MANUFACTURING COMPLETION OF THE FIRST ITER VACUUM VESSEL SECTOR

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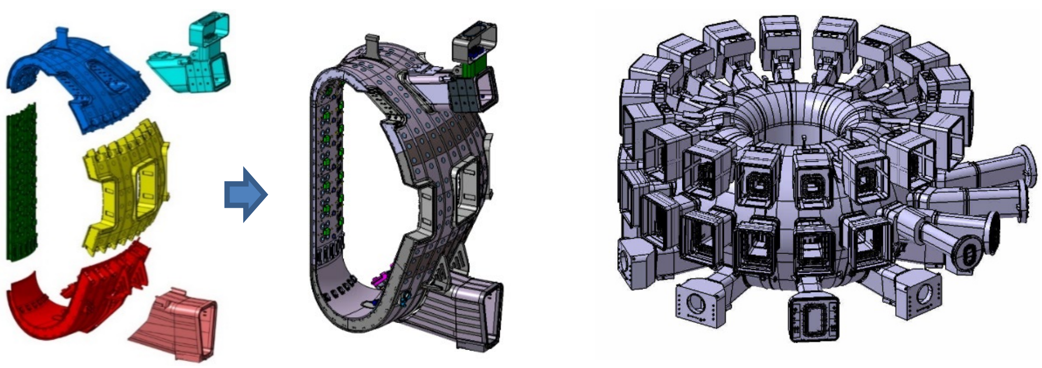
Abstract

In 2020, manufacturing of the 1st sector of the ITER Vacuum Vessel has been completed since manufacturing start in Feb 2012. Each step of the manufacturing was challenge as a First-of-a-Kind (FOAK) and a French Nuclear Pressure Vessel. The paper provides an overview of the major technical challenges which were overcome and lessons learned over the last 10 years.

1. INTRODUCTION

The main functions of the ITER Vacuum Vessel (VV) sector are to provide a high-quality vacuum for plasma operation and a nuclear safety boundary for the ITER project. The ITER VV is composed of 9 sectors including In-wall Shielding (IWS) and Upper/Equatorial/Lower Ports. Each of sector, port and IWS that are procured by 4 domestic agencies (Korea, EU, Russian Federation and India) are finally assembled at ITER site by ITER organization (IO). Korean Domestic Agency (KODA) has a responsibility to supply 4 sectors based on the procurement arrangement and the delegation agreement. A sector is an assembly of 4 poloidal segments, upper and lower port stub extensions, as shown in Fig. 1. As a delivery condition, a sector's height and the total weight are 13.8m and 375 tons, respectively.



Sector as delivery condition　　　　Whole assembled Vacuum Vessel at ITER Site

FIG. 1. The ITER Vacuum Vessel

2. REGULATION AND CODE FOR MANUFACTURING OF THE ITER VV SECTOR

The ITER VV is classified as a Protection Important Component (PIC) according to French Order dated 7 February 2012 (INB Order) and a Nuclear Pressure Equipment (NPE) under French order dated 30 December 2015 (ESPN order). French Nuclear safety authorities (ASN) is the regulatory authority for ITER VV as NPE. Finally, the ITER VV is classified as a level N2 and Category IV NPE according to the guidelines of the ASN for application of the ESPN order.

In accordance with the ESPN order, the conformity assessment based on module-G is checked by an Agreed Notified Body (ANB) during design, material procurement and manufacturing of the ITER VV. The ANB examines the manufacturing of the VV and performs and/or witness appropriate tests prescribed by the regulation to ensure its conformity with the requirements of the ESPN order as described in guidelines set by the ASN [1].

The RCC-MR 2007, edition 2007 is selected as the design and construction code for the ITER VV. The ITER VV sector is classified as Class 2 box structure components and applicable design rules are provided in the RCC-MR RC 3800 chapter and complemented by Appendix 19. The classification of the ITER VV welded assemblies is specified in Appendix A19.3200 of the RCC-MR 2007. For each category, authorized welded joints are defined in RC 3833.3. The VV sector assemblies are classified into 4 categories based on their importance regarding safety, load resistance requirements and compatibility with manufacturing scheme and access limitation during the construction of a double-walled box structure. For pressure-retaining welds on inner shell and outer shell, corresponding to category 1 and 2, only full-penetration joint welds without permanent backing strips and with 100% volumetric examination are allowed. Partial penetration welds can be allowed only for Category 4 welds under the condition of stress level is very low and fatigue is not significant. Except for this case, only full penetration welding is allowed [2].

