Acceptance tests and their results for 1st Pre-Series Cryoline (PTCL) of ITER

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Abstract

The Pre-Series Cryoline (PTCL) for ITER is a representative cryoline from the complicated network of all cryolines for the ITER project. It is ~28 m in length with same cross-section (1:1) including main line (ML) and branch line (BL) as of ITER torus & cryostat cryoline. Geometrically; it has bends at different angles i.e. 90°, 120°, 135° & 160° comprising T-section & Z-section. The PTCL has been fabricated in 5 different elements based on the installation feasibility. The mechanical & instrumentation installation like sensors mounting, displacement sensors, etc. has been completed. The PTCL test has been performed after complete installation of PTCL and integration with the existing test facility at ITER-India cryogenics laboratory in order to verify the thermal performance and mechanical integrity. The primary objectives, which are evaluated during the PTCL test, are (i) Thermal performance of the PTCL (ii) Measurement of temperature profile on thermal shield of PTCL, (iii) Stress measurement at critical locations, (iv) Measurement of Outer Vacuum Jacket (OVJ) temperature during Break of Insulation Vacuum (BIV) test. The paper will summarize the methodology and observed results of PTCL.

1. Introduction

The ITER cryolines are complicated cryogenic transfer lines to transfer the cold helium and nitrogen in order to fulfill the requirements of ITER cryogenic process and cryogenic system users considering various constraints such as intricate layout, limited space availability, stringent heat load restrictions, etc. Hence, it was decided to design, manufacture and test the representative prototype of cryolines, here onwards called as pre-series cryoline (PTCL), with the existing state of the art tailor made test facility at ITER-India Cryogenics Laboratory (IICL) [1], Institute for Plasma Research (IPR) for a) validation of its structural and mechanical integrity, b) measurement of temperature profile & mass flow rate during steady state at 80 K and 4.5 K (helium as process fluid), c) checking thermal profile in thermal shield, d) performing break of insulation vacuum test and e) confirming helium leak tightness of PTCL during all phases to validate the overall design of PTCL. The layout of PTCL is extracted from isometric layout.
of Torus and Cryostat Cryoline (TCC) [1] for ITER comprising the all feasible section (i.e. straight, T, elbow and Z) at 1:1 scale cross section as shown in Figure 1. PTCL comprises six process pipes (3 supply and 3 return) out of which four process pipes are operated at 4.5 K within pressure range of 1.4-1.8 bar (a) and flowrate up-to 2 g/s (designated as C, CR, CC and CD) and remaining two are operated at 80 K within pressure range of 6-7 (a) and flowrate up-to 25 g/s (designated as E and F). All the process pipes are enveloped with a thermal intercept at 80 K to minimize the radiation heat loads and an outer vacuum jacket (OVJ) at room temperature. OVJ is designed and manufactured for external pressure and room temperature condition with ability to transfer mechanical loads from internal components (like process pipes, thermal shield, etc.) to external supports structure. The PTCL has been installed, commissioned and tested at IICL and the acceptance criteria for these phases have been validated and found satisfactory. The PTCL has been bifurcated into five elements in order to carry out smooth transportation, handling & installation at IICL. All elements of PTCL have been installed considering the as built drawings and site (IICL) constraints. The joining between two elements has been referred as interconnection and joining between an element & test box has been referred as interface connection.

![Figure 1. Image of PTCL with external supports during installation.](image)

**Figure 1.** Image of PTCL with external supports during installation.

The exclusive test facility for PTCL mainly consists of a) a screw helium compressor at 300K with capacity of ~37g/s @ 7 bar(abs), b) 80 K cold box which delivers GHe at 80 K through dedicated heat exchangers, c) Three valve boxes (Test Box A/B/C) connected at three ends of PTCL which channels the required flow through cryogenic valves; 4.5 K temperature is achieved with a Liquid Helium (LHe)
dewar of 500L capacity, d) 5000L Liquid Nitrogen (LN₂) storage dewar, e) Two control cabinets integrated with Programming Logic Control (PLC) units to control PTCL process parameters, f) Control room equipped with two workstations programmed with WinCC to monitor, visualize and control all modes of PTCL. The utilities mainly comprises Gaseous Helium (GHe), compressed dry air, three phase electrical power supply for helium compressor, un-interrupted single phase power supply for control cabinets and workstations and cooling water for helium compressor. A simplified process flow diagram [2] of the test facility & PTCL is shown in Figure 2.

