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Chapter 8 - Managing the Design & Construction of ITER

Section 5 - Major Manufacturing and Construction Challenges

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About the ITER Basis Engineering Handbook

This handbook consists of two volumes which describe the ITER design from its inception up to the design, construction and assembly in 2025.

The handbook is not designed to be read as a continuous sequence of chapters. Instead, it is composed of focused, self-contained sections that address specific topics. Each chapter can be read and understood independently, allowing readers to engage with the material most relevant to their needs without requiring familiarity with preceding chapters. As a result, the reader will find certain overlapping content in chapters.

It is to be noted that at the time of writing, the design for some systems is still on-going. Therefore, the reader should consider that whilst there is significant value of this important point-in-time study, an update would be required as the Project progresses.

A broad Project overview is given in the first volume, to provide the reader with background information necessary to understand the context in the subsequent more-detailed chapters of the second volume, dedicated to the individual systems composing ITER.

For the overall table of contents of the Handbook and to access each one of the chapters, please refer to https://www.iter.org/scientists/iter-technical-reports.

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Volume 1
Genesis, Design and Evolution

Chapter 8
Managing the Design & Construction of ITER

Section 5
Major Manufacturing and Construction Challenges

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Chapter 8
Managing the Design & Construction of ITER

8.5 Major Manufacturing and Construction Challenges

Primarily because of its technical complexity and the fact that ITER is the first fusion facility to undergo a strict licensing process, a number of challenges have emerged during the construction process to date. This section highlights some of the main hurdles that had to be overcome and the resulting impact.

The main issues can be categorized as follows:

- Complexity of the procurement scheme

  The procurement of the ITER components is mostly executed through an in-kind contribution from the ITER Members' states, by their designated Domestic Agencies. In this case the responsibilities of selecting the industrial manufacturing partners, controlling the procurement activities and managing the financial risks is transferred to the Members' states (See section 8.3.3). In many occasions, the DAs are to bring the conceptual design and R&D to technological maturity before manufacture.

  This scheme has on one hand the advantages of ensuring a fair sharing of the burden of the construction cost among the ITER Members and of allowing them to access to (or develop)

the key technologies required for a fusion reactor after ITER; on the other hand, it resulted in fragmentation of certain procurement activities and in creating an unavoidable separation between the team in charge of the design of the plant (the "Design Authority") and the entities in charge of its industrialization and manufacturing.

- Technology maturity of FOAK components

  ITER was intended to be the last step before a fusion reactor demonstration plant and thus one of its key missions was to develop and advance the industrial maturity of key technologies required for the construction of DEMO (see Chapter 4 and Chapter 10).

  Designing and constructing ITER necessitated extensive R&D programs characterized by wide-ranging, long-term international collaborations and major innovations. Important key technologies required for the fabrication of the ITER components were either already industrially available or had been extensively developed and studied during the conceptual and engineering design phase (Chapter 7.3). However, at the time of the start of construction, the transfer of the knowledge arisen from these developments to the industry undertaking the construction was only partially achieved due in part to different vendors performing the fabrication from the ones engaged during the earlier phases. It should also be recognised that, often, the introduction and qualification of new materials, technologies, or manufacturing processes is a decades-long effort, without assurance of success.

- Quality of the technical specifications.

  In some cases, the industries were not made sufficiently aware of the codes and standards and other obligations to be followed when procuring safety classified components and even when the adoption of these nuclear codes (namely, RCC-MR or ASME) was specified, these were not fully applicable to fusion components such as the VV sectors.

  Another aspect was that the specifications often contained very demanding and essential requirements, such as very tight limits on impurities in the materials, or limitations on the use of halogens during the fabrication steps. The resulting implications on the cost and on the additional complexity arising from these requirements were initially underestimated and resulted in several non-conformities.

  The complexity and extent of the technical requirements for the fabrication of several ITER components and systems (especially those directly connected to the Tokamak) have proven a challenge in some industrial procurements, since standard fabrication techniques did not fully meet specific ITER requirements, such as presence of impurities in forgings, vacuum compatibility, inspection requirements, tolerances specifications and others. In some cases, specific ITER requirements documentation not provided in the specification to industry lead to omissions or misinterpretation, and to the need to correct and update those specifications. A good example of this aspect were the strict materials specifications on stainless steel forgings under cryogenic applications, where the inclusions sizes, ferrite content, grain size and presence of non-metallic elements to stabilize the austenitic phase are critical to secure their

weldability and the materials ductility at operating cryogenic temperatures. Wrong specifications on apparent minor aspects for steels operating at RT overlooking the degradation of certain materials properties in cryogenic applications will lead to mistakes despite compliance with the stainless-steel alloying elements and metallography specifications. However, the specification terms are unusual resulting specific fabrication processes in steel makers and typically subject of long negotiations and high cost.

- Evolution of the design during the construction phase

  At the start of the fabrication of long lead procurement items, the design of many parts of the plant was still being developed. In addition, as described in Chapter 7.1, the design went through design changes even after construction was started. Although the ITER Organization followed a rigorous approach to assess and minimize the impact of change proposals before accepting them, it was not always possible to avoid implementing changes after detailed specifications had been already provided to industry. This was particularly the case for the nuclear buildings, for plant systems that have strong interfaces with less technically developed systems or components or the diagnostics from various DAs with different design maturity fitting in the same port.

  Another cause of late design changes was intrinsically in the nature of a FOAK. When adopting novel technologies or equipment never constructed before, as part of an effective risk mitigation strategy full-scale prototypes should be implemented before attempting the series production. The trade-off between cost and schedule and R&D for critical components was performed for some visible components during the EDA, however many other fabrication aspects were overlooked and industry had to face them (qualification of nuclear equipment, radiation hardness, fast valves development, CuCrZr machinability, W coating, weldability of dissimilar metals…). However, cost and schedule considerations during the initial construction phase discouraged the inclusion of tasks which would have delayed the project but could have had substantial benefit in reducing the risk of subsequent changes.

In the following sections some specific examples of these issues are provided.

8.5.1 The ITER Procurement Scheme

As discussed in the previous section 8.3.3.1 the procurement of ITER is subdivided among the different Members and it is mostly based on in-kind procurement, in which each Member is responsible for the financial and quality control of their contribution.

The procurements of some key components have been further subdivided upon request of different Members or IO, either to allow the Members to be better prepared for the construction of a future fusion reactor or as a project risk mitigation to involve more than one vendor in procurement of first-of-a-kind items.

The decision of the In-kind sharing of the hardware, defined at the time of signing of the ITER Agreement resulted in increasing the number of interfaces, complicated the logistics and posed problems in the transfer of knowledge and lessons learnt.

The Procurement Arrangements (PAs) were typically understood by the DAs as an IO-DA contract (but without penalty mechanisms) with clear and defined terms and responsibilities, whereas it was often understood by the IO rather as a collaboration agreement with the DAs. This had significant implications.

What initially was intended to be as a Built-to-Print (BtP) PA, where the IO designed and handed it over to the DAs after the Final Design Review, could become a Functional Specification PA, where the DAs assumed responsibility with the signature of the PA, after the Conceptual Design Review. The inherent immaturity in the definition of requirements in the Conceptual Design Phase and the spirit of considering the PA a collaboration agreement rather than a contract from IO side led to a frequent redefinition of requirements based on the right of IO as design authority by the Nuclear Regulator and resulted in differences between the IO and the DAs concerned. The DAs were resource constrained, which impacted the design work and in some cases to a reliance on industry for completing the design. In some cases, this led to schedule delays, and cost overruns. This dynamic was particularly intense for Diagnostics, but not only there.

