

CONFERENCE PRE-PRINT

RECOVERY OF ITER SECTOR MODULES FROM CRITICAL ISSUES

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Abstract

The paper describes the repair of ITER key components - the vacuum vessel thermal shield (VVTS) and vacuum vessel (VV) from the critical issues discovered in 2022. During the site acceptance test of VVTS components, leakage was detected on the equatorial port (E-port) shroud. The root cause analysis revealed an intergranular crack on cooling pipe caused by stress corrosion cracking. The VVTS was repaired by replacing entire set of pipes after 2 mm thick machining from the panel surface in the area the previous pipe had been welded. To mitigate the risk of future corrosion, corrosion-resistant materials were employed for both the pipes and the welding filler. In the first delivered VV sectors, significant geometrical deviations were detected at the bevel joint for VV sector welding. These deviations were corrected through build-up and machining using a newly developed portable milling machine. Following the completion of repair of VVTS and VV welding bevel, the assembly of the ITER sector modules was resumed in September 2024.

1. INTRODUCTION

In ITER, the tokamak chamber consists of nine 40-degree sector modules (SM), each composed of a Vacuum Vessel (VV) providing a vacuum environment for the plasma [1], two Toroidal Field Coils (TFCs) confining the plasma particles [2], and a VV Thermal Shield (TS), whose role is thermal radiation insulation between the VV and TFC [3]. Once all nine SMs are installed in the pit, the VV sectors are welded together to form the VV Torus. In May 2022, the assembly of the first SM was completed, and it was successfully transferred to the pit (Fig.1). However, due to critical non-conformance in the VVTS, confirmed in Sep. 2022 as described below, it was decided to return the first SM to the SSAT and dismantle for repair. Furthermore, it was decided to carry out VV bevel repair outside the pit, as the conditions were found to be more favourable than inside the pit, although in-pit repair had initially been planned. This paper presents the critical issues identified in both the VVTS and VV, the recovery strategy, the repair process, and the lessons learned.

2. CRITICAL ISSUES ON VVTS AND VV

In December 2021, during acceptance tests of the VVTS panels, three leaks were found in the DN8 2 mm thick cooling tube on the three Equatorial Ports (E-ports) of VVTS#2, #4 and #8 (Fig. 2). In May 2022, a preliminary

