Preparations for the ITER Vacuum Vessel Construction

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Abstract. The ITER vacuum vessel (VV) consists of nine 40 degree sectors and ports which will be procured by EU, KO, RF and India. Procurement Arrangements (PA) for the vacuum vessel have been signed by the relevant Domestic Agencies (DA). Each DA will sign fabrication contracts with industries within 2010. After the preliminary approval of the VV design by the ANB, the related DAs will start fabrication work based on this design. R&D for setting up fabrication procedures to meet the demanding tolerance and inspection requirements is the first activity performed and the results of this R&D from each DA are presented.

1. Introduction

The ITER VV as a safety important class component is a critical structure of the ITER tokamak. From the start of the ITER project, there were various R&D and design activities to finalize the ITER VV design, and a finalized design was selected in July 2009. After this decision, there were refinement activities to incorporate modifications. Up to the end of 2009, all PAs for the vacuum vessel have been signed with the relevant DAs. This paper represents the combined activities of the related parties to construct the ITER VV. The major topics are the technical features of the ITER VV, the procurement status, fabrication procedure and schedule.

2. Technical Features and PA status of the ITER VV

The overall ITER VV is a torus shaped, double walled structure with a D shaped cross section and has nine 40 degree sectors, upper, equatorial and lower port structures with VV supports[1]. Compared to previous fusion devices, ITER has a blanket system with a single null divertor. The blanket modules are supported directly by the VV. On the VV inner wall, there are dedicated housings for blanket flexible supports. Between the double walls, there are in-wall shielding (IWS) structures made with borated stainless steel and ferritic steel to reduce magnetic ripples and neutron heating to the magnet system. The main material for the VV is SS 316L(N)-IG with controlled nitrogen content and tight specification of the main alloying elements such as low Cobalt content at less than 0.05 %. Even though the torus outer diameter and height are 19.4 m and 11.3 m, the overall tolerance requirement is within ±10 mm and 100 % volumetric non-destructive examination is mandatory. These are the most demanding requirements that have ever been imposed on a vacuum vessel for fusion devices.

The procurement of main vessel sectors is shared by EU which is responsible for seven sectors, nine blanket manifolds and ten spice plates for sector field joints, KO responsible for two sectors and India which will procure the IWS for nine sectors and field joints. The equatorial and lower port components will be fabricated by KO, and RF is responsible for the upper port packages. As user and manufacturer, the ITER Organization (IO) has responsibilities for the VV design, manufacturing, assembly and operation.

3. Final Design Status of the ITER VV

3.1. The Modified Reference Design of the ITER VV

After intensive studies and assessment of design variants including an alternative design with a self-standing blanket vault and a design with a short housing concept where the housings were connected to the VV outer shell by a network of ribs, the Modified Reference Design[1] was selected during a VV and blanket design review in July 2009. This design is basically the same as the original reference design but includes the following design modifications: (i) The inner shell has a 3D shape in the outboard area; (ii) Enlargement of inner shell splice plates to 160mm for better accessibility during outer shell field joint welding; (iii) Modifications of interfaces for in-vessel coils; (iv) Increase in the structural strength of the lower port gusset; (v) Rearrangement of the lower ports and penetrations, taking into account remote handling maintenance requirements; (vi) VV cooling has now a single loop configuration. Coolant pressure operating conditions were updated with reduced operating and baking pressure.

The first modification was introduced to reduce the number of welds on the inner shell, which will contribute to tolerance control. It also gives more flexibility for these welds to avoid potential clashes with other welds on the inner shell including those for in-vessel component support. In the course of this modification, the inner shell was slightly shifted outwards up to 44mm in the radial direction to provide more room for the ELM/VS coils and the blanket manifolds. The area for the outboard in-wall shielding was slightly reduced accordingly. Due to these modifications described above, re-designing was performed on the VV shells and the structures connected to the shells such as the blanket support housings and keys, the poloidal and toroidal ribs, the transition frames of the port stubs, the triangular supports, the support rails for the ELM/VS coils and the footprints of electrical straps.

