Loads specification and embedded plate definition for the ITER cryoline system

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Abstract. ITER cryolines (CLs) are complex network of vacuum-insulated multi and single process pipe lines, distributed in three different areas at ITER site. The CLs will support different operating loads during the machine life-time; either considered as nominal, occasional or exceptional. The major loads, which form the design basis are inertial, pressure, temperature, assembly, magnetic, snow, wind, enforced relative displacement and are put together in loads specification. Based on the defined load combinations, conceptual estimation of reaction loads have been carried out for the lines located inside the Tokamak building. Adequate numbers of embedded plates (EPs) per line have been defined and integrated in the building design. The finalization of building EPs to support the lines, before the detailed design, is one of the major design challenges as the usual logic of the design may alter. At the ITER project level, it was important to finalize EPs to allow adequate design and timely availability of the Tokamak building. The paper describes the single loads, load combinations considered in load specification and the approach for conceptual load estimation and selection of EPs for Toroidal Field (TF) Cryoline as an example by converting the load combinations in two main load categories; pressure and seismic.

1. Introduction

The ITER CL system is part of overall ITER cryogenic system [1] involving the cryoplant (liquid helium refrigerators and liquid nitrogen system) and the cryodistribution. The CL system [2] consists of 21 multi (two to seven) and 16 single process pipe transfer lines with a total length of about 5 km and 1000 mm outer jacket diameter for the biggest cryoline. It forms a structured network localized inside the Tokamak building, on a dedicated plant bridge, inside the cryoplant building as well as in the cryoplant infrastructure area. Within the Tokamak building the lines are present in six different levels: L3, L2, L1, B1, B2M and B2 level. The lines are routed from the level L3 to level B2 through two dedicated shafts. Figure 1 shows the three-dimensional (3D) schematic layout of the CL system. The conceptual design phase of the CLs has been completed and the detailed design, fabrication and installation will be performed by contractors appointed by Indian Domestic Agency (IN DA), responsible for in-kind supply of the CL system to the ITER project.

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The CLs will be designed for continuous and uninterrupted operation during the entire machine life, which demands very high availability and reliability. This is ensured via stringent design, fabrication, installation, inspection and quality controls requirements. The design of the lines will be such that no mechanical failure or permanent deformations occur during the operational, accidental and incidental scenarios.

2. Loads specification for the ITER CLs
The loads specification comprises reasonably foreseeable main load cases, which are likely to occur during the 20 years life-time of the ITER machine and that will be taken into account to perform the design. It also classifies the loads into four categories and their combinations, based on the expectation of occurrence,

- Category I: Operational Loading Conditions (occurs every day during 20 years)
- Category II: Likely Loading Conditions (occurs ~once/twice in 20 years)
- Category III: Unlikely Loading Conditions (occurs ~once/twice in 1000 years)
- Category IV: Extremely Unlikely Loading Conditions (occurs ~once in 10000 years)

2.1. Single loads
The major loads, which form the design basis, are presented in table 1 together with the origin. These are the single loads acting individually on lines or on the spools of the line. The loads path is a function of the location of the lines at ITER site. For the case of the cryolines, the loads are transferred from the process pipes assembly via the internal supports to the outer vacuum jacket and then transferred to the Tokamak building via the external supports of the lines.

2.2. Load combinations
The load combinations have been categorized according to set of rules to establish event combinations. Load combination category and the relevant acceptable damage limit have been defined as a function of the component safety class. The load combination for majority of CLs inside the Tokamak building is described in table 2. It represents an acceptable damage limit and corresponding structural service criteria as per the selected design codes and standards.
Table 1. Types of loads applicable to all the ITER CLs.

