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# Development of the MELCOR Model for the Analyses of Large Helium Ingress into the DEMO Cryostat

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## ABSTRACT

The accident scenario postulated in this study considers that the cryostat in the DEMO fusion reactor is filled with helium gas through cryogenic system primarily devoted to cool the magnets. Since the DEMO cryostat is designed as a thin-walled structure, over-pressurization would cause its buckling and potential collapse. For this reason, the cryostat boundary fails at the over-pressure of 5 kPa with opening of a rupture disk.

A MELCOR model of the DEMO reactor is under development and will be used to predict this transient phenomenon and to assess the pressure and temperature values in the enclosures between the vacuum vessel and the cryostat.

## 1 INTRODUCTION

The purpose of our research is to analyse the loss of cryostat vacuum due to the helium (He) ingress. The initiating event considers a failure of cryogenic lines used for cooling of the Toroidal Field (TF) coils, resulting in spillage of large amount of He into the cryostat. It is assumed that the loss of cooling in TF coils rises the magnet temperature due to electrical resistance heating. The total He inventory in the DEMO TF coils is estimated at 8 tons [1] and is based on the extrapolation of the total He mass of 5.2 tons in the ITER magnet coils. Since the DEMO cryostat is designed as a thin-walled structure (in ITER the cryostat is a self-standing structure), the cryostat boundary fails at the over-pressure of 5 kPa with opening of a rupture disk [2].

A version of the MELCOR code V1.8.6, specially adapted for fusion reactor safety analyses (MELCOR for Fusion) will be used to perform the analyses. MELCOR is an integral engineering-level code that solves conservation equations of mass, energy and momentum for liquid and vapour phase. It includes several models that describe 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, modifications for water freezing and ice layer formation, enclosure thermal radiation model and others. Input modelling is based on the “control volume” approach that describes the fusion reactor system fluid volumes and the solid structures. The input MELCOR model shall include control volumes for the cryostat, the cryogenic system, the space between the vacuum vessel (VV) and the vacuum vessel thermal shields (VVTS), the interspace between VVTS and the cryostat thermal shields (CTS) that encloses the magnets, the interspace between the cryostat and the bioshield, and the environment. Each control volume is connected by the flow paths. The heat transfer is modelled by the heat structures that involve cryostat walls, VV walls, VVTS, CTS, and magnet coils.

The main goal of this study is first, to develop a generic input MELCOR model for the event of gas ingress into the DEMO cryostat and second, to apply it for the specific scenario of He ingress. A pre-conceptual geometry model of the DEMO Tokamak with the cryostat ([3], [4]) is shown in Figure 1. One toroidal sector is shown. A separate cryostat structure is presented in Figure 2.

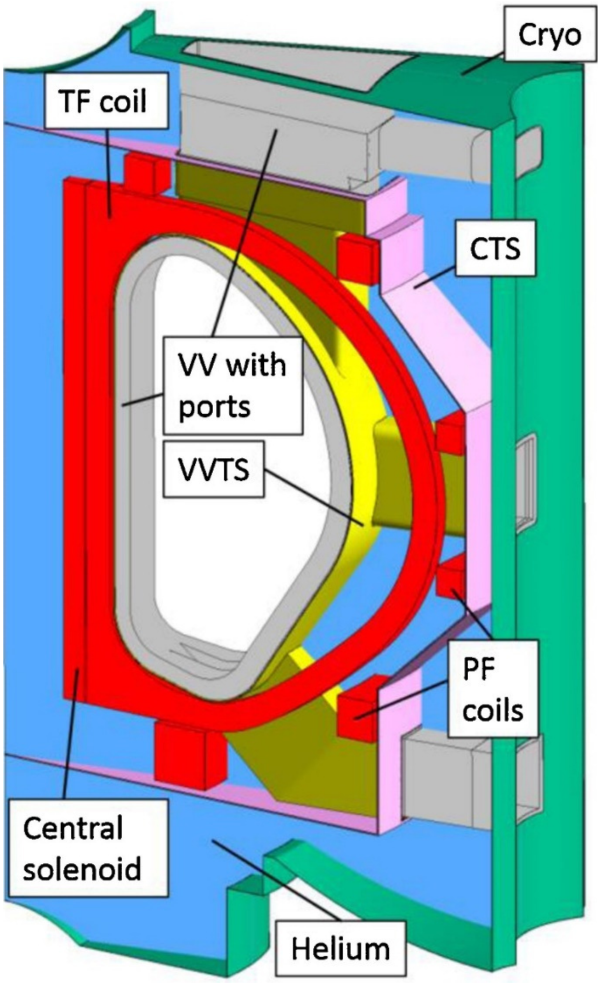

Figure 1: Simplified model of the DEMO tokamak internals. Blue colour represents the available volume that is filled with helium [5].