In another example, the framework driving the in-kind procurement sharing would have been greatly simplified with few TF coil superconductor industries such that one only conductor type would be powering each TF coil, whereas the situation is that Winding Packs include conductors from more than one supplier. For the VV, a nuclear Protection Important Component (PIC) for confinement, procured by Korean (x4 sectors) and Italian (x5 sectors) industry, IO had to accommodate the different manufacturing approaches as legal manufacturer in the regulatory files.

The allocation of Port Plugs for diagnostics resulted in CN-DA, IN-DA and KO-DA having only a single port plug to integrate, whereas EU-DA, RF-DA and US-DA had multiple port plugs that were split between equatorial (EQ) and upper (UP) ports. This allocation resulted in an increased number of interfaces, increased resources to develop an integrated design, duplication of activities, and project management challenges due to the number of Members involved.

The different perception of what a PA meant for the IO and DAs tended in several cases to reinforce the absence of a feeling of project and design ownership by the DAs; to deal with this situation an important step was the creation of the Integrated Product Teams (IPT) around 2008-2009.

The goal of each IPT was to achieve a simpler and more effective management of the interactions among all Members involved in the final design and procurement of complex components. Despite the challenging coordination of staff in many geographical locations, it was considered

that, in addition to providing resources from the DAs for the completion of the design activity, extending the involvement of the procuring DAs in the design of the components would provide them with a sense of design ownership and increase the team spirit among the DAs and IO. The use of IPTs also resulted in better technical specifications which considered feedback from fabrication, and simplified the technical control and resolution of technical issues during the fabrication

This was certainly the case for the Buildings Infrastructure and Power Supplies (BIPS) IPT, whose effectiveness was also due to it being established during the early phase of the design process (conceptual design) with clear possibilities of fully involving the procuring DAs in the design and with enough time until procurement (3-4 years) to build up understanding, trust and team spirit among the IO and DAs. This could have been more difficult if implemented at a later stage. It was important for all in the team (IO + DAs) to go to procurement with an agreed design to which all have contributed. There was no "IO design", nor "DA design", but a "BIPS design". This was also reflected during the Design Reviews, where the DAs were directly involved in defending the proposed design choices. Despite this successful example, delays and over runs were present driven by numerous design changes due to immaturity of interfacing equipment, insufficient contingencies for radiation shielding and due to changes to restore the structural strength of the B2 slab after the initial reduction of the slab thickness.

8.5.1.1 Technology Maturity and Quality of the Technical Specifications

The above-mentioned reluctance to schedule time in a PA for industry to manufacture prototypes prior to series production or the wrong strategy in prototyping during the Engineering Design Activities (EDA) phase is exemplified by the VV sectors. A full-scale prototype had been executed by Japanese industry during the early ITER EDA phase. Important feedback on the design was obtained by this early prototype, as for instance the need to adopt spice plate to join the different sectors, but other potential lessons learnt were lost when eventually the procurement of the VV sectors were allocated to Europe and Korea. In addition, the early R&D had used as Nuclear Code the ASME code rather than the French RCC-MR code. Furthermore, the design significantly evolved reducing the value of the prototype.

In other cases, the fabrication techniques used or developed during the prototyping phase were not prescribed in the technical specification or not fully applicable when proceeding with the serial fabrication. This last point is apparent in the fabrication of the VV sectors, where Korean industry utilized hot forming. This is a faster approach, but meeting tolerance requirements is difficult and increases the risk of high residual stresses compared with machining forgings, which is a slower approach but easier to meet tolerances.

As another example for this was the fabrication of a successful full-scale prototype of the Divertor Cassette Body, which implemented rigorous Nuclear Codes practices. However, financial implications and considerations that the Divertor is not classified as PIC led to the implementation

of a different manufacturing approach for the production series, which eventually generated impacts on cost and schedule equivalent to the qualification of a second prototype.

8.5.1.1.1 Challenges on Materials

The performance and lifetime of materials for fusion systems is among the foremost considerations for the successful development and deployment of future fusion reactor systems. The very demanding operational requirements of materials in ITER (e.g., elevated operating temperature or cryogenic temperatures, cyclic operation with long hold time, prolonged periods of operation, steep temperature and stress gradients, multi-axial loading, neutron irradiation damage as well as corrosion/erosion) that the materials will experience in ITER are beyond existing fusion device The challenge is on prediction of failure mechanisms and lifetime under service conditions. This is further discussed in Vol. 2.

A compromise had to be found between requirements and specifications to suppliers to ensure safe and reliable operation without over-specifying in an unnecessary manner such that industry cannot meet them or driving costs up and generating delays. The examples reported below indicate that only a thorough assessment of the needs and of the specific aspects of the production processes and operational conditions can prevent mistakes with severe repercussions.

8.5.1.1.1.1 Stainless Steel Forgings

Experience in ITER has shown that specifying properly the metal forgings demands the support of materials specialists; it must be done thoroughly without overlooking strict requirements not only on expected performance but also on the impurities, micro-structure and process.

The ITER magnet and vacuum systems required the use of several large structural forgings of different high strength grades of austenitic stainless steels and Ni-base superalloys. For example, the forgings for the vacuum vessel sectors consisted of around 1000 large blocks in 316 LN ITER grade (316L(N)-IG) reaching a total weight of thousands of tonnes with individual forgings that weighed up to 3.75 t. Similar challenges were present in the needed large forgings of unprecedented shape and dimensions of the precompression structure of the ITER Central Solenoid (CS) that were machined from open die forgings with a high strength nitrogen alloyed austenitic stainless steel (S20910 or NITRONIC® 50). In addition, the superconducting jackets issued from multi-directional redundant forging is the pre-material for the hot extrusion of the circle-in-square jackets of the CS and Poloidal Field (PF) magnet coil conductors, and circular jackets of the Toroidal Field (TF) coil conductors. The steel grades were respectively JK2LB for the CS conductor jackets (a special grade of austenitic stainless steel with high Mn, low C content and controlled B addition), modified 316L for the PF conductor and modified 316LN for the TF conductor jackets [1].

Similarly, the high strength, heavy gauge fasteners of the Gravity Supports (GS) of the TF coils and tensioning components permanently installed in the CS are issued from forged rods of precipitation hardened Inconel® 718 with specified cryogenic properties, a high strength nickel base superalloy with an exceptional combination of strength and ductility.

For the components listed above, achieving the set of strict requirements applicable to the final microstructure, required a processing plan that addressed: the final Inspectability of the parts through Non-Destructive Examinations (NDE), and the mechanical properties often specified in a wide temperature range.

For the most critical forgings, the specified steelmaking route had to include Electroslag Remelting (ESR) or alternatively Vacuum Arc Remelting (VAR), to secure the non-metallic inclusions within specification limits and guarantee absence of macro-inclusions that become detrimental for the leak tightness and/or the mechanical strength of the parts, including fatigue strength.

There are essential aspects that differentiate the specifications of materials to be exposed to cryogenic temperatures. These aspects must not be overlooked and experts on cryogenic materials need to be involved to ensure expected performance is secured. For example, while at room temperature it might be appealing to include a ferrite phase in welds of austenitic stainless steels to improve operational weldability and reduce risk of hot cracking, at 4 K the ferrite undergoes a ductile-to-brittle transition, behaving as a dangerous phase, degrading substantially ductility and fracture toughness. Difficulties with the performance of the stainless-steel forgings at cryogenic conditions not reaching the expected elongation because of an improper specification overlooking the strict requirements when operating at cryogenic conditions are known in the fusion community.