3. MANUFACTURING CHALLENGES

Main technical difficulties are caused by strict nuclear regulation. There have been three major challenges to overcome during sector manufacturing: 1) nuclear safety process, 2) tight manufacturing tolerances for a heavy welded structure, and 3) 100% volumetric inspection requirement by ESPN order. In addition, application of unfamiliar RCC-MR 2007 code to Korean industries and complicated interfaces among parties (Involved several DAs, IO and ANB) are also another difficulty for ITER VV sector manufacturing.

3.1. Challenge-1: Nuclear Safety Process

The whole manufacturing procedure of the VV sector for material procurement, welding, inspection, inspection and handling should observe nuclear regulatory requirements and codes. Most fundamental requirement is to maintain traceability for all activities as French nuclear pressure vessel.

In accordance with the requirements, all applicable documents shall be approved by KODA, IO and ANB prior to actual manufacturing. It requires qualifications, demonstrations, and certifications based on essential nuclear safety requirements. All manufacturing activities have been inspected and recorded with approved Manufacturing Inspection Plan (MIP). Identification and quality control of Protection Important Activities (PIA) and Technical Control (TC) are also an important function of the MIP for each activity according to INB Order [3].

In 2015, the IO EPB (Executive Project Board) decided to create the Vacuum Vessel Project Team (VVPT) considering that complexity and nuclear aspects are the main sources of difficulties for the ITER VV manufacturing. VVPT's primary goal is to use IO and DA resources in the most efficient way to simplify processes and complex organizations, accelerate decision making and manufacturing, improve quality stability, and ultimately achieve successful VV construction.

After the implementation of the VVPT, the whole process has been greatly simplified. One of the most important improvements is the simplification of the document control procedure by a time review and approval as one team regardless of IO and DA. Under the VVPT, all inspections were performed at once. Each column of IO and KODA was merged into a column in MIPs. Each of manufacturing step has been inspected by 7 VVPT inspectors and 2 ANB inspectors except HHI quality management personnel. ANB engages to review/approve/inspect all nuclear safety-related documents and manufacturing activities as performing of conformity assessment – module G. A total of 45,000 inspection points were performed and about 500 manufacturing documents have been developed during the manufacturing of the ITER VV sector #6.

End of Manufacturing Report (EMR) as specified by RCC-MR RA 3930 has been prepared and submitted to IO before sector#6 packing according to IO handover procedure.

3.2. Challenge-2: Tight Tolerance Requirement

The second one is very tight manufacturing tolerances for a huge welded heavy structure having a total 1.4 km welding lengths approximately. In order to meet the tolerance requirement, fabrication sequence of each segment has been developed based on the results of welding distortion analysis and manufacturing of full scale mock-ups for PS1/PS2 [4]. Dedicated jigs also have been applied from each segment manufacturing stage to control welding deformation.

Narrow gap gas tungsten arc welding (GTAW) was applied as a basic welding process. Electron Beam Welding (EBW) was also adopted for installation of the Flexible Support Housings/Keys on the PS1 Inner Shell and installation of the Divertor Stop Body on the PS4 Inner Shell to minimize welding distortion. Especially, 20 Welding Procedure specifications (WPS) with 44 Welding Procedure Qualification Records (PQR) have been developed for the ITER VV.

With regards to the tight tolerances, the most important manufacturing step is the final assembly. Each Poloidal Segment (PS) is assembled all together, and then configured into the D-shape structure. Final assembly is one of the most challenging works because each PS has own accumulated deformation during the manufacturing stage and the precise handling on the assembly platform is very difficult due to the double walled PS having maximum 150 tons including jigs.

