility of ITER TBM Frame and Dummy TBMs

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The operation and test of mock-ups of tritium breeding blankets relevant for a future commercial reactor is one of the goals of the ITER machine. To accomplish this goal, mock-ups of breeding blankets, called Test Blanket Modules (TBMs), are installed in three ITER equatorial ports. Each TBM and the associated shield form a TBM-set that is mechanically attached to a steel frame called TBM Frame. A Frame and two TBM-Sets form a TBM Port Plug (TBM PP). The ITER Organization is responsible for the design and manufacture of the TBM Frames and of the Dummy TBMs that could replace the TBM-sets in case they were not available. This paper describes the recent results of the design supporting analyses for the TBM Frames and Dummy TBMs that is presently in the preliminary design stage and their impact on the design.

Keywords: ITER, Test Blanket Module (TBM), TBM Port Plug (TBM PP), Frame, Dummy TBM.

1. Introduction

The ITER machine is an international effort aimed at demonstrating the scientific and technological feasibility of fusion energy. ITER is specified as a Nuclear Facility INB-174 [1]. One of the goals of ITER is to test and validate design concepts of tritium breeding blankets relevant to a power-producing reactor. To accomplish these goals, three ITER equatorial ports are dedicated to the test of test blanket modules (TBMs). Two TBM-Sets are mechanically attached to a TBM Frame to form a whole TBM port plug (TBM PP) which is a Protection Important Component (PIC) (see Fig. 1). Therefore TBM Frame design shall provide a stable engineering solution to hold the TBM Sets, and to provide a means for rapid replacement and refurbishment that is compatible with Remote Handling (RH) operations. In case one or more TBM-Set is not available, it can be replaced by a Dummy TBM. IO-CT is responsible for the design and manufacture of the TBM Frames and of the Dummy TBMs. The TBM Frame has interfaces with neighboring components in the Vacuum Vessel (VV) [2-4].

This paper presents the main results of recent design supporting analyses and of manufacturing feasibility study for the most recent design of a TBM PP with two dummy TBMs, as follows.

- Structural assessment of bolted connection between Dummy TBMs and TBM Frame (also applicable to TBM-sets);
- Flow behavior assessment of the cooling scheme including flow distribution, pressure drop and draining efficiency;
- Summary of preliminary manufacturing feasibility investigation.

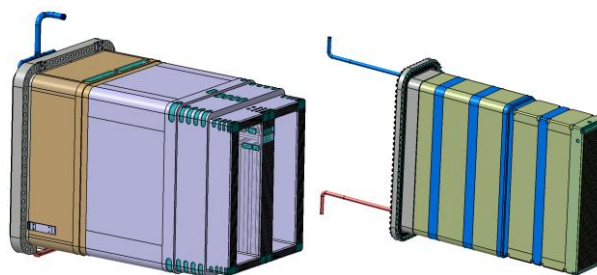


Fig. 1. A TBM Frame (left) and a Dummy TBM (right)

2. Structural assessment of bolted connection

Double metallic gasket seals have been implemented for sealing between TBM Frame and Dummy TBMs (or TBM Sets). The metallic gasket sealing concept is based on the plastic deformation of lining and the elastic compression resistance of spring. In order to allow sealing with metallic gasket, the high pretension load is needed to compress metallic gasket. Therefore, the optimization of joining components like bolts and inserts and their materials selection needs to be performed.

According to several investigations, the joining dimensions and materials between TBM Frame and Dummy TBM have been finalized: M27 bolts (Inconel 718) and M27/M45 inserts (Grade 660) [5]. The austenitic stainless steel with controlled nitrogen content 316L(N)-IG has been selected as the main structural material for the TBM Frame and Dummy TBMs. For the metallic gasket Ag-lined Helicoflex® double metallic gaskets with 10.6 mm diameter have been selected. The material characteristic curve provided by manufacturer is shown in Fig. 2 [6].