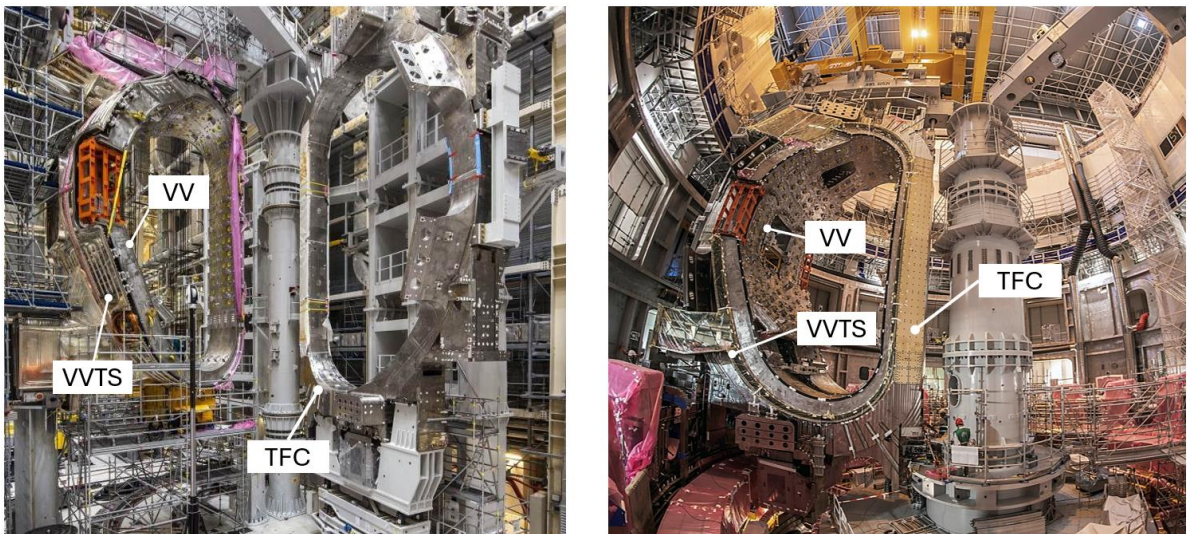


FIG. 1. Sector Module assembly in the Assembly Hall and Transferred to the Pit

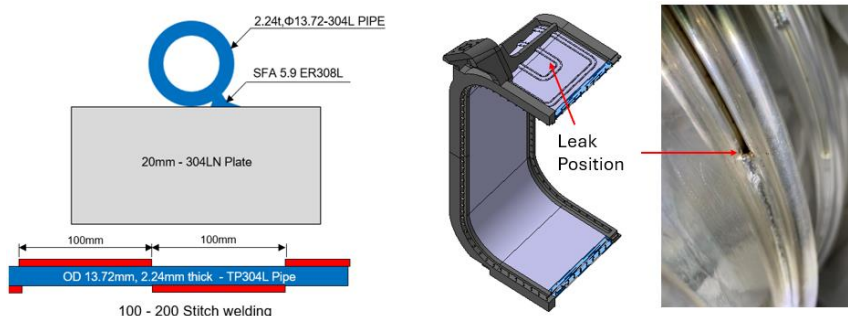


FIG. 2. Pipe stitch welding and leak position on the VVTS E-port shroud

root cause analysis (RCA) indicates that these leaks were caused by stress corrosion cracking (SCC) in the cooling pipes, which had been welded onto the VVTS panels for cooling purposes. Further detailed RCA was required because an impact to the project is significant if SCC happens.

Detailed metallographic examination of pipe specimen from leak panel was carried out. Computed Tomography (CT), Scanning Electron Microscopy (SEM) confirmed SCC on pipe crack in July 2022 [4-5]. In the cooling piping of the E-port, SCC with a depth exceeding the 2.2 mm pipe wall thickness was observed (Fig. 3). In addition, high contents of chloride were detected on surface of pipe. On the other side, considering that the leaks occurred exclusively in the E-port pipes, which have a total length of 1 km, while no leaks were observed in other components despite their total pipe length of approximately 23 km, SCC was suspected to be a phenomenon specific to the E-ports.

Therefore, further detailed studies were performed on the cooling piping of other components. SCC was detected on these pipes in September 2022, however its depth was generally below 0.3 mm. Meanwhile, in the TS panels, only one location at the E-port exhibited propagated SCC with a depth of 2.4 mm. These facts indicate that the E-port provides the necessary conditions for SCC, namely residual stress and the presence of chlorides. Consequently, it is anticipated that SCC progresses more rapidly and penetrates more deeply at the E-port.