In order to satisfy the strict tolerance requirements after the final assembly of the sector, HHI team in collaboration with the VVPT performed a virtual fitting in advance using 1) as-built dimensional inspection data of each segment, 2) required weld root matching tolerance for gap and misalignment, 3) welding distortion analysis results for the final assembly according to HHI's welding sequence. Through this virtual fitting process, the pre-compensation values were decided for the final assembly of each PS, UPSE and LPSE. Finally, target positions in a 3D space have been allocated for all fiducial posts (FP) on PSs, UPSE and LPSE.

Fit-up for PSs, UPSE, and LPSE has been performed on the basis of the defined target position for each FP on PSs, UPSE and LPSE. Precise positional adjustment for each heavy PSs was realized by HHI's own handling technique using chain blocks and customized shoe blocks with Teflon sheets for low friction between PS and steel assembly platform. This precise handling technique was verified before final assembly with a full scale mock-up of PS1 and PS2 as shown in Fig 2.

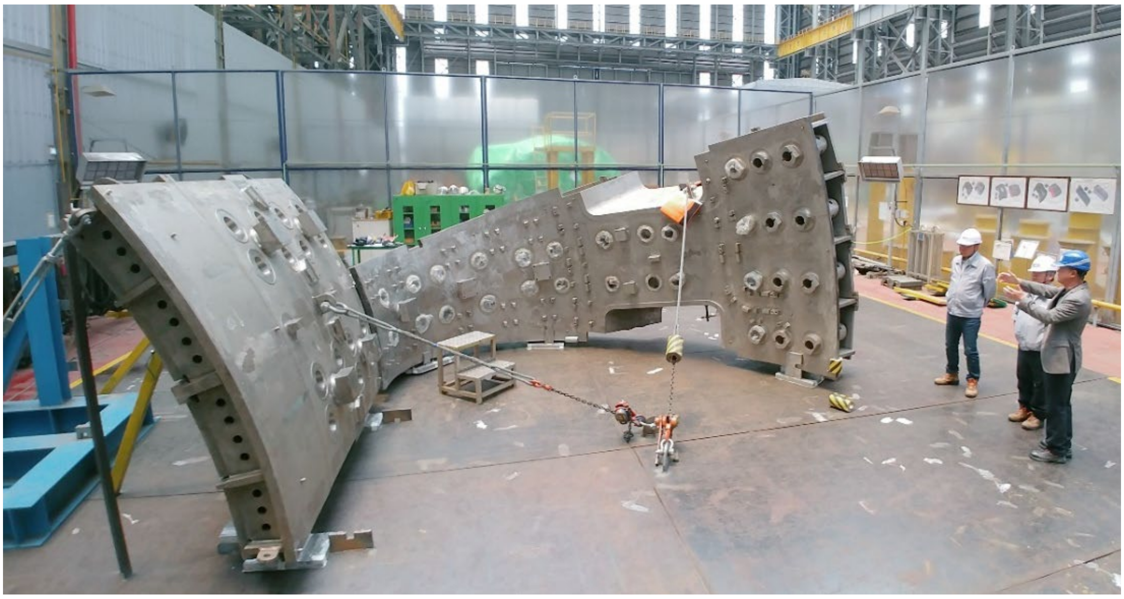


FIG. 2. Verification test of the precise handling technique using full scale PS1 and PS2 mock-ups

After the fit-up of all PSs, cold calibration has been performed for T-ribs of PS1 to make acceptable weld root matching condition with interfacing joints of other PSs which exceeds the allowable range for gap and misalignment. But despite that, a few T-ribs have locally 5~21 mm wide gap weld root matching condition. Therefore, further welding technique has been developed to guarantee welding quality under this wide gap condition. Additional scanning and evaluation techniques of the Phased Array Ultrasonic Test (PAUT) also have been developed to ensure full volumetric inspection which is required by ESPN order. No local cold calibration is required for PS3, UPSE and LPSE interface welding joints as the splice plate (SP) design was applied to accommodate large gaps and misalignment between weld joints.