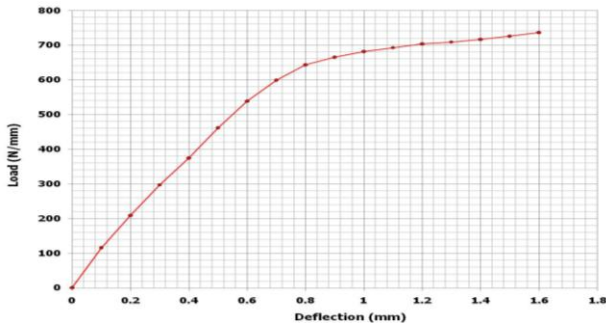


Fig. 2. Material behavior of Helicoflex metallic

The metallic gasket, located in the Dummy TBM flange has been modeled with a finite element model as shown in Fig. 3. The structural assessment was performed to confirm if the bolts/inserts and threaded holes are in the structurally safe state according to RCC-MR [5].

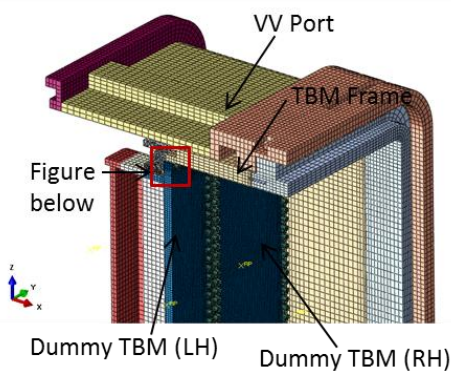


Fig. 3. The overall view of the finite element model for local TBM PP with VV Port

Fig. 4 shows the areas on Dummy TBM flange internal side, on inner side respect to the metallic gasket pockets with double metallic gaskets. It was considered a friction equal to 0.2 in the contacted areas between TBM Frame and flange.

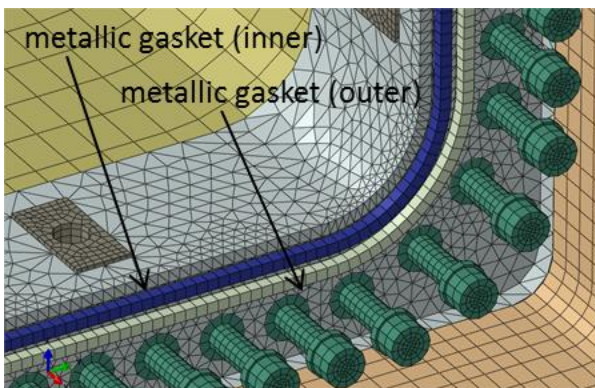


Fig. 4. The detail view of the finite element model for TBM Frame to show the mating surface of metallic gasket

For the loading conditions, the following three conditions were chosen:

- Bolt pretension: 95 kN per bolt at 20 °C
- Baking: 240 °C
- Operation: EM load (MD-II) at 100 °C, see reference from CDR [3]

To ensure the sealing function, the whole metallic gaskets should reach a compression higher than 690 N/mm during the first installation. Since the minimum gasket compression obtained value is equal to 699 N/mm as shown in Fig. 5, it has been confirmed that the whole perimeter of the double metallic gaskets is submitted to the minimum acceptable compression.

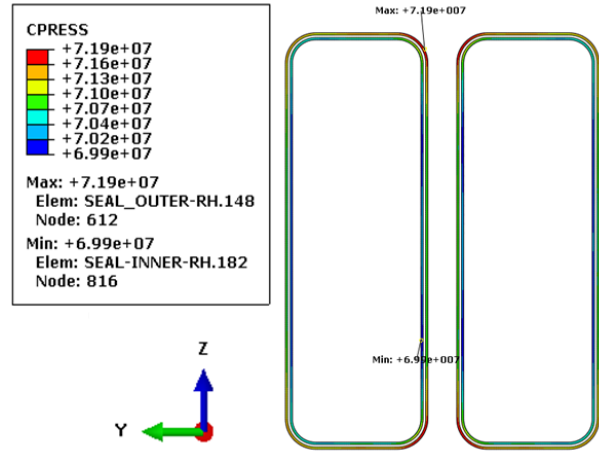


Fig. 5. Metallic gaskets compression [Pa] – bolt pretension phase

The assessed metallic gasket compressions at all concerned phases were summarized in Table 1.

Table 1. Metallic gasket compression in each state.

