ITER cryostat accidental scenario: fluid dynamics analysis of Ingress of Coolant Event Accident

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Abstract. ITER (International Thermonuclear Experimental Reactor) is an experimental reactor aimed at demonstrating the technological and scientific feasibility of fusion technology. A future fusion power plant producing large amounts of energy power will be required to breed all of its own Tritium. ITER will demonstrate this essential concept of Tritium self-sustainment.

Among the most important components of that reactor there is the cryostat that is, specifically, a large stainless steel structure surrounding the vacuum vessel and the superconducting magnets, providing a super-cool vacuum environment.

The aim of this paper is to evaluate the effects caused by a suddenly rupture of one of the cryogenic lines with release of helium inside the cryostat, event known as CrICE: Ingress of Coolant Event in Cryostat.

The CrICE accident scenario has been simulated by ANSYS©CFX. To the purpose, a suitable model representing a 20° sector of the overall ITER structures, vacuum vessel, magnets, thermal shield, ports and cryostat was set up and implemented, in order to characterize and define the free volume to be filled by the gas that would be released eventually as well as the air inside the bioshield.

The numerical model, the geometrical characteristics and the materials properties used as input in the simulation of the accidental scenario have been presented and discussed.

The results obtained indicated that the cryostat is capable to sustain the pressure and the thermal loads generated by the accident conditions.

It is also worthy to remark that these results (raw outcomes) will be used for a further detailed investigation of the structural performances of cryostat itself.

1. Introduction

ITER (International Thermonuclear Experimental Reactor) is an experimental reactor based on the Tokamak concept of magnetic confinement, where the plasma is contained in a doughnut-shaped vacuum vessel. The fuel is heated up to temperatures of 100 million K, which forms hot plasma. Strong magnetic fields are used to keep the plasma away from the walls; these fields are produced by means of superconducting coils surrounding the vessel and by an electrical current driven through the plasma [1].

ITER magnet system comprises 18 superconducting toroidal field and 6 poloidal field coils, a central solenoid and a set of correction coils that magnetically confine, shape and control the plasma inside the vacuum vessel. To maximize the efficiency and limit the energy consumption, ITER uses superconducting magnets that lose their resistance when cooled down to very low temperatures. The toroidal and poloidal field coils lie between the vacuum vessel and the cryostat, where they are cooled and shielded from the heat and the neutrons generated from the fusion reaction.

The superconducting material is made of a special alloy of Niobium and Tin (Nb_3Sn) for both the central solenoid and the toroidal field coils, which is designed to achieve operation at high magnetic field (13 Tesla). The poloidal field coils (consisting of six horizontal coils outside the toroidal magnet structure) and the correction coils use a different Niobium-Titanium (NbTi) alloy. In order to achieve superconductivity, all the coils are cooled with supercritical Helium in the range of 4 K [2].

The 18 toroidal field (TF) magnets, producing a maximum magnetic field of 11.8 Tesla, produce a magnetic field around the torus, the primary function of which is to confine the plasma particles.

The coils will weigh 6,540 tons in total. They will be made of cable-in-conduit superconductors contained in a structural jacket, in which a bundle of superconducting strands is cabled together and cooled by flowing helium.

The poloidal field (PF) magnets pinch the plasma away from the walls contributing in this way to ensure the plasma's shape and stability. The poloidal field is induced by both the magnets and the current drive in the plasma itself.

The main plasma current is induced by changing the current in the central solenoid which is essentially a large transformer. It contributes to the inductive flux that drives the plasma to the shaping of the field lines in the divertor region and to vertical stability control.

Superconducting coils maintain their properties only at very low temperatures, therefore to maintain the magnets at this value of temperature, without excessive energy consumption, two solutions are applied:

- the vacuum is maintained inside the cryostat in order to avoid convective heat transfer;
- the thermal shields (cooled at 80 K) envelope the high temperature components facing magnets in order to avoid the radiant heat transfer.

