Cold Test and Performance Evaluation of Prototype Cryoline-X

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Abstract. The multi-process pipe vacuum jacketed cryolines for the ITER project are probably world’s most complex cryolines in terms of layout, load cases, quality, safety and regulatory requirements. As a risk mitigation plan, design, manufacturing and testing of prototype cryoline (PTCL) was planned before the approval of final design of ITER cryolines. The 29 meter long PTCL consist of 6 process pipes encased by thermal shield inside Outer Vacuum Jacket of DN 600 size and carries cold helium at 4.5 K and 80 K. The global heat load limit was defined as 1.2 W/m at 4.5 K and 4.5 W/m at 80 K. The PTCL-X (PTCL for Group-X cryolines) was specified in detail by ITER-India and designed as well as manufactured by Air Liquide. PTCL-X was installed and tested at cryogenic temperature at ITER-India Cryogenic Laboratory in 2016. The heat load at 4.5 K and 80 K, estimated using enthalpy difference method, was found to be approximately 0.8 W/m at 4.5 K, 4.2 W/m at 80 K, which is well within the defined limits. Thermal shield temperature profile was also found to be satisfactory. Paper summarizes the cold test results of PTCL-X

1. Introduction

The ITER project is being constructed at south of France for demonstration of feasibility of nuclear fusion energy. It involves one of the largest helium cryogenic system in the world. The complex network of almost 5 km of cryogenic transfer lines (cryolines) connect various cryogenic equipment, valves boxes of cryoplant, cryo-distribution system as well as users like superconducting magnets and cryo-pumps [1]. ITER cryolines, which mainly connects cryoplant to users, are divided in to two main types, Group-X which are multi-process pipe cryolines with number of process pipe per cryoline typically more than 4 while Group-Y cryolines have number of process pipe per cryoline less than 4.

The major challenge associated with design of ITER cryolines is stringent technical specifications and quality requirements. Therefore, in order to mitigate risks related to design and quality validation, the prototype was planned long back [2]. The present paper describes the warm and cold test results of prototype cryoline for Group-X cryolines (PTCL-X) carried out during September-October 2016 at ITER-India Cryogenics Laboratory (IICL) in Gandhinagar, India.
2. Prototype Cryoline
The 29 meter long and DN 600 size PTCL-X represents one of the complex multi-process pipe
cryolines of the ITER cryogenic system at 1:1 scale in diameter and roughly 1:5 scale in length when
compared to torus and cryostat cryolines of the ITER. It constitutes all types of layout singularities
like 90 degree elbow, 160 degree elbow, Tee, out-of-plane Z and straight elements. The Figure 1 (a)
shows 3D layout of PTCL-X as per design while Figure 1 (b) shows actual layout of PTCL-X,
designed, manufactured and installed by Air Liquide at IICL as a part of contract with ITER-India and
Figure 1(c) shows cross sectional view of actual PTCL-X. The dedicated test facility [3] with PLC and
SCADA system at IICL has been tailor made for warm (room temperature) and cold testing of PTCL-
X at 80 K and 4.5 K temperature level.

![3D design model of PTCL-X](image1)

![PTCL-X installed at ITER-India cryogenics laboratory](image2)

![PTCL-X cross section](image3)

**Figure 1.** PTCL-X: 3D model and actual photograph of PTCL-X

3. Warm (Room Temperature) Tests
The successful completion of mechanical installation of the PTCL-X at IICL was followed by the
provisional acceptance tests which included the pressure test and helium leak test. Pressure test was
done using nitrogen gas at room temperature as per standard EN 13480-5. The test pressure for each
process pipe was 30.2 bar(a) and it was achieved using dedicated control panel in steps of 2 bar →
bubble test → 16 bar → 19 bar → 22 bar → 25 bar → 28 bar → 30.2 bar as shown in Figure 2. The
Outer Vacuum Jacket (OVJ) was under vacuum during the pressure test. The pressure test was
successfully completed without any physical damage or leak. The stresses and displacements
measured were mostly below the calculated values, while it was slightly higher than calculated values
in few cases, but it never exceeded allowable limits defined by design code EN 13480. After the
pressure test, controlled depressurization was done, followed by the global leak test between process
pipes and insulation vacuum as well as between atmosphere and insulation vacuum.
4. Cold Test
After successful completion of provisional acceptance tests, PTCL-X was connected to Test Boxes A, B and C for final acceptance cold test. The cold test involved following major phases.

(a) Purging of process pipes and filling with pure helium gas.

(b) Room temperature to 80 K cooldown of all six process pipes (CC, CD, C, CR, E and F) including thermal shield (connected to process pipe E – conduction cooling mainly) using 80 K helium gas at 6 bar(a) in closed loop operation.

