Analysis of Large Helium Ingress into the DEMO Cryostat Using MELCOR for Fusion

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ABSTRACT

The accident scenario postulated in this study considers that the cryostat in DEMO fusion reactor is filled with helium gas through a break in the cryogenic system primarily devoted to cooling the magnets. Computer code MELCOR for Fusion is used to predict this transient phenomenon and to assess the pressure and the temperature values in the enclosures between the vacuum vessel and the cryostat. Since the DEMO cryostat is designed as a thin-walled structure, over-pressurization would cause its buckling and potential collapse. For this reason, firstly, mass of the released He needed to reach the design pressure inside the cryostat is estimated. Secondly, a parametric study is performed to determine the diameter of pressure relief rupture disk in order to maintain the pressure below the pressure limit.

1 INTRODUCTION

The purpose of our research is to analyse the loss of cryostat vacuum due to helium (He) ingress. The initiating event considers a failure of cryogenic lines used for cooling of superconducting magnet coils, resulting in spillage of large amount of He into the cryostat atmosphere, which is normally kept at very low pressure (vacuum).

MELCOR for Fusion code, which is based on the MELCOR code version 1.8.6, is used to perform the analysis. MELCOR is an integral engineering-level code that includes several models for describing the physics during the considered accident phenomena. The main fusion related modifications of the MELCOR code, relevant for this analysis, include cryogenic He or air as a primary fluid, and modifications for water freezing and ice layer formation. Input modelling is based on the “control volume” approach that describes the fusion reactor system fluid volumes and solid structures.

The postulated accident starts with a double guillotine break with a diameter of 0.2 m of a pipe in the cryogenic system in the interspace between vacuum vessel thermal shield (VVTS) and cryostat thermal shield (CTS), where the superconducting magnets are located. The total He inventory in the DEMO cryogenic system is estimated to 20 tons. Due to the narrow gaps between the VVTS ports, VVTS and CTS, the helium spreads out into the neighbouring interspaces filling all the previously vacuumed space between the vacuum vessel (VV) and the cryostat (Figure 1). The conditions for heat transfer due to natural convection are thus established, which can cause a significant cool-down of the cryostat walls.

A 32-hour long loss of off-site power is assumed to coincide with the considered transient, which disables the cryostat depressurization system, the heating, ventilation and air conditioning system (HVAC), and venting detritiation system (VDS) in the tokamak hall and galleries. Nevertheless, the temperature of the magnets is kept constant at 4.2 K. The emergency cooling system in the vacuum vessel primary heat transfer system (VV-PHTS) is able to sufficiently remove the decay heat from the VV during this postulated accident and keep VV at constant temperature of 473 K [1,2].

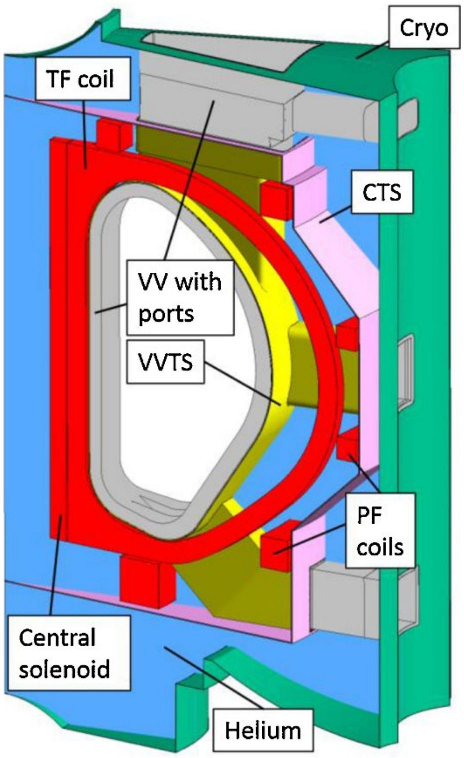

Figure 1: Simplified model of the DEMO tokamak internals. Blue colour represents the available volume that is filled with helium from cryogenic system [3].

Since the DEMO cryostat is designed as a thin-walled structure, the cryostat boundary fails at the internal pressure of 109 kPa [4]. To avoid any uncontrolled damage of the cryostat structure, a rupture disk opens at an overpressure of 5 kPa (compared to the pressure inside cryostat and bioshield interspace) to relieve the pressure and to discharge the gas into the interspace between cryostat and bioshield.

