Manufacturing Completion of the First ITER Vacuum Vessel Sector

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on behalf of VV Project Team

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Outline

• Introduction

• Technical Challenges
  - Nuclear Safety Process
  - Tight Tolerance Requirement
  - Full Inspection Requirement
  - Other Challenges

• Lessons learned
Introduction
ITER Vacuum Vessel - Overall Description

- A torus shaped double wall structure
  - To provide the high vacuum for plasma and the primary radioactivity confinement boundary
  - To support in-vessel components (Blanket, Divertor, etc)

<table>
<thead>
<tr>
<th>Major dimensions</th>
<th>Weight (ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter</td>
<td>19.4 m</td>
</tr>
<tr>
<td>Height</td>
<td>11.4 m</td>
</tr>
<tr>
<td>Double wall thickness</td>
<td>0.34-0.75 m</td>
</tr>
<tr>
<td>Interior surface</td>
<td>850 m²</td>
</tr>
<tr>
<td>Interior volume</td>
<td>1600 m³</td>
</tr>
<tr>
<td>Main vessel</td>
<td>1611</td>
</tr>
<tr>
<td>Shielding</td>
<td>1733</td>
</tr>
<tr>
<td>Ports</td>
<td>1781</td>
</tr>
<tr>
<td>Supports</td>
<td>111</td>
</tr>
<tr>
<td>Total</td>
<td>5236</td>
</tr>
</tbody>
</table>
## ITER VV - Procurement Sharing

<table>
<thead>
<tr>
<th>EU</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Items</td>
<td>5 Sectors of Main Vessel</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RF</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Items</td>
<td>18 Upper Ports</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>KO</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Items</td>
<td>(2 + 2) Sectors of Main Vessel</td>
</tr>
<tr>
<td></td>
<td>17 Equatorial Ports</td>
</tr>
<tr>
<td></td>
<td>9 Lower Ports</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IN</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Items</td>
<td>In-Wall Shields/ribs</td>
</tr>
</tbody>
</table>
### Requirement

#### Regulatory Requirements

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>• PIC (Protection Important Class) components according to French order dated 7 Feb 2012 (<a href="#">INB Order</a>).</td>
</tr>
<tr>
<td>Nuclear pressure vessel</td>
<td>• Level N2 and Category IV NPE according to the guidelines of the ASN for application of French Order dated 30 Dec 2015 (<a href="#">ESPN Order</a>).</td>
</tr>
<tr>
<td></td>
<td>• Agreed Notified Body (ANB) involvement for conformity assessment.</td>
</tr>
</tbody>
</table>

#### Technical Requirements

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>316L(N)-ITER-Grade with special requirements</td>
</tr>
<tr>
<td>Design load</td>
<td>Dead weight, coolant pressure, various electromagnetic loads</td>
</tr>
<tr>
<td>Tolerance</td>
<td>Accurate field joint fit-up and precise assembly of in-vessel components</td>
</tr>
</tbody>
</table>
| Welding Inspection | Full penetration welding  
                     | 100% volumetric NDE even at single side accessing region                                       |
| Testing         | Baking condition: 200 °C  
                     | Testing pressure: 0.5 MPa, Vacuum leak rate: < 10⁻⁸ Pa-m³/s                                    |
Brief history of the 1st sector manufacturing

Needs 101 months for 1st sector manufacturing

ITER VV sector #6 (1st sector)
Technical Challenges
Technical Challenges of ITER VV

• Main technical difficulties are caused by strict nuclear regulation
  
  1. Nuclear Safety Process
  
  2. Tight manufacturing tolerances even a heavy welded structure having total 1.4 km lengths weld seams
  
  3. 100% volumetric inspection requirement by ESPN order
  
  4. Complicated interfaces among related parties, for example,
     - Involved several DAs, IO and ANB
     - Manufacturing of IWS by INDA (ATL), Upper Port Stub Extension by RFDA (MAN)
     - Assembly into Sector : by KODA (HHI)
Technical Challenges