METALLIC GASKET	Installation phase 20 [°C]		Operation phases 100 [°C]		Baking phases 240 [°C]	
	COMPRESSION [N/mm] MAX	MIN	COMPRESSION [N/mm] MAX	MIN	COMPRESSION [N/mm] MAX	MIN
Inner LH	712	699	717	704	720	709
Inner RH	712	699	717	704	720	709
Outer LH	719	706	723	711	725	713
Outer RH	719	706	723	711	725	713

For leak tightening, it is required to have a limited in-plane displacements value (in-plane displacement < 0.2 mm). Therefore it has been checked if these requirements are satisfied. Considering the worst conditions, the result shows that the current design has sufficient margin (max ~ 0.13 to y-direction in Fig. 6, 0.09 to z-direction in Fig. 7).

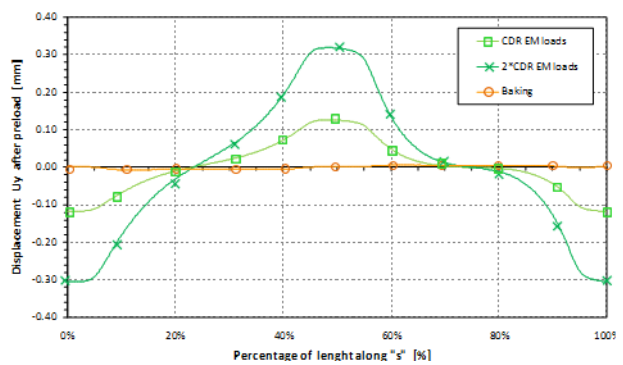


Fig. 6. Inner RH metallic gasket displacement (Y direction)

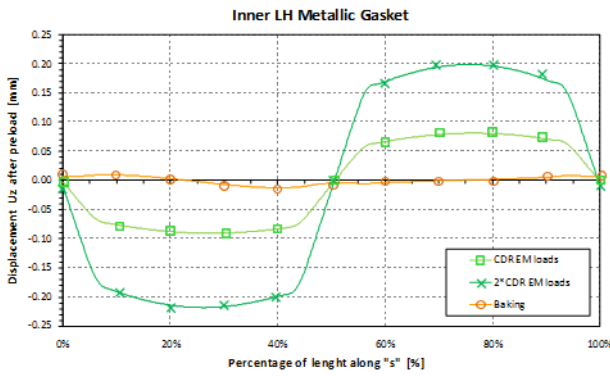


Fig. 7. Inner RH metallic gasket displacement (Z direction)

The structural assessments for bolts, inserts and TBM-Frame threaded holes are given herewith. Dummy TBMs joints (M27 Inconel718 bolts + M27/M45 Grade660 inserts) satisfies all the RCC-MR structural requirements considering gasket installation settlement, preload, baking, operation, as summarized in Table 2. In particular the factor 1.6 of safety margin can be reached during operation (160% of operation).

Table 2. Safety margin on bolts, inserts, threaded holes at each state.

	BOLTS	INSERTS	THREADED HOLES
INSTALLATION	1.47	N/A	N/A
BAKING	1.49	1.14	1.37
OPERATION	1.31	1.22	1.76
OPERATION (FACTOR 1.6)	1.00	1.10	1.60

3. Assessment of the cooling circuits

3.1 Flow analysis with 1D code

The cooling system thermal-hydraulic behaviour has been investigated under nominal and off-nominal steady state conditions, assessing the distribution of mass flow rates, velocities and pressure drops under reference conditions and suggesting proper design revisions of its lay-out to allow mass flow rate balancing and a proper integration with global cooling loop. According to the requirements of RELAP5 code family, a realistic finite volume model of the TBM PP cooling system has been set-up, consisting in a geometrical, a constitutive and a hydraulic model. The development and validation of a realistic finite volume model of the TBM PP cooling system were made as shown in Fig. 8. The cooling circuits are composed of three independent circuits, devoted to cool respectively the Frame and the two dummy TBMs. These three circuits are connected in parallel to the inlet/outlet manifolds system.

It has been deduced that the overall pressure drop amounts to 0.322 MPa and that the predicted values of Frame and dummy TBMs cooling circuits mass flow rates are respectively $GF = 6.215 \text{ kg/s}$ and $GD = 7.992 \text{ kg/s}$. The hydraulic characteristic function of a TBM PP is shown in Fig. 9.

