Design of ITER Relief Lines

N. Shah1, K. Choukekar1, M. Jadon1, B. Sarkar1, B. Joshi2, H. Kanzaria2, V. Gehani2, H. Vyas2, U. Pandya2, R. Panjwani2, S. Badgujar2, E. Monneret3

1ITER-India, Institute for Plasma Research, Bhat, Gandhinagar - 382428, India
2Inox India Private Limited, Vadodara, India
3ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St. Paul Lez Durance Cedex, France

E-mail: nitin.shah@iter-india.org

Abstract. The ITER Cryogenic system is one of the most complex cryogenic systems in the world. It includes roughly 5 km of cryogenic transfer line (cryolines) having large number of layout singularities in terms of bends at odd angles and branches. The relief lines are particularly important cryolines as they collect the helium from outlet of all process safety valves of the cryogenic clients and transfers it back to cryoplant. The total length of ITER relief lines is around 1.6 km with process pipe size varying from DN 50 to DN 200. While some part of relief lines carries warm helium for the recovery system, most part of the relief line is vacuum jacketed cryoline which carries cold helium from the clients. The final detailed design of relief lines has been completed. The paper describes the major input data and constraints for design of relief lines, design steps, flexibility and structural analysis approach and major design outcome.

1. Introduction
The recovery of helium gas coming out of safety release system is one of the most essential requirements in large cryogenic systems due to high cost and scarcity of helium gas in the market. The ITER cryogenic system, being one of the largest helium cryogenic system in the world [1], has been designed with due consideration for recovery of helium gas released by cryogenic process safety devices. However, like in any complex system, there are inherent constraints on amount of helium gas that can be recovered due to space limitations and finite capability of recovery gas management system.

The cryogenic architecture of ITER consists of superconducting magnets, cryopumps and tokamak thermal shield as major cryogenic users. The supply and distribution of cryogens to these users is managed by cryoplants and cryo-distribution system including complex network of cryolines amounting to ~ 5 km and warmlines ~ 6 km. The ITER relief lines recover cold helium gas from cryogenic users inside tokamak building as well as cryoplant building and direct it to helium recovery system after heating of helium gas to room temperature in the heater as shown in Figure 1. Relief line inside tokamak building is vacuum jacketed to avoid condensation on outside when cold helium flows inside it. However, once a relief line comes outside tokamak building, it is bare all the way till heater to minimize heater power requirement. Another set of relief lines is routed from cold users inside cryoplant building up to the common heater as shown in Figure 1. The relief line after the heater is
bare as it carried room temperature helium gas. This relief line also collects helium gas from other warm (room temperature) helium users and finally connects to gas bag. Last part of the bare relief line connects the gas bag to recovery compressor.

He: Helium, LHe: Liquid Helium, CTCB: Cryoplant Termination Cold Box, PB: Plant Bridge, SIC: Safety Important Component, SW: South West, NW: North West, CTB: Cold Termination Box, CVB: Cold Valve Box, ACB: Auxillary Cold Box, TS: Thermal Shield, NB: Neutral Beam

**Figure 1.** Simplified process flow diagram of ITER relief lines

2. **Design input**

The functional specifications for relief lines have been summarised in Table 1.

| From                  | To                         | Pressure drop limit mbar |
|-----------------------|-----------------------------|--------------------------|
| Tokamak level B2      | Tokamak-PB penetration      | 175                      |
| Tokamak level B1      | Tokamak-PB penetration      | 175                      |
| Tokamak level L3 north| Tokamak-PB penetration      | 175                      |
| Tokamak-PB penetration| Heater                      | 50                       |
| Cryoplant cold users  | Heater                      | 50                       |
| Heater                | Gas Bag                     | 5                        |
| Gas Bag               | Recovery compressor         | 5                        |

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| Tokamak level L3 north| Tokamak-PB penetration      | 175                      |
| Tokamak-PB penetration| Heater                      | 50                       |
| Cryoplant cold users  | Heater                      | 50                       |
| Heater                | Gas Bag                     | 5                        |
| Gas Bag               | Recovery compressor         | 5                        |
The input process parameters as mentioned in Table 1 for design of relief lines are based on helium release due to static heat in-leak in ITER cryogenic users. Relief lines, therefore, are not sized for helium release due to accidental cases like Loss of Insulation Vacuum (LIV) of cryogenic users. General technical specifications are mentioned in Table 2. The 3D layout of relief lines inside tokamak building (11), cryoplant building (52) as well as cryoplant area (53) is shown in Figure 2.