3.2. The Design Activities on the Ports, IWS and Support

To ease allocation of the blanket manifolds and ELM/VS coil feeders, a common chimney of a maximum allowable size was developed for the upper port. The pipes and feeders are isolated from the cryostat vacuum with a special compartment connected to the port cell environment. This will simplify maintenance procedures. Interfaces with the port plugs and the RH cask were developed in detail. Regarding the lower ports with the branch pumping duct, the duct cooling configuration has been modified using internal channels instead of welded pipes to enhance the overall reliability. The design of the NB ports was updated and finalized focusing on a better definition of the interfaces and improved manufacturability. In particular, the in-wall shielding design was developed for the port stub extensions and the port extensions. To finalize the IWS design, electromagnetic analysis and nuclear shielding analysis have been performed. Based on these analyses, the design of the brackets and bolts for the IWS are updated and the installation tolerances of the IWS are relaxed. The reference design of the VV support was changed from a sliding type to a dual hinge type that withstands all combinations of loads, including gravity from the VV and in-vessel components, thermal loads, electromagnetic loads, VDE, plasma disruption and seismic loads. All these loads have been taken into account in the safety demonstration of the VV which is the first confinement barrier for the VV radioactive inventory. This hinge type support design has been developed to simplify the fabrication.

3.3. Conformity Assessment of the ITER VV Design

The VV manufacturer must demonstrate that the applicable essential safety requirements and radioprotection requirements are satisfied. Licensing of the ITER VV according to ESPN is in progress and a conformity assessment is being performed by AIB-Vinçotte International, which has been selected by IO as the agreed notified body (ANB). The IO is the manufacturer of the complete VV and responsible for the conformity assessment. The VV is an assembly of ESPN components including sectors and ports. IO submitted to the ANB a set of documents that consist of the design description, load specifications, hazard analysis, stress report, drawing package, radioprotection guide, approach for pressure test, particular material appraisals, material procurement specifications, etc. and subsequently gained preliminary design approval for the ITER VV. The approval for the material specifications is also finished. Due to design modifications, a set of complementary documents on the VV modified reference design were further assessed by the ANB to confirm that the design changes are structurally acceptable. The process will continue with a full update of the required documentation package before the start of fabrication activities for the VV components.

4. DA Preparations for Fabricating the ITER VV

Even though IO provides technical requirements and final 3D multi-body CATIA models to each DA, the fabrication design including preparation of 2D drawings and fabrication procedures with supporting documents are fully under the responsibility of the related DAs. All DA activities shall follow the ITER quality assurance procedures. Each DA will prepare a quality plan and manufacturing and inspection plan before the start of manufacturing. IO recommended the baseline method for sector manufacturing and assembly which consists of welding the finished poloidal segments. Based on previous R&D results and available technologies, DAs will perform R&D or make mock-ups to establish their own fabrication methods.

4.1. R&D, Preparations for Fabrication and Contracts by F4E

4.1.1. R&D and Preparations for Fabrication

A) Non Destructive Examination

A.1 PT Camera

The use of liquid dye penetrant techniques for crack detection in high vacuum compatible systems such as the vacuum vessel may create issues in ITER, as it may create a virtual leak. A contactless NDE technique has been developed by AREVA, Chalon, to detect cracks on the surface of metals and up to 1 mm underneath by the use of a scanned laser beam on the surface. The Photothermal Camera combines an infrared sensor (internal) and a laser (external) as an excitation source and relies on the detection of infrared emission after the transient thermal excitation of the surface adjacent to the heated spot and on-line analysis of the image enables the cracks, acting as a thermal barrier, to be clearly shown by their characteristic flaw footprint. The technique has been demonstrated on 316 steel to be able to detect all flaws normally found by dye penetrant testing.

A.2 One-sided UT Inspection

Due to the manufacturing sequence, the outer shell of the VV cannot be volumetric inspected from both sides of the weld. The RFUT project analyses the feasibility to apply advanced ultrasonic inspection techniques by automated methods (phased array, multi-probe and Tandem) as a replacement to 2 sided inspection. The work done by CEA, PHOENIX and Sintez/ECHO+ demonstrates the detection of fabrication indications during four, partially blind, mock up and inspection exercises. Technical evidence is shown to qualify these UT techniques under French Certification Authority standards, for use during the fabrication of the ITER VV.