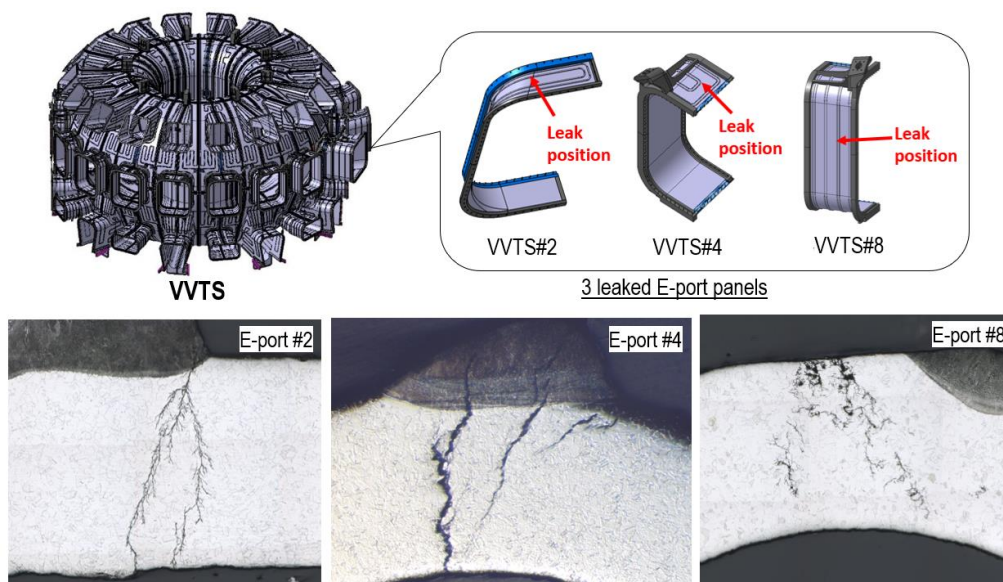


FIG. 3. Leaked E-port panels and crack cross-section by CT scan

Furthermore, almost simultaneously, in first three delivered VV sectors, relatively large geometrical deviations were detected at the bevel joints for welding the VV sectors together. Welding of VV sectors in the pit would be performed by narrow-gap mechanized TIG which requires tight tolerances at the welding joint bevel. Some of them represented in Fig. 4. Bevel nose thickness, nose flatness in toroidal direction and distance between inner and outer bevels are considered most critical dimensions for VV Sectors welding.

Major difficulties of the relatively large dimensional deviations on VV sector bevels are:

- Difficulties to adapt welding parameters to irregular bevel profile, particularly when the nose thickness shows large variation outside the specified tolerance. Example of high variations on bevel nose thickness (Fig. 4) is represented in Fig. 5a.
- Difficulties to adapt the welding machine to significant trajectory changes. Representation of VV sector field joint with splice plate with high deviations in toroidal direction is shown in Fig. 5b.
- Difficulties for splice plate customization and onsite alignment to the field joint bevels in Fig. 5b.
- Potential clashes with welding tools, biscuit¹ hole machining tools and NDE tooling. In Fig. 5c : in left figure, biscuit hole milling machine is clashing with T-rib due to reduced distance from outer bevel to T-rib; in right figure: Splice plate welding head clash with inner bevel due to reduced distance between inner and outer bevel.

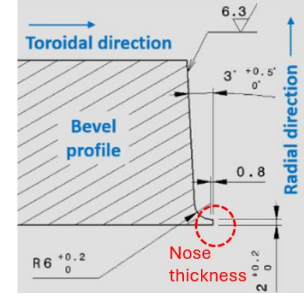


FIG. 4. VV welding bevel: profile dimensions

From these difficulties, it was concluded that repair of field joint bevels was necessary to have VV sector bevels at acceptable dimensional conditions (in terms of bevel dimensions, and toroidal & radial position) compatible with VV sectors welding process and tools.

The remedial actions (RA), such as correcting these deviations using customized splice plates and repairing the VV welding bevels in the pit, were considered at that time to minimize the delay. However, a detailed study about the repair in the pit found significant technical challenges, such as limited access to the bevels, potential clashes of tools and equipment needed for the repair with the installed VVTS, difficulties to maintain pit cleanliness requirement, etc, resulting preventing the execution of this approach. In addition, it was decided to remove the SM from the pit for repair of VVTS. Therefore, it became much easier to repair the VV bevel outside the pit.

Although disassembling the SM was expected to result in a significant delay of approximately three years, it was decided to proceed with removing the first SM from the pit and disassembling it to facilitate repairs of both the VV and VVTS, thereby mitigating significant future risks.