| S. N. | System (Cryoline)            | Length (meter) | Max. size of OVJ | Safety class | PED Category | Quality class (QC) | Seismic class (SC) | Line type          |
|-------|-------------------------------|----------------|------------------|--------------|--------------|-------------------|-------------------|--------------------|
| 1     | Relief lines inside tokamak building | 938            | 300              | SR           | I            | QC1               | SC1 (SF)          | Vacuum jacketed    |
| 2     | Relief lines on plant bridge  | 133            | 200              | Non SIC      | I            | QC2               | SC2               | Bare               |
| 3     | Cold Relief lines inside cryoplant building | 207            | 200              | Non SIC      | SEP          | QC2               | NSC               | Vacuum jacketed    |
| 4     | Warm Relief lines inside cryoplant building | 557            | 200              | Non SIC      | I            | QC2               | NSC               | Bare               |

OVJ: Outer Vacuum Jacket, PED: Pressure Equipment Directive, SE: Sound Engineering Practise, (SF): Structurally and functionally safe

Figure 2. 3D layout of ITER relief lines

3. Design approach
For any engineering design, the reliability and ruggedness of design is directly proportional to the level of standardization involved. In the absence of single code/standard for design of cryolines, use of multiple standards and commercially proven software tools with seamless integration have been used to improve the reliability of the design. Moreover, the valuable experience gained in design, manufacturing, installation, and testing of Prototype Cryoline and its components [2] [3] has been utilised in comparatively simpler design of relief lines.
Cryogenic grade stainless steel 1.4306 has been selected as a material for Process pipe (PP), internal fixed supports as well as vacuum barriers and 1.4306/1.4307 for Outer Vacuum Jacket (OVJ). Glass Fibre Re-enforced Plastic (GFRP) G10 CR has been selected for internal sliding supports. The major design steps for relief lines are shown in Figure 3. The text in square bracket shows the major code/standard used as a reference while the text in circular bracket shows software tools used.

(a) PP sizing has been done to respect allowable pressure drop limits as defined Table 1. The flow velocity has been ensured below 10% of sonic velocity to avoid flow induced vibrations.

(b) OVJ sizing has been done considering process pipe sizes, provision of sufficient annular space for Multi-Layer Insulation (MLI), thermal compensators (bellows, hoses), vacuum conductance, limit for maximum diameter as per Configuration Model, manufacturing feasibility and standard pipe size as per ISO 1127.

(c) The major input for flexibility analysis includes various load cases like nominal operation, test pressure, purging, seismic events of different magnitude and probability, accidental cases like loss of insulation vacuum, accidental pressurization of ambient space inside tokamak building, transport and handling accelerations, environmental loads like snow and wind for lines open to atmosphere etc.

(d) Location of supports has been optimized to avoid resonance due to superimposition of natural frequency to seismic event frequency.

(e) Forces and moments obtained from flexibility analysis as well as dimensional constraints as per PP and OVJ sizes have been used as an input for design of fixed and sliding supports. The
3D modelling of supports has been done in CATIA V5 software. Forces from external supports on embedded plates (EPs) [4] are controlled to respect the load bearing capacities of EPs.

4. Flexibility analysis
Adequate structural flexibility is an essential requirement for any piping system to withstand various types of loads, and relief lines are no exceptions. The flexibility analysis therefore is an important design step to not only validate the piping design but also to optimize the supports locations and support design. Two types of flexibility analysis have been performed as follows.

(a) PP flexibility analysis in CAESAR II– for PP of vacuum jacketed relief lines and bare relief lines
(b) OVJ flexibility analysis in ANSYS – for OVJ of vacuum jacketed relief lines

The inherent flexibility associated with routing of relief lines has been found insufficient to take care of various loads. Therefore, thermal compensators such as bellows and hoses have been used to enhance the flexibility to the level sufficient to withstand the stresses induced due to the applied loads. While use of axial bellows was restricted for axial compensation, hoses have been used at bends to take care of lateral movements. Example of input file in CAESAR II software created for flexibility analysis of typical segment of relief lines with associated supports and thermal compensators is shown in Figure 4.

\[\text{Figure 4. Input model for flexibility analysis of typical segment in CAESAR II software}\]

5. Thermo-mechanical analysis of internal supports
The forces and moments obtained from flexibility analysis of PP were applied on internal fixed supports and sliding supports to estimate the stresses. Considering the complex geometry and number of forces and moments due to various load cases, the ANSYS software was used for analysis. Since large numbers of internal fixed and sliding supports are present, only critical supports, having maximum resultant forces and moments per type and per size are analysed. The maximum Von Mises stress in the typical fixed support during nominal and pressure test case has been found to be 75.5 MPa (acceptance limit 166.7 MPa) and 156.9 MPa (acceptance limit 237.5 MPa) respectively as shown in Figure 5. Similarly, the maximum principal stress in the typical sliding supports during nominal and pressure test case has been found to be 34.2 MPa and 60.8 MPa respectively as shown in Figure 6. The internal supports of vacuum jacketed relief lines are also designed to avoid condensation on OVJ when cold helium passes through PP of relief line as well as to minimize back pressure during opening of OVJ safety relief device. The thermal analysis of internal supports has been performed in ANSYS to check for condensation on OVJ. The geometry and dimensions of long conduction path of internal
fixed support and slots of sliding supports have been optimized to ensure no condensation on OVJ when PP carries cold helium.