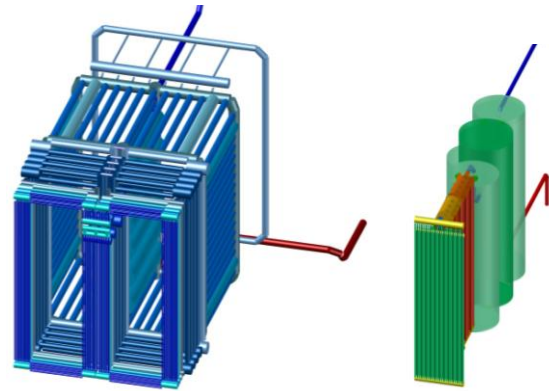


Fig. 8. Finite volume model of a TBM Frame (left) and a Dummy TBM (right) for RELAP analysis

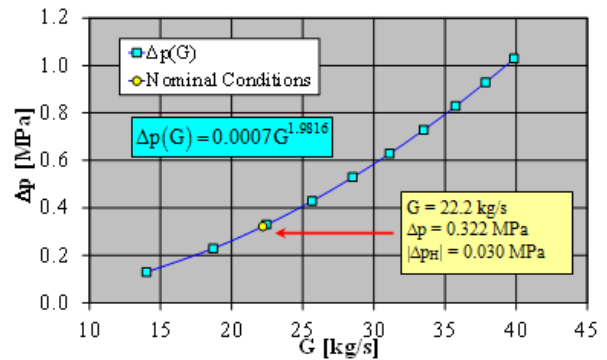


Fig. 9. TBM PP (a Frame + two Dummy TBMs) cooling circuit hydraulic characteristic functions

In order to allow balanced flow rate ($GF = 11.1 \text{ kg/s}$ and $GD = 5.55 \text{ kg/s}$), an effective concentrated hydraulic resistance was introduced within the inlet/outlet manifolds of each dummy TBM cooling circuit. This can promote water flow through the Frame cooling circuit and re-balancing mass flow rate distribution. In this case, an overall pressure drop of 0.922 MPa has been obtained across the TBM PP cooling system, with a net increase of 0.6 MPa with respect to its original configuration (natural flow). In order to reach the nominal mass flow rate under the imposed pressure drop (1.35 MPa), a local pressure drop of 0.428 MPa has to be added by effective concentrated resistance.

3.2 Flow analysis with 3D CFD

In order to validate the RELAP analysis result, 3D CFD analysis has been performed with the ANSYS CFX commercial code. For the mesh generation, the domain was discretized with a mixed approach (hexahedral and tetrahedral). The total numbers of cells are around 19 million and 6.5 million for a TBM Frame and a Dummy TBM, respectively. For analysis, $k-\omega$ SST model was used for modelling turbulence, and y -plus parameter was kept under control with material properties of water at 4 MPa and $98 \text{ }^\circ\text{C}$ with density of 961.59 kg/m^3 and a viscosity of $2.89 \times 10^{-4} \text{ Pa}\cdot\text{s}$. To compare 3D analysis (CFX) result and 1D RELAP5 result, several zones of a TBM Frame cooling circuit were identified as shown in Fig. 10.

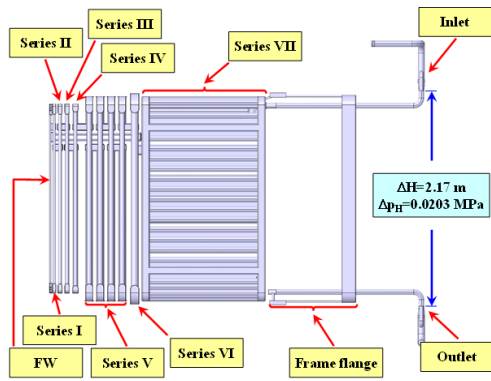


Fig. 10. Nomenclature of cooling circuits in a TBM Frame.