The challenges of properly specifying and eventually fabricating forgings were apparent in the failure of one Toroidal Field coil Gravity Support (TFGS) heavy gauge forged fastener, which demanded bespoke NDE techniques and ensuing replacement of several studs identified as potentially failing [2]. The 18 TFGS of ITER sustain 11 000 tonnes of dead weight and will be exposed in operation to electromagnetic transverse forces and possible seismic loads. 26 high strength fasteners (M60 and M85 threaded bolts issued from forged rods of Inconel® 718) fix each of the TFGS to the cryostat base. The components of the TFGS interface at the top with the TF coil, operating at 4 K, while the bottom is at approximately room temperature (RT). The material was procured based on a stringent specification imposing Vacuum Induction Melting (VIM) followed by VAR, while allowing possible further remelting by VAR or ESR. Despite this and the extensive quality controls applied to the forged pre-material and to the bolts, a complete break of one M85 bolt was discovered, that occurred about 40 days after its installation and moderate preloading at 1.41 MN (60 % of their specified elastic limit), far below specified operating stress. The upper half of the part blew out from the bolthole and was found lying horizontally on the Cryostat Base near the TFGS while the lower half part shot downward and lay in the confined space of Cryostat Base. Based on mill certification (properties were assessed per lot by sampling

on extra lengths of the forged bars), the chemical composition, the fabrication route, the heat treatment, the mechanical properties and the microstructure were according to specification, with the exception of the steelmaking route which was VIM+ESR in place of specified VIM+VAR but featuring similar attributes. The bars were examined by UT in accordance with ASME Section V, Article 5, while the examination procedure and acceptance standard were in accordance with ASME Section III, NB-2542. The cause of the failure was difficult to determine, but CERN were invited to advise and came to a conclusive assessment. Based on the investigations performed, the delayed rupture of the stud was compatible with a failure under sustained tensile stress, initiating from a central position featuring very poor ductility and severely weakened by the presence of a large network of cavities not closed by the forging operations. [3] The study concluded that, if the forgings fabrication process is improperly operated or insufficient remelting takes place, it may result in defective ingots that cannot be remediated through the subsequent forging steps, even if the chemical composition is within the allowed ranges. Therefore, more stringent and conservative ranges need to be applied to the fabrication process of sensitive components to preserve the resilience of the products in case of stress concentration due to concurrent imperfections. In addition, more stringent NDE than the standard ones need to be imposed for critical components in which high reliability is essential.

8.5.1.1.1.2 Superconducting Magnets Insulation

In the ITER magnets, there are two types of insulation: high and low voltage insulations. High voltage insulation is used in coil windings to withstand from 100 V to 30 KV typically. The low voltage (below 50 V) insulation is applied to the magnet structural elements to break the electrical loops for eddy currents during the electromagnetic transients. The mechanical limits on the high voltage insulation are more stringent since microscopic mechanical damage such as cracking can create voids that lead to electrical degradation when the operating voltages exceed the Paschen minimum for gas breakdown. If low voltage insulation maintains a separation between the metallic surfaces, cracks are not significant.

The main challenge for the high voltage insulation is to satisfy both electrical and structural requirements under radiation conditions. To withstand high mechanical stresses caused by thermal cycling from RT to 4 K and electromagnetic loads and, at the same time provide the high voltage electrical barrier the ITER coil insulation is based on a fibre-glass composite with multilayer polyimide barriers. The resins based on cyanate ester are used to provide required strength and radiation resistance. The glass content is adjusted to minimize difference in thermal contractions reducing the thermal stresses.

Despite all precautions, during some magnet HV tests, degradation was observed leading to electrical breakdown through a reaction of the hardener used in the resin mixture and the Kapton. Despite the sound design with the cable covered with a protective sheath over the polyimide coating and the cable being interleaved with the glass-polyimide layers to increase the tracking length, the hardener seemingly entered in contact with the polyimide causing Environmental

Stress Cracking that led to a reduction of the electric strength causing Paschen breakdown during tests needing repair actions.

During the factory acceptance testing of the ITER coils (apart from the Correction Coils, which operational voltages are low in comparison with the other coils) and the Feeders, the manufacturers encountered failures during high voltage testing. Whilst most of the coils and feeders presented no failures, a minority did, and these faults were almost exclusively located in the vicinity of the high-voltage (HV) wire extraction positions. These HV wires carry the quench detection signals from the coil or feeder, and by necessity must penetrate through the coil or feeder's ground insulation.

All the HV wires were centrally procured by the ITER Organization (who had them tested) and dispatched to the Coil and Feeder manufacturers. However, the manufacturers were free to develop and adopt their own HV wire extraction procedures, if they passed qualification tests. The result is that the manufacturers used different materials (e.g. resins), structures and techniques for the HV wire extraction, which was therefore not consistent across all the magnet components.

When it came to repairing faults associated with the HV wire extractions, the manufacturers again developed and qualified their own repair procedures, again based on the materials and techniques they were familiar with. Except for the Feeders which used a glass pre-preg system, all the repair procedures employed room-temperature curing resin systems (wet-winding systems). The repairs were carried out in the manufacturers' factories, which facilitated access to the area to be repaired, and the companies executed the repair adopting their best practices experiences, provided tools and laboratory equipment. The validity of this flexible approach was confirmed by the fact that the locally repaired areas on the Coils and Feeders passed local Paschen tests within dedicated Paschen chambers, often after the repair area had been thermally cycled to 77K.

Important lessons for the designer are that the number of HV wire extractions by design needs to be minimized since this is the weakest area of the superconducting magnets together with the joint; also, it is advisable to develop, qualify and specify a unique HV wire extraction and repair procedures to be deployed to all manufacturers. Surface tracking is a well-known consideration for high voltage insulation, but it can be overlooked especially if not properly experienced industry is involved in the manufacturing. Thus, it is indispensable to specify the tracking length of the extraction to avoid flashover breakdown with the extraction of the HV wire performed together with the glass-polyimide insulation layers.

8.5.1.1.1.3 Pre-Compression Rings

In the ITER TF magnet system, the Pre-Compression rings help to provide the required compression for efficient action of the poloidal shear keys linking the TF Coils to reduce the cyclic stresses at operation. They also reduce tensile loads on the bolts of the Outer Intercoil Structure. The pre-compression system is based on two sets of 3 rings fabricated in fibre-glass epoxy

composite, located on top and bottom of the inner straight leg region, that reduce the radial outward movement. These rings provide a required constant radial position under cryogenic conditions. The pre-compression rings pull inward the TF coils into contact, particularly where the poloidal shear keys are located, and reduce the gap between the poloidal shear keys and their keyways during operation (0.35 mm) maintaining the fatigue resistance of the Inner Intercoil Structure (IIS) during the nominal cycles. The main design objective is to have the resulting radial force due to the pre-load of the rings as close as possible to the IIS to maintain together the facing keyways in the most effective way during the pulse.

An efficient design of these rings requires a material with thermal expansion coefficient close to that of steel and a Young's modulus lower than that of the case of the TF coils (the low Young's modulus provides a higher elongation during pre-tensioning that minimizes the influence of TF coil assembly tolerances and/or settlement effects). The use of metals for the rings was found unsuitable given that a dummy coil (open spiral) formed of metal thin sheets interleaved with insulating layers is required to prevent eddy currents.