The cryostat is 29.3 m tall and 28.6 m wide single wall cylindrical construction made of stainless steel that surrounds the vacuum vessel and superconducting magnets, providing a vacuum environment. It is completely surrounded by a concrete layer known as bioshield. Above the cryostat, the bioshield is two metres thick [3].

In order to protect the vacuum vessel and magnets from the thermal radiation two set of thermal shields made of stainless steel surround these components. Thermal shields have many openings, some as large as four metres in diameter, which provide access to the vacuum vessel for the cooling systems, the magnet feeders, the auxiliary heating, the diagnostics and the removal of blanket and divertor parts. Large bellows are used between the cryostat and the vacuum vessel to allow for thermal contraction and expansion in the structures.

The main functions of the cryostat are to provide a vacuum environment in order and to avoid the application of excessive thermal loads to components operating at cryogenic temperatures so that the convective heat transfer between the magnets and the cryostat is negligible during the normal operation. Otherwise, convection can occur causing a drop in temperature of the cryostat structure. In this framework three types of event may be identified, as also indicated in [4]:

1. Helium leakage (CrICE: in Cryostat Ingress of Coolant Event): the supercritical helium, from the magnet and thermal shield cooling system, is released inside the cryostat;
2. Water ingress (CrICE): the water in the vacuum vessel cooling system is released into the cryostat;
3. Air ingress (CrLOVA: in Cryostat Loss of Vacuum Accident): the air moves from the outside of the cryostat to inside until the external and internal pressures are equalized.

In this study it has been postulated that the CrICE events could cause the quenching of magnets (MQ): if this happens the temperature of conductors will increase of 55 K quite instantaneously [5] determining an accident condition.

The accident events analysed are listed in Table 1.

The simulation CrICE_II_NMQ assumes 500 kg of helium leakage whereas the temperature is 15 K inside the system. The magnets system is considered in "no quench" condition.

The simulation CrICE_III_NMQ/MQ assumes 2600 kg of helium leakage, 15 K temperature inside the system and magnets respectively in "no quench" or "quench" condition.
The simulation CrICE_IV_NMQ/MQ assumes 4000 kg of helium leakage, 15 K temperature inside the system and magnets respectively in "no quench" or "quench" condition.

Table 1: Analysed cases

Event name	Event description
CrICE_II_NMQ	500 kg He leak. No Magnet Quench
CrICE_III_NMQ	2600 kg He leak. No Magnet Quench
CrICE_III_MQ	2600 kg He leak. Magnet Quench
CrICE_IV_NMQ	4000 kg He leak. No Magnet Quench
CrICE_IV_MQ	4000 kg He leak. Magnet Quench

In this study therefore the effects caused by a sudden rupture of a cryogenic line, with release of helium inside the cryostat, have been investigated. Results obtained are presented and discussed in the following.

2. Description of the modelling

In this section a description of the geometrical and FEM model of a 20° sector of ITER structures is given.

The entire vacuum vessel (Figure 1) is enclosed within a cryostat, or cold box, which provides insulation for the superconducting magnet system and other components.
In Figure 1 is represented a section of the overall reactor cavity with all its most important components, such as the vacuum vessel, magnets, the thermal shield, ports, and the cryostat. These structures allow to define the volume of the gas.

