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Development of DEMO Thermal Shield Concept: Design Requirements and Expected Thermal Loads

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ABSTRACT

The main function of thermal shields is to minimize the thermal radiation load from the warm components, like vacuum vessel and cryostat to superconducting magnets operating at cryogenic temperature of about 4 K. Initial concept of DEMO thermal shields, based on the recent DEMO baseline design is presented in this study. Main TS functions, its design features and requirements are described. These include also space requirements for TS installation that are based on thermal expansion study of relevant DEMO tokamak components. Critical locations for TS placement are identified. In addition, the expected static heat loads on thermal shields at normal DEMO operating conditions are evaluated using the validated theoretical model. Thermal radiation between the surfaces and heat conduction loads through the TS physical supports are considered. The results show that thermal radiation from the vacuum vessel presents by far the largest contribution to the overall TS heat load.

1 INTRODUCTION

Like ITER, the future demonstration power plant DEMO will rely on superconducting magnets to confine and control the plasma within the vacuum vessel. The superconducting magnets are housed (along with a number of other systems) inside a second vacuum chamber called the cryostat. The systems operate at high vacuum conditions and at very different temperatures. The superconducting magnets in DEMO will be actively cooled by helium at about 4 K and enclosed between the hot vacuum vessel, with operational temperature of 200ºC, and the cryostat at the room temperature. One of the key components protecting the magnets and mitigating the radiation heat transferred from the vacuum vessel and the cryostat are the thermal shields, which have to be placed on both sides of the magnet system. To effectively reduce thermal radiation, thermal shields should have surfaces with low emissivity and should be actively cooled in the temperature range between 80 K and 120 K [1],[2].

This paper describes the initial concept of thermal shields for DEMO power plant that is based on the recent DEMO baseline design with 18 toroidal sectors [3]. Main functions and design requirements are given first and are followed by description of the design concept with its main features characteristic for DEMO. The assessment of space requirements for TS installation between the vacuum vessel (VV) and the superconducting magnets is based on the thermal expansion analysis. The initial TS design is used to estimate the expected static heat loads on TS at normal operating conditions. The presented heat loads include thermal radiation loads and heat conduction losses through the physical supports.

2 THERMAL SHIELD MAIN FUNCTIONS AND DESIGN REQUIRMENTS

At the present stage of DEMO development, the designs of the vacuum vessel, ports, magnets, cryostat and support structures are still subjected to changes. Therefore the presented thermal shields (TS) design should be considered as preliminary, moreover it neglects some of the components, such as TS manifolds and TS instrumentation. Also the supporting structures of the thermal shield as well as the gravity supports of the Toroidal Field Coils (TFC) are modelled on the pre-conceptual level for the purpose of thermal analysis. Design concepts of the supports are strongly based on ITER experience [4]. The main functions, design requirements and system interfaces are assumed to be similar as in ITER [4],[5]. They are briefly summarized in this section.

The main role of thermal shield (TS) is to minimize the thermal radiation from the warm components, like vacuum vessel and cryostat to the magnets operating at cryogenic temperature of 4 K. TS system shall be robust and reliable in terms of long-term operation. Following [5] and [4] the thermal shields shall:

- provide an optically opaque barrier to thermal loads from the warm components to the superconducting coils and structures maintained at about 4 K,
- provide an acceptably low thermal radiation emissivity such that the heat loads to the TS system and magnet systems can be handled cost effectively by the cryogenics plant. Optimal TS cooling temperature depends on TS configuration and VV operating conditions. In DEMO it is expected to be in the range between 80 K and 120 K.
- The operating pressure and pressure drops shall be compatible with the cryoplant warm compressors providing He coolant to the TS cooling system.
- Some other relevant design requirements at the moment follow ITER specifications and are described in detail in ITER System requirments docoment [5].

3 DESIGN CONCEPT

Main features of the TS design concept are taken from ITER TS design and are adapted to the current DEMO design [3] taking into account the DEMO TS shape and its surfaces. Initial TS design concepts are described.