(c) Depressurization and isolation of 4.5 K process pipes (CC, CD, C and CR) from 80 K circuit followed by cooldown to 4.5 K level using liquid + vapor helium from liquid helium Dewar.

(d) Liquid helium flooding in 4.5 K process pipes for temperature sensors calibration and offset measurement.

(e) Removal of liquid helium from process pipes using sufficiently high flow of warm helium vapor.

(f) Controlling steady slow flow of 80 K gas helium in process pipes E-F and around 7 K vapor helium in process pipes CC-CD-C-CR and waiting to reach reasonably steady state temperature in process pipes, thermal shield and internal supports.

(g) Continuous recording of temperature, pressure and flow rate at inlet and outlet of PTCL-X for heat load estimation using enthalpy difference method – this phase is called Steady State Measurements-1 (SSM-1).

(h) Warm-up to 80 K followed by thermal cycling (3 times) of PTCL-X process pipes between 80 K and room temperature.

(i) Cooldown of process pipes to their nominal temperature (80 K or 7 K as applicable) and waiting for steady state followed by SSM-2 measurements.

(j) Controlled break of insulation vacuum to check OVJ temperature, displacement and safety valve functioning.

(k) Visual inspection.

Figure 3 shows the process pipe temperature evolution during cold test of PTCL-X.
5. Results
The main results of the cold test are summarized below.

5.1. Leak rate
The leak tests were carried out at room as well as cold temperatures and the results are summarized in Table 1.

Table 1. Leak rate values

| Leak type                              | Temperature                          | Measured values (mbar l/s) | Specifications (mbar l/s) |
|----------------------------------------|--------------------------------------|-----------------------------|---------------------------|
| Global – process pipes to insulation   | room temperature                     | $5 \times 10^{-10}$         | $1 \times 10^{-7}$        |
| vacuum                                 | cryogenic temperature                | $3 \times 10^{-9}$          | $1 \times 10^{-6}$        |
| (process pipes and thermal shield)     |                                      |                             |                           |
| Global – atmosphere to insulation      | room temperature                     | $3.7 \times 10^{-6}$ (including vacuum isolation valves and instrument feedthrough) | $5 \times 10^{-6}$ | vacuum |

5.2. Heat load
Various approaches have been used in past for cryogenic heat load measurement [4]. In case of PTCL-X, the temperature on process pipes at inlet and outlet along with helium pressure and flow rate were measured during steady state measurement phase to calculate heat load using enthalpy difference method [5]. High accuracy Cernox temperature sensors with good thermalization and new Lakeshore 240-P for PLC/Profibus were used for temperature measurement at 4.5 K level. An estimated overall (sensor + mounting) error for Cernox sensors was less than 0.05 K per sensor or 0.1 K in temperature difference (dT). Similarly, an estimated overall (sensor + mounting) error for PT-102 sensors was less than 0.1 K per sensor or 0.2 K in temperature difference (dT). Two sensors, 1 nominal and 1 redundant were installed at each location (pipes inlet and outlet) and difference between these two sensors was observed to be less than 20 mK in most of the cases.

Helium flow rate in process pipes of PTCL-X was measured at exit side using thermal mass flowmeter (2% error) after heating helium gas to room temperature in atmospheric heaters. The error
for pressure measurement was less than 50 mbar. Table 2 shows typical process parameters during SSM phase. Overall uncertainty in heat load measurement was close to 8%.

Table 2. Typical parameters of PTCL-X during SSM phase

|                      | Unit | Process pipe CC-CD loop | Process pipe C-CR loop | Process pipe E-F loop |
|----------------------|------|-------------------------|------------------------|-----------------------|
| T in*                | K    | 8.04                    | 7.7                    | 78.86                 |
| T out*               | K    | 12.11                   | 13.01                  | 88.49                 |
| Flow                 | g/s  | 0.40                    | 0.51                   | 2.32                  |
| Pressure#            | Bar  | 1.14                    | 1.14                   | 1.12                  |
| Enthalpy in$^5$      | J/kg | 54391                   | 52437                  | 425095                |
| Enthalpy out$^5$     | J/kg | 76712                   | 81544                  | 475101                |
| Heat load            | Watt | 8.9                     | 14.8                   | 115.8                 |
| Total measured heat load | Watt | 23.7 at 4.5 K | 115.8 at 80 K |
| Heat load specification | Watt | 33.5 at 4.5 K | 126 at 80 K |

*after offset correction and averaging of the 2 or 3 sensors per location

#average of inlet and outlet

$^5$calculated using HePak© version 3.4

Figure 4. Heat load: specification and measured values

The heat load measured at 4.5 K and 80 K was 29.3% and 8.1% lower respectively compared to allowable limits as shown in Figure 4. Better and more correct results obtained during SSM-2 were due to longer thermalization period (even if steady state was still not fully reached).