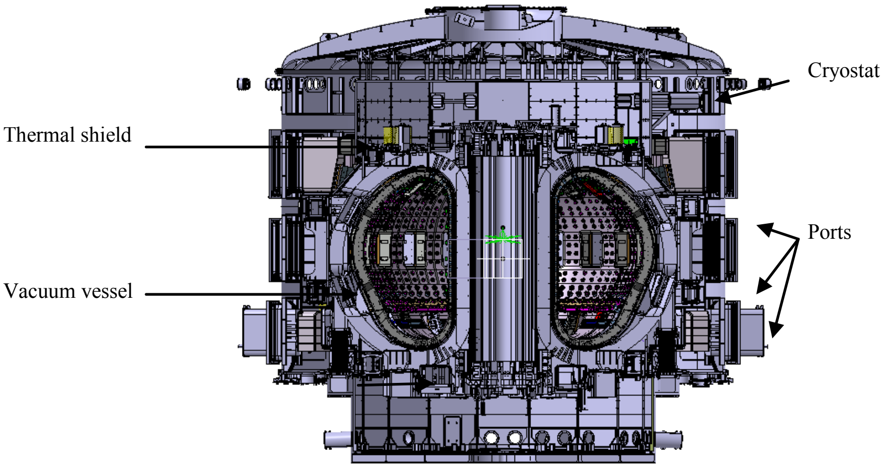

Figure 1: ITER's main components cross section

In Figure 2 is instead represented the numerical model implemented by using ANSYS© CFX. For a complete and real, as much as possible, representation of the structure under study a further volume has been added in order to simulate the behaviour of the air contained in the bioshield.
Furthermore to reduce the computational costs, several assumptions have been done along with some simplification for what concerns the structures, which specifically are:

- Smooth surfaces: the cryostat reinforcement ribs and the small surface irregularities, as the screw heads, are not considered in order to reduce the geometrical complexity and mesh size;

- No feeders: the complex pipeline system of the coolant systems, not relevant for the intent of this study, has been not modelled to simplify the geometry and reduce the mesh size;
- No support elements: the support elements of the components have been not taken into account so to avoid to introduce complexity in geometry and symmetry;
- Perfect symmetry in ports: since the ITER structure is not perfectly axial-symmetric because of the ports, used for the injection of neutral beams, to reduce the geometry to a 20° sector it was assumed that all the ports are symmetric.