Glass fibre-epoxy composite was perceived as the ideal material due to its very high strength and high electrical resistivity. Its lower thermal expansion coefficient compared to that of stainless steel or Inconel 718 and the general improvement of mechanical properties at low temperatures, implies some additional preloading at Room Temperature to get the required load at 4 K condition.

The main challenge of the Pre-Compression Ring manufacturing was to provide the stable ring shape with large cryosection and high mechanical properties. As a result of extensive R&D the fabrication pultrusion process was eventually developed. The inspection of the final rings followed Phase Array UT techniques. Final proof test of the fabricated rings was performed at 600MPa, despite the rings final pre-load being substantially reduced because of refinement of the FE analysis. The reduction of the required pre-load and the test performed mitigated the risks of rings performance degradation.

8.5.1.1.1.4 Halogen-Induced Corrosion

The known impact of the presence of halogens, particularly Cl, in the corrosion of stainless steel is an issue often overlooked that reiteratively appears in big science projects. ITER is not unique, and the Large Hadron Collider (LHC) and the Jules Horowitz Reactor, incurred long delays because of the appearance of Stress Corrosion Cracking.

Thermal Shields (TS) act as a barrier against the transfer of the heat load due to the radiation arising from warm components such as the Vacuum Vessel (VV) and the Cryostat, to magnets operating at 4.5 K. The TS consists of VV thermal shield (VVTS), Cryostat Thermal Shield (CTS) and Support Thermal Shield (STS). The VVTS and CTS are made of silver plated actively cooled elements. The active cooling is provided by circulation of 80K pressurized He gas with 1.8MPa

inlet pressure in AISI 304L cooling pipes welded to AISI 304LN panels. A total of approximately 23 kilometres of DN8 pipes (OD 13.7 mm × 2.24 mm thickness) are welded onto the panels through fillet Tungsten Inert Gas (TIG) stitch welds with AISI 308L filler metal (see Figure 8.5-1).

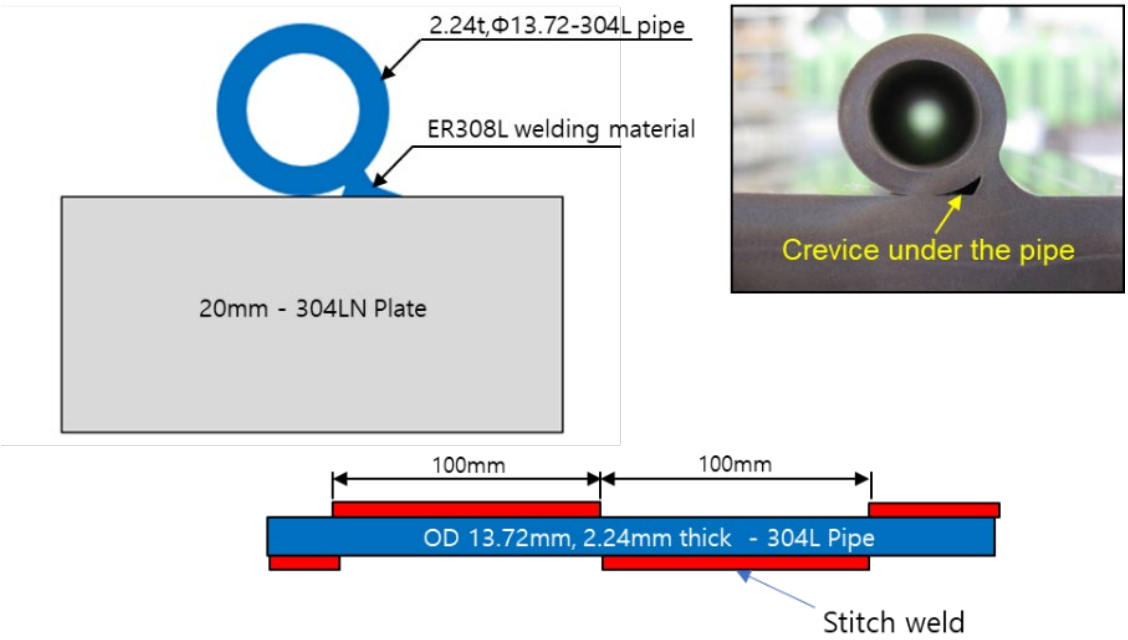


Fig. 8.5-1: Layout of cooling pipe attachment in the ITER Thermal Shield

A few microns thick Ag coating, was applied to obtain a nominal thermal emissivity of 0.05 during operation. The coating was done on all sheet surfaces once the cooling pipes had been stitch-welded. The proper adherence of the Ag coating to stainless steel demands an activation of the surface with an HCl bath and an ensuing Ni <1 µm layer (strike), which in turn is obtained by means of chemicals also containing Cl. The TS panels were intensively rinsed to remove the traces of Cl; however, the stitch weldments on the cooling pipes unavoidably trapped traces of Cl. The presence of Cl residual combined with the stress induced in the pipes by their welding to a substantially more rigid structure led to Stress Corrosion Cracking, which was detected by three unexpected leaks during the Site Acceptance Tests [4]. This eventually resulted in the need to repair the thermal shield panels already delivered to the ITER site and in the change of the manufacturing process for the remaining ones. The repair consisted in removing completely the Ag coating from both sides of the panels, removing completely the cooling pipes, machine 2 mm deep path 100 mm around the cooling pipe route and reweld TIG with a corrosion resistant stainless steel filler metal. The stainless-steel surfaces would be in turn mirror-polished reaching emissivity values comparable to Ag coating and not degrading with time as the Ag coating undergoes through oxidation in contact with air.

The use of halogens is always critical and is to be used with utmost care and avoided if alternative solutions are available. Pipes of the Gas Injection System in ITER were manufactured according to ASME-SA312, ASME B36.19, following the suggested pickling and passivation processes to meet the roughness specifications of the inner surface of the pipes. This process was aligned with their industrial experience and approved by IO. However, during site acceptance tests, the inert surface of pipes showed traces of halogens induced sensitization. Cr depletion was detected and as a result, the piping had to be removed, a track 2 mm deep in the material was machined in the routing and new pipes in 316L were TIG welded with 317N.

Joining of dissimilar materials is always a challenging task. Different melting temperatures and metallographic structure of metals often impede the efficient welding of two different metals. The typical example for this is joining Cu and stainless steel, which is often done in fusion components. An even greater challenge is joining insulating ceramic materials with metals. Brazing differs from soldering by the use of higher temperature and closely fitted parts to levels that technology allows. During the brazing process, a suitable filler metal with melting temperatures below the dissimilar joining materials, flows into the designed gaps between both close-fitting parts by capillary action. The process shall be carried out in absence of O that could oxidize surfaces and impede the binding. This is achieved typically with a halogens-based flux, which enhances the risk of corrosion phenomena appearing in the future. Vacuum brazing is the optimal choice, however the dimensions of joining pieces often makes it impossible for industry without unaffordable investments. Brazing process difficulties are often underestimated both by design engineers and manufacturing companies. Utmost attention is required in the selection of brazing equipment to meet the design goals.

Several experiences with vacuum leaks induced by halogen residues due to halide activated fluxes used during brazing or soldering operations, led CERN to ban activated fluxes, or in any case fluxes activated by halides, in all critical applications where preserving leak tightness and corrosion resistance is paramount. This prohibition extends to cable sheaths that had to be halogen-free. Indeed, surprising leaks were found in the Proton Synchrotron accelerator, decades after it went into operation in 1959, caused by the leaching of halides onto beam pipes. In ITER, the lesson learnt from CERN has been implemented with flux brazing operation following CERN procedures.