The external supports have been designed in ANSYS. The major constraints were space restrictions, specifically inside tokamak building due to presence of nearby systems, pre-defined locations of EPs, minimum permissible temperature of -40 C at EP in LIV case and load bearing capacities of EPs. Typical examples of external supports are shown in Figure 7.
6. Vacuum conductance calculation
The vacuum jacketed relief line inside tokamak building is connected to Cryogenic Guard Vacuum System (CGVS) at six locations for evacuation of OVJ. The limited pumping capacity (max. 400 lps of Turbo-molecular pump) of CGVS demands for good vacuum conductance inside OVJ for each of the vacuum space. The major restriction in annular space between PP and OVJ is that of internal supports. The sizes and locations of holes in internal fixed supports and slots in internal sliding supports (refer Figure 6) have been optimized to ensure evacuation of OVJ to $10^{-3}$ mbar within 100 hours. The two additional vacuum barriers have been introduced inside the line to divide the vacuum space and optimize the vacuum conductance.

7. Temperature rise in cold bare relief line
The relief line from tokamak exit to heater in cryoplant area has been routed via Plant Bridge. The purpose of heater is to bring the temperature of cold helium to ambient level before sending it to helium recovery system. In order to minimize heater power consumption, it is necessary to maximize the heat transfer from ambient to cold helium so that helium temperature just before heater is as close as possible to environment temperature. This has been achieved by removing OVJ and keeping bare pipe only from tokamak exit till heater. The thermodynamic model used to calculate heat transfer and estimate the rise in helium temperature in this cold bare relief line has been shown in Figure 8. For heat transfer with ambient, it has been assumed that till temperature reaches 90 K (boiling point of oxygen), there will be oxygen condensation on outside surface of bare relief line. After this point, heat transfer with ambient takes place by virtue of free/natural convection. For the environmental temperature of 313 K, the minimum and maximum temperature of helium at heater entry has been thus found as 119 K (for helium flow rate of 1.5 kg/s and temperature 10 K at Tokamak exit) and 307.5 K (for helium flow rate of 0.06 kg/s and temperature 110 K at Tokamak exit) respectively.

![Figure 8. Thermodynamic model basis to estimate temperature rise in bare cold relief line](image)

8. Major outcome of design
The outcome of detailed design of ITER relief lines has been summarised below
(a) Vacuum jacketed relief lines include 81 number of internal fixed supports, 283 number of internal sliding supports, 61 number of vacuum barriers, 65 number of internal bellows with maximum size of individual bellow DN 150 and maximum length of individual bellow 296 mm, 99 number of internal hoses with maximum size of individual hose DN 150 and maximum length of individual hose 950 mm, 76 number of OVJ bellows with maximum size of individual OVJ bellow DN 250 and maximum length of individual OVJ bellow 550 mm
(b) Bare relief lines include 24 number of fixed supports, 139 number of sliding supports, 30 number of bellows with maximum size of individual bellow DN 200 and maximum length of individual bellow 550 mm, 15 number of hoses with maximum size of individual hose DN 150 and maximum length of individual hose 950 mm
The maximum stress values in different critical components of relief lines for different load cases have been summarised in Table 3 below
Table 3. Maximum stresses in critical components

|                  | Nominal Operation (NO) | Pressure Test | Seismic: SL2+NO | Transport |
|------------------|------------------------|---------------|-----------------|-----------|
| PP               | 116 (143)              | 112 (204)     | 119 (143)       | 37 (143)  |
| OVJ              | 87 (143)               | 122 (204)     | 127 (143)       | 47 (143)  |
| Internal Fixed Support | 98.4(166.7)          | 157 (237.5)   | 101.5(166.7)    | 41.5(166.7) |
| Vacuum Barrier   | 131.3(166.7)           | 150.2(237.5)  | 132.5(166.7)    | 31.36(166.7) |
| Internal Sliding Support | +56.4(83)/           | +60.8 (125)/  | +57.6 (83)/     | +53.4(83)/ |
| Support          | -90.2(-133)            | -115.7 (-200) | -89.7(-133)     | -49.3(-133) |

9. Conclusion
The detailed design of ITER relief lines has been completed. The sizing of lines has been done to comply with functional requirements and defined pressure drop constraints for different scenarios. The locations of thermal compensators and supports have been optimized to respect the load cases. The structural design has been optimized to ensure that the stresses in the line as well as supports are within allowable limits defined by the design codes. Manufacturing, transport, site constraints and installation aspects have been taken into account to arrive at efficient and workable design. Relief lines are now ready to enter manufacturing phase.

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11. Disclaimer
The views and the opinion expressed herein do not necessarily express those of the ITER organization and the ITER partners.

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