Experience with helium leak and thermal shocks test of SST-1 cryo components

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Abstract. A steady state superconducting Tokamak SST-1 is presently under its assembly stage at the Institute for Plasma Research. The SST-1 machine is a family of Superconducting SC coils for both Toroidal field and Poloidal Field. An ultra high vacuum compatible vacuum vessel, placed in the bore of the TF coils, houses the plasma facing components. A high vacuum cryostat encloses all the SC coils and the vacuum vessel. Liquid Nitrogen (LN₂) cooled thermal shield between the vacuum vessel & SC coils as well as between cryostat and the SC coils. There are number of crucial cryogenic components as Electrical isolators, 80 K thermal shield, Cryogenic flexible hose etc., which have to be passed the performance validation tests as part of fulfillment of the stringent QA/QC before incorporated in the main assembly. The individual leak tests of components at RT as well as after thermal cycle from 300 K to 77 K ensure us to make final overall leak proof system. These components include, Large numbers of Electrical Isolators for Helium as well as LN₂ services, Flexible Bellows and Hoses for Helium as well as LN₂ services, Thermal shock tests of large numbers of 80 K Bubble shields In order to validate the helium leak tightness of these components, we have used the calibrated mass spectrometer leak detector (MSLD) at 300 K, 77 K and 4.2. Since it is very difficult to locate the leaks, which are appearing at rather lower temperatures e.g. less than 20 K, We have invented different approaches to resolve the issue of such leaks. This paper, in general describes the design of cryogenic flexible hose, assembly, couplings for leak testing, test method and techniques of thermal cycles test at 77 K inflow conditions and leak testing aspects of different cryogenic components. The test results, the problems encountered and its solutions techniques are discussed.

1. Introduction
In SST-1 Tokamak, hundreds of electrical isolators have been used in the SST-1 machine to isolate the LHe feed nozzles, which are at ground potential from the magnet system, expected to at high voltage ~ 2 kV during fault condition. Similarly, LN2 Electrical Breaks connects the whole LN₂ distribution to the 80 K thermal shield hydraulically but at the same time it provides electrical isolation between sub-systems up to the desired voltage level (~ 1 kV). High voltage is expected during any transient operation in SST-1 e.g. eddy current flow during the magnet quench, plasma disruption; ramp-up / down of PF coils etc. As a part of quality control and acceptance criteria, these insulation breaks has been undergone the performance tests at IPR to meet our design criteria and operation needs. In SST-1 Tokamak, the thermal shield ‘[2]’ will be maintained at 80 K with Helium leak tightness of $< 1.0 \times 10^{-8}$ mbar-l/s at service conditions in order to reduce the heat load on superconducting magnet system at 4.5 K.
2. Design considerations and requirements
The major considerations are the helium leak tightness < 1.0 x 10^-8 mbar l/s at cryogenic temperature. In the ‘Table 1’, description of the different types of cryogenic systems and component’s technical requirements, acceptance criteria at our site will be discussed in this section.

| Cryogenic components | Technical specification |
|----------------------|-------------------------|
| Helium and Nitrogen Electrical Insulation Breaks | Compatibility with temperature at 4.5 K and 77 K | Working condition (inside): 4 bar SHe flow at 4.5 K and 2.5 bar LN2 flow at 77 K, Compatibility with vacuum (outside): 10^-5 mbar |
| | Helium leak rate better than 10^-8 mbar l/s @ 4.5 K and 77 K with Super-critical helium flow, LN2 flow with to vacuum respectively. | Acceptable Helium leak tightness after minimum 5 thermal shocks using LN2: < 1.0 x 10^-8 mbar-l/s |
| | Electrical Isolation: ~ 2 kV in Helium breaks and ~ 1 kV (maximum) due to eddy current in LN2 breaks |

| Cryogenic components | Technical specification |
|----------------------|-------------------------|
| LN2 thermal shield | Type of the shield and material: Bubble type, SS304L |
| | Working temperature range: 80 K – 300 K |
| | Cooling loop: Inlet/supply at bottom and outlet/return at top. |
| | Allowable temp on the shield: ≤ 85K (max.) |
| | Allowable He leak rate: < 10^-8 mbar-l/s at service conditions. |

| Cryogenic components | Technical specification |
|----------------------|-------------------------|
| Flexible hose | Material and structure: S S 316 L, Corrugated Stainless steel structure with a stainless steel braided hose cover of SS 304 wires |
| | Dimension as per DN standard: ø 25.5 ID/35 mm OD, length 500-600 mm with both end welded ASME B1.3 Section IX of 1” NB Sch 40 S pipe |
| | Working Operating Pressure Environment: (a) Internal pressure Maximum 12 bar at 300 K and 4 bar at 4.5 K inside hose (b) External vacuum of order of 10^-5 mbar over hose |
| | Working Temperature range: 4.5 K – 300 K, Flow medium: Helium gas/Liquid |
| | Acceptable Helium leak rate: ≤ 1x 10^-9 mbar- l/s at 300 K and after five thermal cycles from 300 to 77 K and reverse |
| | Bending radius/requirement (Minimum): ~ 0-250 mm (In static & dynamic conditions) |

| Cryogenic components | Technical specification |
|----------------------|-------------------------|
| Dummy Heat Exchanger Assembly | Material: Copper, tube dimensions: ø 11 mm, 1 mm thick, Length: ~ 80 m |
| | LN2 fluid inflow condition in the Cu tube and Helium leak rate of heat exchanger at 77 K: <1 x 10^-8 mbar l/s |