The comparison result shows the considerably good agreement between 1D and 3D predictions showing 3.8% of difference regarding overall pressure drop as shown in Table 3. According to result, the highest contribution to the overall pressure drop is localized into the FW and the Frame flange, where the deviations between 1D and 3D predictions remain below 1% and 12%, respectively. In case of the largest deviations between 1D and 3D predictions reaches up to 600 %. However their pressure drops are very small so this effect is negligible. Hydraulic characteristic functions were obtained by the two different approaches and the comparison of the results shows that two characteristic curves are in good agreement and their respective deviations remaining lower than 10% throughout the whole mass flow rate range between 1 kg/s to 12 kg/s, as shown in Fig. 11.

Table 3. Static pressure drop distribution within the Frame cooling circuit [MPa].

	1D [RELAP5]	3D [ANSYS]	Abs. difference	ε [%]
Inlet	0.058	0.049	0.009	18.2%
FW	0.247	0.249	-0.002	-0.8%
Series I	0.081	0.049	0.032	64.8%
Series II	0.035	0.035	0.000	-0.8%
Series III	0.025	0.040	-0.015	-38.7%
Series IV	0.044	0.036	0.008	21.4%
Series V	0.027	0.033	-0.006	-17.6%
Series VI	0.008	0.005	0.003	66.5%
Series VII	-0.001	0.020	-0.021	-107.1%
Frame flange	0.351	0.397	-0.046	-11.7%
Outlet	0.007	0.001	0.006	618.9%
Frame	0.881	0.915	-0.034	-3.8%

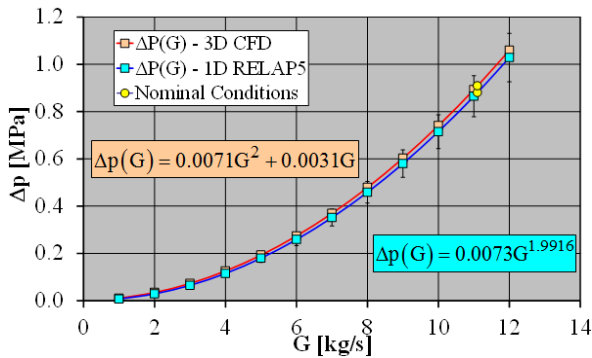


Fig. 11. Two hydraulic curves with 3D CFD and 1D RELAP5 for a TBM Frame

3.2 Assessment on draining performance

Because of scheduled replacement plan during ITER life time, the TBM PP needs to be designed with sufficient draining capability. Therefore, the amount and the distribution of residual water within the circuits were assessed and some TBM PP design modification was performed to improve the draining performance. Regarding the TBM Frame cooling circuit, our draining pipes (5 mm in diameter) were inserted in order to allow draining of the residual water directly to the bottom part of the flange. In order to improve the draining performances of Dummy TBM cooling circuit, the revision of its draining configuration was done by doubling the number and the increasing the diameter from 5 mm to 12.5 mm (see Fig. 12).

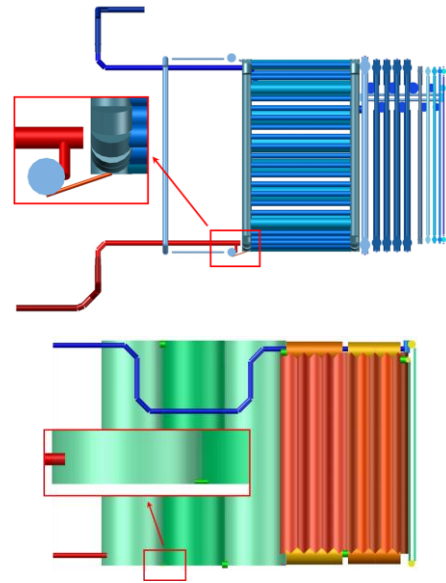


Fig. 12. Revised draining holes in TBM Frame (upper) and Dummy TBM (lower).

During the gravity draining scenario, before the design revision, the obtained results have indicated that the TBM PP cooling system draining performances are somewhat poor and asymmetric since a residual amount of 985 kg of water has been predicted after draining during 20000 sec, mainly located within the Frame cooling circuit (943.3 kg). After the design revision, the draining performances were significantly enhanced with a residual amount of 78.4 kg of water after 1400 sec of draining duration time (see Fig. 13).