3.1 Dimensions and placement

The vacuum vessel thermal shield (VVTS) is placed between the VV and the magnet structure. The VVTS fully surrounds the VV and four VV ports and is extended up to the cryostat thermal shield (CTS). Very large and long ports in the current DEMO design [3] present the main difference between the DEMO and ITER VVTS design. The geometry of DEMO tokamak and a 20^{o} sector of the DEMO VVTS are shown in Figure 1. Due to the large ports, the ratio between the torus part of the VVTS and the VVTS panels surrounding the ports is significantly higher for DEMO than in the case of ITER. In the case of DEMO tokamak, the VVTS surface surrounding the 18 upper ports is much larger than the torus surface surrounding the VV.

The CTS is placed between the cryostat and the magnet structure, protecting the magnets from radiating cryostat surfaces. As schematically presented in Figure 1, the CTS consist of 3 parts: Upper CTS (UCTS), Lower CTS (UCTS) and Equatorial CTS (ECTS). The initial geometry of the UCTS follows the shape of the cryostat. Current CTS dimensions are 34.4 m in height and 35.2 m in its maximum diameter (see Figure 1 right). Main TS dimensions and surfaces are listed in Table 1.

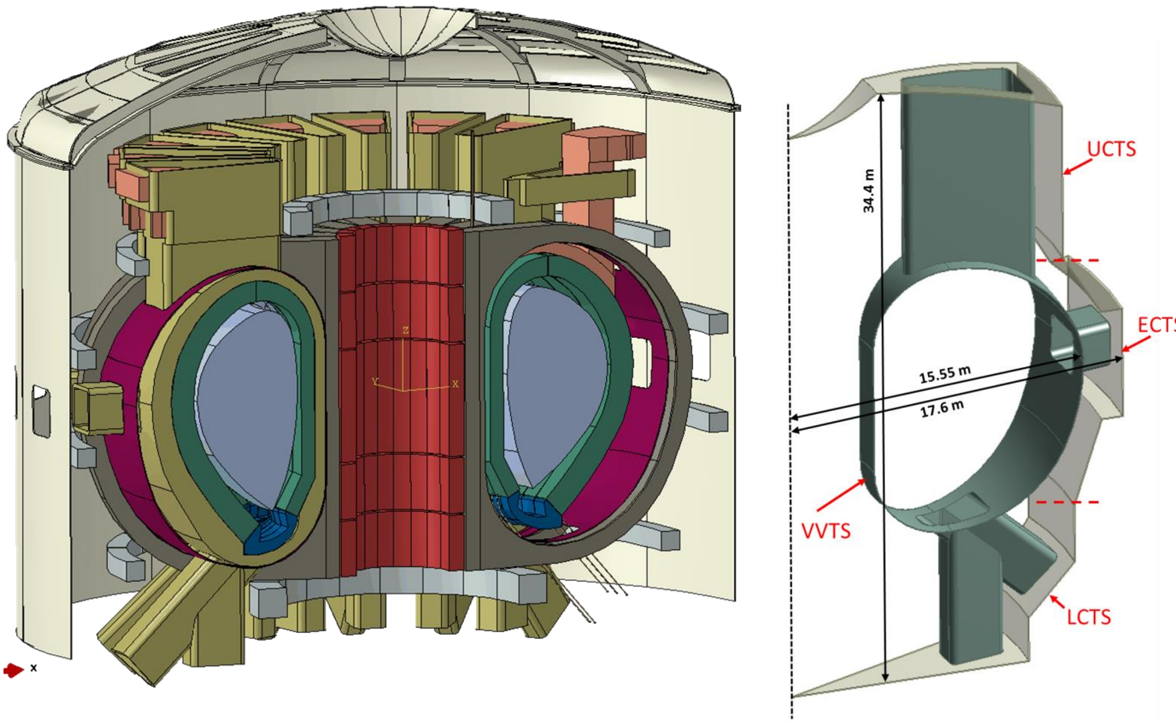

Figure 1: CAD geometry of DEMO tokamak (left). Initial design concept of DEMO thermal shields with main dimensions. 20° sector is presented (right).