5.3. Thermal shield temperature

The temperature of PTCL-X thermal shield, made of aluminum, was measured at various locations during cold testing using Lakeshore PT-102 temperature sensors and compared with theoretical analysis. The typical locations of PT-102 on thermal shield are shown in Figure 5.
The temperature at various locations on thermal shield during the cold test is shown in Figure 6. It was observed that the maximum temperature of thermal shield was well within 10 K window of thermalization process pipe temperature; except at 2 places in Z and V section due to long overhang thermal shield. However, this has no impact on thermal performance as overall heat load at 80 K was found to be sufficiently within the allowable limit.

5.4. Insulation vacuum
The first pumping of PTCL-X was done after its installation. Due to rainy season, the air had humidity in the range of 85%. The combination of roughing and Turbo Molecular Pump (TMP) of 350 l/s was
used and it took almost 69 hours to reach vacuum level of $5 \times 10^{-3}$ mbar in OVJ of PTCL-X, where vacuum is measured quite away from DN 100 pumping port. After pressure test, OVJ vacuum was broken with dry nitrogen gas and re-evacuated again. This time, $5 \times 10^{-3}$ mbar was achieved in less than 3 hours, thanks to much less outgassing, while $1 \times 10^{-3}$ mbar was achieved in close to 100 hours. During cold test, the vacuum remained mostly below $1 \times 10^{-4}$ mbar while during steady state measurement it was below $1 \times 10^{-5}$ mbar as shown in Figure 7.

The global PTCL-X vacuum conductance between the far end of the PTCL-X and the pumping port has been measured with 2 vacuum gauges, the pumping speed being known by the characteristic of the TMP installed directly on the DN 100 pumping port. The measured value, $65 \text{ l/s}$, was higher that the calculated conductance using dedicated software (VACTRAN) with pessimistic assumptions on the internal geometry (clearance between Multi-Layer Insulation (MLI) blanket and OVJ, slits in internal/external spacers, holes in thermal barriers of fixed points etc.).

![Figure 7. Insulation vacuum of PTCL-X during cold test](image)

5.5. **Internal supports and MLI temperature**

The temperature of internal fixed supports, internal sliding supports and MLI was measured and recorded during cold test as these temperatures are important to decide whether steady state conditions are achieved or not.

Internal fixed supports constitute major part of heat load. Therefore, stabilization of internal fixed support temperature is important to measure correct heat load of cryoline. The minimum stable temperature of internal fixed support was close to 20 K.

Internal sliding supports are divided in two parts, inner spacer and outer spacer which are separated by thermal shield. Minimum temperature of inner spacer was close to 55 K during SSM-2 while outer spacer temperature was close to 230 K.

There were 3 blankets of MLI on thermal shield, each having 10 layers and temperature sensors were mounted on few locations on outer layer of inner (close to thermal shield) blanket and middle blanket. Lowest MLI temperature of 194 K was observed near T section at outer layer of inner blanket while highest temperature was observed at outer layer of middle blanket near Z section of PTCL-X. Typical stabilization time of MLI temperature was observed to be higher than 2 days.
5.6. **Break of Insulation Vacuum Test**

The insulation vacuum of PTCL-X was broken in a controlled manner using nitrogen gas after SSM-2 phase. After the initial phase of cryo-pumping of nitrogen gas on process pipes, the increase in OVJ pressure was observed which steadily reached above atmospheric pressure and followed by opening of OVJ safety valve at approximately 1.02 bar(g), thereby conforming to its design and functionality. The expected displacement in OVJ bellow was also observed as a consequence of thermal contraction of OVJ due to lower temperature and ice formation as shown in Figure 8. The minimum temperature of OVJ observed was close to -50 C at one of the internal fixed support location.

![Figure 8](image)

(a) OVJ thermal profile check using infrared camera (b) Ice formation on OVJ

6. **Conclusion**

The warm and cold test of PTCL-X was successfully completed and conformity with stringent specifications for heat load, thermalization, leak tightness and mechanical integrity was demonstrated, paving the way for the final design of Group-X ITER cryolines.

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**Acknowledgement**

The authors would like to thank Director, IPR and Project Director, ITER-India for their support to carry out the present work. The views and the opinion expressed herein do not necessarily express those of the ITER organization and the ITER partners.