| Type of load                        | Originated by                                                                 | Single loads | Category |
|-------------------------------------|-------------------------------------------------------------------------------|--------------|----------|
| Inertial                            | Gravity acceleration                                                         | G            | I        |
|                                     | Transport acceleration                                                        | TA           | II       |
| Seismic actions                     | (Seismic level 1 - SL1, Séismes Maximaux Historiquement Vraisemblables= Maximum Historically Probable Earthquakes -SMHV, Seismic level 2-SL2) | SL1, SL2     | II, IV   |
| Interface equipment vibrations      |                                                                               | IEV          | I        |
| Flow-induced vibrations             |                                                                               | FIV          | I        |
| Wind actions in the structural bridge which is used as a support of the lines |                                                                               | WN           | I        |
| Snow load                           | Snow accumulation on the lines                                               | SN           | I        |
| Relative support displacements      | Static deformations of the structural bridge which is used to support the lines | DST          | I        |
| Pressure                            | Dynamic fluid pressure during nominal operation                             | NP           | I        |
|                                     | Static fluid pressure during tests                                           | TP           | II       |
|                                     | Internal pressurisation of the vacuum jacket and process pipes due to an accidental loss of insulation vacuum 1 (LIV1) – Air ingress in vacuum jacket | LIV1         | III      |
|                                     | Internal pressurisation of the vacuum jacket and process pipes due to an accidental loss of insulation vacuum 2 (LIV2) – Rupture of internal process pipe in CL | LIV2         | III      |
|                                     | External pressurization of the lines due to an incidental pressurization of the Tokamak confinement (ICP) – Galleries | ICP          | III      |
|                                     | External pressurization of the lines due to an accidental pressurization of the Tokamak confinement (ACP1) – Port cells (B1) | ACP1         | IV       |
|                                     | External pressurization of the lines due to an accidental pressurization of the Tokamak confinement (ACP2) – Lower pipe chase (B2M) and port cell shafts | ACP2         | III      |
|                                     | Purge and evacuation (process pipes under vacuum during installation)         | PG           | II       |
| Thermal                             | Fluid temperature during nominal operation                                   | NT           | I        |
|                                     | Fluid temperature during cold test                                           | TT           | II       |
| Assembly                            | Pre-compression of bellows (as applicable)                                   | AL           | I        |
|                                     | Lifting loads                                                                 |               |          |
| Magnetic                            | Magnetic field in the Tokamak building                                        | ML           | I        |

NOTE: WN, SN and DST are not applicable for the lines inside the Tokamak building

3. Embedded plates (EPs) definition

The design of the ITER Tokamak building has been done taking into account the loads from systems supported by the building. The building will be equipped with EPs (cast-in-place fastening system with anchors passing through the rebar of concrete), which will be used for fixation of the external supports and/or structures. The fixation of the external supports to the EPs will be done by welding.

The finalization of the building EPs to support the lines, before the start of detailed design, is one of the major design constraints as the usual logic of the design may alter and has made the execution of ITER CL project technically more challenging. Generally, the flexibility analysis of the inner pipe defines the location of the thermal compensation devices (bellows/flexible hoses/compensators). The position of the compensation devices imposes the location of the internal fixed points and the external supports shall be placed at the same location of the fixed point to transfer the generated internal loads.
Table 2. Load combinations for majority of the CLs inside the Tokamak building.

| Load combinations | Category | Damage limits | Design criteria level |
|-------------------|----------|---------------|-----------------------|
|                   |          |               | ASME B31.3 | EN 13480 |
| G                 | I        | Normal        | Sustained | Normal |
| AL                | I        | Normal        | Sustained | Normal |
| TA                | I        | Normal        | Occasional | Occasional |
| TP + TT           | I        | Test          | Test      | Test    |
| PG                | II       | Upset         | Occasional | Cleaning |
| NP + NT=NO       | I        | Normal        | Sustained | Normal |
| NO + ML           | I        | Normal        | Sustained | Normal |
| NT + LIV1         | III      | Emergency     | Occasional | Exceptional |
| NT + LIV2         | III      | Emergency     | Occasional | Exceptional |
| NO + SL1          | II       | Upset         | Occasional | Occasional |
| NO+SMHV           | III      | Emergency     | See note   | See note |
| NO + SL2          | IV       | Faulted       | See note   | See note |
| NT + SMHV + LIV1  | III      | Emergency     | See note   | See note |
| NT + SMHV + LIV2  | III      | Emergency     | See note   | See note |
| NT + SL2 + LIV1   | IV       | Faulted       | See note   | See note |
| NT + SL2 + LIV2   | IV       | Faulted       | See note   | See note |
| NO + ICP          | III      | Emergency     | See note   | See note |
| NO + SMHV + ICP   | III      | Emergency     | See note   | See note |
| NO + SL2 + ICP    | IV       | Faulted       | See note   | See note |
| NO + ACP1         | IV       | Faulted       | See note   | See note |
| NO + ACP2         | IV       | Faulted       | See note   | See note |