Table 1: Dimensions and surfaces of main TS components

Component	
CTS cylinder outer diameter	35.2 m
CTS height	34.4 m
Upper CTS surface	1269 m^2
Lower CTS surface	1172 m^2
Equatorial CTS surface	1702 m^2
VVTS torus outer diameter	31.1 m
VVTS torus height	11.6 m
VVTS surface without ports	2100 m^2
VVTS surface enclosing ports	5247 m^2

3.2 TS panels and supports

The structure of the TS panels is assumed to be the same as in ITER [4] and should consist of a single wall structure primarily fabricated of stainless steel, covered on both sides with a thin, low emissivity layer of silver to keep the emissivity value below 0.05.

At the present stage, VVTS and CTS in DEMO are modelled as a shell element with panel thicknesses similar to ITER. In ITER single wall panels with the thickness of 20 mm are used for the VVTS and 10 mmm thick panels are used for the CTS and the Support Thermal Shield (STS) [4]. The panel thickness does not have a significant effect to the thermal load calculation, but is important for estimation of required clearances for installation of thermal shields between the VV and TF coils.

Basic concepts of the TS supports are described in this study, mainly for the purpose of estimation heat conduction loads. The locations of TS supports are the following:

- Equatorial part of the VVTS is supported from the TF coil in the proximity of the upper edge of the equatorial port.
- Supports for the VVTS part around the ports:
    - Upper port VVTS is supported by the UCTS.
    - Equatorial port VVTS is attached to ECTS
    - The two lower ports VVTS (inclined and vertical) are supported by LCTS
- CTS supports:
    - Upper CTS is attached at several locations to the cryostat top lid by beam supports. ITER solutions can be adopted [4]
    - Lower CTS is attached at several locations to the cryostat floor by flexible plate supports. ITER solutions can be adopted [4]
    - Equatorial CTS is attached to the VVTS ports

Cooling of the thermal shields will be established by the cooling pipes attached to the TS panels and filled with pressurized helium gas that maintains the TS temperature in the range between 80 and 120 K. The final TS temperature is subject of optimisation analysis [6].

3.3 Space requirements for the installation of thermal shields

Space requirements for placing of CTS between the cryostat and the magnets reveal no critical gap locations [7]. The most critical is the placement of VVTS between the VV and TF coils. The actual ITER structural thickness of the VVTS including panel, cooling tubes, bolting joints and flanges is 56 mm [4]. Note, that in the gap assessment study for DEMO the same VVTS panel and pipe thicknesses as for ITER are considered. The DEMO design of the VVTS assumes also the installation of one passive Multi-Layer Insulation (MLI) package (15 mm thickness) on the warm side of VVTS [8]. The overall thickness of DEMO VVTS without flanges and bolting joints can be estimated to 50 mm and to approximately 65 mm for the overall structure thickness.

The displacements due to thermal expansion of DEMO components have been assessed in the previous study [7], undergoing from the initial state at room temperature to the "hot" operational state. Recent analysis rather adopted the strategy with the initial baseline design assumed at hot operating state [9], where the tokamak components are subjected to the expansion or contraction at the transition towards the final state at room temperature. Table 2 lists the component temperatures used in the analysis.

Table 2: Temperatures and materials of the components

Component	Initial state Operating T (K)	Final state Room T (K)	Material
Magnets	4	293	SS-316
CTS	80	293	SS-304
VVTS	80	293	SS-304
VV	473	293	SS-316
Blankets	573	293	F82H-Eurofer
Divertor	573	293	F82H-Eurofer
Cryostat	293	293	SS-304