2 MELCOR MODEL

In Figure 2 input MELCOR model used is shown. The MELCOR model for the analysis of He ingress into the DEMO cryostat includes control volumes representing the space between VV and VVTS, the interspace between VVTS and CTS that encloses the magnets with cryogenic system, the interspace between CTS and cryostat, the interspace between the cryostat and the bioshield (cryostat space room), and also the environment. Each control volume is connected by several flow paths representing the lower, equatorial and upper ports, which enable heat transfer by natural convection. However, in Figure 2, only a single flow path is presented for better clarity. Heat transfer due to the conduction and the radiation between heat structures that include VV walls, VVTS, CTS, all magnet coils, cryostat walls, and the bioshield wall is also modelled. The model was developed for this specific event of gas ingress into the DEMO cryostat [5,6].

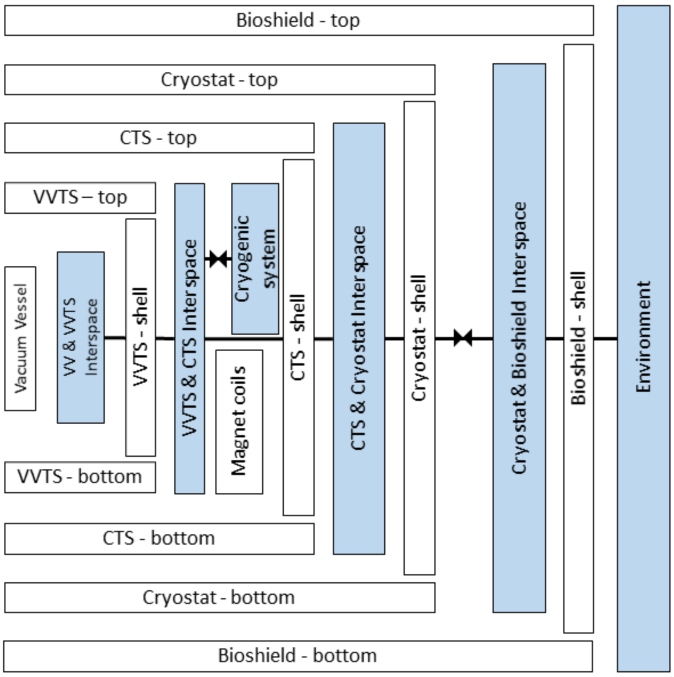

Figure 2: MELCOR nodalization.

3 RESULTS

3.1 Sealed cryostat (without rupture disk)

Figure 3 shows mass of the helium leaked through the break in the cryogenic system into the interspace between VVTS and CTS. For this analysis, a model without the rupture disk was used. It may be observed that the design pressure is reached at t = 0.07 h (250 s), but most of the helium (19 tons of 20 tons) was already released to the atmosphere inside the cryostat in the first 150 s. During such fast transient, the temperature of the He inside the cryostat at approximately 0.07 h (250 s) is only 50 K (Figure 4 right) and the pressure still needs to increase due to the thermal expansion of the gas.