8.5.1.1.1.5 Chemical Impurities

Materials under neutron irradiation undergo nuclear transmutation, thereby becoming radioactive. The level of activation depends on neutron flux, energy spectrum, total fluence, irradiation history and time after shutdown. It also depends on chemical composition, and not only on the main alloying elements but also on the presence of impurities or alloying elements with very high activation cross-section and decay gamma yields (cobalt, tantalum, niobium). It should be noted that specific alloying elements are essential to ensure the required physics and mechanical properties and any attempts to reduce them upfront in the fabrication cycle may lead to unsatisfactory materials and/ or substantial additional costs as described below. Consequently,

activation depends on the presence of impurities or special alloying elements and this impact nuclear safety aspects such as occupational radiation exposure, accident consequences, environmental releases, and radwaste.

Following already existing nuclear industry practices in this respect, where this problem is known, and considering specificities of the fusion neutron environment, ITER introduced requirements related to these impurities in procurement arrangements: see typical values in the Table 8.5-1 for areas of high radiation exposure.

Tab. 8.5-1: Limits of impurities in different metals.

Material	Co *%w*	Ta *%w*	Nb *%w*	Ni *%w*
Aluminium alloy	0.025	*N.A.*	*N.A.*	0.025
Carbon steel & Cast iron	0.01	*N.A.*	*N.A.*	0.05
Copper alloy (inc. 660[a] & XM-19[b]	0.05 ([a]0.1)	0.01	0.1 ([b]0.3)	*N.A.*
Nickel alloy	0.1	0.01	*N.A.*	*N.A.*

Compliance with these requirements is typically achieved through dedicated procurements with specialised material suppliers to produce specific batches certified for compliance; but a non-negligible cost is associated with such specific material production and certification. The vast majority of the massive tokamak components was procured in this way in a relatively straightforward manner, at the corresponding cost. Still, a significant number of deviations and non-conformities were encountered during manufacturing because of the following:

- The requirements were propagated despite the immaturity of the knowledge of radiation conditions throughout the facility. Thus, some crucial shielding structures like Port Cell doors, Port Plug, Bioshield Plug or top lid had too stringent requirements.
- Cost control which limited the number of certifications.
- The use of Components Off-the-Shelf (COTS) and standard parts, for which the above individual specialised materials are not cost-effective or acceptable to the manufacturers, and which are therefore typically made of uncertified, OTS material instead. This use was particularly extensive outside the tokamak, where a very large number of systems are located.
- Insufficient knowledge of the typical impurity levels expected in such OTS material, and lack of provisions for testing it.

This led to a need to invest significant efforts in the preparation, management and assessment of these deviations. Moreover, the management was more difficult because (a) inconsistencies in

the propagation and procedures dealing with the requirements, and (b) impracticality to perform accurate radiological impact assessment for each individual deviation. Corrective actions at project level were proposed and implemented to the extent possible.

8.5.1.1.2 Challenges on Manufacturing

Equipment exposed to the extreme operational conditions during operation requires careful assessment of the extensive qualification processes to efficiently cope with the demanding requirements. Examples of qualification processes include those for in-vessel components which used special processes requiring R&D activities: Hot Isostatic Pressing (HIPping) bonding, laser & Electron Beam (EB) welding, dissimilar materials brazing, Phased Array UT. Compliance with the qualification requirements and their incorporation into a realistic procurement schedule was not always straightforward. In addition, commercial strategies aiming to increase competition and reduce cost can, conversely, engender increased costs due to overheads induced by the redundant qualification needs in the suppliers' chain. It was observed that industry tends to underestimate the challenges to meet the stringent non-standard ITER requirements during the tendering process. When technology transfer between industries takes place, it is typically not done smoothly and may require long re-qualification of the specialized processes under schedule pressure.

In addition, the nature of FOAK equipment and poor integration and engineering practices resulted in unnecessarily tight dimensional tolerances in the requirements, which proved to be very challenging, if not impossible, to achieve. This was particularly noticeable in in-vessel equipment and interfacing VV sectors.

The deviation from the nominal tolerances has been overcome in ITER with the extensive use of time-consuming Virtual Fitting plus Reverse Engineering exercises, that provide the possibility to anticipate the final shape of the component and therefore to understand the implications at the level of integration/assembly into the machine. Lack of manufacturing expertise in the design is the underpinning reason for the presence of too rigorous geometrical requirements, which combined with the accumulated delays and schedule pressure led to the acceptance of non-conformities in delivered equipment and the frequent concept of 'use-as-is' with impacts on other equipment. An example of this was the geometrical non-conformities accepted in the VV sectors, which deviated substantially from the specified values for the development of the automatic welding robot leading to an unacceptable situation, which was solved by repairs on the ITER site of the delivered VV sectors to meet the nominal specifications (see Figure 8.5-2).



Fig.8.5-2: Vacuum Vessel sector geometric non-conformities in the field bevel joints were addressed by the repair.

It is fair to say that the project overall has underestimated the complexity and the impact of the application of nuclear codes developed for fission reactor to fusion components, which are significantly different in geometry and in the operating conditions. The ITER vacuum vessel was considered as a pressure vessel and therefore subjected to the French directive for nuclear pressure vessel (ESPN). and design standards (RCC-MR) specific for future fusion power plants. While an extended discussion on the issues to comply with the nuclear regulations can be found in Section 6.2.13, here it can be just highlighted that the manufacturing companies were sometimes suffering for the incomplete specifications, insufficient training of the involved staff, cumbersome interactions with the mandatory Authorised Notified Body (ANB) and the need to justify the use of some specific manufacturing and inspection.

In a more global manner, none of the existing nuclear codes (namely, RCC-MR or ASME) is adapted for fusion components like the VV sectors and that the involved industry affected by the codes had not adequate experience in complying with RCC-MR.

The need for having adequate codes and standards specifically for future fusion power plants is an important lesson learnt.

8.5.1.1.3 Joining Techniques and Tolerances Definition

The quality of the materials joints is indispensable, not only for PIC equipment but also for non-PIC components to secure the required performance and reliability of the affected equipment. Gas tungsten arc welding (GTAW), more widely known as tungsten inert gas welding (TIG), and brazing for dissimilar materials are extensively used for joining.

A special challenge became the development of welding techniques spanning from 2.54 mm of cryogenic piping to 290 mm cryostat wall.

The cumbersome geometries and demanding tolerances forced the fabrication of extensive and expensive welding mock-ups prior to manufacturing to mitigate the risk of distortions during the welding operations. Maintaining strict control on dimensional tolerance for large thickness weld joints with limited accessibility for welding and Non-Destructive Examinations (NDE) posed significant challenges during manufacturing.

The 60 mm double wall VV sectors fabrication demanded rigorous tolerances. In particular, the tight shape tolerances of the welding bevels as per Figure 8.5-2 were used as the requirements for the development of a welding robot. A robot is necessary since the narrow gap between sectors and the wide distance between inner and outer wall of the VV prevents the use of manual welding and adherence to the rigorous quality requirements (100% NDE of welding and repair of any detected defect). These tight tolerances were impossible to meet without a final machining of the finished structure, that required the development of expensive tooling. A proper assessment of the requirements, cost and time to enhance the industrial capabilities was not carried out resulting in delays and in non-conformities that eventually demanded repair.

