Experiences during Design, Fabrication, Assembly and Factory Acceptance Test of the ITER Cryoplant Termination Cold Box

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Abstract. The ITER Cryodistribution (CD) system distributes cryogenic power from the cryoplant to the applications, namely superconducting magnets, cryopumps, etc. The ITER CD system comprises seven cold boxes of which the Cryoplant Termination Cold Box (CTCB) is the largest one. The CTCB plays a pivotal role in distributing the cold helium fluid with the highest mass flow rates of 4 kg/s coming from one of the 80 K plants to the applications. The physical connection between the CTCB and different applications is through nine cryolines (CLs) having diameters ranging from 0.45 m to 1.0 m. The CTCB has been manufactured and assembled with various large size components such as electrical heater system of 600 kW capacity, cryogenic control valves of size DN200, bubble panel thermal shield (TS) made of stainless steel, etc. The CTCB, which withstands interface loads of ~1.4 times of its own weight, has been analysed for its functional and thermo-structural requirements under various load conditions. Components & subsystems were manufactured and factory tested individually in various locations in Europe and India to be finally assembled in one place. The CTCB has also been integrally tested, of which major activities were the pressure and helium leak tightness tests, followed by functionality checks of all instruments. The present paper describes the challenges involved and how they were resolved as well as lesson learnt during the design, fabrication, assembly, and factory acceptance test (FAT) phase of the CTCB project.

1. Introduction
The ITER cryogenic system includes the CD system, complex CLs, three liquid helium (LHe) plants [1], two 80 K helium plants, one LHe tank, and many other auxiliary systems. The ITER CD system apportions cryogenic power equivalent to 75 kW at 4.5 K and 1300 kW at 80 K, from the ITER cryoplant to the applications, namely superconducting magnets, cryopumps, current leads and 80 K thermal shield of the tokamak, etc. The ITER CD system includes seven cold boxes, out of which the CTCB is one of the largest CD cold box, located in the ITER cryoplant building. The simplified architecture of ITER cryogenic system with the interconnection of cryoplant with CD system is shown in figure 1.
The CTCB is responsible to distribute the cold power to the applications and cryoplant as per functional requirements at various temperature levels i.e. 4 K, 50 K and 80 K [2] [3]. The onus of parallel operation of the three LHe plant is on the CTCB, which ensures the normal operation of the applications. In the case of a failure of any single LHe plant, the CTCB redistributes cold power of the other two plants without stopping the Tokamak plasma experiment. The existence of CTCB is also beneficial for the LHe plant commissioning, heating of the gaseous helium (GHe) during warm-up of the ITER SC magnets from 4 K to 300 K and purging of the interfacing CLs before initial cool-down.

The CTCB, which is a horizontal cylinder of 20 m length, 3.5 m diameter and ~70 tons weight, has nine interfaces with CLs having diameters in the range of 0.45 m to 1 m separated by vacuum barrier on the CTCB side. The loads from CLs are transferred to the CTCB and then to the floor through embedded plates (EPs). The CTCB outer vacuum jacket (OVJ) must be strong enough to carry the CL-interface, gravity, differential pressure and thermal (emergency load condition) loads while respecting the load bearing capacity of 20 tons/m² of the floor and EPs. Being designed, manufactured and assembled with various components like cryogenics valves, internal piping, TS, cryogenic inline heaters, filters, vacuum system, instrumentation and control systems. The CTCB has been successfully tested at factory integrating the Cold box, control cabinets, electrical cabinets, junction box and interconnecting cables while warm panels (WP) were tested separately. The experiences gained during the CTCB manufacturing will be useful while designing and manufacturing of the other cold boxes of CD system.

2. The overall methodology for execution of CTCB from design to factory acceptance test

The CTCB is designed for the continuous operation of at least one thermal cycling (from normal operating temperature to room temperature) every two years during a Tokamak machine life-time of 20 years. Figure 2 represents the methodology for the execution of CTCB from design to the factory acceptance test.
3. Description of Design, Manufacturing and factory acceptance test of CTCB

3.1. Design
As the first step for the CTCB design, process and instrumentation diagram (P&ID) (figure 3 indicates a simplified process flow diagram) [3] is to be developed as per the functional process and different operation mode requirements [4], which also includes component sizing and selection. The CTCB OVJ has been designed as per EN 13458 & 13445 code and its piping as per EN 13480-3. After fixing the sizing of all the components, a detailed 3D model has been developed as shown in figure 4(a).

![Figure 3: Simplified process flow diagram for CTCB.](image)

The CTCB has been designed and analyzed considering several load cases and its combinations including the severe interface loads from CLs as summarized in figure 4(b). Out of total ten load combinations, the worst load combination has been identified as “normal operation + seismic load + loss of insulation vacuum + interfacing CLs loads”, which has been chosen to perform detailed analysis i.e., buckling and EPs load verification.