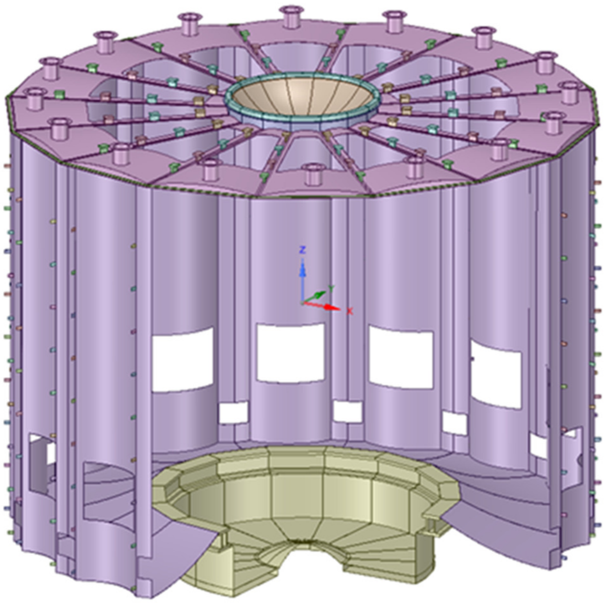

Figure 2: Conceptual design of the cryostat structure [2].

## 2 ACCIDENT SCENARIO

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

The He ingress causes pressure increase, and as soon as the pressure in the interspace between the cryostat and CTS reaches an arbitrary value, the plasma shutdown procedure is activated. This pressure set point value is based on the remaining He inventory in the cryogenic system and the cooling capability of the system. When the cooling in the TF coils is lost, the magnet temperature rises due to electrical resistance heating.

A 32-hour long loss of off-site power is assumed to coincide with the plasma shutdown, which disables the cryostat depressurization system, the heating, ventilation and air conditioning system (HVAC), and venting detrition system (VDS) in the tokamak hall and galleries. However, the emergency cooling system in the VV-PHTS is able to sufficiently remove the decay heat from the VV during this postulated accident and keep VV at constant temperature [6], [7].

To avoid any 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.

## 3 MELCOR MODEL – CONTROL VOLUMES AND FLOW PATHS

The developed MELCOR model will be used to study the pressurization and the change of the temperature of the VVTS, CTS, superconductive magnets, cryostat, and interspaces during the postulated accident described in Section 2.

Heat and fluid transfer including radiation, conduction and convection are modelled between solid structures and control volumes. The input model includes control volumes for cryogenic system, interspace between VV and VVTS, interspace between VVTS and CTS that encloses the magnets, interspace between CTS and cryostat, and interspace between cryostat and bioshield. Furthermore, also a control volume representing the environment is included in the model, as a final heat and fluid sink. The heat transfer is modelled by the heat structures that represent VV, VVTS, superconducting magnets, CTS, cryostat and bioshield. The model nodalization is shown in Figure 3.