2. Installation

2.1. Mechanical Installation

All elements of PTCL have been fabricated as per manufacturing drawings at M/s. Inox India Limited workshop with continuous monitoring of ITER-India during critical phases. The quality checks like visual examination of weld joints, radiography examination of weld joints, helium leak tightness test, thermal shock test of 100% process pipe welds (100% radiography was performed after thermal shock test), etc. have been performed during fabrication as well as during & post installation. Before commencement of PTCL installation at IICL, the survey has been carried out with survey station unit to validate the layout of PTCL & co-ordinates of Test Boxes already installed at IICL. The survey data points have been recorded for three ends of Test Boxes A, B & C interfacing with PTCL. Based on the survey data points of Test Boxes, the layout of PTCL has been developed and linear mismatches of 36 mm to 77 mm have been observed at interface locations of Test Boxes. The interface pieces accordingly have been designed and installed accommodating the linear mis-matches.

The five elements of PTCL have been transported to installation site (IICL) in two batches, element 1, 4 & 5 were part of the first batch delivery including structural supports and the remaining elements (element 2 & 3) were part of second batch delivery. The delivery sequence has been decided considering transportation constraints.

During installation, it has been noticed that some of the weld joints could not be tested by X-ray machine due to site constraint and orientation of process pipes. Hence, an in house case study was carried out for comparing the results obtained by RT with X-ray machine and Se 75 gamma source. After comparing these results, it was concluded to use Se 75 gamma source for carrying out RT during installation wherever required. The global distribution of radiography performed on process pipe and OVJ by X-rays and Se-75 source weld joints is 44% by X-rays and 56% by Se-75 gamma source. The total weld joints were 96 in number including repair. The repair for radiography with X-rays was 07 weld joints in number and no repair was observed in radiography with Se-75 source.

2.2. Instrumentation Installation

2.2.1. Temperature Sensor mounting. In order to measure the thermal performance and the temperature distribution in the thermal shield of the PTCL, 53 temperature sensors of PT-103-AM RTD type and 32 temperature sensor of CX-1070 CERNOX™ type have been mounted on critical locations based on thermal analysis. To standardize the temperature sensor installation, the mounting method was type tested for validation and specially developed aluminum and copper sensor housings have been used.

Cleaning and surface preparation activities have been performed before mounting of the temperature sensors. Apiezon-N grease has been used as a thermal coupler. Standard thermalization techniques have been employed during mounting of the temperature sensors.

2.2.2. Strain gauge mounting. In order to measure stress at critical locations of PTCL during various test phases, 35 foil type strain gauges (tri-axial) along with dummy gauges (for thermal compensation) have been mounted with special assembly.

Cleaning and surface preparation activities have been performed before mounting the strain gauge referring to the standard procedure of the manufacturer. Dynamic strain data has been recorded for various test phases and compared with analysis results.
2.2.3. Development & simulation of the PLC programming with its Graphical User Interface (GUI). In order to monitor, record and control the process parameters through control valves and electric heaters, programming with its GUI (Graphical User Interface) have been developed in PLC software and SCADA (Supervisory Control And Data Acquisition). Simulation of PLC programming was performed after giving the forced expected process parameters through the PLC simulator and monitored the right actions of control valves and heaters in SCADA. Functionality of control valves were performed through SCADA.

3. Test Phases
The test phase mainly includes pressure test, helium leak tightness test, vacuum retention and radiography test by X rays and by Se-75 source.