3.1.1. Loads from interfacing CLs: The CTCB has interfaces with nine CLs of size up to DN1000. The loads from CLs through these vacuum barriers have to be transmitted to floor through the CTCB. Table 1 shows the loads from the two main CLs to the CTCB during the nominal and exceptional cases.
Considering all the above inputs, detailed analysis has been performed on the ANSYS® platform. The equivalent stress and deformation results for the worst loading case of the CTCB are shown in figure 5(a) and (b). As shown in figure 5(a), the maximum deformation of 11 mm is observed in the OVJ close to the vacuum barrier. Figure 5(b) shows that the maximum stresses observed is 477 MPa at the heater nozzle of the OVJ due to a high thermal gradient. These stresses are observed at the nozzle weld location and very localized. The overall equivalent stresses in the CTCB OVJ are well below the limit of 710 MPa.

![Figure 5](image_url)

**Figure 5.** Summary of results on (a) deformation and (b) equivalent stress for CTCB.
In ITER, all the components are classified based on the different categories such as safety, seismic, quality, and vacuum quality classification and the CTCB is categorized as non-Safety important class, Non Seismic class, Quality class-1 and Vacuum Quality Class-4A/4B [5]. The manufacturing requirement as per these categories has been considered from the start of the design to the fabrication and installation phase. After the final design of the CTCB, due to the fact that multiple sub-contractors are working under the instruction of a single integrator for the earlier-mentioned components, corresponding manufacturing readiness reviews (MRRs) have been conducted at various places in Europe and in India as indicated in figure 6.

The CTCB has been manufactured under stringent criteria such as non-destructive tests of weld with 100% radiographic test as per the requirement for QC1 components and inspection of components as per manufacturing inspection plans (MIPs) defined before MRR. After, the prefabrication of all components integration took place at one location where the CTCB FAT is performed.

![Simplified manufacturing flowchart of CTCB.](image)

### 3.3 Factory acceptance test

The FAT is one of the vital steps before installation of components at the operation site and is intended to validate the performance and functions of each CTCB components after their fabrication and final integration. As shown in figure 6, for major components of the CTCB, individual factory tests were performed at their manufacturing site and the integrated test was performed after being assembled into the CTCB. For simplicity, the FAT has been divided into the mechanical FAT and functional FAT. The mechanical FAT includes overall dimensional check, pressure test, helium leak test of components whereas the functional FAT includes functionality test of instruments, verification of each item specification and quantity, verification of hardware and software test, loop test for I/O (input/output) signals, a test of PLC (programmable logic controller) program, verification of HMI (Human-Machine Interface) implemented using a simulator.

### 4. The outcome of factory acceptance test

#### 4.1 Mechanical FAT

The mechanical FAT of the CTCB as per specified acceptance criteria has been performed successfully and results are summarized in table 2.

#### 4.2 Functional FAT

Before the functional FAT, i) hardware FAT has been conducted to check functionality of electrical cabinets and the healthiness of all the installed equipment inside as per approved drawings and MIP at respective manufacturer sites. ii) the software FAT of the CTCB has been performed using PLC and simulator as shown in figure 7 (a). For the finalization of HMI screens (one of the CTCB HMI screen of line C shown in figure 7 (b)), checking of all alarm signals, control loops (17) and I/O signal (~500) test as per logic diagram in simulation mode has been completed.
Table 2. Summary FAT results of CTCB and its component.

| Description                                      | Test fluid/items | Observed results                  | Acceptance criteria          |
|--------------------------------------------------|------------------|-----------------------------------|------------------------------|
| Overall dimensional check                        | Sleeve/OVJ/saddle support | As per manufacturing drawing     | As per manufacturing drawing |
| Hydraulic continuity check                       | Process pipes    | As per P&ID                       | No permanent deformation, no pressure decrease |
| Pressure test (PT) - Line A,B,D,H (at 15.7 barg) | 50% nitrogen gas (GN2) & 50% GHe | No permanent deformation, no pressure decrease | No permanent deformation, no pressure decrease |
| PT-Line C, E & F (at 30 barg)                    | 100% GN2         |                                   |                              |
| PT-WP 1&2 (at 28.6 barg)                         | 100% GN2         |                                   |                              |
| Leak Test (LT) Global-Process to vacuum          | Internal piping  | $1.4 \times 10^{-8}$ (mbar·l/s)   | $1 \times 10^{-7}$ (mbar·l/s) |
| LT Atmosphere to Vacuum                         | A,B,D,H & C,E,F  | $1.6 \times 10^{-7}$ (mbar·l/s)   | $1 \times 10^{-6}$ (mbar·l/s) |
| LT Global - Process to the atmosphere            | Vacuum sleeves, feedthroughs | $2.1 \times 10^{-6}$ (mbar·l/s)   | $1 \times 10^{-5}$ (mbar·l/s) |
|                                                  | All circuits (Warm panel 1&2) |                                   |                              |

The functional FAT has been performed with the CTCB and all electrical cabinets connection identical to the site configuration. All instrumentations such as pressure transmitters, differential pressure transmitters, temperature sensors, and transmitters, control and gate valves opening and closing, valve position feedback, electric heaters resistance check, flow and temperature switch and vacuum pumps were successfully executed using the PLC. Thyristor functionality was confirmed using dummy lamps. The functional tests were found to be in conformance with approved design documents throughout the integration chain.