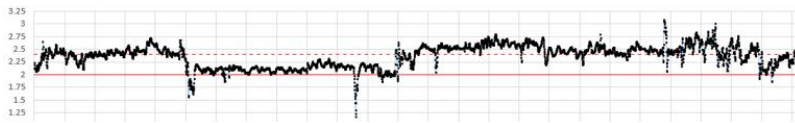


Fig. 5a. High variations of bevel nose thickness

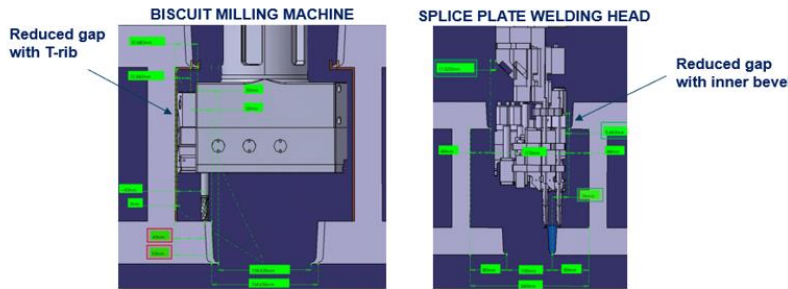


Fig. 5c. Potential clashes with bevels and T-rib

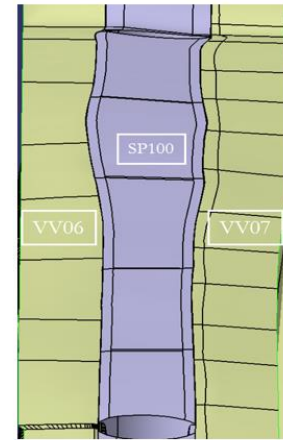


Fig. 5b. Toroidal deviations at the bevel nose

FIG. 5. VV bevel deviation

3. RECOVERY OF VACUUM VESSEL THERMAL SHIELD

3.1. Recovery of VVTS from SCC

Once SCC has propagated, its removal becomes practically impossible. In the cooling pipes on thermal shield and panel surfaces on E-port, SCC progression was observed, therefore it was decided to replace all the cooling pipes

¹ Biscuit is the name applied to intermediate circular plates located between two consecutive splice plates, whose function is to access to the backside of the splice plates field joint welds to allow welding and NDE.

from thermal shield component and all E-ports. On the other hand, since no SCC propagation was observed in panels other than those in the E-port, they were deemed repairable.

Since repair approach shortened the time for recovery of critical issue of thermal shield comparing with new manufacturing which required for the panel material procurement and its forming which takes approximately one year or more, repair of thermal shield was prioritized. However, re-welding of the pipes will cause panel deformation and VVTS required tight tolerance for manufacturing, two VVTS segment repair and two VVTS re-manufacturing was launched together at the same time considering technical difficulties of repair and schedule impact of material procurement for re-manufacturing in case of failure of repair.

In addition, the new pipes are 316L grade, and ER317L Mn Mod welding filler was employed to improve corrosion resistance. For conservative reasons, since further repair of the VVTS is not feasible owing to its confined position between the VV and the superconducting magnet, a new filler material was adopted to eliminate the risk of potential SCC caused by residual chloride from the surface. The newly adopted filler material, characterized by low carbon and high molybdenum content, provides enhanced resistance to pitting, crevice corrosion, and stress corrosion cracking.

For the repair of VVTS, a clean panel was selected based on the systematic visual inspection. Subsequently, NDE was performed to verify the panel condition in the areas showing suspicious indications of severe corrosion. Fig. 6 describes the work process to repair the panel checking the soundness of the panel from risk of SCC. Visual inspection for all pipe stitch welded regions had been carried out. The inspection focused on the pipe attachment area, where the risk of SCC propagation was considered higher due to the presence of residual chlorine. Locally highly corroded area was examined precisely by Fluorescent Penetrant Testing (FPT) on the panel surface after partial removal of cooling pipe. The inspection particularly targeted the pipe welded area and welding joint between panels, since at room temperature (non-operational condition) there is almost no stress on the panel, and residual chloride does not cause an issue on the unwelded panel surface.

When there is no indication on the test part, all pipe removal and panel 2 mm thick layer in the vicinity of the pipes was performed. Since complete removal of existing chloride to deactivate crack propagation is difficult by grinding, panel were machined to ensure the complete removal of the chloride where high chloride contents were detected. And then the panel surface was polished to achieve lower thermal radiation emissivity. After panel machining and polishing, FPT was performed to confirm the absence of SCC on the panel before new pipe attachment.

3.2. Newly found problem in VVTS during repair and its recovery

Numerous corrosion spots were observed on some panels that had been shipped to the supplier for repair. Upon investigation, it was determined that these panels were exposed to high humidity conditions at the port after being inspected by customs. The Ag coating layer thickness was examined and found to be only a few micro-meters, whereas the required thickness is greater than 5 μm . Such a thin Ag coating leads to discontinuities in the protective layer and defects such as pinholes and scratches. These weaknesses, combined with high humidity conditions during shipping and at repair sites, facilitated corrosion. Furthermore, chlorides trapped beneath the Ag coating contributed to galvanic corrosion under conditions of high humidity and elevated temperatures during transportation and repair work at the supplier's premises.

