# A computational procedure for the investigation of whipping effect on ITER High Energy Piping and its application to the ITER divertor primary heat transfer system

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The Tokamak Cooling Water System of nuclear facility has the function to remove heat from plasma facing components maintaining coolant temperatures, pressures and flow rates as required and, depending on thermal-hydraulic requirements, its systems are defined as High Energy Piping (HEP) because they contain fluids, such as water or steam, at a pressure greater than or equal to 2.0 MPa and/or at a temperature greater than or equal to 100°C, or even gas at pressure above the atmospheric one. The French standards contemplate the need to consider the whipping effect on HEP design. This effect happens when, after a double ended guillotine break, the reaction force could create a displacement of the piping which might affect adjacent components.

A research campaign has been performed, in cooperation by ITER Organization and University of Palermo, to outline the procedure to check whether whipping effect might occur and assess its potential damage effects so to allow their mitigation. This procedure is based on the guidelines issued by U.S. Nuclear Regulatory Commission. The proposed procedure has been applied to the analysis of the whipping effect of divertor primary heat transfer system HEP, using a theoretical-computational approach based on the finite element method.

Keywords: ITER reactor, HEP, TCWS, whipping effect, structural analysis.

## 1. Introduction

Within the framework of the Research and Development (R&D) activity intended to investigate the ITER potential safety issues on a reactor design basis, the ITER Organization (IO) and the Department of Energy, Information Engineering and Mathematical Models of the University of Palermo (DEIM) have launched a research campaign with the specific aim to investigate and assess the performances of ITER High Energy Piping (HEP), focusing the attention on the potential consequences of their whipping effect.

High energy piping are components containing, under normal operating conditions, high energy fluid, such as water or steam, at pressure greater than or equal to 2.0 MPa and/or temperature greater than or equal to 100°C. Components containing gas pressurized above atmospheric pressure are also considered to be HEP [1].

The research activity has been focussed on the investigation of whipping effect in ITER HEP, with the specific aim to outline an operative procedure for the assessment of its consequences, inspired to acknowledged international standards, to be proposed as ITER reference as well as to adopt it for the assessment of whipping effect consequences in the ITER Tokamak Cooling Water System (TCWS) DIVertor Primary Heat Transfer System (DIV PHTS) pipes.

This paper summarizes the operative procedure proposed, critically discussing the results obtained once applied to the investigation of the whipping effect in ITER TCWS DIV/PHTS pipes.

## 2. Outline of the whipping effect

Whipping effect takes place in a pipe when, after a double ended guillotine break (DEGB), the reaction force exerted on the pipe itself, due to either its high velocity fluid or to the difference between inner and outer pressures, determines its sudden and inadvertent displacement which might affect adjacent components, potentially jeopardizing their structural integrity and mission. This effect could lead the so called "aggressor" pipe to cause an extensive damage to components, instrumentation and equipment located near by the rupture area that would result to be the "victim" components. The dynamic of whipping effect is schematically represented in Fig. 1.

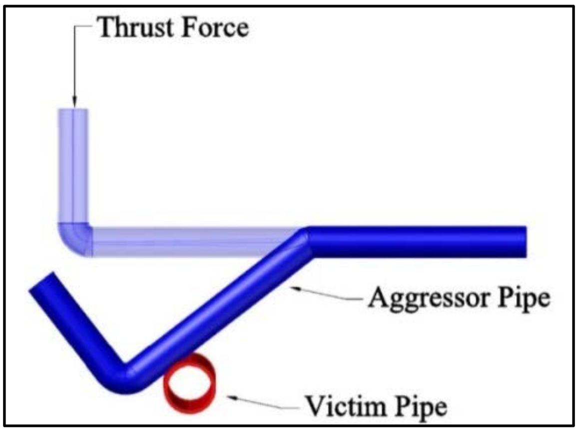


Fig.1. Schematic of whipping effect.

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## 3. The whipping effect analysis procedure

The research campaign has allowed outlining an operative procedure for the analysis of whipping effect in ITER TCWS HEP that is articulated in three main steps. The first step is devoted to the identification of the piping areas where a rupture, inducing whipping effects, is much likely to be expected. The second step is intended to analyse the impact of "aggressor" pipe on "victim" pipe and the third step is dedicated to the evaluation of the possibility to prevent and/or mitigate the whipping effect by means of particular restraints.