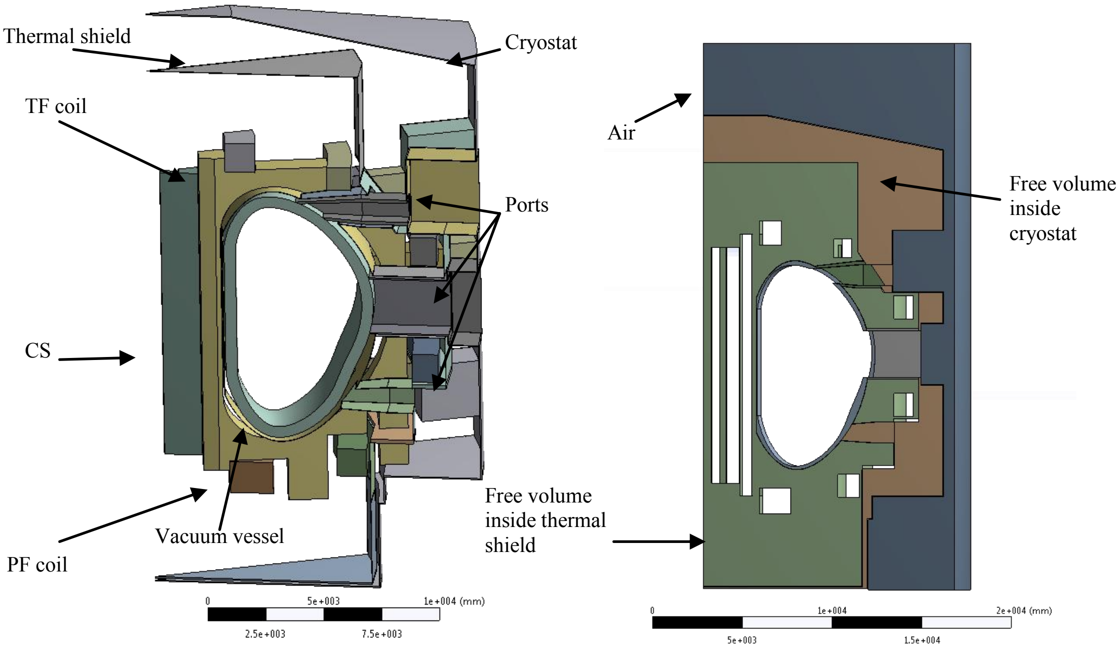

Figure 2: Overview of the 20° sector model

The numerical model has more than 200000 elements (tetrahedrons). This mesh allowed to implement finite volumes which were used to preserve relevant quantities such as mass, momentum, and energy. All solution variables and fluid properties are stored at the nodes (mesh vertices). A control volume is implemented around each mesh node using the median dual.

As above indicated, the superconducting material is made of a special alloy of Niobium and Tin (Nb3Sn) for both the central solenoid and the toroidal field coils. Average materials properties have been used in input for each configuration of these magnets [6], while stainless steel (316LN) properties has been input for all the other elements [7].

The helium was simulated adopting the Peng-Robinson model for real gas [8]; the air instead was considered like an ideal gas.

The initial temperatures of each component, representing the initial condition of the simulations, are summarized in Table 2.

A uniform distribution of helium at 15 K inside the cryostat has been also assumed as initial condition. Knowing the mass released in each case and the volume (about 9200 m^3) it is possible to calculate the density. Based on the density and temperature and on the fluid properties, the initial pressure was so determined (Table 3). Furthermore the air outside cryostat is assumed at t=0 s at 298 K and 100 kPa.

The boundary conditions are the following:

- The inner wall of vacuum vessel (first wall) was assumed to have zero heat flux because it faces a void room.

- The surfaces of the ports inside the thermal shield were assumed to have zero heat flux because at normal operation they are sealed and therefore no heat is exchanged inside it.
- The bottom of the cryostat was at 298 K, in order to simulate the contact with the concrete constituting the building.
- The external boundaries of the Tokamak building atmosphere were set with a constant pressure of 100 kPa.
- All the other surfaces were assumed to exchange heat with the fluids.

The main issue to face in this study is the transient natural convection inside a cavity. Upwind advection scheme and second order backward Euler transient scheme were selected.

Standard k-e turbulent model was used.

The initial time-step of the analyses carried out was 0.01 s. An automatic time-steps' adaptation feature, based on the number of the iterations, was implemented in order to obtain convergence. The duration of the transient analyses is 50000 s.

Table 2: Solid bodies settings

Component Acronym	**Material**	**Initial Temperature**	
		NoMQ	**MQ**
VV	Steel	370 K	370 K
CS	CS average material	5 K	60 K
TF	TF average material	5 K	60 K
PF	PF average material	5 K	60 K
TS	Steel	80 K	80 K
Cr	Steel	298 K	298 K
Ports	Steel	298 K	298 K

Table 3: Helium settings

Case	**Density**	**Pressure**
CrICE II (500 kg)	0.0544 kg/m^3	1.70 kPa
CrICE III (2600 kg)	0.2826 kg/m^3	8.80 kPa
CrICE IV (4000 kg)	0.4348 kg/m^3	13.54 kPa
Volume: 9200 m^3	**Temperature:** 15 K	

The results obtained are given in terms of wall temperature, heat transfer coefficient (HTC) and bulk temperature, this latter, in particular, was carried out for each surface of the cryostat (Figure 3). In addition it is important to remark that these values are averaged over the area or volume.

It is worthy to note that CFX© code allowed directly to calculate the values of pressure, temperature and heat flux, while HTC has been calculated subsequently as:

$$HTC = \frac{q''}{T_b - T_w} \tag{1}$$

Where q'' is the wall heat flux, T_b the bulk temperature and T_w the wall temperature.

Five points have been defined inside the cryostat (Figure 4) because of the strong temperature stratification (Figure 5 and Figure 6) obtaining a bulk temperature for each surface, that is defined accordingly to the nomenclature shown in Figure 3.