To mitigate further corrosion risk, it was decided to remove the Ag coating from the VVTS panel surfaces. The panel surfaces were then buffed ($R_a < 0.1 \mu\text{m}$) to ensure adequate emissivity. From tests on different surface roughness conditions, it was found that polished stainless steel with a surface roughness of less than $0.2 \mu\text{m}$ can exhibit emissivity similar to that of a previously silver-coated surface at cryogenic temperatures. The emissivity of a well-polished VVTS surface is expected to be 0.05–0.06, compared to 0.03–0.05 for a silver-coated surface at 80 K [6]. Fig 7 presents the repaired thermal shield surface.

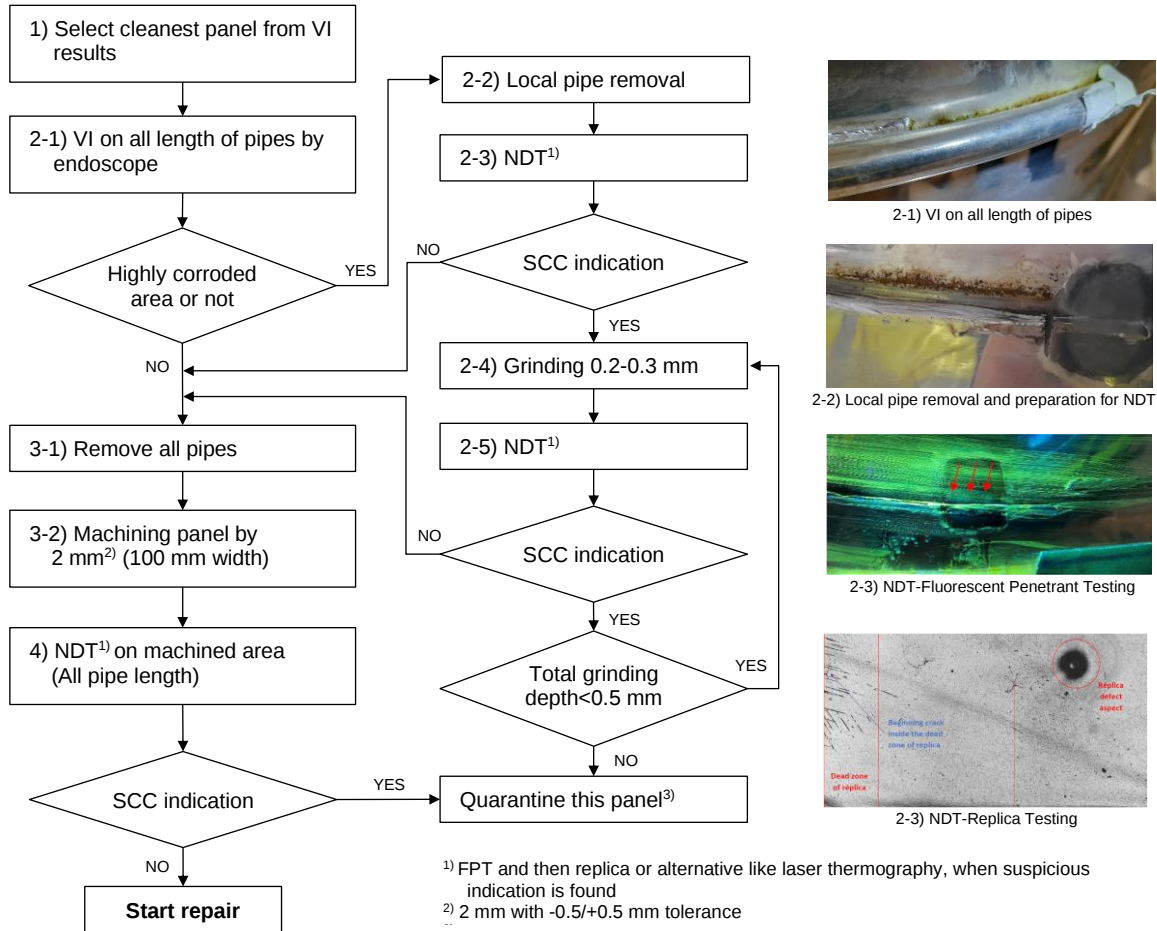


FIG. 6. Panel examination to delete SCC risk before starting of repair

3.3. Achievement

Five VVTs have been successfully repaired by mid of 2025. The success of repair was confirmed geometrically by the pre-assembly test and survey. Thermal shield repair approach shortened the time of recovery from the critical issue of thermal shield as mentioned previously.

3.4. Lessons Learned

- Silver coating on the pipe stitch welding should be avoided due to potential risk of residual chlorides from the coating process.
- For ensuring the long-term reliability of the cooling circuit during manufacturing and storage under environmental exposure, high corrosion-resistance material should be selected, such as 316L grade pipe combined with specialized filler metals.
- At cryogenic temperatures, a well-polished stainless-steel surface can provide favourable thermal radiation emissivity. Therefore, rather than applying silver coating, which carries the risk of SCC, enhancing the cooling performance through polished stainless steel can also be considered a practicable alternative.

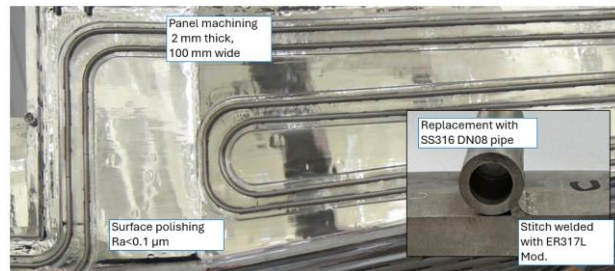


FIG. 7. Repaired thermal shield panel

4. RECOVERY OF VACUUM VESSEL

