Design Progress and Analysis for ITER Thermal Shield

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Abstract. The thermal shield (TS) system of ITER plays the role of reducing thermal loads to the cold structures that operate at 4.5 K. This paper presents the results of the detail design of TS, which are the design of joints, design of cooling panels. The results of structural analysis and thermal analysis to support the detail design are also reported. The detailed design of joints is done to satisfy both structural stability of the TS and assembly and manufacturing feasibility. Structural analysis under various design loads was conducted in order to support the new joint design. Detailed design of cooling panels was performed to minimize panel deformation due to tube welding by applying a new tube attachment scheme and cooling line layout. The result of thermal analysis for the new design of cooling line layout is reported in this paper.

1. Introduction

The thermal shield (TS) system of ITER plays the role of reducing the heat load transferred by thermal radiation and conduction from warm components to the components and structures that operate at 4.5 K [1]. The ITER thermal shield consists of equatorial TS (ETS), upper cryostat TS, lower cryostat TS and support TS (STS). Thermal radiation to the superconducting magnets is minimized by operating the thermal shields at low temperature and by providing surfaces with low emissivity using silver coating. Figure 1 shows the configuration of ITER thermal shields [2].

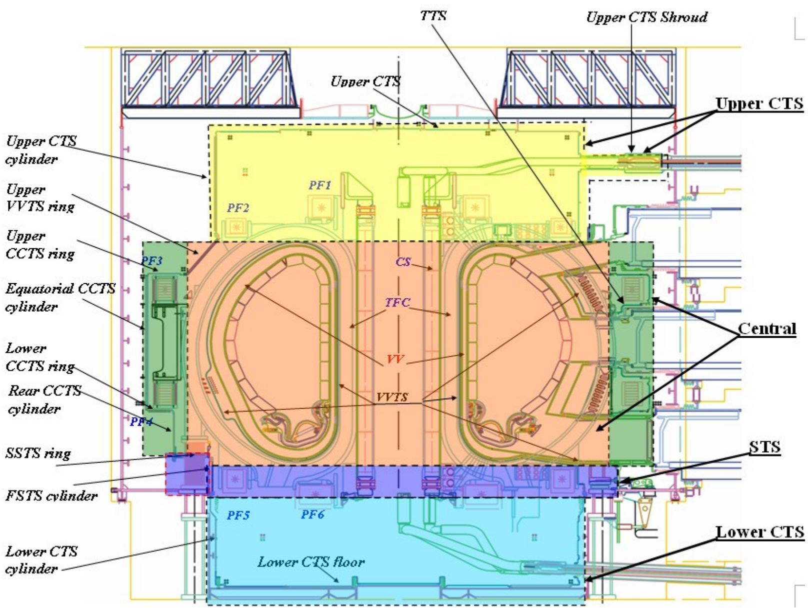


FIG. 1. Configuration of ITER thermal shield.

The ITER Thermal Shield is composed of many panels and joints which connect each panel. Cooling tubes are attached to the panel to maintain the temperature of the TS within the range of 80~100 K during plasma operation. The thermal shields are cooled by a pressurized helium

gas. Pressurized helium gas from the main cryogenic plant, with an inlet temperature and pressure of 80 K and 1.8 MPa, respectively, is used to cool the thermal shield system.
The design of the ITER thermal shield is not fixed yet and some modification must be made of for some TS components compared with the concepts described in the DDD-2004 and other papers [1,3,4]. In particular, design concepts for vacuum vessel thermal shield (VVTS) cooling tubes have not been studied in detail, so far. Various joints which connect the thermal shield panels need to be changed, also. So, this paper concentrates on the design of joints and cooling tubes and verification of the design in aspect of structural stability and heat load.