1. Nuclear Safety Process
**Challenge-1: Nuclear Safety Process (1/2)**

- **Whole manufacturing procedure of the ITER VV should observe nuclear regulatory requirements.**
  1. To maintain traceability for all activities as nuclear pressure vessel
  2. All applicable documents shall be approved by KODA, IO and ANB prior to actual manufacturing
  3. All manufacturing activities have been inspected and recorded with approved Manufacturing Inspection Plan (MIP)

→ A great deal of time and effort are required to proceed the manufacturing by a long documents review & approval process, and the complicated work interface

*A necessity arose for process simplification!!*
In 2015, IO EPB (Executive Project Board) decided to create the Vacuum Vessel Project Team (VVPT)

1. Purpose
   - One team sprit : IO-CT + IO-DAs
   - Simplification of project management of the VV

2. The whole process has been greatly simplified after implementation of the VVPT,
   - The simplification of the document control procedure by a time review and approval as one team
   - All inspections were performed at once
   - A total of 45,000 inspection points were performed and about 500 manufacturing documents have been developed for manufacturing of the ITER VV sector#6
Technical Challenges

2. Tight Tolerance Requirement
Challenge-2: Tight Tolerance Requirement (1/8)

- Interface with in-vessel components

BLANKET MODULES
MANIFOLD
DIVERTOR
INTERNAL COILS
RAILS/KEYS FOR INSTALLATION
• Welding distortion analysis to determine counter deformation during final assembly

Calculated welding distortion based on HHI final assembly sequence
Virtual Fitting in advance based on final 3D result of each PS and UPSE/LPSE for fit-up baseline (Reference position set-up for each Fiducial Posts based on 1) required tolerance, 2) as built dimension for each segment, 3) required weld root fit-up tolerance, 4) welding distortion analysis results)
• Final Assembly based on Virtual Fitting

PS1+PS3+PS2 Fit-up based on the Virtual Fitting Result

PS1+PS3+PS2+PS4 Fit-up based on the Virtual Fitting Result and Welding/NDE

UPSE/LPSE Assembly & Jig removal
Challenge-2: Tight Tolerance Requirement (5/8)

• Technical requirements - Tolerance

Required tolerance for FSH
• Angle of Thread Hole:
  ✓ Max 0.7° (common)

Final results of S6 PS1 FSH Thread Hole Angle

(Angle A)

(Angle B)

<A angle Max = Max: 1.09° (0.7° + 0.39°)>

<B angle Max = Max: 0.47°>
Challenge-2: Tight Tolerance Requirement (6/8)

• Technical requirements - Tolerance

Final results of S6 PS1 FSH Thread Hole Position

Required tolerance for FSH
• Location:
  ✓ +/- 2mm (for edge)
  ✓ +/- 4mm (for body)
Challenge-2: Tight Tolerance Requirement (7/8)

**Technical requirements - Tolerance**

Final results of S6 Inner & Outer Shell

**Required tolerance for Shells**

- **Inner Shell:**
  - Max: 6.59 mm, Min: -9.335 mm

- **Outer Shell:**
  - Max: 14.38 mm, Min: -1.787 mm
• Welding technology for wide root gap & misalignment

PS4 setting for final assembly

Welding Procedure Specification for wide root gap & misalignment (Max. 21 mm)
Technical Challenges

3. Full Inspection Requirement
**Challenge-3: Full Inspection Requirement (1/5)**

- **PAUT: Qualification for various VV weld configurations**

<table>
<thead>
<tr>
<th>UT-Q Group 1</th>
<th>UT-Q Group 2</th>
<th>UT-Q Group 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>III.1 T Weld</td>
<td>II.1 Butt Weld</td>
<td>III.2 T Weld</td>
</tr>
</tbody>
</table>

- T-rib Welding
- IWS Support Rib
- Outer Shell
- FSH to Outer Shell

- 15 times of UT qualifications were successfully completed (with 157 qualification blocks and 141 documents) under VVPT & ANB witness.
• **PAUT**: modifications on the general configurations, mainly to difficult access, bring difficulties during the production.