### 3.1. Safety code and standards

ASME B31.3 has been selected as standard code relevant to TCWS piping systems [2], anyway it does not include standard references to approach the whipping effect analysis. Therefore, in the development of the whipping effect analysis procedure, it has been decided to make reference to further acknowledged US Codes&Standards and relevant guidelines issued by U.S. NRC. In particular, the adopted ones are:

- ANSI/ANS 58.2 [3];
- Standard Review Plan (SRP) 3.6.1 [4];
- Standard Review Plan (SRP) 3.6.2 [5];
- SRP Branch Technical Position (BTP) 3-4 [6];
- ASME Code Section III [7].

### 3.2. First step: rupture localization

Potential pipe rupture is predicted by comparing the stress level in a critically loaded region of the HEP with a code-fixed stress limit.

According to [7], the stress level of Class 2 piping is evaluated by the Von Mises equivalent stress (S) due separately to sustained loads ($S_S$), occasional loads ($S_{OL}$) and thermal expansion loads ($S_E$), as follows:

$$S = S_S + S_{OL} + S_E \qquad (1)$$

Therefore, once calculated S, the presence and location of ruptures are determined according to the following conditions [6]:

$$\begin{cases} S < 0.4\left(1.8S_h + S_A\right) \\ 0.4\left(1.8S_h + S_A\right) < S < 0.8\left(1.8S_h + S_A\right) \\ S \geq 0.8\left(1.8S_h + S_A\right) \end{cases} \qquad (2)$$

where $S_h$ is the allowable stress at maximum operating temperature and $S_A$ is the allowable stress for expansion stress. In the first case, no rupture may be assumed. In the second case, pipe leak is foreseen but the pipe integrity is assumed to be not completely lost. In the last case, pipe complete rupture is predicted and it is mandatory to study the dynamic reaction of the piping system. In all the pipe terminal ends ruptures are directly postulated. This is a further safety assumption and its verification is independent from Eq. (2).

### 3.3. Second step: thrust force calculation

In the procedure second step, the dynamic impact of the "aggressor" pipe undergoing whipping effect on the "victim" pipe has to be assessed. To this purpose, the thrust force, due to flowing fluid acting on a ruptured pipe, can be determined by Newton's second law of motion for open systems. Anyway, according to [3], standard prescribes to assume a most simplified and extremely conservative way to evaluate it, given by:

$$T = C_T P_0 A_e \qquad (3)$$

where $C_T$ is the steady state thrust coefficient, $P_0$ is the initial total (static + dynamic) pressure in the pipe and $A_e$ is the break area. Concerning the steady state thrust coefficient, dedicated paper [5] indicates that the Regulator could consider as acceptable values of $C_T$ not less than 1.26 for steam, saturated water and steam-water mixtures or 2.0 for subcooled and nonflashing water. The thrust force shall be assumed to rise to the steady state value in 0.001 s and, then, to remain constant in time. Once evaluated the thrust force, several dynamic analysis models could be used to study the pipe postulated rupture and the restraint system response to its action. Acceptable models for HEP, proposed in [5], include: Lumped Parameter Analysis Model, Energy Balance Analysis Model, Static Analysis Model and Dynamic Time History Analysis Model.

### 3.4. Third step: methods of protection

In the final step of the proposed procedure, whether whipping effect is predicted to occur, a method of protection against its consequences on the "victim" pipe has to be find out, mainly based on the adoption of a system of proper restraints and its effectiveness has to be checked. According to [8], some types of protection could be pipe whip restraints, jet shields and energy absorbers.

## 4. Analysis of the whipping effect of DIV/PHTS

The procedure proposed has been applied to the investigation of whipping effect in the ITER TCWS DIV/PHTS HEP and the results obtained are herewith reported and critically discussed. In particular, the study has aimed to verify the current HEP layout and supports. Inlet and outlet pipes, relevant to divertor cassettes, penetrate (6 tubes per port) the cryostat and the vacuum vessel through the divertor port cells. The domain taken into account for the whipping effect analysis includes the divertor piping from the Vertical Shafts (VS) to the inlet of each divertor cassette, as reported in [9]. A numerical approach based on the Finite Element Method has been followed and quoted commercial codes have been adopted to assess the structure stress state [11].

### 4.1. Piping characteristics and problem data

Geometrical characteristics of piping, terminal ends, and supports are reported in [9]. Stainless steel 304L has been assumed as piping material.