Fig. 3 shows positional measurement results for all FPs on each segment of the ITER VV sector #6 after fit-up and inner shell welding, respectively. All measurement results are evenly best fitted for each PS's final dimensional result. After each PS fit-up, the mean values of PS2 and PS4 are relatively larger than those of PS1 and PS4 as shown in Fig. 3 (a). HHI and the VVPT have decided to complete fit-up and to start final assembly welding under this deviational condition because more precise fit-up is difficult for these heavy PS structures having complex curved configurations. Fig. 3 (b) shows the measurement results for all FPs after inner shell welding. The measurement result after inner shell welding is also the best fitted for D-shaped fit-up reference and the results is shown in Fig. (c). Due to the welding deformation, PS2 and PS4 are shifted 6.0 mm and 6.2 mm as a mean value, respectively.

Welding, PAUT and Remote Visual Examination (RVE) of the final assembly of sector have been successfully completed with application of biscuits design concept to ensure visual examination on backside welds. Dimensional inspection has been performed in parallel at major final assembly step for each FP to precisely monitor dimensional change and to determine a removal time of the Jig which minimize welding distortion at the final assembly. The major process for the final assembly of the ITER VV sector#6 are summarized in Fig. 4.

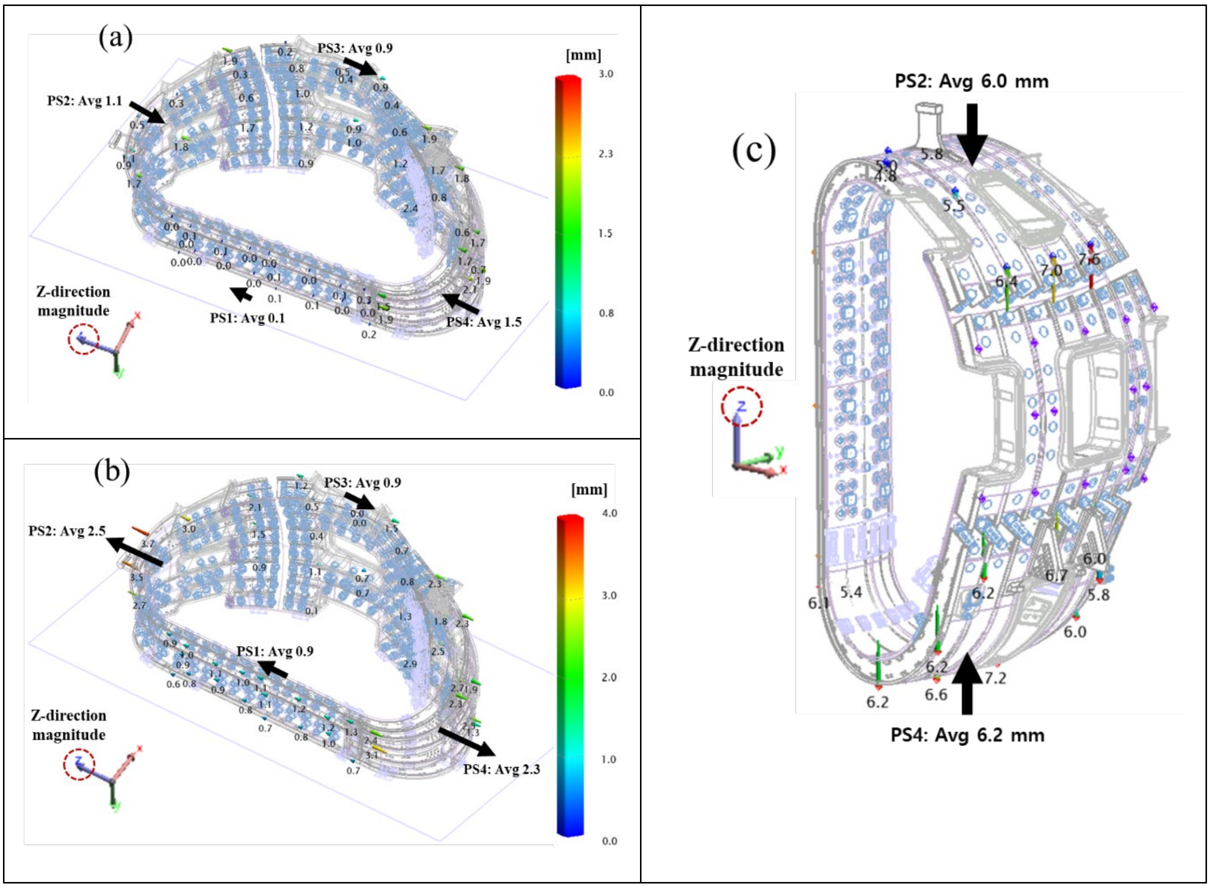


FIG. 3. Position deviation of each FP for poloidal direction: (a) after fit-up before inner shell welding start, (b) after inner shell welding, (c) after inner shell welding (best fitting result for D-shape fit-up reference) [5]

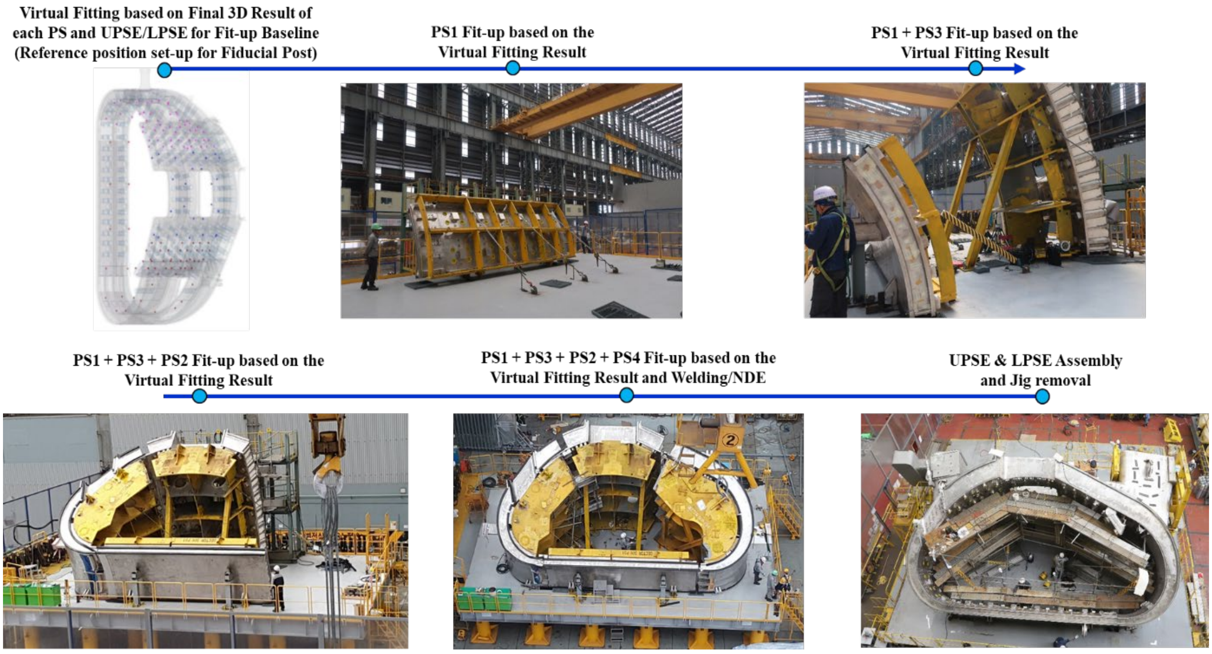


FIG. 4. General process of ITER VV sector #6 final assembly

3.3. Challenge-3: Full volumetric inspection requirement by French Regulation

The third technical challenge is the full volumetric inspection requirements such as entire volumetric examination for pressure-retaining welds and 100% visual inspection for the backside welds because ITER VV sector is classified as ESPN Level N2 component. All weld bevels are subject to surface examination before welding.