5. Challenges involved during design, fabrication, assembly and FAT

For the ITER CD system, starting from the conceptual design of the CTCB to the factory acceptance test, it has encountered many challenges. Table 3 summarizes all the challenges faced and the resolution steps take to overcome such challenges.

The CTCB TS is made of hydro-formed bubble panels consisting of total 48 elements connected in parallel/series. Figure 8 shows the configuration of one segment having 4 elements. During the FAT of the CTCB, it was reported that the helium leak of the bubble panel of the TS is higher than acceptable limit of $1 \times 10^{-5}$ mbar·l/s. The CTCB being a very large cold box, the localization of the helium leak is quite cumbersome. In order to localize the leak, each accessible element was checked and found that among 48 TS elements, three elements are suspected for the leak. The helium circuits of those elements were by-passed as the repair or replacement was not feasible. The final helium leak result has been measured to be $2.9 \times 10^{-8}$ mbar·l/s and it is within the acceptable limits. Thermal and hydraulic analysis
has been performed and investigated that heat load on the 80 K TS is almost unchanged and the average surface temperature is observed to be around 88 K, which is below the given limit of 100 K. The total heat load on the 4 K surface after by-passing TS elements is about 211 W which is within the maximum allowed heat load of 275 W.

**Table 3. Summary of Challenges and its resolution steps.**

| Challenges | Resolution steps and lesson learnt |
|------------|-----------------------------------|
| Meeting the balance between the interface tolerance of ±25 mm with CLs and the interface loads from CLs | Interface tolerances for CTCB has been reduced from ±25 mm to ±10 mm in order to reduce interface loads i.e., bending load. Interface should be frozen before final design, whenever feasible. |
| Management and validation of interface coordinates between CLs and CTCB at design and manufacturing phase | Managed and validated proper interface coordinates between CLs and CTCB with exact available 3D model through design database platform (ENOVIA) which is very useful tool for complex interface management. |
| Progressing in the cold box design of this big scale while interfaces are at a different level of maturity | Design with a higher safety margin for CLs interface load (conservative design) with provision to adopt additional stiffeners on CTCB OVJ. Saddle support design has been optimized for distributed load transfer to the ground. CL interface loads should be envisaged from the conceptual design phase and inherent line flexibility should be provided by proper layout. |
| Recovery of helium through a common safety relief header line was not possible due to limited downstream mass flow rate handling capacity. | Recovery valves have been installed upstream safety relief valves (SRVs) in order to recover the helium prior to the opening of the SRVs in case of pressurization events. Helium recovery from large volumes are possible using the automatic recovery valves. |
| Bigger size (≥DN150) cryogenic valves to handle mass flow 4 kg/s were not readily available. | Cryogenic valves of DN200 which fulfil the process requirements were specified, designed, manufactured and factory tested. Opening and closing time of bigger valve sizes to be considered for integrated control system development and commissioning. |
| Warm-up requirement of the SC magnets having cold mass of ~9,000 tons | Large capacity 600 kW electrical heater designed, manufactured and factory tested for functionality. |
| Control system development for the parallel operation of LHe plants and disconnections with interface system. | Global level controls (where extensive signal exchange with CTCB is required) were assigned through cryogenic system master controller while process control within CTCB managed by CTCB control system. |

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![Figure 8](image_url) (a) Flow paths in a TS segment and (b) their layout.
After the successful completion of the FAT, as shown in figure 9(a) and (b) the CTCB has been delivered from Switzerland to France via road and waterways to ITER Organization (IO) for installation and final acceptance test.

![CTCB delivery through road and waterways](image)

**Figure 9** (a) CTCB delivery through road and (b) waterways.

### 6. Conclusion

The design, fabrication, assembly and factory test of CTCB has been successfully completed with fulfilling all the functional and technical requirements. The CTCB and its components have been delivered to IO in February 2019. The installation of the CTCB is planned in the last quarter of 2019 at IO site to match the commissioning of the three LHe plants. The performance of the CTCB in normal operation condition will be demonstrated during the site acceptance test at IO. The experiences observed and lessons learnt during the execution of the CTCB project will be implemented in other cold boxes of the ITER CD system in order to avoid any mishap during the design, fabrication and acceptance test itself.

### 7. References

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### Disclaimers

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

### Acknowledgments

Authors would like to thank the colleagues in ITER-India and ITER Organization and as well as Linde Kryotechnik for their contribution to the ITER Cryodistribution project execution.