1. Special cases (mainly poor accessibility for UT): Jigs/Fixtures for welding distortion, Surface curvature, Geometrical shape, Thread holes, Water cooling holes, Existing weld lines, etc
2. Special cases leads to higher UT sensitivities and modified acceptance criteria
   → Applied compensation gain

→ **To achieve 100% volumetric examination requirement, all special cases were technically verified and successfully qualified.**
Challenge-3: Full Inspection Requirement (3/5)

- **PAUT**: Special case for various VV weld configurations

![Diagram of outer splice plate and port stub](image1)

![Example of line scanning](image2)

Figure 29. Isometric view of corner joint

Figure 30. Example of line scanning.
• Remote Visual Examination for weldments (100% Visual examination)
Challenge-3: Full Inspection Requirement (5/5)

- Remote Visual Examination for weldments (100% Visual examination)
  1. RVE technology has been successfully qualified (resolution capability at least equal to that of direct visual examination).
  2. Nuclear requirement (100% VT on backside welds) was satisfied using RVE technology.

Weld Reinforcement Width    Weld Reinforcement Height
Technical Challenges

Others
Other Challenges (1/3)

• Factory Acceptance Test

  Pre-pumping
  Pressuring
  Pressure Test

  Pre-pumping done before Pressure Test
  - Reduced (0.5 MPa) pneumatic pressure test done
  - Exemption of deformation check during pressure test of the sector by DR-IO-007-2019

  Flow test on sectors replaced by visual test to detect blockages by DR-IO-001-2019
  - Background of the leak test relaxed (10^{-9} \rightarrow 10^{-7} \text{ Pam}^3/\text{s}) according to DR-IO-011-2019
  - The leak rate acceptance criteria remains as 1x10^{-8} Pa·m^3/s

  Removal of baking on sector before the leak test at factory by DR-IO-018-2019
  - All location of the FPs measured
  - Point measurement & Surface scanning carried out
Other Challenges (2/3)

- **Factory Acceptance Test**
  - He Leak Test was passed successfully
    - The calculated leak rate: $6.08 \times 10^{-9} \text{ Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}$
    - (The acceptance criteria: $1 \times 10^{-8} \text{ Pa} \cdot \text{m}^3 \cdot \text{s}^{-1}$)

He Leak Test of the ITER VV sector #6
• Transportation

✓ **ITER VV transportation is considered as PIA** according to French Regulation
  ▪ Transportation Plan, Quality Plan and MIP have to be approved by ANB in advance
  ▪ Following documents also have to be approved before shipping
    • 1) Packing Procedure, 2) Packing List, 3) Technical Information, 4) Invoice
    • 5) Packing Control Record, 6) Certificate of Compliance, 7) Deliverable Documentation,
    • 8) Delivery Report, 9) Shipping Requirement, 10) Release Note, 11) EMR
    • 12) Equipment storage & preservation requirement by IO TRO
    • 13) Hazard analysis & specification for transportation/storage by IO TRO

**ITER VV sector #6 Hermitical Covering and Transportation**
LESSONS LEARNED
• **Expected significant manufacturing schedule reduction for the remaining KO sectors by,**

1. Use developed manufacturing documents and techniques for 1st sector
2. Improved document management system and the updated quality control to prevent similar non-conformities
3. Several technical improvements such as additional splice T-rib between PS1 & PS4 for the final assembly, the improved weld joint design for PAUT feasibility, the improved jig system and welding sequence

![Expected manufacturing duration for KO 4 sectors [months]](image)
LESSONS LEARNED (2/2)

• Significance of the regulation and code for vacuum vessel manufacturing,

1. It is clearly recognized that the importance of the regulation and code for manufacturing of the ITER VV sector.
2. 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.
3. In order to achieve this goal, the simplified vacuum vessel design also has to be developed in parallel.
Thank you for attention!