**NOTE:** Whenever the selected design code does not provide any indication, the specific allowable stresses for emergency and faulted damage limits are specified by ITER

Based on load combinations in table 2, conceptual estimations for the reaction loads from the CLs located inside the Tokamak building has been carried out. The estimation has been done with the current layout, the conceptual dimensions and the thermo-hydraulic parameters of each line, to identify the most demanding loads, which size the fixation points. Based on the load combinations specified for the lines and an assumed supports span, the quantity of required EPs per line have been defined taking into account the maximum loading capacity of the EPs. The EPs have been foreseen on the ceiling, wall or on the floor based on the routing of the line. Adequate numbers and sizes of EPs for each line have been defined (as a function of applied loads), integrated in the building design to avoid any significant issue during the detailed design of the lines and will serve as mandatory input to perform the final design of the CLs. Table 3 summarizes the number of EPs foreseen for the lines per level of the Tokamak building. The EPs are foreseen at the locations of change of direction (before and after Tee, Elbow, Step and Change of angle).

Table 3. Number of EPs foreseen for the cryo and warm lines in Tokamak building.

| Level in Tokamak building | No. of EPs | EP sizes |
|---------------------------|------------|----------|
|                           | Ceiling    | Wall     | Floor | [P300 = Dimension 300 mm x 300 mm] |
| B2                        | 383        | 46       | --    | P300, P500, P700 |
| B2M                       | 41         | --       | --    | P700b[b=small anchor length/non-standard] |
| B1                        | 82         | --       | --    | P500, P500b |
| L1                        | --         | 69       | --    | P300, P400, P400b, P500, P600 |
| L2                        | --         | 69       | --    | P300, P300b, P400b, P500, P600 |
| L3                        | 100        | 288      | 192   | P300, P400b, P500, P500b, P600, P600b, P700 |
During the detailed design phases, the actual reaction loads applied on the EPs will be defined by the contractor and shall be within the limits of the allowable load bearing capacity of the EP. If the design requires the change in the capacity of the EP, the design of the supports will be optimized to distribute the load between adjacent EPs.

Figure 2 shows the layout and conceptual cross-section of the TF CL which supplies the helium from TF Auxiliary Cold Boxes (TF ACB) to the TF magnet coil termination box (TF CTB). The line has 5 internal process pipes (PP) assembled inside the thermal shield (TS) and outer vacuum jacket (OVJ). There are two separate lines; one connected to 5 CTBs (named as CL 34.2C.TN) and the other to 4 CTBs (named as CL 34.2C.TS). The process parameters during nominal operation and conceptual dimensions of the TF CL are summarized in table 4.

![Figure 2. (a) Layout of TF CL with associated EPs (b) Conceptual cross-section.](image)

| Process pipe description               | Normal operation parameters | Pipe Size | Effective area of expansion joint [mm²] |
|----------------------------------------|-----------------------------|-----------|---------------------------------------|
|                                        | Pressure [MPa (a)] | Temperature [K] | Flow rate [kg/s] | DN |                                |
| CC: 4.3 K supply                       | 0.6                        | 4.3       | 1.225                                | 100 | 13560                          |
| CD: 4.7 K return                       | 0.48                       | 5.0       | 1.225                                | 100 | 13560                          |
| H: 50 K for current leads              | 0.4                        | 50.0      | 0.05                                 | 50  | 4520                           |
| E: 80 K supply                         | 1.75                       | 80.0      | 0.085                                | 80  | 8810                           |
| F: 100 K return                        | 1.65                       | 100.0     | 0.085                                | 80  | 8810                           |
| WL : Outer jacket                      | Vacuum                     | 300.0     | N.A.                                 | 500 | 224400                         |