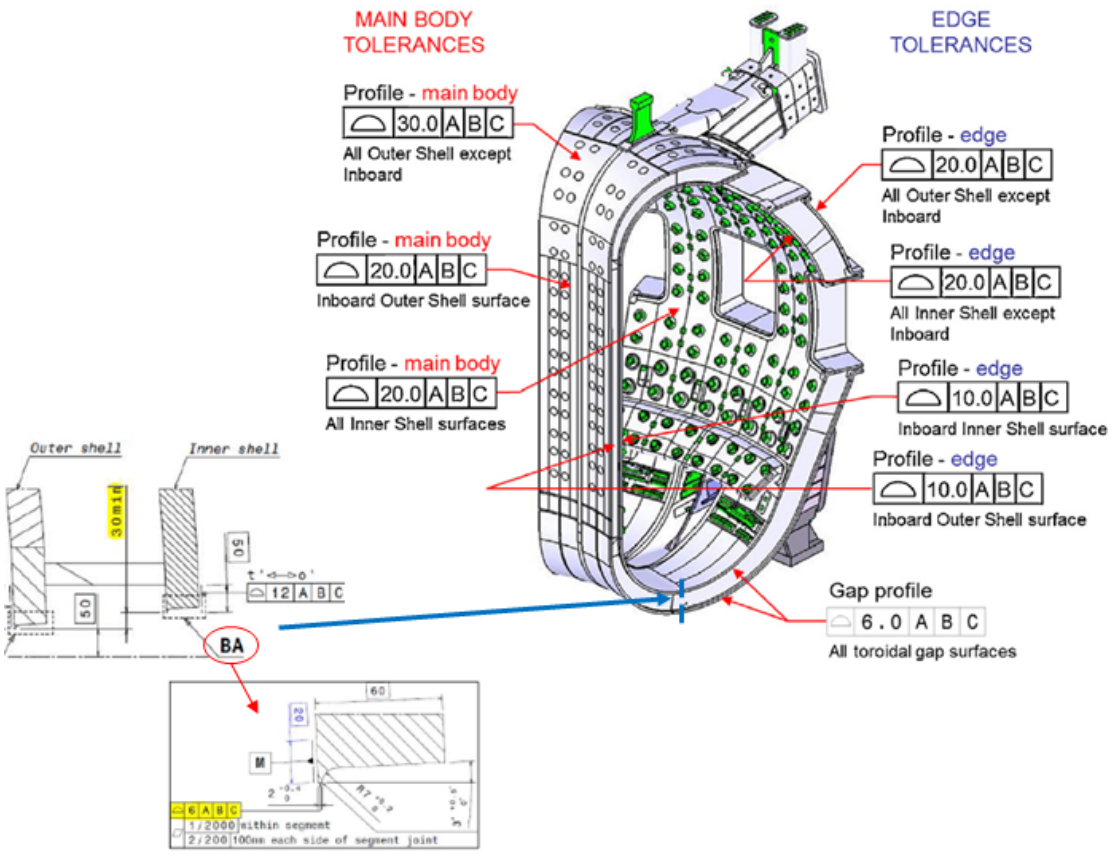


Fig. 8.5-3: Main tolerances requirements of VV sectors

The ITER Cryostat (PIC-2 component) is a stainless-steel large vessel (~30 m dia. and ~30 m height), which houses and supports critical components such as the vacuum vessel and superconducting magnets and envelopes the entire core systems of the ITER Tokamak at insulation vacuum conditions. The weight of the complete Cryostat is more than 3 850 t and to meet the assembly sequence inside the Tokamak building, the Cryostat is divided into four main sections (Base Section, Lower Cylinder, Upper Cylinder and Top Lid). The design, manufacturing and inspection of the cryostat was carried out as per ASME Section VIII Division 2 in compliance with the additional requirements of the ITER Vacuum Handbook. Stringent but achievable tolerances specified impacted the assembly. Narrow Hot Wire TIG (HWT) welding was implemented on the Base Section Pedestal Ring, which is the optimal technique for thick joints, for example those > 250 mm. In addition, due to the limited view access for the welding operations, two cameras, one for front side image and other for rear side image, were built into the oscillating W torch. The ultimate flatness requirement was 12 mm on the overall surface of 20m diameter that supports the >13 000 t weight of the VV and magnet system. Achieving these tolerances was very challenging due to the thick welding involving multiple sections, multiple interfacing positions and multi-site manufacturing.

Other welding techniques like e-beam welding or laser welding are prone to smaller distortions of the structures welded given that the total energy required is substantially lower and thus the welding Heat Affected Zone (HAZ) is far smaller and more concentrated; however, these other welding technique are not suitable for such big structures given the even tighter tolerances required between the joining parts and requirements for vacuum conditions in the case of e-beam.

The initial phases of the ITER project, particularly when the final design of the main tokamak system was developed, were marked by a significant gap between the design requirements and what can be realistically achieved during manufacturing. The importance of incorporating manufacturability constraints in the design was not widely recognized or implemented as a critical step before issuing manufacturing contracts, driven by the pressure to move fast. Furthermore, industrial feedback and awareness regarding fusion technologies were scarce. These factors culminated in considerable challenges during the later stages, once large-scale manufacturing activities started.

The dimensional risk associated with the manufacturing of large mechanical components with strict tolerances was not initially regarded as critical. The definition of geometrical tolerance requirements was developed with a poor understanding of the impact of tight, and sometimes unjustified, tolerances (see Figure 8.5-2 for an example of too rigorous geometry requirements) impacting cost and complexity of both manufacturing and metrology.

The metrology process and approaches were not imposed by IO and thus the implementation was not uniform across the project. In many cases IO relied on the industries themselves to propose

suitable metrology approaches to deal with complicated geometrical specification and occasionally this resulted in the relaxion of the metrology requirements.

The design engineers did not fully appreciate the difference between the detailed designs, whose responsibility rests with IO and DAs, and the fabrication drawings to be developed by industry in accordance with the tolerances defined in the detailed designs.

This resulted in often inconsistent and ambiguous results with either lack of details or over-specification of the geometrical requirements apparent in 2D drawings, which often disregarded the two basic principles that an engineer must respect in his/her designs:

A. Never set in a drawing a tolerance not needed,
B. Never set in a drawing a tolerance that cannot be accurately measured

leading to increased oversight by industry, difficult negotiations and even development of expensive and unnecessary industrial techniques.

During the years, the project has been benefiting from valuable insights gained through addressing past errors. Eventually, technical specifications have become significantly more developed and precise. Design requirements were increasingly aligned with manufacturability considerations. Standards for defining geometrical product specifications are strictly adhered to during the preparation of technical documents. Additionally, centralized metrology and a process to rebuild geometries based on as-built information from manufactured/assembled systems [5] has been established and implemented. It includes the analysis and management of as-built dimensional data from Tokamak Machine and Tokamak Complex, the impact assessment of transverse tolerance deviations and the implementation of as-built 3D configuration models for recording and reporting as-built surface geometries. This exercise has become an essential tool for the assessment of tokamak assembly, the magnets position and their impact on error fields [6] and the alignment of the In-vessel components.

When necessary, these as-built models are used instead of the as-designed models for the validation and optimisation of the assembly process, for the assessment of tolerance deviations impact and for risk mitigation during the construction phase. In addition, the as-built models can be used to validate various types of analyses and serve as a foundation for the future upgrades and/or modifications of ITER.