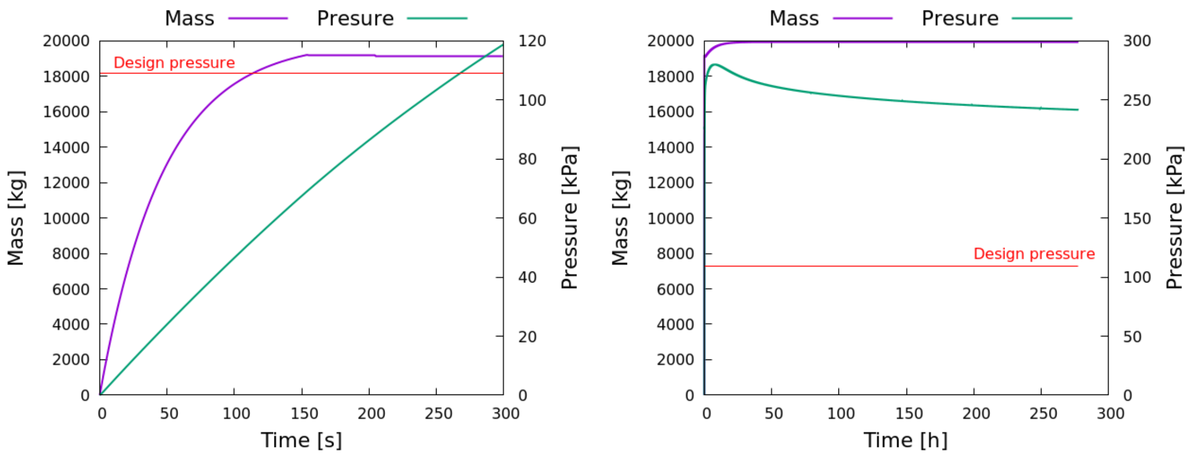

Figure 3: Leaked helium mass into the interspace between VVTS and CTS and the pressure inside the cryostat. The red line represents design pressure at 109 kPa. The graph on the right

shows the same quantities as the graph on the left, but only the initial development for the first 300 s.

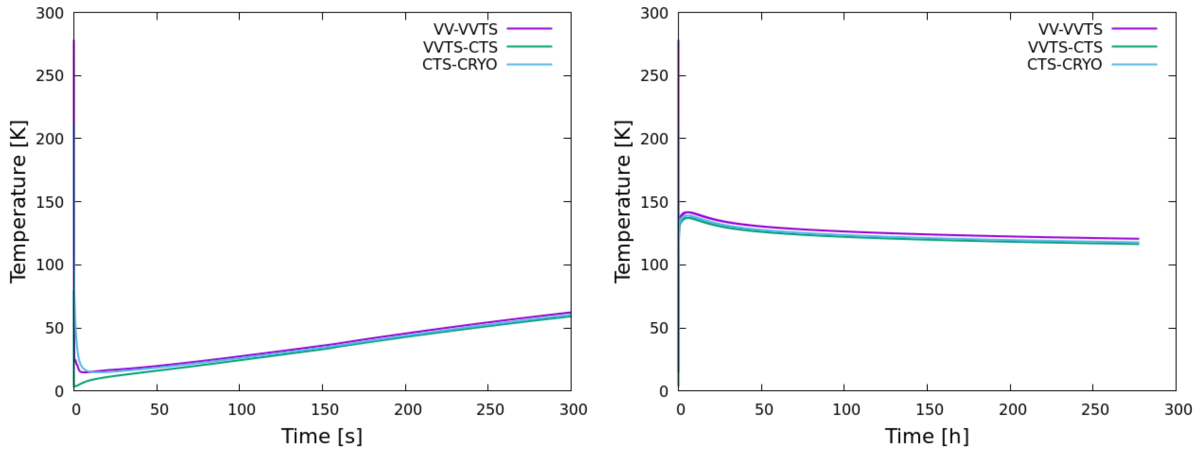

Figure 4: Gas temperature in control volumes (interspaces). The graph on the right shows the same quantities as the graph on the left, but only the initial development for the first 300 s.

The pressure (p) of the gas spread into a known volume (V) can be estimated using the ideal gas law. Figure 5 shows estimated pressure inside the cryostat (V = 20,163.2 m^3) regarding the He mass, in the case of $T_{He} = 120$ K. It can be observed that p = 100 kPa is reached when the cryostat is filled with 8,100 kg of He. To reach the cryostat design pressure (109 kPa) 8,800 kg of He are needed.

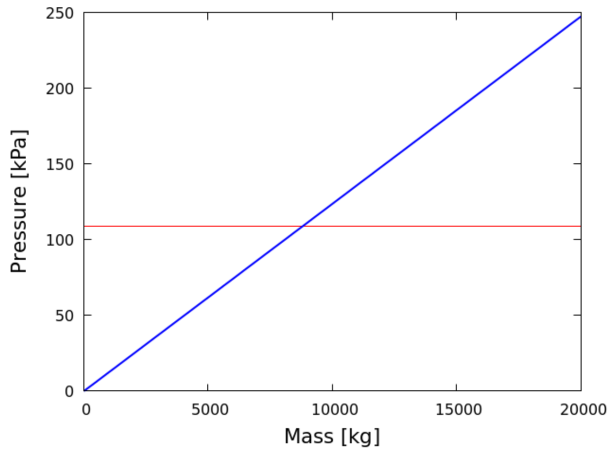

Figure 5: Estimated pressure inside cryostat using ideal gas law. The red line represents design pressure at 109 kPa.