4.1 Recovery of VV

Analysis of as-built deviations and potential repair solutions begun with full and precise 3D scan of the field joint bevels all along the VV sector. The raw scan data are used to create accurate reconstructed surfaces of the as-built bevels with an accuracy of < 0.1 mm (Fig. 8). The analysis of potential repair solutions starts with the 3D CAD model of the as-built bevels reconstructed surfaces. Specific dedicated software and high level of expertise are required for the postprocessing of the 3D scan captured raw data and modelling of 3D reconstructed surfaces.

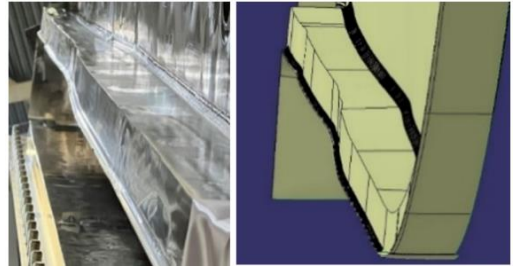


FIG. 8. From VV sector as-built bevel (left) to CAD Model of reconstructed surfaces (right)

Different designs were carefully assessed to choose the most suitable bevel repair configuration. The proposed repair solutions aimed to adjust the VV sector bevels to correct radial and toroidal positions, ensuring that the profile dimensions met the required tolerances and that the toroidal and radial deviations between two consecutive VV sectors were reduced to acceptable ranges for splice plate customization.

Fig. 9 (left) shows the identified expected toroidal and radial misalignment between two VV sector bevels before repair (as-built bevels), and the resulting splice plate, in comparison with projected bevel position after repair. The right images illustrate the two VV sectors with bevel position corrected after repair and the corresponding splice plate.

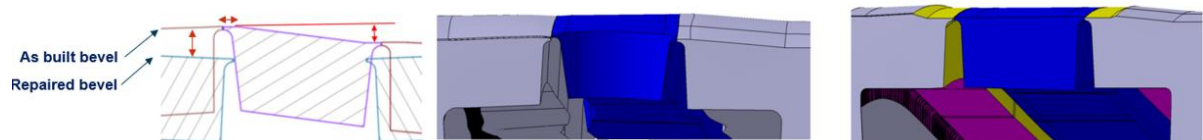


FIG. 9. Repair solution: VV sector as-built field joint (center) – Repair bevel field joint

Major challenges were encountered in selecting and implementing the most appropriate repair configuration, requiring extensive feasibility analysis to identify the best compromised solutions that satisfied both technical and quality requirements.