In general, the global awareness of dimensional risk has been enhanced, and tools for managing this risk have been implemented aiming at avoiding and anticipating the detection of potential geometrical non-conformities to ensure timely implementation of remedial actions.

8.5.1.1.4 Electronics and Cardboards

A fusion device like ITER has a unique operating environment that includes neutrons and gamma rays at higher energies than in fission reactors and stray static and variable magnetic fields from superconducting magnet coils. Fusion operation requires sophisticated instrumentation and controls (I&C) equipment in the vicinity of a vacuum vessel directly exposed to both radiation and magnetic fields. Electronic Integrated Circuits are sensitive to nuclear radiation and potentially suffer damage such as single event upsets or the like when exposed to these operational conditions. In addition, the stray magnetic field can potentially disrupt functionality of some electrical and electromechanical components like pulse transformers, fans, solenoid pilot valves, relays, etc. The sensors, actuators and control system hardware required to build I&C system include a combination of such devices; hence, their availability is impacted. Radiation and magnetic field hardness is to be carefully qualified. Adequate redundancies should be put in place as per Reliability, Availability, Maintainability, Inspectability (RAMI) analysis to secure expected availabilities.

The Service Vacuum System (SVS) entails pressure sensors to measure absolute pressure from 1 kPa – 200 kPa for about 4000 clients with high accuracy. Many of these sensors are in port-cells, subjected to gamma doses up to 1 MGy, neutron fluences up to 5x 10^{12} n/cm^2 and static magnetic field of about 80 mT. The sensors demanded careful design under R&D tasks to secure their performance. In turn, in a simplistic approach, the signal conditioning electronics may be relocated to a place where there is no radiation or magnetic field; however, there are limitations in the cable length which, given the dimensions of ITER, the electronics are unavoidably exposed to radiation and stray magnetic fields. As a result, some electronics are still subject to gamma radiation up to 1 kGy or even more, neutron fluence up to 1x10^{12} n/cm^2 and static magnetic field up to 45 mT. There are no commercial off-the-shelf electronics hardware capable to reliably operate under these conditions, which has led to the development of custom solutions.

Four circuit boards were included in the design: Analog Front End (AFE), Front End Acquisition and Control (FEAC), Power Manager (PM) and Profinet Device Interface (PDI) to properly acquire and efficiently transmit the signal. The AFE boards included an excitation circuit and instrumentation amplifier for integration of signals from piezo pressure sensors. The FEAC digitized the signal, serialized all data and transmitted the data stream in optical format. The PDI board received the data stream and converted it into Profinet format using programmable Field Programmable Gate Arrays (FPGA) for integration with the Programmable Logic Controller (PLC). In turn, the PM board used power regulator ICs to derive various voltages required for AFE and FEAC circuit components. The AFE, FEAC and PM boards were housed in a wall mounted cubicle. Seventy-seven wall mounted cubicles were used for the entire SVS scope. As there was no limit on distance for the fibre link between FEAC and PDI, the PDI was placed away into control cubicles located in a shielded corner, low in radiation. The design of the electronic boards was based on radiation qualified GBT ASICs developed by CERN, which were acquired through a trilateral DA-IO-CERN strategic agreement.

To power the electronics, power supply modules are required, which are susceptible to static magnetic field. To enhance availability, the power supply modules are located into control cubicles in shielded corners far from harsh conditions, where the magnetic field is less than the one that the selected power supply module is qualified for. AFE, FEAC and PM boards do not include any component susceptible to static magnetic field, but PDI boards do. Despite being located far from the vacuum vessel, the cubicles in which the PDI boards are located are still subject to a static magnetic field up to 14 mT. PDI boards have a great overlap in terms of use of components especially the ones susceptible to static magnetic field like the DC fed fan of the FPGA, which are to be qualified to hold 20 mT in all directions.

8.5.1.2 Challenges During the on-Site construction and Assembly.

The planning and management of the on-site construction activities for a plant of the complexity of ITER are formidable tasks both for technical aspects, related to the size of the components to be handled, the accuracy to be achieved, the tight space available, the level of cleanliness required in many areas but also from management aspects, as those related to coordinate the arrival and storage of components from different supply chains, the need to accommodate for on-site repair work, and to coordinate different consortia in charge of assembly works. Not surprisingly, the on-site construction and assembly had to face a number of important challenges. Some of them are like the ones covered earlier as part of the overall construction challenges.

Others are listed below and grouped in different categories for information, with more details provided on a couple of specific examples to illustrate their major impact.

8.5.2 Quality of the Received Components

During the component fabrication phase, there was willingness for a greater alignment on the importance and role of quality-control activities. Independent controls, inspections, and the presence of ITER personnel on the shop floor were not always fully integrated into the fabrication approach around the world and were sometimes viewed as potentially disruptive to ongoing activities.

In 2015, driven by cost containment efforts, the number of missions was further limited. The engineers of IO responsible of equipment under fabrication in the DAs could not follow the contracts and had to rely on the quality system of the DAs and suppliers. In some cases, not even the Factory Acceptance Tests (FAT) were witnessed by IO technical staff. This resulted in the pervading ‘use-as-is’ concept when non-conformities were found on-site and led to a significant increase of the on-site work as many tests had to be repeated and corrective actions implemented. Only in 2022, with the appointment of Pietro Barabaschi as Director General, a new framework was established aimed at providing a strong technical leadership and reinforcing the quality system across the whole project.

An example of this deviation of quality of components is apparent with the non-conformities found in the first four VV sectors delivered. S6, S7 and S8 were originally accepted despite the strong geometrical deviations, whereas S1, whose shipping was already scheduled was blocked and forced to be repaired, but eventually shipped to IO for final repair given the impossibility in industry to flip it to accomplish the repair. The assembly of the Thermal Shield and the pair of TF coils was accomplished (without the intercoil structures fixtures) in the Sub-Assembly tool and inserted in the tokamak pit in May 2022.

Left unrepaired, these non-conformities would compromise the access and operation of the bespoke automated welding tools planned for the in-pit welding of the sectors. Thus a difficult decision of repairing the sectors on-site was taken, as shipping them back to the supplier was impossible since the roads from Fos-sur-Mer to the ITER site were adapted for a uni-directional travel. The ITER Organization needed to organize on-site the difficult repair by building-up welds, precise metrology and fine machining to reach nominal values (see Figure 8.5-3). Another important point was considered by adopting an integrated approach in the investigation of adjacent sectors' geometry. Instead of considering a sector's geometry only against its nominal manufacturing drawings, each sector was assessed in relation to the adjacent sectors on either side to which it would be joined through spliced plates with the automatic welding developed robots. The repair on-site was done on vertical position for S6 and S7 (vertically, in sector sub-assembly tooling in the Assembly Hall), and S8 and S1 (horizontally, in the former Cryostat Workshop). A special tool needed to be developed to be able to flip the sectors horizontally placed to access both sides of the 400 Tons VV sector for repair. The bottle neck of the assembly during repair times was the availability of the crane in the assembly hall thus the decision to repair in horizontal position or in vertical in the Sector Sub-Assembly Tool (SSAT) aimed to optimize its usage.

In turn, the repair of the Thermal Shield to overcome the stress corrosion cracking observed in the cooling pipes was carried out combining work at the ITER site and works in companies' premises. The goals sought was three-fold: reliability of the repair, rapidity and cost. The 304L cooling pipes were removed as well as the Ag coating from both sides of the panels to get rid of possible traces of chlorine. 316L cooling pipes were re-welded.