Initial clearances in the tokamak geometry and the main results of thermal expansion analysis are summarised in **Error! Reference source not found.**. The results in Table 3 present absolute and relative displacements of components at specific positions of the tokamak geometry that are illustrated on Figure 2. For each component absolute displacements in radial (U_r) and vertical (U_z) directions are given. Relative displacements between the VV and TFC components in the relevant direction (vertical or radial) at the specified positions are provided. Note that only negative relative displacements cause shrinking of the initial gap between the components. To assess the required space for installation of VVTS the initial geometry clearances at the operating state are compared with the final clearances at the room temperature. Taking into account the estimated overall thickness of the VVTS structure (65 mm), two critical positions can be identified where the shrinking of the gap between the VV and TFC can be expected. The gap at the position H shrinks in radial direction from 120 to 82 mm, which still seems to be wide enough for VVTS placement. The final clearance may however become insufficient if the thermal expansion of the VVTS would be considered. Position L is the second critical point, where the shrinkage of the gap in vertical direction (from 120 to 67 mm) takes place. The final gap is barely wide enough for VVTS installation, even without taking into account the expansion of VVTS. Both positions can be treated as critical, requiring larger initial clearances in the design.

Table 3: Absolute and relative displacements at the points of interest in radial (Ur) and vertical (Uz) directions

Point of interest	Component	U_r (mm)	U_z (mm)	Relative displ. (mm)	Initial clearance at operating state **Error! Reference source not found.** (mm)	Final clearance at room temp. (mm)	Required min. space (mm)
C	VV	-32	-86				
	TFC	40	96	182 (vert)	110 (vert)	292 (vert)	
H	VV	-17	-57	-38 (rad)	120 (rad)	82 (rad)	critical
	TFC (in)	21	60				
I	VV	-54	-57	127 (rad)	960 (rad)	1087 (rad)	
	TFC (out)	73	60				
L	VV	-31	-29				
	TFC	39	24	-53 (vert)	120 (vert)	67 (vert)	critical

*Negative value indicates that relative displacement is decreased.

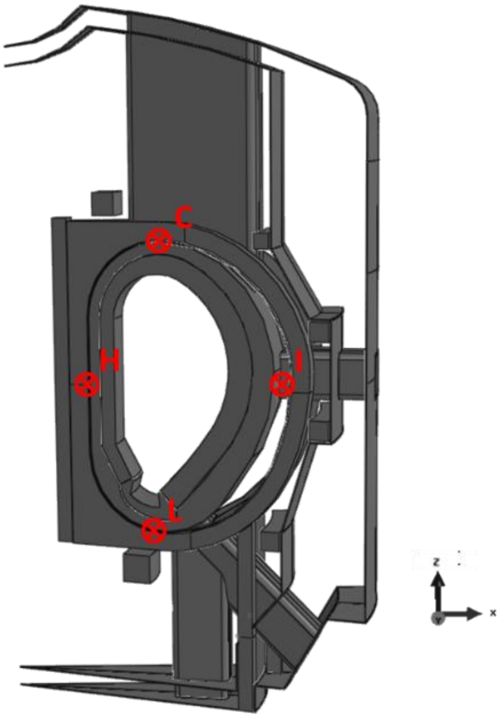

Figure 2: Points of interest in the geometry of the DEMO Tokamak model.

4 HEAT LOADS ON THERMAL SHIELDS

The expected static heat loads on thermal shields at normal operating conditions (see Table 2) are presented. The accumulated heat is removed by active cooling system connected to the cryogenic plant. The heat loads are calculated by analytical methods that are in detail described in [10], and have been prior validated by numerical simulations [11],[12]. The calculated heat loads include thermal radiation exchange between the hot surfaces (VV and cryostat) and cold surfaces (thermal shields) and the heat conduction losses through the supports and attachments. It should be noted that nuclear heating is not considered in this analysis. Though it may importantly affect the heat load on magnets [13], the relative effect on thermal shields, being the main focus of the present study, is not expected to be high. In the ITER case [14], the neutron heating contributes to about 1% of the heat load on the thermal shields.

The calculated thermal radiation and heat conduction contributions at the normal operating conditions are summarized in Table 4, assuming that VVTS and CTS oprate at the temperature of 80 K. Temperatures of the hot and cold components (denoted as T_{hot} and T_{cold}) and the corresponding heat load sources are listed in the first two columns of Table 4. The calculated heat loads on the VVTS and CTS are collected in the next columns. It can be seen that VVTS intercepts more than 80% of the total heat load (912.6 kW) due to the thermal radiation from the vacuum vessel. The heat load on the CTS is nearly five times lower (189.4 kW) with thermal radiation being the main contributor. Heat conduction through the TFC gravity supports (38.4 kW) also presents a substantial portion of the total CTS heat load.