The pressure test of PTCL at 29.2 kg/cm2 (g) with temperature as 25 °C has been carried out without connection to the Test Boxes and a dedicated arrangement has been prepared for performing pressure test considering safety aspects for personnel and equipment. The source of pressure has been placed outside IICL and the entry point into PTCL has been maintained near to the test box A. The strain gauges have been used to measure the deformation values at critical locations (35 numbers). Gaseous Nitrogen (GN₂) has been used to pressurize all the process pipes of PTCL. The hold time for pressure inside process pipe has been kept as 30 minutes as per EN 13480.

The helium leak tightness test has been carried out for a) process pipe by use of process to insulation vacuum technique, b) OVJ by use of atmosphere to insulation vacuum technique.

The evacuation of OVJ has been carried out to vacuum level of 6.7 X 10⁻⁴ mbar after 100 hours with active pumping. The vacuum retention was noted after 73 hours and vacuum reading was observed to be 3 X 10⁻³ mbar.

The requirement of Radiography Testing (RT) for PTCL has been considered as 100% on process pipes. Radiography procedure has been developed as per EN 17636-1, and the acceptance criteria has been chosen as per EN-5817 level B (for e.g. porosity, misalignment, tungsten inclusion, etc.).

4. Test Methodology
Figure 3 depicts the major phases of PTCL [3] test which includes cool down of PTCL from 300-4.5K, steady state measurements, thermal cycling and break of insulation vacuum. The total duration of PTCL test was 21 days.

![Test Methodology Diagram]

Figure 3. Major operation modes and associated operation sequence for PTCL test.
In 300-80 K cool down phase, 80 K gaseous helium has been supplied with average mass flow rate of 28g/s to 6 process pipes of PTCL & thermal shield of test boxes simultaneously; the flow bifurcation to process pipes of PTCL, C-CR (4.5K), CC-CD (4.5K) & E-F (80K) has been established through control valves V4, V5, V9, V10, V11, V12, V13, V14 and V17 (refer figure 2) in order to attain steady state condition at 80K.

80-4.5K mode has been initiated by restricting the 80K GHe flow (through valve V5) (refer figure 2) from 80K cold box to 4K process pipes (C, CC & CR and CD). Helium vapors from LHe Dewar have been transferred to the 4K process pipes via control valve (V6) for cool-down at ~7K with an average mass flow rate of 2 (g/s).

Flooding activity has been performed to calibrate (for accurate heat load measurements) the temperature sensors (T1, T2, T3, T4, T5 and T6) mounted on 4.5K process pipes by supplying the LHe at a flow rate of 2g/s from LHe dewar.

The supply of vapor helium has been kept continuous for ~24 hours in order to ensure the steadiness of temperature readings (T1, T2, T3, T4) in 4.5K process pipes during steady state measurements (SSM1, SSM2 & SSM3) at 4.5K. Steady state has been ensured by observing negligible change in fixed support temperature and almost stable temperature (below 90K) in thermal shields of PTCL.

The 80-4.5 K and steady state measurement modes have been performed in open loop configuration. Pressure and flow meter transmitters (P2, F2, P3 and F3) have been measured for heat load estimation.

The warm-up from 4.5K to 80K and 80K to 300K has been performed through control action of V5, V6 & V3 respectively. Three thermal cycles (300-80K & 80-300K) have been performed in order to ensure the reliability of PTCL.

Break of insulation (BIV) has been performed by disconnecting the test facility, with allowing the entry of Gaseous Nitrogen (GN₂) into OVJ at regulated flow rate and pressure from nitrogen gas cylinders with the help of specially made setup in order to determine the lowest temperature on OVJ.