B) Metrology

The main outcome of this R&D project by AREVA, Erlangen, is the practical demonstration on a full-sized metrology mock-up of measurement techniques achieving accuracy better than ±0.2 mm and closer to ±0.1 mm specified for point measurements inside the vacuum vessel with reference to the Tokamak datum. To achieve this accuracy detailed planning and qualified application of the recommended measurement system's Laser tracker (for fiducials) and digital photogrammetry (for detailed inspection over a smaller area) is recommended.

C) Fabrication of Mock ups

C.1 Poloidal Sector Mock-Up (VVPSM)

The VVPSM mock up by Ansaldo has helped in the development and fabrication of a full scale mock-up of a poloidal sector of the ITER VV within the prescribed geometric tolerances, so thus gaining knowledge, experience and confidence in manufacturing a complete ITER VV sector[2].

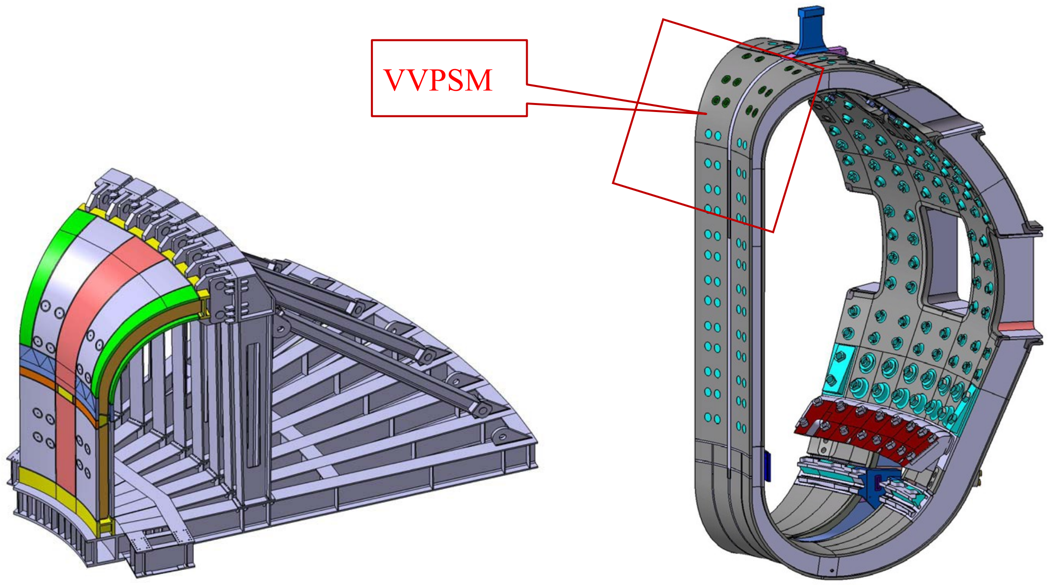

FIG. 1.The schematic view of VVPSM

The 3D Final surface of the VVPSM inner & outer Shell (measured by Laser Tracker) comply with the required tolerances (±10 mm).

C.2 Vessel Advanced Technology Segment (VATS)

This prototype is built by DCNS to confirm the distortion calculation methodology, distortions measurements, EB welding quality process and release the inboard segment manufacture route [3]. The VATS, using an alternative assembly method and only employing EB welding, is a trial version of the VV inboard section of 6 meters length by 2 meters width and 60 mm depth with a total weight of 17 tons. Before manufacturing the full size VATS mock-up and with the purpose to determine the optimum EB welding sequence with a minimum of jigs, a smaller validation mock-up called VEC "Validation E-beam Welded Coupon" was constructed and is about 1 metre square with inner and outer-shell, two ribs and four flexible housings. The double-walled VATS, made with actual ITER-grade stainless steel, is sufficiently representative of the inboard segment and demonstrates conclusively the manufacturing feasibility for production series and highlights and resolves several problem areas, such as the need to use partial penetration welding from both sides for circular welds.