### 4.2. Intermediate rupture analysis

According to the first step of the proposed procedure, intermediate rupture analysis has been performed following a theoretical approach based on the Beam

Theory to calculate the stress state of the DIV PHTS inner pipes. The analysis has been carried out with reference to three different load combinations encountered by the HEP and reported in Table 1.

Tab. 1. Load combinations considered.

| Load Conditions | Equivalent Loads |
|---|---|
| Plasma Operation + Seismic event SL-1 | $(P_1 + D_w + T_1) + SL\text{-}1$ |
| Water Baking + Seismic event SL-1 | $(P_2 + D_w + T_2) + SL\text{-}1$ |
| Gas Baking + Seismic event SL-1 | $(P_3 + D_w + T_3) + SL\text{-}1$ |

where $D_w$ represents the dead weight, $T_1$, $T_2$ and $T_3$ represent the thermal loads due to the expansion up, respectively, to plasma operating temp. (150 °C), to water baking temp. (240 °C) and to gas baking temp. (350 °C). $P_1$, $P_2$, $P_3$ represent, respectively, the water operating pressure (4 MPa), the water baking pressure (4.4 MPa) and the gas baking pressure (2.0 MPa). SL represents the seismic load. According to IAEA safety guide NS-G-3.3 (2002), Seismic Load 1 (SL-1) and 2 (SL-2), respectively corresponding to Operating Basis Earthquake (OBE) and Safety Shutdown Earthquake (SSE). The values of equivalent stress, S, have been calculated by 1-D FEM code CAESAR II and have been compared to the limits of eq. (2) and reported in Table 2.

Tab. 2. Stress limits.

| $0.4(1.8\ S_h + S_A)$ [MPa] | $0.8(1.8\ S_h + S_A)$ [MPa] |
|---|---|
| PLASMA OPERATION | |
| 135.377 | 270.754 |
| WATER BAKING | |
| 142.919 | 285.838 |
| GAS BAKING | |
| 134.755 | 269.510 |

The analyses have shown that during Plasma Operation no leaks or ruptures are predicted, while during Water Baking and Gas Baking some leaks and no rupture are envisaged. Finally, it is possible to conclude that no rupture can be envisaged and no further step of the analysis has to be performed, the DIV PHTS inner lines resulting verified for intermediate ruptures [11].

### 4.3. Terminal ends analysis

According to the proposed procedure, in all piping terminal ends a DEGB has to be postulated. Inner terminal ends of DIV/PHTS pipes are supposed to be located at the connection with divertor cassette. There are two kinds of terminal end layouts, located at ports and interports of the Vacuum Vessel (VV), respectively. The passage through the cryostat is performed by a system of three bellows welded to the cryostat itself. For the sake of brevity and without any lack of generality, an interport and a port have been studied as representative examples and the results obtained have been extended to all other similar systems [11].

*FEM models and boundary conditions*

In order to carry out the analysis, a FEM model of each DIV PHTS HEP (port and interport) has been set up, adopting ANSYS MECHANICAL (Ver. 14.0). Concerning both the port and the interport FEM models, a mesh has been set-up adopting the sweep method with a characteristic element size of 0.05 m [11]. The models (Fig. 2) have been constrained according to supports spatial distribution reported in [9]. It has been assumed the presence of gravitational acceleration and the highest coolant pressure (4.4 MPa), occurring under the water baking operational scenario. The thrust force has been calculated by means of eq. (3), it has been applied to the cross section of a single terminal end and it has been posited rising to the steady state value in 0.001 s. The ultimate tensile strength, calculated at 240°C (the highest water baking temperature), amounts to 360 MPa [10] and it has been hired, in the lack of other indications, as the limit stress value beyond which pipe collapses.

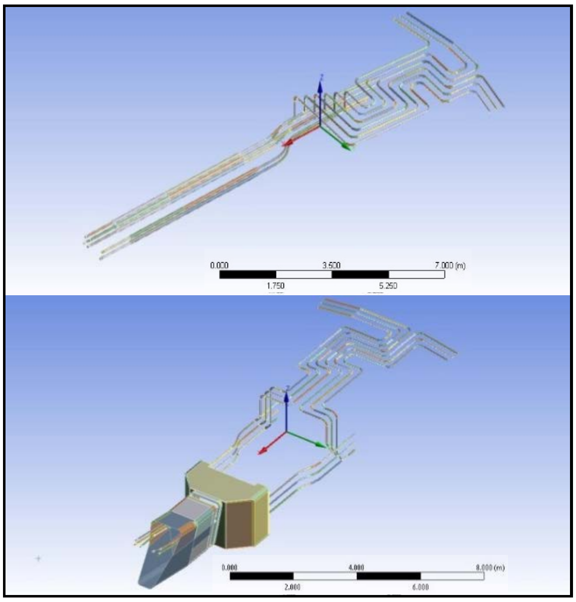

Fig.2. Layout of interport and port divertor pipes.