3.2 Cryostat with rupture disk

A parametric study was performed to determine the minimum diameter of the rupture disk and relief pipe in order to maintain the pressure inside the cryostat below the pressure limit (109 kPa). Figure 6 shows the maximum pressure value reached inside the cryostat (in the interspace between the CTS and the cryostat) during the transient for different diameters of the relief pipes. It can be seen that for a rupture disk with a diameter of 0.55 m, the pressure remains below the cryostat design pressure of 109 kPa. It should be noted that the design leakage of the cryostat is not yet taken into account in the MELCOR model, and if it is considered, the pressure will be even lower.

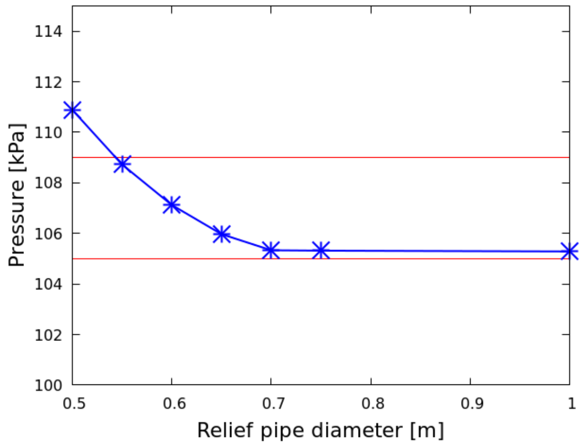

Figure 6: Maximal pressure inside cryostat regarding the relief pipe diameter.

A model with a pipe diameter of 0.55 m was used for the following analysis. Figure 7 shows the pressure inside the cryostat and in the cryogenic system. After the break, the pressure rapidly increases and reaches 105 kPa at t = 4.25 min (255 s), when the safety disk ruptures. Since the vacuum boundary is breached, the pressure inside all interspaces eventually stabilizes at an ambient pressure of 100 kPa.

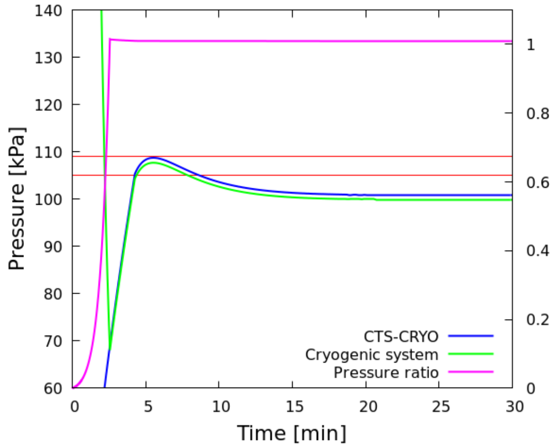

Figure 7: Pressure in the cryostat and in the cryogenic system, and the ratio between the pressure values.

Figure 8 shows the gas temperature in different interspaces between the VV and the bioshield. Since the VV is kept at 473 K, and the superconductive magnets are actively cooled at 4.2 K, the temperature eventually stabilizes between these values, at approximately 120 K. However, the considered postulated accident is expected to last 32 hours, for the duration of the loss of off-site power.

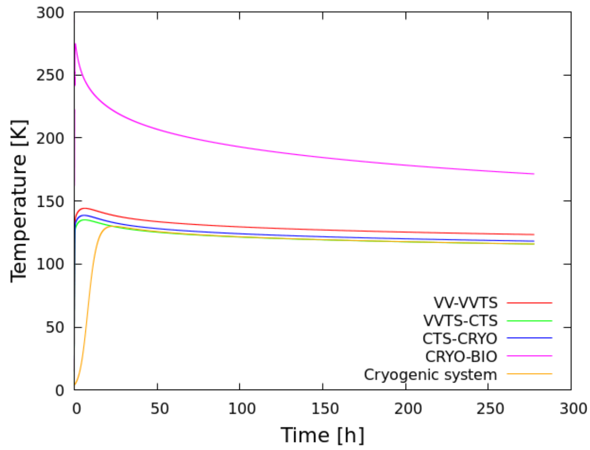

Figure 8: Gas temperature in different interspaces.