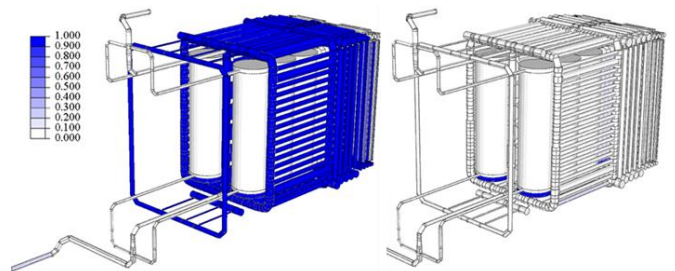


Fig. 13. Water inside TBM PP after draining: initial model at 20000 sec (left), (b) improved model at 1400 sec (right)

4. Preliminary assessment of manufacture feasibility

A preliminary investigation was performed to assess manufacturing feasibility of the baseline design of TBM Frame and Dummy TBM including schedule impact. The main objectives of this assessment are to provide feedback to the design from the manufacturer's perspective, to identify potential feasibility issues of the design, and to develop possible improvements of the design with the aim to facilitate the fabrication and to reduce the construction cost.

The obtained results show that the general manufacture route has no showstopper even though there are several aspects for which it will be necessary to validate with mock-up before the final manufacturing [7]. The main manufacturing aspects were summarized as follows.

- Global tolerance +/-5mm, Front Tolerance +/-2mm
- Axial Welding to fix the volume geometry done with EB technology
- Front Frame manufacture from welded plates
- Volume machining to achieve tolerance
- Transverse internal welding with manual TIG
- Transverse external welding with automatic TIG narrow gap welding
- The parts integrate an extra length to compensate the shrinkage
- EB + TIG welding for thick parts
- Drilling the first layer of Front Frame in the "last" operation to ensure minimum thickness between cooling holes and plasma facing area

A revised manufacturing route for the TBM Frame has been proposed and it is shown in Fig. 14.

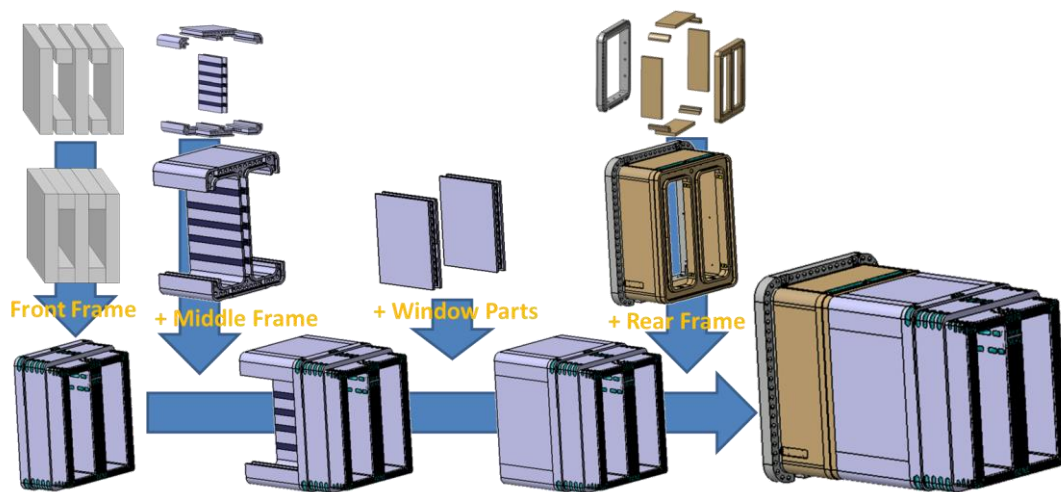


Fig. 14. Updated manufacture route for a TBM Frame

5. Conclusions

In this paper, the main results of supporting analyses for the TBM Frame and Dummy TBMs designs were presented focusing on the structural assessment of the bolted connection with metallic gasket seal and on the flow and draining performance assessment. The structural results showed that the design can ensure the sealing tightness under all conditions such as installation, baking and the operation condition with sufficient margin. In the flow analysis, the pressure drop of TBM PP was found within the imposed value and need of effective concentrated resistance to compensate it. Also design modifications have been adopted to improve the draining TBM PP performance. A preliminary manufacture feasibility study has been performed and no show stopper has been found although mock-up validations are needed in several cases.

Disclaimer

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

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