3. Thermal shock test at 77 K
As acceptance criterion, we have carried out the thermal cycles of the components from 300 K – 77 K - 300 K for 5 cycles considering the European standard ANSI/EIA-364-32C-200. The thermal cycles tests have been performed in two ways:

- Inflow of LN2 fluid in the components, as shown in Fig. 1(a).
- Dipping the LN2 fluid into the components chamber, keep submerged in liquid until boiling has subsided to its original rate (approx. minimum 30 minutes) till components is returned to thermal stability at standard ambient conditions and then repeat this cycle up to 5 times as shown in Fig. 1(b).

The liquid nitrogen for the test has been used from the LN2 tanks of 35-m³ storage capacity at
2.75 bar (g) maximum operating pressure. We have introduced a metal cryogenic flexible hose with high-pressure vacuum sealing Viton ‘O’ ring assembly for thermal cycle test connection assembly. In past, we have faced cracking and leaking problem of PVC hose during the thermal shock test and it is vital considering the safety aspect of cryogen hazards.

4. Helium leak testing of cryogenic components at 300, 77 and 4.2 K and test results
To ensure the complete leak tightness at cryogenic temperature, leak testing of different cryogenic components are carried out at following three stages:
- Helium leak testing at 300 K of individual insulation breaks, helium flexible hoses, LN$_2$ panels and dummy heat exchanger assembly to assure elimination of any leak components before it is welded to the respective assembly.
- Helium leak testing of components along with weld joints.
- Leak test of whole assembly at 77 K inflow condition and after passing this temperature, test is to be performed at 4.2 K as per operational needs.

4.1 Electrical Insulation Breaks helium leak test at 4.5 K
The insulation breaks isolator assembly integrated with superconducting toroidal field coil accommodated as shown in Fig. 2. Helium leak observation monitored with the vacuum gauge reading deterioration at different temperature level from 300 K to 4.5 K and RGA instrument was used to detect the helium atomic mass with varying partial pressure of helium with respect to time. The test results are:
- Vacuum level in test chamber at 5.0 K (magnet average temp): $1.7 \times 10^{-6}$ m bar
- Gross helium leak rate from RGA helium acceptable partial pressure: $1.7 \times 10^{-7}$ m bar l/s
4.2 LN2 panel helium leak test at 77 K
Helium leak testing of different panels integrated assembly has been performed in the test chamber as shown in ‘figure 3’ at 77 K, by pressuring the total hydraulic assembly with the helium gas @0-8 bar, 300 K. The vacuum level and RGA partial pressure readings continuous monitored. If any deterioration in the vacuum and RGA pressure readings beyond the acceptable limit tend to helium leak at 77 K, that assembly after warm upto 300 K and then check the helium leak rate to locate and identify the sections of leak.

4.3 Cryogenic flexible helium hose leak test at 77 K and 4.5 K
The helium leak test was also carried out inflow condition of LN2, hose welded with supply pipe and test chamber as shown in ‘figure 4’. When the temp maintained 77 K then pressurizes the loop with helium gas and any leak can be monitored on helium leak detector online that is mounted on the test chamber, the test result shown below:
- Helium leak rate observed on flexible hose at 300 K: 5.0 x 10^-9 mbar l/s
- Helium leak rate after thermal shock observed: 3.0 x 10^-9 mbar l/s
- Helium leak rate LN2 inflow condition: 1.2 x 10^-9 mbar l/s

The helium leak tightness, minimum bend radius test as per BS 6501: Part 1:1991 standard of hose assembly in static condition at @4 bar, 4.5 K is to planned to ensure the flexibly criteria for uses, the test set up assembly is shown in ‘figure 5’.

4.4 Dummy heat exchanger helium leak test at 77 K
Helium leak testing at 77 K has been done inflow condition of LN2 (approx. 100 liter LN2 consumed) as shown in ‘figure 6’. The test results and parameters are listed below:
- Helium leak rate observed at all brazing joints, over tube surface: <1 x 10^-8 mbar l/s
- Pressurized by Nitrogen gas through pressure device: 1-10 psi

5. Problem encountered and solutions techniques:
We have faced problems in the different components described above during thermal shock; leak test at cryogenic temperature, experience of cold leak, investigation and solutions will be discussed in this section.