The types and geometry of supports are not fully defined at the conceptual stage; their design will be performed during detailed design by the contractors. For the load estimation, the supports have been considered as beams elements for positioning of the EPs in the building. The fixation point is
considered at every 2.5 m along the length of the TF CL. For the estimation of the reaction loads at the
building interface, two types of loads are considered: inertial (gravity, seismic only) and pressure
originated due to all the load cases summarized in table 1. The supports are assumed to be at the center
of the EP for load estimation without any eccentricity (which reduces the load bearing capacity of the
EP).

3.1. Forces induced by seismic actions
Forces induced by seismic actions have been calculated using the equivalent static analysis method.
This method includes the application of an equivalent static acceleration, from the floor response
spectrum, on the lines while the natural frequency is unknown. The force induced by seismic action, in
each direction, is calculated according to $Force_{seismic} = Mass \times Acceleration \times 1.5 \text{ Amplification factor}$
to take into account that the structure does not behave as a single degree-of-freedom. The mass is the
total mass of the CL taking into account the mass of the internal PPs, fluid, internal supports, thermal
shield, OVJ etc. and acceleration ($a_x$, $a_y$, $a_z$) is the static acceleration in X (Horizontal), Y (Horizontal)
and Z (Vertical) directions in respect of the global coordinate system inside the Tokamak building.

Static accelerations are taken from the various data points [3] available at different levels in the
Tokamak building. When a line runs through different levels (L3, L2, L1, B1, B2 etc.) the maximum
equivalent acceleration (first peak) for the applicable levels is considered. Accelerations for the
damping factor of 4% has been used as defined in the loads specification for the piping systems. For
the TF CL, the maximum static acceleration in X, Y and Z directions is $a_x=8.41 \text{ m/s}^2$, $a_y=8.41 \text{ m/s}^2$, $a_z=34.5 \text{ m/s}^2$ (Refer figure 3) and the mass is about 300 kg/m. The axial forces have been calculated
considering support span of 10 m (assumed span between two fixed supports) and the lateral loads are
calculated considering support every 2.5 m (distance between two sliding supports/EPs). This will
provide the flexibility in the detailed design to choose any of the foreseen support as fixed support.

![Figure 3. Floor response spectrum - Level B2/B2M (SL-2) used for the TF CL [3]](image)

3.2. Forces induced by pressure
Pressure thrust is normally carried as an axial load by the pipe. For the estimation of pressure loads, it
is assumed that the design of the CL will include bellow/expansion joints to cope with the thermal
contraction at cryogenic temperatures. The presence of bellow generates the pressure thrust force in
addition to the spring force caused by the displacement of bellows due to thermal contraction. The
pressure thrust force acts on the main pipe anchors (fixed supports). The pressure values used for the
calculation of the forces induced by pressure in TF CL are presented in table 5. For multi-process
pipes cryoline, the total axial force due to pressure (Pressure x Cross-section area of bellow [in table 4]
as worst load) on the extremity fixed support is obtained by vector addition of the pressure thrust force
for individual process pipe and outer vacuum jacket.
Table 5. Internal ($P_i$) and External ($P_o$) pressures for the TF CL components.

| Pressure case | $P_i$ (MPa) | $P_o$ (MPa) |
|--------------|-------------|-------------|
| PP           | 3.0         | 0.1         |
| PP           | 2.1         | 0.1         |
| LIV1         | 2.1         | 0.12        |
| LIV2         | 0.4-1.8     | 0.12        |
| NO           | 0.2         | 0.12        |
| PG           | 0.4-1.8     | 0          |
| ACP 1/2      | 0.4-1.8     | 0          |
| ICP          | 0.4-1.8     | 0          |

3.3. Result and load combinations

Table 6 summarizes the result of estimated loads to size the fixation points for TF CL. The moments are calculated based on the seismic force in x, y and z directions, pressure force in axial (x) direction, the support span and support length from CL to EP. For the calculation of moments, three EP configurations have been considered; (i) Fixation points on the top (EP on ceilings), (ii) Lateral fixation points (EP on walls) and (iii) Fixation points on the bottom (EP on floors). The loads obtained during individual load cases are combined as per load combinations defined in table 2. It has been observed that accidental load combination NT+SL2+LIV2+G is the most demanding among all cases.