5. Acceptance criteria and test results

5.1. Acceptance criteria

The tests on PTCL have been conducted at different indispensable phases and results have been compared with the acceptance criteria. Table-1 shows the tests carried out on PTCL with their results and acceptance criteria.

| Sr. No. | Test details | Acceptance criteria | Observed Results |
|--------|--------------|---------------------|-----------------|
| 1.     | Helium leak tightness (mbar-l/s) | 1X10⁻⁷ 1X10⁻⁶ | ³.3X10⁻¹⁰ ³.6X10⁻¹⁰ |
| 2.     | Pressure test | No permanent deformation | No permanent deformation |
| 3.     | Mechanical integrity | Process pipe/OVJ | No water condensation or ice formation on OVJ |
|        |               | External supports | No rupture or permanent deformations |
| 4.     | Vacuum level of OVJ at cold condition (without active pumping) | 5 X 10⁶ mbar | ².1 X 10⁷ mbar |
5. Maximum temperature on thermal shield during nominal operation

| Condition | Value |
|-----------|-------|
| < 90 K OR | Not greater than 10 K of process pipe E temperature |

\[ ^c \text{Process pipe E temperature: 80.25 K} \]

\[ ^c \text{Thermal shield maximum temperature: 86.73 K} \]

\[ ^a \text{at } t=-263^\circ \text{C} \]

\[ ^b \text{at } t=25.9^\circ \text{C} \]

\[ ^c \text{average value considering SSM-2 and SSM-3 (138 hours to achieve this value from } 1 \times 10^{-3} \text{ mbar)} \]

5.2. Test Results

The flow scheme of representative supply and return has been referred in below sections and same has been shown in Figure 4.

5.2.1. Flooding. Flooding has been performed using Liquid Helium (LHe) for 4.5K lines independently (i.e. C-CR, CC-CD). The flooding operation has been performed with an average liquid helium mass flow rate of 2 g/s. The reference temperature corresponding to the saturation pressure of liquid helium dewar at the inlet of PTCL has been considered to determine offset for the temperature sensors. It was ensured that all temperature sensors were displaying consistent readings (comparable to the reference temperature) for certain duration as depicted in the Figure 5. The range of offset observed for C-CR is 0.103 – 0.346 K and for CC-CD is 0.088 – 0.438 K.

![Figure 4. Flow scheme of representative supply & return process pipes of PTCL.](image)

![Figure 5. Liquid Helium flooding results.](image)
5.2.2. Pressure Test Results. The measured results in terms of stresses during pressure test have been shown for few locations in Figure 6. The measured results have been compared with Ansys® values.

![Figure 6. Comparison of stress values measured during pressure test and Ansys® values at few locations.](image)

5.2.3. Steady State Measurement Results. Steady state measurements have been performed at two temperature levels (i.e. at 4.5K and 80K). The process conditions for 4.5K measurements are 0.5-1 g/s with an inlet temperature of 6-8K and for 80K measurements are 25-30 g/s with an inlet temperature of 80-82K. Figure 7 & Figure 8 show the temperature behavior with mass flow rate during steady state measurement.

![Figure 7. SSM data for E-F line.](image)

![Figure 8. Steady state measurement results.](image)

5.3. BIV Test Results
The BIV test has been carried out by externally injecting GN\textsubscript{2} to OVJ at a mass flow rate of 10 g/s with intermittent flow scheme. Several temperature sensors were mounted on OVJ external surface to record the lowest temperature. Figure 9 shows the temperature behaviour of these sensors during BIV event. However, the lowest measured temperature on the surface of OVJ using a thermal infrared device was -34.4°C.

**Figure 9.** Temperature profile during BIV event.

5.4. Global PTCL Test Results

The temperature profile of process pipes with duration for different operational modes of PTCL has been shown in Figure 10. The cool-down time from a) 300K to 80K for mass flow rate of 28 g/s has been observed to be \(\approx 32\) hours and b) 80K to 4.5K for mass flow rate of 0.55 g/s has been observed to be \(\approx 9\) hours. The total consumption of LN\textsubscript{2} considering 2 cool-down (300-80K), 3 thermal cycles (80-300K and 300-80K) with 3 steady state measurements and Net Evaporation Rate (NER) of LN\textsubscript{2} dewar has been \(\approx 31000\) liters. The total consumption of LHe considering 3 cool-down (80-4.5K), flooding, 3 SSM & NER of LHe dewar has been \(\approx 4300\) liters.

**Figure 10.** Temperature profile with duration of PTCL process pipes (80K & 4.5K) for all operational modes.

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