From a technical point of view, the entire volumetric examination requirement is the most difficult and required much effort to develop an alternative solution where radiographic examination (RT) is not applicable. RT is a reference volumetric examination method. If radiographic examination (RT) is not possible due to film accessibility and suitable source distance, ultrasonic examination (UT) can be applied as the alternative according to RCC-MR RS 7720. However, Generally the UT on the austenitic welds is regarded as a great challenge due to the high attenuation and dispersion of the ultrasonic signal [6]. Furthermore, ANB requires UT with data acquisition. Therefore, PAUT was selected as the alternative solution for RT.

In order to perform the PAUT inspection on actual products, the supplier shall develop an examination method and criteria with details, and supporting evidence demonstrating the sensitivity and reliability of the method, for approval from VVPT and ANB. Total 60 scanning techniques have been developed for typical welding configurations of the VV sector, such as T-welds with double J, T-weld with single J and butt welds with single U as shown in Fig. 5. Special scanning techniques (e.g. line scanning for curved surface, etc.) have been developed also for PAUT inspection on complicated scanning surfaces of the sector final assembly. For demonstration of developed PAUT technique, total 15 times of UT qualifications were successfully completed (with 157 qualification blocks and 141 documents) under VVPT & ANB witness.

Grinding to achieve surface waviness condition which (allows maximum 0.5 mm misalignment only per each 50 mm area considering applied PAUT probe wedge size) including surface profile measurement before cosmetic welding and after grinding are also huge time-consuming work in addition to an qualification for the impact on PAUT signal by cosmetic welding. Table 1 shows the accumulated volumetric NDE results for whole weld joints of the ITER VV sector#6.

Another technical challenge is 100% visual inspection on backside welds by ESPN Order. Direct visual inspection is not possible on backside welds due to the limitation of the access path of box structure. Therefore, RVE using a precise endoscope is selected as a visual inspection method for the backside of outer shell welds. A dedicated guiding tool system was developed to ensure full access of the endoscope through the cooling water channel in the double-walled structure.

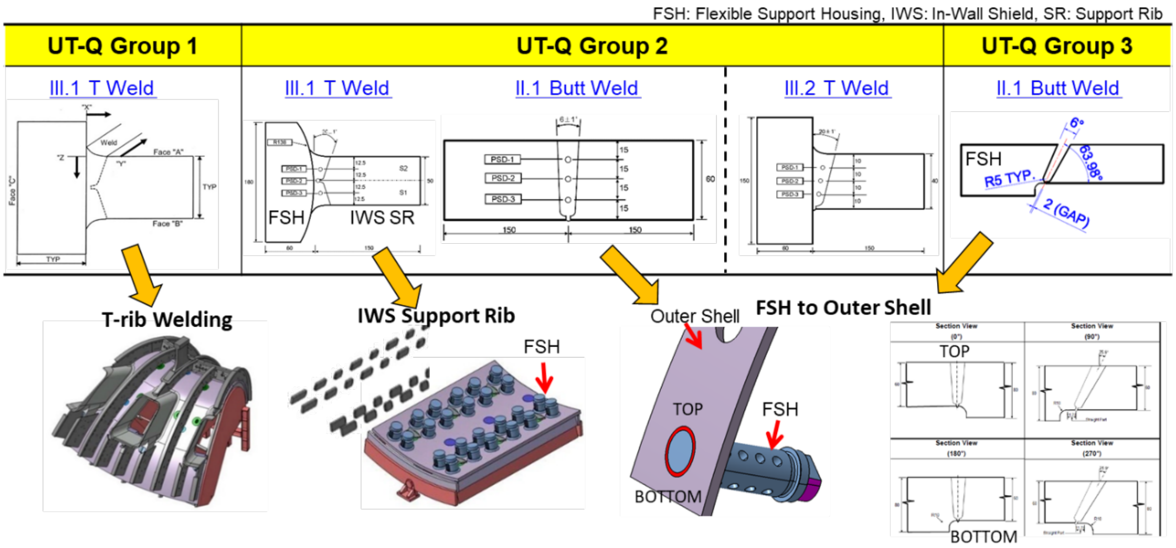


FIG. 5. UT Qualification groups for typical welding configuration of the ITER VV sector