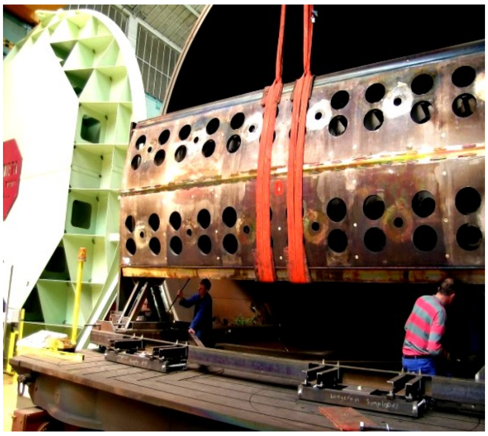

FIG. 2.The VATS mock-up

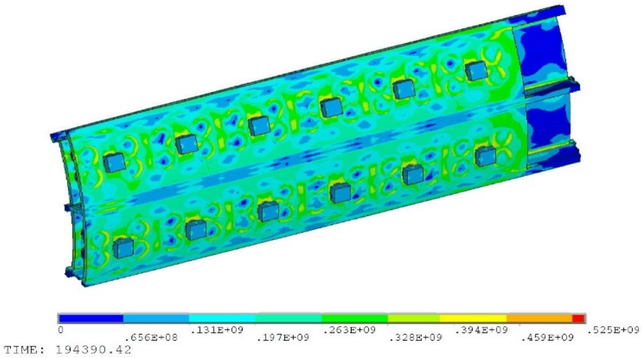

FIG. 3.Distortion analysis

D) Simulation of Distortions

One of the most critical ITER VV manufacturing challenges is the low value of distortions ~0.1 % compared to the global VV dimensions, so several simulation studies with calibration mock-ups have been done[4,5]. The use of finite element simulation of distortions due to welding is needed to predict the final geometry and meet tolerances. Several methodologies, software (Sysweld, Ansys) and mock ups are used to calibrate the simulation models. Due to the complex geometry of the VV and the large number of welds, a new simulation methodology is developed. This method can calculate in parallel many different welding sequences of the same component to find the optimum to reduce final distortions. The methodology is based on thermo-mechanical transient non-linear analysis and therefore is able to introduce any stiffener or supporting jig at any time in the simulation. During the fabrication of the VV, in case of unexpected distortions (not matching with predictions), this method is able to start from the distorted geometry and recalculate another welding sequence to correct the distortions and meet the final tolerances.

4.1.2. Preparation of the Contract Tender Phase

Following a qualification procedure in 2009, the bidders arranged themselves into two consortia, MADE (MAN Turbo from Germany and ENSA from Spain) and AMW (Ansaldo, Walter Tosto and Magiarotti from Italy)[6]. Once the preliminary offer of the bidders was received (7th May), F4E started the process of assessment with several queries to the bidders to complete the preliminary offer. Following the closure of the negotiations phase (7th July) the bidders presented the final offer including the feedback acquired during the previous process. After receipt of the final offers (15^{th} August), F4E has been evaluating the final tenders, using a relative performance index with different weightings for each of the 69 technical award criteria, and will make a decision using the "Best-Value-for-Money" approach by the sum of the technical award (40%) and financial award points (60%). The decision is planned to be announced on September 24^{th} if the F4E committee meeting approves.

4.2. R&D and Status of Preparations for Fabrication by KO DA

After the decision to adopt the modified reference design as the final ITER VV design in July 2009, KO DA proceeded to contract with industry fabrication of two VV sectors along with the equatorial and lower port structures. As the first step, KO DA launched the official call for tender in September 2009. Two companies submitted the tender documents with their technical proposals by the end of October 2009. After the technical evaluation meeting with the participation of IO officers, price bidding followed and KO DA finally made a contract with HHI in January 2010.

4.2.1. Fabrication of R&D Mock-ups

As the first activities for contract implementation, two mock-ups named VISM (Vacuum Vessel Inboard Segment Mock-up) and VUSM (Vacuum Vessel Upper Segment Mock-up) are under fabrication by HHI to develop their fabrication procedures [7]. The VISM is the lower 1/3 part of the inboard segment and the VSUM is half of the upper segment. Fig.4 shows schematic views of the mockups.