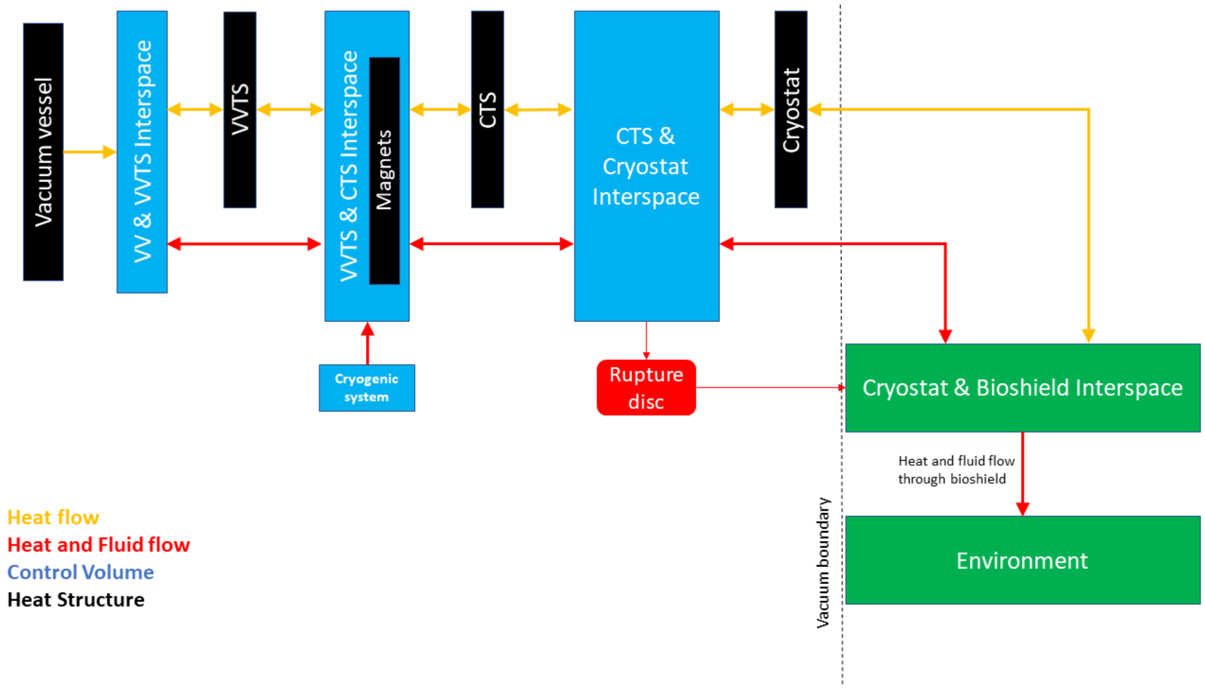

Figure 3: MELCOR nodalization.

Cryogenic system stores 8 tons of helium at pressure of 1.8 MPa and temperature of 4 K [8]. Depending on the accident scenario, this He is released into the interspace between VVTS and CTS or the interspace between CTS and cryostat.

The volume of the VV is approx. 6260 $m^3$. The pressure inside the VV is 100 Pa and the assumed average temperature of the VV wall is 453 K [5]. The VV leak rate is 1%/day at ± 100 Pa. During the postulated accident scenario adopted in this work, the VV maintains its integrity and the emergency cooling system in the VV is able to sufficiently remove the decay heat from the VV to the tokamak cooling room without heating up the cryostat [6], [7].

Vacuum vessel thermal shield (VVTS) and cryostat thermal shield (CTS) that shield the magnets from the heat radiation of the VV and cryostat are constructed as thin wall structures with a thickness of 3 cm [1]. The volumes of the interspaces between VV and VVTS and between VVTS and CTS are 1900 $m^3$ and 6840 $m^3$, respectively. The VVTS completely surrounds the VV and VV ports up to the CTS [9]. The contact between the VVTS and CTS should be loose to allow thermal expansion and provide thermal shielding function at the same time. In ITER, a labyrinth seal provides such loose contact between both thermal shields [8]. In our model, same gaps between thermal shields are adopted as in Draksler et al. [5]. Figure 4 shows the locations of the gaps between VV, VVTS and CTS near the ports. The spacing between VVTS and the VV ports is 12 cm (Figure 4 (a)), while the spacing between VVTS and CTS is 5 cm (Figure 4 (b)). These gaps allow He to fill the entire free space between VV and cryostat.