Table 4: Heat load contributions at normal operating conditions

Temperatures T_{hot}/T_{cold}	Heat load source	VVTS heat load	CTS heat load	Total heat load on TS
473 K / 80 K	Thermal radiation from VV	912.8 kW	/	
293 K / 80 K	Thermal radiation from cryostat	/	149.5 kW	
293 K / 80 K	Gravity supports heat conduction	/	38.4 kW	

293 K / 80 K	CTS support heat conduction	/	1.5 KW	
Total		**912.8 kW**	**189.4 kW**	**1,102.2 kW**

Unlike the superconducting magnets, that have to operate at 4K, the optimal working temperature of the thermal shields depends on the heat load distribution between the components and consequently influences the overall efficiency of the cryogenic plant [15]. Heat load contributions over the range of thermal shield temperatures is shown in Figure 3. Equal temperatures of the VVTS and CTS, denoted as T_{ts} are assumed. Thermal radiation and heat conduction flows over the range of thermal shield temperatures T_{ts} (between 70 and 200K) are shown in Figure 3. It can be seen that the heat load on VVTS and CTS decreases with increased T_{ts}. Thermal radiation to the VVTS represents the largest heat load contribution. Heat conduction losses due to thermal shield supports and attachments represent only a smaller part of the total TS heat load.

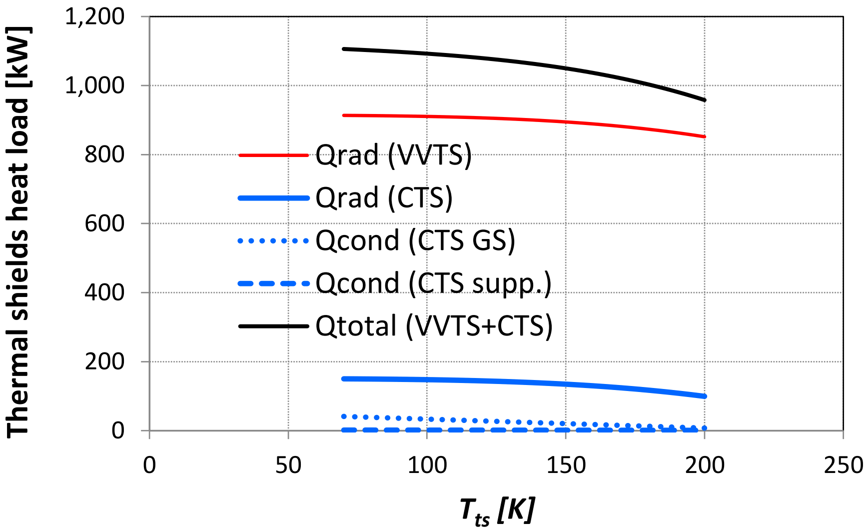

Figure 3: Heat load contribution to thermal shields at varied TS temperature.

5 CONCLUSIONS

The initial concept of thermal shields based on the recent design of DEMO tokamak has been presented. Main TS functions and design requirements have been defined and the heat load contributions at normal operation were evaluated.

DEMO design options and constraints are to the great extent based on the ITER experience, for example the same thermal shield panel thickness and cooling pipe dimensions are adopted. Due to high thermal radiation at normal operating conditions, an additional space on the VVTS side for the passive thermal shielding with the thickness of 15 mm should be reserved. The estimated overall thickness of the TS structure is estimated at 65 mm. Thermal expansion analysis of the current baseline tokamak design reveals two critical locations, where the installation of VVTS in the interspace between the VV and TFC is questionable.

Thermal radiation on the VVTS presents by far the largest contribution to the total heat load on thermal shields (more than 80%). Consideration of heat conduction through the physical support affects primarily the heat load on CTS, but even here it presents only a smaller contribution.

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