The bulk temperatures of the volume inside the thermal shield and of that outside the cryostat are volume-averaged values, of course calculated in each corresponding volume.

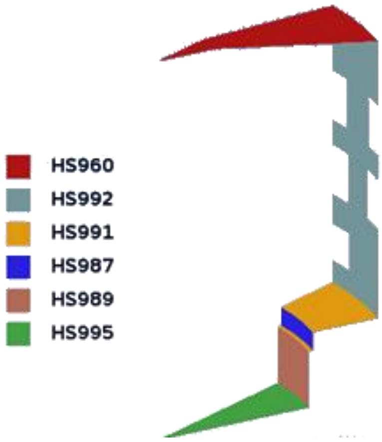

Figure 3: Name of cryostat surfaces

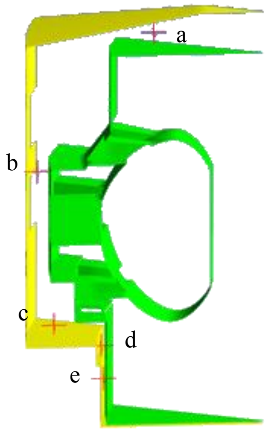

Figure 4: Bulk temperatures evaluation points

Figure 5: Temperatures at the end of simulation (CrICE II)

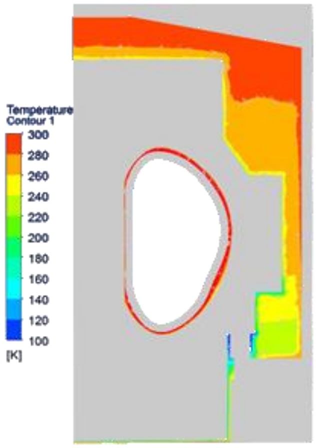

Figure 6: Temperature stratification between Cryostat and CrTS (CrICE II)

3. Analysis of the results

In the simulated events, the presence of helium establishes convective motions inside the structures. The cryostat thermal shield separates the volume in two parts which are connected only by the small gap of the labyrinths; so, two different fluid regions are set.

Inside the cryostat, the helium is heated by the cryostat walls which are kept warm by the convective heat exchange with the external environment; the cryostat thermal shield, instead, is a heat sink that keeps increasing temperature during the accident, subtracting heat to helium.

The cryostat thermal shield transfers heat from that region to the gas located in its internal volume. Here there are the components with the lowest temperature, the magnets, and the vacuum vessel thermal shield. This structure directly faces the vacuum vessel, the hottest component, and so it acts as bridge for the heat transfer between vacuum vessel and the volume inside the thermal shield. The presence of all these different bodies creates complex convective flux inside this region.

The gas in the small gap between vacuum vessel and vacuum vessel thermal shield is heated by the vacuum vessel and cooled by the heat exchange of the thermal shield; this volume is connected with the volume inside the cryostat by the small gaps between the ports and the thermal shield and so contributes to heat directly all the gas.

Helium is heated by all these contributions and, as result of the isochoric process, its pressure increases.

3.1. CrICE II

The simulation started with the assumption of the presence of 500 kg of helium at temperature of 15 K inside the system. The magnets were under "no quench" condition.

The pressure behaviour increases faster at the beginning of transient and after few seconds slowly with a rate of about 1 kPa each 3.6 hours (Figure 7). The maximum theoretical value that could be reached (when all the system is at 298 K) is 33.48 kPa (the maximum allowed value for the structures of 200 kPa).

The cryostat thermal shield separates the volume in two parts, which highlight considerable difference in temperatures as visible in Figure 5 and Figure 8. At the end of the simulations, the temperature of the volume between the cryostat and the thermal shield increases up to 267 K with a rate of about 1 K in 1.5 hours.

The volume inside the thermal shield reaches instead 148 K with a rate of about 2 K each hour.