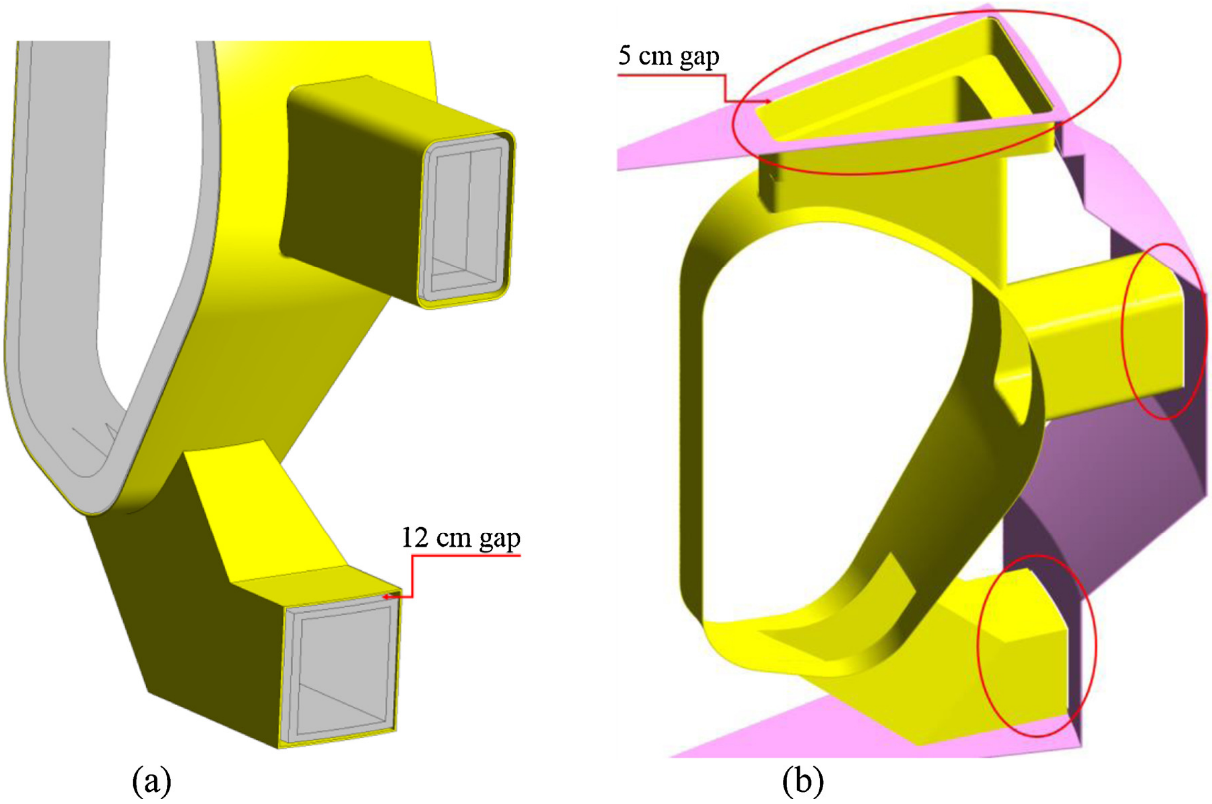

Figure 4: Vacuum vessel model with ports, VVTS (yellow) and CTS (pink) [5].

Superconductive magnets located in the interspace between VVTS and CTS are the main heatsink, which decreases the temperature in the compartments. The magnets are assumed to be at constant temperature of 59 K, which is established due to the fast discharge of the coil currents [5]. This is a conservative assumption that enables a strong natural convection inside the cryostat with the highest possible cooling of the cryostat walls.

Cryostat represents the vacuum boundary between internals (VV, VVTS and CTS) and the environment. The cryostat is a cylindrical structure, with a free volume of 41500 m$^3$ [8][10], and the leak rate of the cryostat is 1%/day at ± 100 Pa. During the normal operation it is vacuumed, while for abnormal conditions it is designed to withstand the internal over-pressure of 9 kPa [2]. To avoid any damage of the cryostat structure, a rupture disk opens at an overpressure of 5 kPa, which breaks the integrity of the cryostat. The developed MELCOR model will enable to compare the effect of the rupture disk venting lines discharge towards cryostat and bioshield interspace, tokamak cooling room, and tokamak hall. Due to any possible activated corrosion products in the interspaces, the rupture disks system must contain additional filtration system. Such “Filtered Containment Venting System” would relieve the pressure inside the cryostat, transport the exhaust through the filters, where any possible radioactive material is captured, and finally release the exhaust towards the environment, through additional interspaces.

Bioshield is a 2 m thick cylindrical structure made of borated concrete built around the cryostat. It is intended as a radiation shield for corridors used during the normal operation of the power plant [11]. The interspace between cryostat and bioshield has a volume of 13280 m$^3$ and is filled with air at 293 K pressure of 98 kPa. The leak rate of the bioshield is 100 %/day at 300 kPa.

A control volume representing the environment with normal conditions (T = 293 K and p = 101.3 kPa) is also included in the model. The environment acts as the final sink for released heat and fluid.

In Table 1 control volumes, heat structures and flow path geometrical properties are listed.

Table 1: Control volumes, heat structure and flow paths geometrical properties [3], [6], [7].

| | Type | Area [$m^2$] | Volume [$m^3$] |
|---|---|---|---|
| VV | Heat Structure | / | 6260.00 |
| VV & VVTS Interspace | Control Volume | / | 1898.97 |
| Gap between VV ports & VVTS | Flow Path | 83.12 | / |
| VVTS | Heat Structure | / | 216.70 |
| VVTS & CTS Interspace | Control Volume | / | 6842.70 |
| Gap between VVTS & CTS | Flow Path - Gap | 34.63 | / |
| CTS | Heat Structure | / | 168.20 |
| CTS & Cryostat Interspace | Control Volume | / | 11421.53 |
| Cryostat | Heat Structure | / | 130.20 |
| Cryostat and bioshield Interspace | Control Volume | / | 13275.45 |
| Environment | Control Volume | / | / |

## 4 CONCLUSIONS

An accident scenario of the loss of vacuum inside the DEMO cryostat due to large ingress of helium gas was postulated. Based on this accident scenario, a MELCOR input model of the DEMO fusion power plant was developed to reproduce the transient process. Heat and fluid transfer including radiation, conduction and convection are modelled between solid structures and control volumes. The input model includes control volumes for cryogenic system, interspace between vacuum vessel and vacuum vessel thermal shield, interspace between vacuum vessel thermal shield and cryostat thermal shield that encloses the magnets, interspace between cryostat thermal shield and cryostat, and interspace between cryostat, bioshield, and environment. Each control volume is connected by the flow paths for heat and or fluid. The heat transfer is modelled by the heat structures that represent vacuum vessel, vacuum vessel thermal shield, superconducting magnets, cryostat thermal shield, cryostat and bioshield.

## ACKNOWLEDGMENTS

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