Table 6. Loads for sizing of the TF CL fixation points (EP on ceilings).

| Single Load/Load combination | Fx [kN] | Fy [kN] | Fz [kN] | Mx [kN.m] | My [kN.m] | Mz [kN.m] |
|------------------------------|---------|---------|---------|-----------|-----------|-----------|
| G                            | 0       | 0       | 7       | 0         | 9         | 0         |
| Seismic                      |         |         |         |           |           |           |
| SL1                          | 12      | 3       | 13      | 2         | 19        | 15        |
| SMHV                         | 28      | 7       | 28      | 5         | 43        | 9         |
| SL2                          | 37      | 9       | 38      | 6         | 57        | 12        |
| Pressure Test                | 119     | 0       | 0       | 0         | 82        | 0         |
| LIV1                         | 99      | 0       | 0       | 0         | 68        | 0         |
| LIV2                         | 108     | 0       | 0       | 0         | 74        | 0         |
| NO                           | 23      | 0       | 0       | 0         | 16        | 0         |
| PG                           | 5       | 0       | 0       | 0         | 3         | 0         |
| ACP                          | 19      | 0       | 0       | 0         | 13        | 0         |
| ICP                          | 19      | 0       | 0       | 0         | 13        | 0         |
| NT+SL2+LIV2+G                | 145     | 9       | 45      | 6         | 140       | 12        |

This combination load is then used for the selection of the EP from the ITER EP catalogue [4] using the interaction diagram defined for each size of the EP (for nominal or accidental scenario). The forces and moments of the sizing case are converted (using force conversion) into three equivalent forces and moments; NEd (axial force), VEd (shear force) and MEd (bending moment) which defines the characteristics of the EP and are interconnected to each other. The number and the size of the EPs are function of these characteristics. Figure 4 shows 10 interaction diagrams for P700 EP [4]. Each interaction diagram defines maximum MEd for NEd=0, maximum NEd for MEd=0 while VEd is kept constant and the area under the curve is the resistance of plate for specific values of MEd and NEd for a given value of VEd. It can be seen from figure 4 (Point 1 well within the diagram) that; one P700 EP can safely resist the loads imposed by TF CL under NT+SL2+LIV2+G load case. For the same load, based on the interaction diagram of EP P500, we would need two P500 EPs instead of one P700.

All the cryolines at ITER are essentially different from each other; therefore their design, type and location of supports will be different. Efforts have been made to have similar layouts as much as possible and in the most of the cases, individual supports with dedicated EPs have been foreseen. At few locations, the supports have been grouped when individual supports are not feasible. At these
locations, the numbers of EPs have been increased to cope with expected higher loads. The presence of nearby EPs reduces the resistance of the EP. Figure 4 (Point 2) shows the effect of nearby EPs with center of next plate at 2.5m along length \( L \), 1.5m along height \( H \). Point 2 is very close to the characteristic \( V_{Ed} \) of the plate, which indicates the reduction in load bearing capacity of the EP.

**Figure 4.** Interaction diagram for standard EP P700 [4] selected to support TF CL.

### 4. Conclusion

The maximum reaction loads on the fixation points of ITER CLs have been estimated at conceptual stage, for each level of the Tokamak building. Adequate numbers (~1300) and sizes of EPs per line have been defined for cryolines as well as warm lines and integrated in the building design. To improve the flexibility in terms of location of external fixed supports, the seismic reaction loads at all the EPs have been estimated for larger support span than in the current design. The approach described will be sufficiently comfortable to allow design of the CLs and their external supports without major changes. The actual reaction loads on the EPs will be defined by the contractor based on technical solutions chosen for the detailed design of CLs and supported by detailed dynamic analysis.

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**Disclaimer**

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