The most important consequence of this temperature gradient is that cryostat faces a hotter gas than in the case of absence of the thermal shield; so the thermal gradient across the structure should be smaller

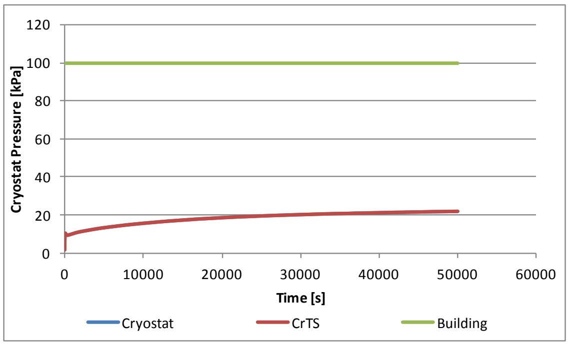

Figure 7: CrICE II: pressures

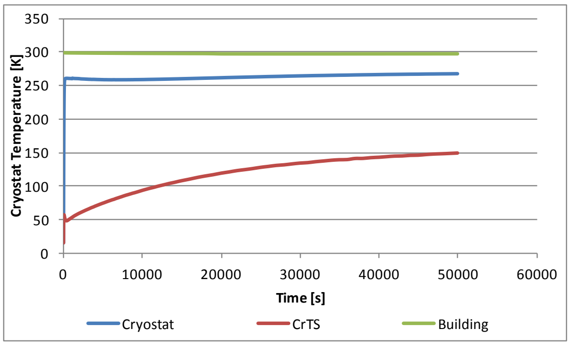

Figure 8: CrICE II: gas mean temperatures

In Figure 9, Figure 10 and Figure 11 the diagrams of wall temperatures, convective heat fluxes and heat transfer coefficients are presented.

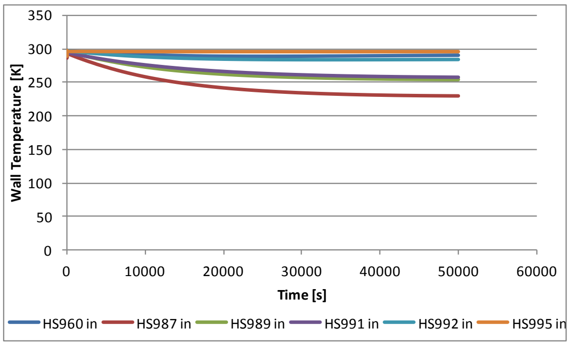

Figure 9: CrICE II: wall temperatures

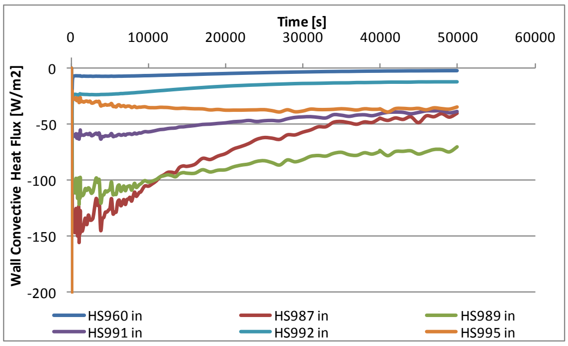

Figure 10: CrICE II: wall convective heat fluxes

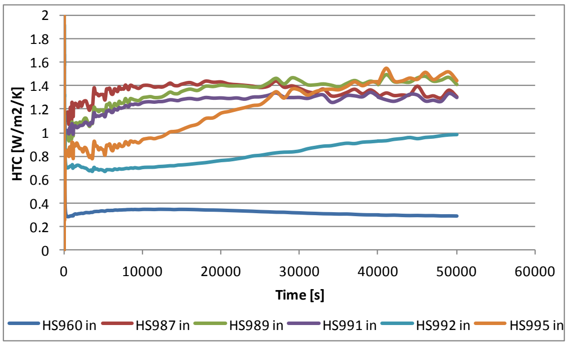

Figure 11: CrICE II: heat transfer coefficients

3.2. CrICE III

The simulation started with the assumption of the presence of 2600 kg of helium at temperature of 15 K inside the system. Two cases were simulated: with and without magnet quench, i.e. the starting temperature of the magnets was 60 K (MQ) or 5 K (NMQ).