TABLE 1. Volumetric NDE Results of the ITER VV sector#6

NDE Method	Test Length	Accept	Reject	Acceptance Rate (%)
RT (mm)	672,823	671,539	1,284	99.8%
PAUT (mm)	718,887	687,280	31,607	95.6%

Regarding developed RVE system, the technical qualification was successfully carried out on the performance of the colour recognition, resolution and measurement accuracy considering the maximum working distance of the endoscope camera from backside welds in the double-walled space. Based on the technical qualification results, a validation test report and RVE procedure/personal qualification procedure/work instruction have been prepared, and approved by VVPT and ANB. FIG. 6. shows the typical image of endoscope during ITER VV sector #6 RVE.

Biscuit design has been introduced on final splice plates to provide the last access route of the endoscope for backside welds of the final splice plates. After the biscuit welding, the RVE on backside welds of the biscuit was performed through plug holes on the side T-ribs. In spite of biscuit application, RVE is impossible for backside welds of the last plugs on side rib and last biscuits on UPSE/LPSE inner splice plate by lack of access route. For this case, RVE was finally excluded exceptionally after ANB approval for VVPT's official proposal considering less criticality for a relevant area during ITER operation.

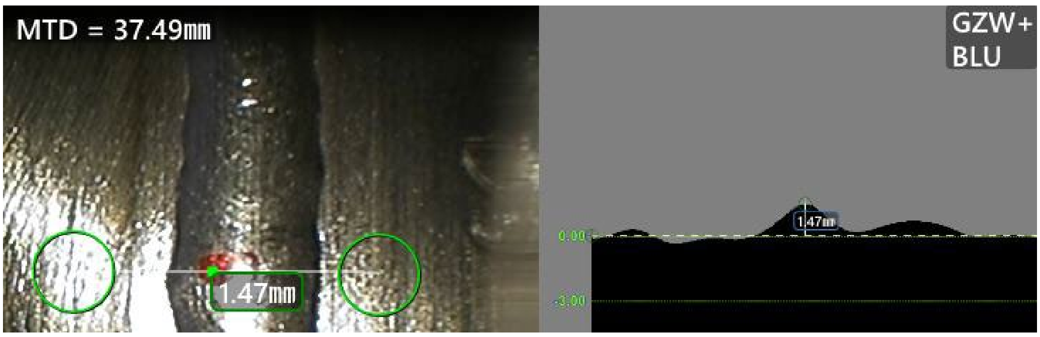


FIG. 6. Typical image of RVE on sector#6 backside welds using endoscope with depth profile

3.4. Other Challenges

The qualification of the VV sector vacuum performance for safety function is a PIA. Thus Helium leak test is a part of Final Acceptance Test (FAT) of the ITER VV sector.

200 °C baking was considered to achieve the low background leak rate which makes the test possible, especially considering probable contamination of the VV sector. However, there were many risks associated with the baking, and the final decision was to perform the leak test without baking. KODA/HHI checked the feasibility of the leak test by pre-pumping the VV interspace, which discovered that the background leak rate, as well as the total pressure is low enough to perform the leak test without baking. A leak test procedure which incorporates the result of pre-pumping was developed based on the test equipment arrangement as shown in Fig. 7, and after successful completion of the Pneumatic Pressure Test with 5 bar of Nitrogen gas, which is also a part of the FAT, Helium leak test followed immediately. VV sector as a test object is enclosed by tracer Helium gas, and the VV interspace is continuously pumped and evacuated gas is monitored by a mass spectrometer. If leak paths are present, Helium would penetrate through the paths and the mass spectrometer senses the change of the amount of Helium in the evacuated gas. Test was passed successfully as shown in Fig. 8. The calculated leak rate (6.08×10^{-9} $Pa \cdot m^3 \cdot s^{-1}$) satisfied the acceptance criteria, which is 1×10^{-8} $Pa \cdot m^3 \cdot s^{-1}$. It is a criterion for clean, unbaked stainless steel.