- Need of significant level of build-up to bring repair bevel to new toroidal/radial position, requiring specific qualification through dedicated representative build-up welding coupons proposed demonstrate: Feasibility of build-up in different welding positions, Soundness of performed build-up and conformity of mechanical properties of the assembly “build-up + fielding join”.
- To limit the distortions induced by the deposited weld build-up material: an “optimized” repair solution² combining local build-up (only at some locations) and machining of bevels (all around the Sector) was selected (Fig. 10).
- Dedicated UT qualification to be developed for the Non-Destructive Examination (NDE) of the specific build-up to be applied in the bevel repair solution.
- Solution to machine bevels to the final required dimensions and tolerances. Since transporting the sectors to industry for bevel machining on a portal machine was not feasible, portable milling machines were proposed for the final bevel machining, which required dedicated customized design to be adapted to the shape of the



FIG. 10. Illustration of “optimized” repair solution combining build-up and machining

² Build-up (added material) is only applied at some locations of the field joint bevels around the VV Sector, while at other locations new bevel position is reached only by machining (removal of material). All areas with build-up are machined after to achieve required final bevel tolerances.

VV Sector, and specific development and qualification to demonstrate feasibility of machining within required tolerances.

- Final validation of selected repair design shall be granted following careful verification of all parameters involved in the implementation of the VV sectors welding, including boundary conditions required for the use of welding, machining and NDE tools.
- Schedule, logistics and peripheral potential impacts were also assessed and quantified.

The VV sectors are manufactured in accordance with the RCC-MR code, and all manufacturing processes applied to the repair the VV sector bevels have been previously qualified through dedicated welding coupons (for build-up and NDE qualifications) and mock-ups (for machining and metrology qualification). Both build-up and machining were qualified to enable the repair of VV sectors in vertical and in horizontal position.

Three different configurations of build-up have been applied to recover material on VV sector bevels (Fig. 9), depending on the level of deviation to be corrected at any specific location:

- Build-up case A, performed to correct small deviations (< 5 mm) at the level of the bevel nose.
- Build-up case B, local build-up performed to correct local deviations at the level of the bevel nose and radius beyond the limits of case A.
- Build-up case C, full build-up performed along the plate thickness (60 mm), at the specified thickness required by the repair solution.

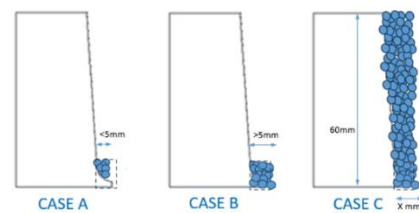


FIG. 11. VV sector build-up: Case A, B, C

To perform this build-up, two different welding processes have been qualified through dedicated representative build-up coupons: Manual TIG welding and partially mechanized TIG welding. Both processes are applicable for build-up Case C, whereas Case A and B are carried out exclusively using manual TIG. The welding coupons were executed in various welding positions (PC, PF, combination PF/PA, PC/PA). Different NDE techniques are applied to verify the quality of build-up: Surface examination by visual inspection and penetrant test are applied to Case A, B, and C. In addition, volumetric examinations are also applied to Case B and C: manual ultrasonic test is applied to both Case B and C, while radiographic test is applied exclusively to Case C.

For the final machining, customized portable milling machines have been developed to work in any required position. Five different models of milling machines are used, depending on the area of the VV sector to be machined (Fig. 12).

The portable machines are clamped to the VV sector using threaded holes drilled on the plate (T-rib) located between inner and outer bevels all around the VV sector. The milling machines are precisely aligned with the VV sector permanent metrology network using a temporary metrology network, which is referenced to the VV sector network. This precise alignment ensures that bevels are machined at required global position within the VV sector. The temporary metrology network is defined by target nests tack welded close to the field joint bevels all around the VV sector. After completion of bevel machining and final validation, target nests are removed.