The velocity at which helium can exit the cryogenic system through the break depends on the ratio of the pressure inside the cryostat (p_{cryo}) to the pressure inside cryogenic system (p_{CS}). Figure 9 shows the velocity at which He exits the cryogenic system. Helium fills the interspace at a critical velocity (u^*) for up to 2.5 min (150 s) after the break. When the pressure in the cryogenic system and in the interspace between VVTS and CTS equalizes, the velocity decreases and even becomes negative. Namely, the He gas flows back into the cryogenic system, as the temperature in the interspace between the VVTS and CTS increases faster, as shown in Figure 8. After approximately 6 min (360 s), the velocity approaches 0 m/s.

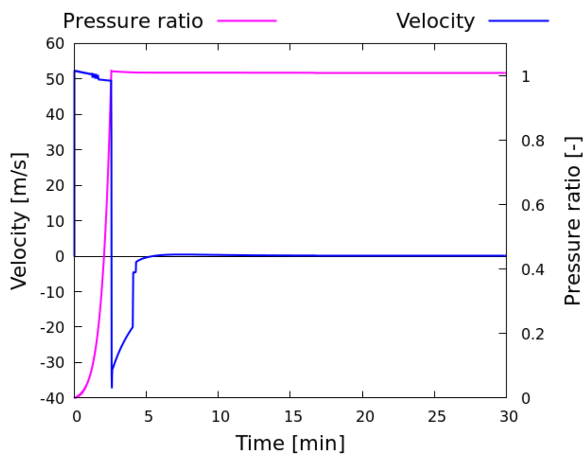

Figure 9: Helium velocity through the break in the cryogenic system.

Figure 10 shows the He mass flow through the break. At the beginning of the transient, the mass flow is the highest at 430 kg/s and decreases until 2.5 min (150 s) when it becomes slightly negative – it changes direction (-1 kg/s). After t = 6 min (360 s) the mass flow is approximately 0 kg/s.

To put our results into perspective, during a similar He ingress accident in ITER, 21 m^3 of helium at $T = 4.5$ K will be released from the toroidal field magnetic coils through a break in the magnetic cooling line into the cryostat at a mass flow rate of 231 kg/s during the first 2.5 s and 60 kg/s thereafter [7].

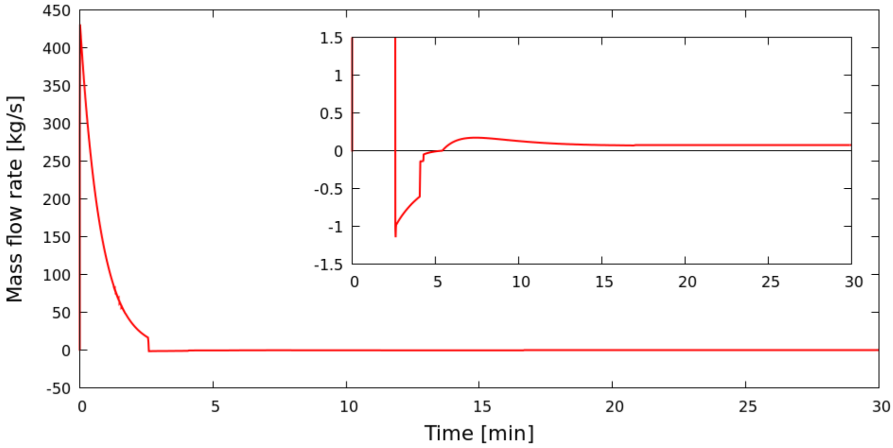

Figure 10: Helium mass flow through the break in the cryogenic system.

4 CONCLUSIONS

A MELCOR model of the DEMO fusion power plant was used to analyse the transient process after the break in the cryogenic system and the ingress of helium gas into the cryostat. The mass of released He, needed to reach the design pressure inside the cryostat, is estimated at 8,800 kg. Through a parametric study it was determined that a pressure relief safety system with 0.55 m diameter rupture disk and relief pipes is needed to ensure that the maximum design pressure would not be reached during the considered transient.

Since the initial pressure in the cryogenic system is higher than the pressure in the cryostat, the helium fills the interspace between the vacuum vessel thermal shield and the cryostat thermal shield initially at a critical velocity. A maximum mass flow of 430 kg/s is reached through the 0.2 m diameter break in the cryogenic system, and almost the entire He supply is released in 150 s. Due to the pressure relief safety system, a final pressure of 100 kPa is expected inside the enclosures between the vacuum vessel and the cryostat. However, a very low temperature value of 120 K is expected in the enclosures.

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