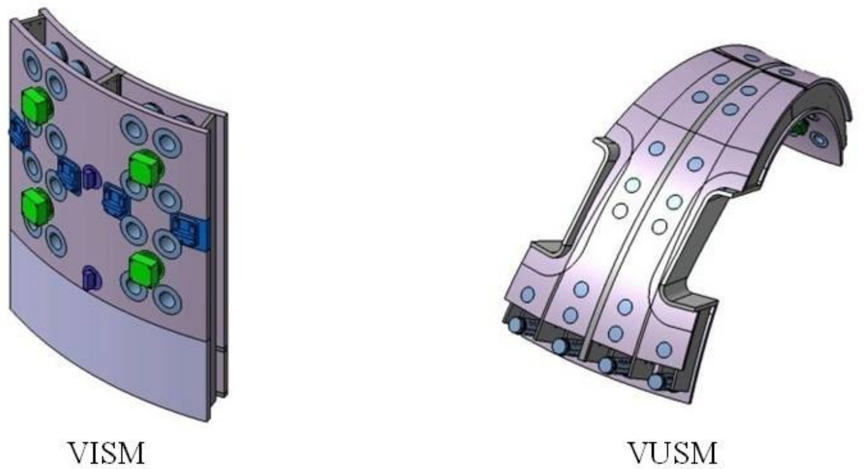

FIG. 4. The R&D mock-ups of KO DA

For the VISM, the EBW of the attached components on the inner shell is the key process in developing the procedures to apply for main production. The verification of forming, machining technique, welding sequence optimization and distortion control will be done by fabrication of the VUSM. The EBW test on the small specimen and the fabrication of components of each mock-up are in progress. In addition, a partial mock-up for triangular support of the lower segment and port forming mock-up are in preparation.

4.2.2. Preparations for Fabrication and Supporting Design

After the approval by the IO of the HHI VV quality plan, the first subcontract for raw material fabrication was established with Industeel (Plate material) and R. Kind (Forging material) according to the ITER material procurement specifications. The mill maker certification documentation to meet regulatory requirements was prepared and submitted to IO to obtain the approval from the ANB. The submission of the quality plan, manufacturing and inspection plan of the mill makers will follow for approval from the ANB before the start of mass production.

The design thickness of the inner and outer shells of the main vessel sectors is 60 mm. A rough estimation of plate thickness reduction during the forming process is about 5 - 9 %. To have reliable thickness of the plates before production, the effects of shell thickness reduction on structural integrity was assessed. The main vessel with 10% thickness reduction of inner and outer shells due to plate bending still has enough strength margin but supplemental analysis to obtain approval from the ANB is required. Most of the raw material plate will have a thickness of 60 mm but plates thicker than 60 mm will also be used in some areas.

The optimum welding sequence and restriction jigs are crucial to meet the tolerance requirements of the ITER VV. To predict welding deformation and optimize the welding sequence, welding distortion in the vacuum vessel at each fabrication process is evaluated and the principal distortion factor is identified. Based on the results, proper control methods for excessive distortion will be proposed. The narrow gap GTAW and EBW procedures will be used as the main welding processes for the VV. GTAW processes are divided into a manual type and a machine type in terms of their accessibility and productivity. Most welding joints are narrow gap type in order to minimize welding distortion and increase productivity. Three different welding equipments are being developed by HHI for consideration on the fabrication sequences. Qualification processes for welders and NDE personnel conforming to the RCC-MR code is in progress.

4.3. R&D and Status of Preparations for Fabrication by RF DA and IN DA

RF DA is also fabricating a full scale mock-up of the upper port and will select the upper port supplier in the near future. The procurement of the raw material this year will be performed after the IO and ANB approval of documents from mill makers. Thermal-hydraulic analysis of the upper port to support design changes is in progress.

IN DA selected the material supplier and the manufacturer for the IWS. With regards to supporting R&D, an out gassing rate test of the IWS coupon and cutting test of the borated steel were performed. The detail design of the IWS and assembly tools including assembly sequences of the IWS into the VV sectors and field joint is ongoing. Structural analysis and the preparation of engineering drawings are also in progress.

5. Summary

After the final design review of the ITER VV in 2008, experts reviewed the design of the VV and its interfaces. The conclusion of the review was to proceed with the original reference design with a few modifications. Accordingly these changes have been implemented. Preliminary approval of the ITER VV modified design was provided by the ANB. All of the PAs for the main vessel sectors, including ports and IWS, have been signed. In accordance with the PAs, all DAs have made or will make contracts with industries to construct the ITER VV by the end of this year. IO and DA's will assure supplier's supervision. Relevant documentation on R&D and fabrication process will be available for possible inspections by DA's or IO and DA's or by the French Nuclear Safety Regulator. To integrate the VV components from each DA, IO will establish an integrated project schedule and adjust the delivery schedule of items between the DAs. The first delivery of a VV sector is expected in 2015.

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

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