For both two cases the pressure has the same behaviour: after an initial fast rise, it slowly increases with a rate of about 1 kPa each hours (Figure 12). The maximum theoretical value it can reach in the case that all the system is at 298 K, is 175 kPa while the maximum values calculated are respectively 115 kPa in the magnet quench case and 109 kPa in the case without magnet quench.

As for the volume between the cryostat and the thermal shield, the temperature is similar in MQ and NMQ: in fact it reaches the value of 255 K in the latter case and 259 K in the former. At the end of the simulations, the temperature growth rate resulted about 1 K each 2 hours.

The change of the temperature of the magnets creates a difference of 11 K inside the thermal shield for magnet quench case respect the case without magnet quench (153 vs. 142 K). The final rate is in any case about 1 K each hours. Temperature diagrams are presented in Figure 13 and Figure 14.

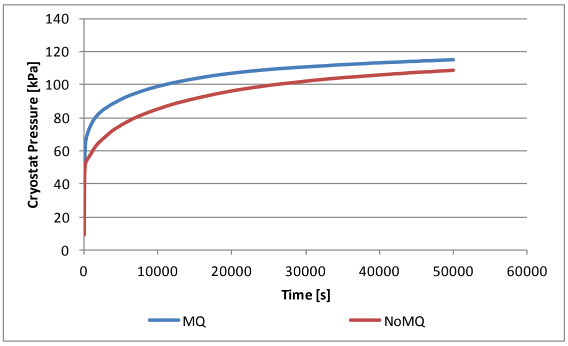

Figure 12: CrICE III: pressures

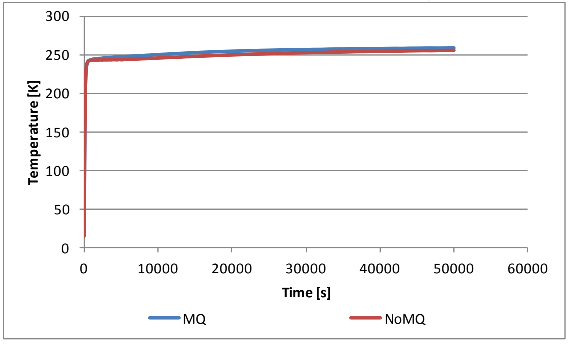

Figure 13: CrICE III: gas mean temperature in cryostat

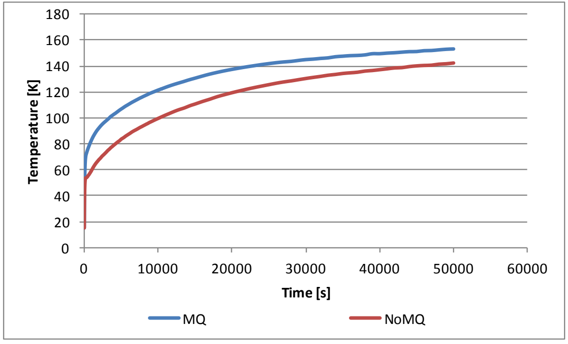

Figure 14: CrICE III: gas mean temperature in thermal shield

Figure 15 and Figure 16 show the behaviour versus time of the convective heat fluxes and the heat transfer coefficients: analysing them it is possible to observe that the main differences are concentrated on the structure inside the thermal shield.