The ITER VV sector #6 was packed with double hermetically sealed using special sealing material which approved in advance after the dimensional inspection and the final cleaning. The Sector #6 transportation activities are also classified as PIA according to French nuclear order. Therefore, the transportation plan including quality plan and inspection plan were approved by VVPT and ANB before implementation. Inspection by VVPT and ANB inspectors was carried out on the major operations of the transportation activities based on the approved documents.

After long sea transport, the sector #6 was unloaded on 22 July 2020 at FOS in France and delivered to ITER site on 7 August 2020. After arrival at IO site, site acceptance test including Helium Leak Test was completed without major issue and certificate of acceptance was issued and approved by IO on 6 October 2020.

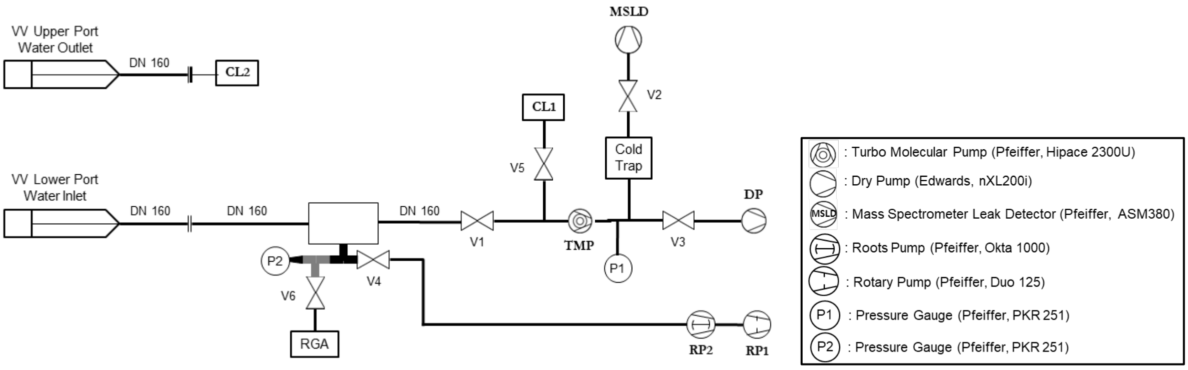


FIG. 7. Diagram for He Leak Test of the ITER VV sector #6

FIG. 8. He Leak Test of the ITER VV sector #6

4. LESSONS LEARNED

Following lessons learned are identified and realized during the ITER VV sector #6 manufacturing over the last 10 years.

4.1. Significance of the regulation and code for vacuum vessel manufacturing

It is clearly recognized that the importance of the regulation and code for manufacturing of the ITER VV sector. The appropriate regulation and code need to be developed for VV of a future fusion power plant which well balanced between economic and safety point of view. In order to achieve this goal, the simplified vacuum vessel design also has to be developed in parallel.

4.2. Lessons learned for remaining ITER VV sectors manufacturing

In comparison with 1st sector (sector #6), significant reduction of the manufacturing duration is expected for the remaining sectors which are under KODA responsibility as shown in Fig. 9 by 1) use as the developed manufacturing documents and techniques for 1st sector, 2) the improved document management system, 3) the updated quality control to prevent similar non-conformities, and 4) the several technical improvements such as additional splice T-rib between PS1 and PS4 for the final assembly, the improved weld joint design for PAUT feasibility, the improved jig system and the welding sequence.

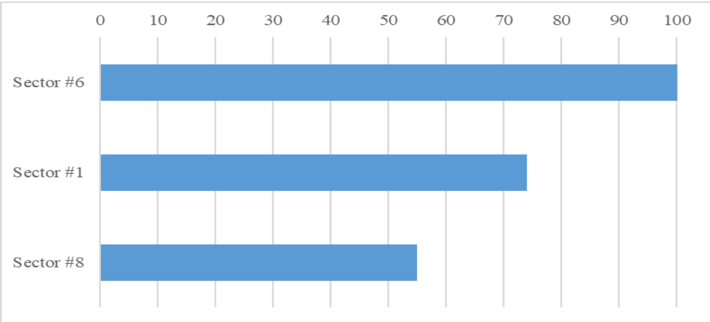


FIG. 9. Expected manufacturing duration for KO 3 sectors [months]

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DISCLAIMER

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

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