Issues Related to the Design and Planning of the Construction Activities

- Inadequate size of assembly building to service the delayed and compressed delivery schedules for the major components;
- Insufficient size of the ITER site to accommodate developing (additional) facility needs, which have compromised storage space;
- Insufficient heavy-lifting capacity in the assembly building – the main crane is the critical resource at the current (delayed) stage of assembly operations (mid-2025, sector sub-assembly / sector module transfer to the pit);

- The assembly building (B13), initially a concrete building, was changed to a steel framed building for cost and schedule reasons. At the time of the change, it was decided to cover the steel beams with fire resistant Vermiculite, but this was later found to be not consistent with the clean condition requirements for B13;
- Failure to qualify the upending tool and the process
- Overall failure to qualify process and personnel before working on the real components.

Assembly Contracts

- Limited early engagement with industry in preparation for tenders and contracts contributed to a relatively small pool of tenderers, reducing competitive pressure, impacting performance and contributing to higher prices
- Limited experience with large contracts within the IO and the way to negotiate them;
- FIDIC contract model was probably too complex. IO in any case did not have the necessary experience for their management in addition to the inherent complexity of these contracts due to their high value and technical complexity;
- Failure to base since the start of the construction activities, assembly contracts on a 2- 3 shift working system from the outset to maximize the work done to build float into the schedule. The ITER legal team managed then to have special concessions that allow ITER works to be organized on two shifts during the day, while the night shift is to make x-ray to welds when applicable;
- Failure to include process and personnel qualification and training as mandatory requirements and deliverables;
- Failure to place contracts with sufficient time to allow the contractor to prepare properly;
- Absence of personnel within IO with the mentality to drive proper qualification to ensure right first-time outcomes;
- Tendency to hide behind the first of a kind process excuse.

8.5.2.1 General Lessons Learned

8.5.2.1.1 Project Management and Culture

- Insufficient numbers of appropriately experienced personnel in middle-management, impacting the recruitment of Suitably Qualified and Experienced Personnel (SQEP);
- Insufficient personnel with construction experience to specify and tender the assembly contracts, which led to inadequate technical specifications, poor tenders and poor contracts;
- Over-reporting of status and progress, impacting schedule and resource estimates and procurement activities;
- In addition, poor scheduling and cost management presented some major challenges as highlighted below.

Unrealistic schedule and budgets skewed the decision-making process and contributed further to many of the problems mentioned and to the failure to adopt and implement an agreed schedule for construction including corresponding timely delivery

The difficulty to produce (until recently) a realistic (demanding but achievable) schedule and corresponding cost estimate and budget, which was acceptable to the Members, has undermined the application of basic project management and monitoring tools such as Schedule Performance Index (SPI) and Cost Performance Index (CPI). The absence of such a schedule, which was acceptable to the ITER Council, also increased the difficulty of managing the expectations of the stakeholders.

8.5.3 Regulations and Codes

- IO decision to submit the VV design to ESPN regulations was an error as pressure is not the design driver for the VV;
- This in turn led to the selection of RCC-MR, which is difficult to interpret and to apply, especially for non-EU partners;
- Different codes applicable to interfacing systems leading to mixed requirements – e.g. RCC-MR for VV and ASME for cooling pipes;
- A nuclear safety regime appropriate for nuclear fusion should be developed. The application of nuclear fission regulations and culture to fusion is not appropriate and adds significantly to cost, complexity, and regulatory inspection.

Glossary

AC	Alternate Current
ADEME	Agence de la Transition Écologique (French Agency for Ecological Transition)
AE	Autorité Environnementale (Environmental Agency)
AFE	Analog Front End
Ag	Silver.
AIF	Agence ITER France
ANB	Authorized Notified Body
ASIC	Application-Specific Integrated Circuit
ASME	American Society of Mechanical Engineers
ASN	Autorité de Sûreté Nucléaire (Nuclear Safety Authority)
ASNR	Autorité de Sûreté Nucléaire et Radioprotection
BEGES	Bilan des Émissions de Gaz à Effet de Serre
BIPS	Buildings Infrastructure and Power Supplies
BtP	Built-to-Print
CEA	Commissariat à l'Energie Atomique et aux Énergies Alternatives
CERN	European Organization for Nuclear Research.

Cl	Chlorine.
CN-DA	China Domestic Agency.
Co	Cobalt.
COTS	Commercial Off-the-Shelf.
CPI	Cost Performance Index.
CS	Central Solenoid.
CTS	Cryostat Thermal Shield.
CuCrZr	Copper Chromium Zirconium.
DA	Domestic Agency.
DEMO	Demonstration fusion power plant.
DG	Director General.
DN	Nominal Diameter.
DREAL	Direction Régionale de l'Environnement, de l'Aménagement et du Logement
EB	Electron Beam.
EDA	Engineering Design Activities.
EQ	Equatorial (Port).
ESPN	Équipements sous pression nucléaires.
ESR	Electroslag Remelting.
EU-DA	European Domestic Agency.
FAT	Factory Acceptance Test.
FE	Finite Element.
FEAC	Front End Acquisition and Control.
FIDIC	International Federation of Consulting Engineers.
FOAK	First-of-a-Kind.
FPGA	Field Programmable Gate Array.
GBT	Gigabit Transceiver.
GS	Gravity Support.
GTAW	Gas Tungsten Arc Welding.
HAZ	Heat Affected Zone.
HCl	Hydrochloric acid.
He	Helium.
HIP	Hot Isostatic Pressing.
HV	High Voltage.
HWT	Hot Wire TIG.
I&C	Instrumentation and Controls.
ICPE	Installation Classée pour la Protection de l'Environnement under French law
IIS	Inner Intercoil Structure.
IN-DA	India Domestic Agency.
INB	Installation Nucléaire de Base under French law
IO	ITER Organization
IOTA	Installations, Ouvrages, Travaux et Activités impacting the water resource
IPT	Integrated Product Team.
ITER	International Thermonuclear Experimental Reactor.

KO-DA	Korea Domestic Agency.
LHC	Large Hadron Collider.
Mn	Manganese.
N.A.	Not Applicable.
Nb	Niobium.
NDE	Non-Destructive Examination.
Ni	Nickel.
OTS	Off-the-Shelf.
PA	Procurement Arrangement.
PDI	Profinet Device Interface.
PF	Poloidal Field.
PIC	Protection Important Component.
PLC	Programmable Logic Controller.
PM	Power Manager.
RAMI	Reliability, Availability, Maintainability, Inspectability.
RCC-MR	Design and Construction Rules for Mechanical Components of Nuclear Installations.
RF-DA	Russian Federation Domestic Agency.
RT	Room Temperature.
SPI	Schedule Performance Index.
SQEP	Suitably Qualified and Experienced Personnel.
SSAT	Sector Sub-Assembly Tool.
STS	Support Thermal Shield.
SVS	Service Vacuum System.
Ta	Tantalum.
TF	Toroidal Field.
TFGS	Toroidal Field coil Gravity Support.
TIG	Tungsten Inert Gas.
TS	Thermal Shield.
UP	Upper Port.
US-DA	United States Domestic Agency.
UT	Ultrasonic Testing.
VAR	Vacuum Arc Remelting.
VIM	Vacuum Induction Melting.
VV	Vacuum Vessel.
VVTS	Vacuum Vessel Thermal Shield.
W	Tungsten.

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