*Preliminary analysis of terminal ends*

The analyses have been carried out considering the thrust force applied separately on three terminal ends for each model and three cases have been identified [11]. Both interport and port pipes, in all the three cases considered, are not endowed with supports that can react against the thrust force. The performed analyses [11], which for the sake of brevity are not herein reported in detail, have shown large pipe displacements that jeopardize the structural integrity of adjacent pipes and structures. The propagation of whipping effect is ensured and may involve a dangerous domino effect [11].

*Investigated protection solutions*

It has been decided to propose a modification in the existing radial bellows welded both to the pipe and the cryostat, implementing guide stoppers made by steel rods connecting the bellow flanges (Fig. 3) [11].

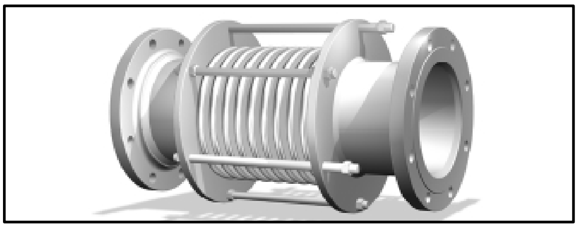

Fig.3. Bellows guide stopper.

Under normal operation, bellows result free to move accomplishing the piping thermal expansion, while, during an over unlikely break in the terminal end, guide stoppers have to react against the thrust force. The rod allowable displacement has been calculated performing a stress analysis of bellows, simulated as a free guide in radial direction, under the load combination of gas baking at 350°C plus SL-2. The highest value of displacement, for the considered load combination, has been incremented by the 20%, as additional safety factor. Therefore, further static analyses have been carried out taking into account the new kind of support [11]. The calculated displacements and the Von Mises equivalent stress values obtained are shown in Table 3 [11].

Tab. 3. Revised support configuration.

| | Case | Displacement [mm] | Stress [MPa] |
|---|---|---|---|
| Interport | 1 | 78.76 | 3.479E+02 |
| | 2 | 77.02 | 3.372E+02 |
| | 3 | 77.90 | 2.643E+02 |
| Port | 1 | 101.50 | 6.842E+02 |
| | 2 | 83.12 | 5.840E+02 |
| | 3 | 87.11 | 7.468E+02 |

For the revised support configuration of interport pipes, the maximum Von Mises equivalent stress calculated has resulted lower than ultimate tensile strength (360 MPa), therefore, the proposed solution avoids the propagation of ruptures [11]. For the revised support configuration of port pipes, the maximum stress calculated has resulted higher than ultimate tensile strength. Therefore, further analyses have been performed considering breaks to check whether these pipes would hit neighbouring components. Calculated displacements are summarized in the Table 4. In all three cases, the displacements move the pipes toward an empty region, avoiding any impact and excluding the need for any additional analysis intended to check the integrity of their neighbouring components [11].

Tab. 4. Max. displacements due to ruptures of port pipes [mm].

| | | |
|---|---|---|
| Port | Case 1 | 73.87 |
| | Case 2 | 46.78 |
| | Case 3 | 63.09 |

## 5. Conclusions

Within the framework of the R&D activity intended to investigate the ITER potential safety issues on a reactor design basis, DEIM and IO have performed a research campaign focussed on the assessment of the potential consequences of the ITER HEP whipping effect. An operative procedure intended to the analysis of the HEP whipping effect has been outlined according to internationally qualified Codes&Standards and it has been selected as IO reference. It has been applied to the study of the whipping effect in ITER TCWS DIV/PHTS HEP. The analyses [11] have indicated that both interport and port pipes are not endowed with supports reacting along the radial direction allowing the thrust force to produces large displacements as well as stresses higher than the ultimate tensile strength. The solution proposed is to introduce bellows guide stoppers with maximum displacement of 69.58 mm and maximum force reaction of 44.22 kN, that allow to mitigate whipping effect consequences at pipe terminal ends [11].

## Disclaimer

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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