5.1 Observation of cold leak in helium insulation breaks
When one finds the leaks at cold temperature, it is essential that the test set up assembly warmed up to 300 K and carried out the helium leak test in vacuum mode to localize and confirm the leak. Usually the high-pressure helium gas based sniffer method is adopted ‘[1]’. The HLT 560 helium leak detector was used in sniffer mode, and soap bubble was observed at one end of the interface of G-10/SS of insulation breaks as shown in ‘figure 7 and figure 8’.

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Fig. 4. Schematic of helium leak test of cryogenic flexible assembly hose at 77 K
Fig. 5. Helium leak test at 4.5 K

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Fig. 6. Dummy Heat Exchanger Helium Leak Test at 77 K

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Fig. 7. Observation of cold leak in helium insulation breaks
Fig. 8. Sniffer Method for Cold Leak Detection
5.2 Failure of cryogenic flexible hose at cryogenic temperature

We observed the helium leak in 3 numbers of cryogenic flexible hoses in after thermal cycles test at 77 K, the helium leak rate at 300 K detected of order of \((2 \times 10^{-6} \text{ to } 1 \times 10^{-7}) \text{ mbar l/s}\) at one end of flexible hose, Helium leak rate was detected \(7 \times 10^{-5} \text{ mbar l/s}\) at 300 K the interface weld joint as shown in black circle marked as shown in the ‘figure 9’.

In other cryogenic flexible hose of helium leak rate \(9.0 \times 10^{-3} \text{ mbar l/s}\), the helium leak detector was tripping due to over range of its sensitivity and pressure range < \(10^{-3} \text{ mbar}\) in leak detector after spraying the helium on suspected weld joint area. In order to locate the leak, masking technique was developed i.e. covered with sealed polythene bag and rest area is sealed by adhesive tape. The initial helium background was \(3.0 \times 10^{-5} \text{ mbar l/s}\); changed to \(5.2 \times 10^{-5} \text{ mbar l/s}\) after the suspected marked weld area covered with PU bag with adhesive tape. Removing the adhesive tape at one location helium background was increased to \(2.5 \times 10^{-5} \text{ mbar l/s}\) indication of leak in that particular location as shown in ‘figure 9’. We have repeated this on all location by masking and unmasking of the entire weld to find and locate the leak. Thus the leak was located and cryogenic flexible hoses were sent for re-welding or replacement.

5.3 Problems during thermal cycles test of LN\(_2\) panels

In order to save the LN\(_2\) fluid consumption, we have performed the test 1-4 numbers of in batch. During the test of LN\(_2\) shield top port panel section type, which consists of 2 panels, both panels were not able to cooled to LN\(_2\) temp during helium leak at 77 K experiment, the same set up of panels had not also cooled in thermal cycle test. After that we cut the U pipe inter connection of both panel, single panel has been cooled entirely as shown in ‘figure 10’. We analyses that possible factors/reasons could be for this phenomenon are listed in the following paragraph:
(i) More pressure, velocity and flow requirement of LN$_2$ fluid through panels due to its not straight and plane geometry construction as hydro-forming bubble type or some portion may be blocked during fabrication (ii) high heat flux rate requirement (iii) thermal resistance between LN$_2$ fluid and SS panel surface (iv) parallel cooling hydraulic is recommended for application

5.4 Problems and solution during helium leak test at 300 K with silicon flexible tube
For helium leak testing at 300 K, silicon tube was used in past, during test we experiences that due to flexibility, a small components can not be stand in vertical position as in case of Electrical breaks, application of sealing material as vacuum grade tacky tape at the interfaces of tube to component, holding the electrical breaks by hand during spraying helium for test, replacement of tacky tape after number of times of its uses. As large quantities of cryogenic components had to test, vacuum grade especially grade high-strength silicone rubber bush sealing was designed and used for the leak test, all problems specified above were eliminated. The helium background was also improved from $1.0 \times 10^{-8}$ mbar l/s to $10^{-9}$ to $10^{-10}$ mbar l/s range and much time reduction of leak test. The photographs of silicon tube and silicon bush arrangement for helium leak test are shown in Fig. 11 and Fig. 12.

6. Conclusion
For the quality control, performance validation and to ensure the helium leak tightness at cryogenic temperature, SST-1 cryogenic components viz. LN$_2$ panels, Electrical Breaks, Cryogenic flexible hoses were subjected to thermal cycles test at 77 K in actual operating scenario prior to the integrated assembly in the SST-1 machine. We have in-house developed the test facility and successfully carried out the testing of large numbers as 184 numbers of LN$_2$ panels, 400 numbers of electrical Insulation breaks of helium and nitrogen service, 50 numbers of cryogenic flexible hoses. Cold leaks which were developed at cryogenic temperature and after thermal cycle at 77 K, a masking/unmasking and thermal cycle-pressure helium test techniques were developed to locate the leaks and make cold leaks accessible to 300 K temperature environment. The cryogenic flexible leakage at the weld interface joint, we analyses that due to low temperature, inner bellow pipe contracts and exert force on the outer pipe since end pipe, inner pipe and braded wire are welded together. The electrical breaks, LN$_2$ panels have been installed, tested and integrity with the SST-1 machine found satisfactory and acceptable.

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