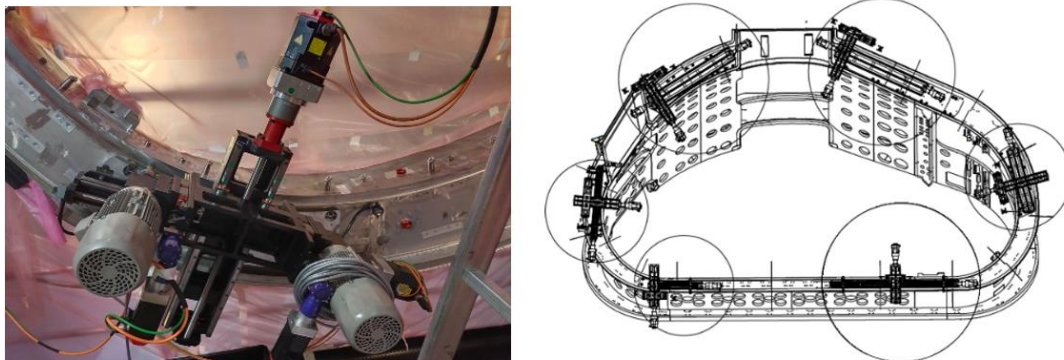


FIG. 12. Portable milling machine installed in the VV sector and illustration of different milling machines on the VV Sector

Validation of achieved bevel tolerances after final machining is performed by 3D scanning. Fig. 13 illustrates an example before and after bevel repair, and some results of scanned machined bevel.

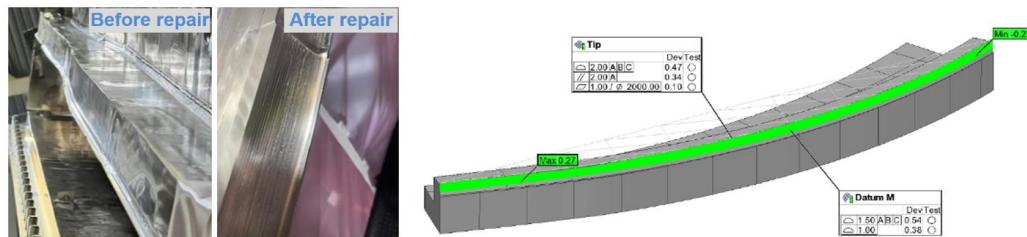


FIG. 13. Repaired VV bevel: Bevel shape before and after repair (left); achieved tolerances after bevel machining (right)

4.2 Achievements

Four VV sectors have been fully repaired by mid of 2025. VV sector 6 and VV sector 7 have been transferred to pit after SM assembly. VV sector 5 and VV sector 8 are installed in the SSAT for the assembly process, which is currently on going. Bevel repair of VV sector 1 and VV sector 4 is under process, foreseen to be completed in Q4 2025. Dimensions and tolerances achieved after final bevel machining are in the acceptable ranges for the VV Sector field joints welding and NDE, therefore purpose of VV bevel repairs has been fulfilled.

4.3 Lesson Learned

- VV sector bevels, which require tight tolerances for automatic welding and NDE, shall be machined at the final stage of VV sector manufacturing.
- Tight tolerances on field joint bevels must be achieved by machining. If the use of a fixed machine is not feasible, using a portable machine is a suitable alternative.
- It has been demonstrated that a significant level of build-up can be applied to recover lost material without defects satisfying specified quality requirements.
- Key factors for success are: accurate analysis of as-built deviations, qualified welding & machining process, preliminary trials through dedicated mock-up, and skilled, experienced welders and operators.

5. SUMMARY

The repair of two VVTS and VV sectors was completed by August 2024 for ITER sector module reassembly, and the repair of other sectors is progressing as planned schedule. The first repaired SM assembly began in September 2024. The first two repaired SMs have been moved into the pit in April and June 2025, respectively. After approximately three years, the recovery from the critical problem has been successfully accomplished, preventing further delays by removing technical risk in the ITER project. These achievements represent a significant contribution to the overall progress of the ITER.

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