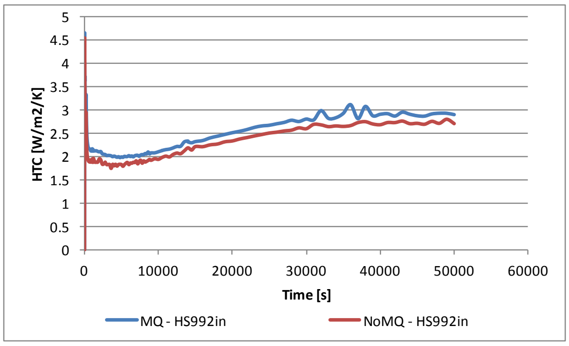

Figure 15: CrICE III: heat transfer coefficients

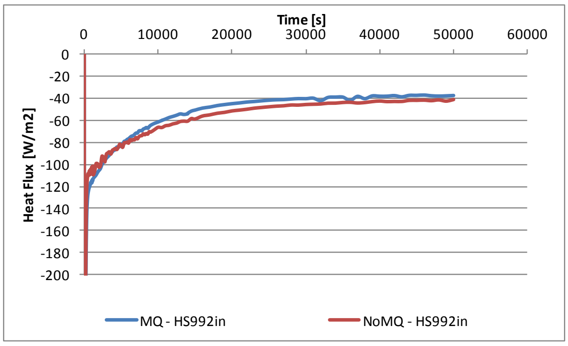

Figure 16: CrICE III: wall convective heat fluxes

These results indicate that the huge amount of helium inside the system determines a higher value of pressure and a more intense heat exchange between the fluid and structures resulting in lower walls temperatures.

3.3. CrICE IV

The simulation started with the assumption of the presence of 4000 kg of helium at temperature of 15 K inside the system. Two cases were simulated: with and without magnet quench.

For both the NMQ and MQ case the pressure has the same behaviour: an initial fast rise followed by a slow increase with a rate of about 1 kPa each hour. The maximum theoretical value it can reach, assuming all the system at 298 K, is 270 kPa while the maximum calculated one is 176 kPa in the case of magnet quench and 168 kPa in the case without magnet.

In the volume between the cryostat and the thermal shield the temperature resulted similar (251 K for NMQ and 255 K for MQ), the increase rate is about 1 K in 2.5 hours. The change of the temperature of the magnets determines a difference of 10 K in the thermal shield inner temperature for MQ respect NMQ (145.5 vs. 155.5 K). The final increase rate in any case resulted about 1 K each 40 minutes.

The values of the wall temperatures, the convective heat fluxes and the heat transfer coefficients are similar for the cryostat walls in both the two cases analysed; the main differences are observed on the structure inside the thermal shield.

In Table 4 the most important results obtained from the simulation of inlet gas into the cryostat are summarized. It was observed that the pressure increases along with the mass of gas released. The temperature, instead, decreases with the mass because of the greater quantity of gas that must be heated with the same amount of heat stored in the structures. "Magnet Quench" events seemed to have a small influence on the results carried out and the most important effect is related to the increase of the pressure and temperature values, even if of small extent.

Table 4: Results Summary

Case	p [kPa]	T [K]	HTC of cryostat main vertical surface [W/m/K]
CrICE II	22.09	268	0.98
CrICE III NoMQ	108.94	255	2.71
CrICE III MQ	115.02	259	2.90
CrICE IV NoMQ	167.65	251	3.25
CrICE IV MQ	176.14	255	3.47

4. Conclusion

In this study has been investigated the evolution of an accident scenario dealing with the loss of vacuum inside the ITER cryostat.

In doing that an adequate numerical model has been set up and implemented by means of ANSYS© code.

The attention has been particularly focused on the heat exchange at the cryostat walls , which should withstand the pressure and thermal loads induced by such a type of accident.

In all analysed cases, the pressure never reaches the allowable limit value of 200 kPa that is the design limiting pressure in the cryostat.

Moreover, the results showed the dependence of the heat exchange rate on the convection of the fluid released inside the structures

Finally, it is important to remark that these results will be used in turn as boundary conditions for a more detailed evaluation of the structural performances of cryostat itself.

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