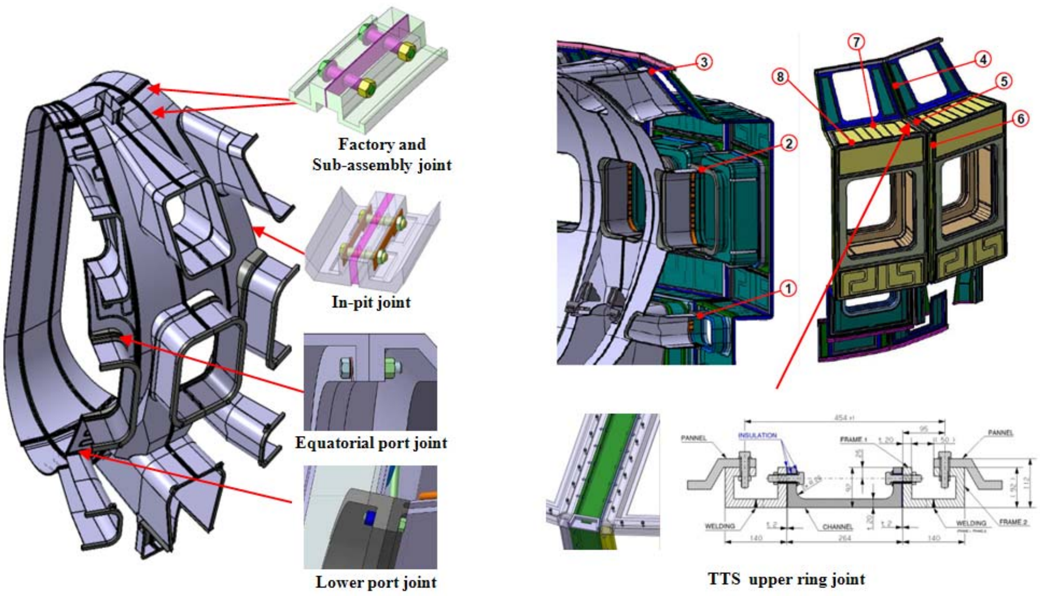
The detailed design of joints for the VVTS and equatorial cryostat thermal shield (ECTS) is done to satisfy both structural stability of the TS and assembly and manufacturing feasibility. Structural analysis under various design loads was conducted in order to support the new joint design. Detailed design of cooling panels was performed to minimize panel deformation due to tube welding by applying a new tube attachment scheme and cooling line layout. The results of thermal analysis are reported in this paper.

2. Design Progress

2.1 Structural Joints

Joint designs for VVTS and ECTS have been developed for the ITER Thermal Shield. The design of these joints was improved for structural strength and for easy assembly and manufacturing. Electrical insulation and compensation of misalignment are also considered in the design.

The VVTS factory joint is a bolted type, and its detailed dimensions were determined through structural analysis. The field port joint design is a bolted type rather than a stud weld type to ensure good accessibility. Detailed designs of transitional Thermal Shield (TTS) ring joints, ECTS sector joints and equatorial port joints were also conducted and 3D CATIA modeling for all joints was performed as shown in Figure 2.



(a) Joints of VVTS (b) Joints of CTS

FIG. 2. Design of joints for ITER thermal shield.

VVTS joints are classified according to its function and the location. Sub-assembly insulated joints are connecting VVTS inboard and outboard. Factory insulated joints are located between VVTS 10˚ sector. Sub-assembly joints are located VVTS 20° outboard sectors. Field joints are located between VVTS 40° sectors on site assembly. Field port joint are bolted type joint like previous joints but port joints are welded type joint. Figure 2 shows the current design of sub-assembly joint and field joint. We are trying to change welded type into bolted type for the in-pit joint as shown in Figure 2 for easy assembly in the ITER site.

Joints for the ECTS are designed to provide the compensation of the misalignment for the assembly and insulation. ECTS sector joint located between ECTS 20° sectors. TTS ring joints connect Upper/Lower TTS ring and VVTS/STS ring. VVTS/TTS joints connect Equatorial Port/Lower Port and TTS.

2.2 Cooling Panel

The design of the cooling panel for the VVTS has been carried out, which determines the distance between cooling lines, cooling tube attachment scheme and cooling line layout. And the design of the cooling panel for the ECTS is also modified based on the previous design.

The main design parameters for the cooling panel are the thickness of the panel, the size of the cooling tube, the temperature of the coolant, the welding method, and the layout of the cooling tube. The dimensions of the cooling tubes are 13.5 mm and 2 mm for the outer diameter and wall thickness respectively. These were determined taking into consideration the pressure drop and to minimize the possibility of burn-through during welding. The method of attaching the cooling tube to the panel of the thermal shield is important in aspect of heat transfer and manufacturing. The previous design concept for the cooling tube attachment is continuous welding with 2.5 mm thick copper clad stainless steel L-brackets, but this method is hard to satisfy the manufacturing tolerance due to the deformation of the panel caused by welding [5]. So, we designed cooling tube to be welded directly on the panel in a staggered fashion to minimize welding distortions and to maximize thermal contact. And welding path and length of the welding was determined by thermal analysis.

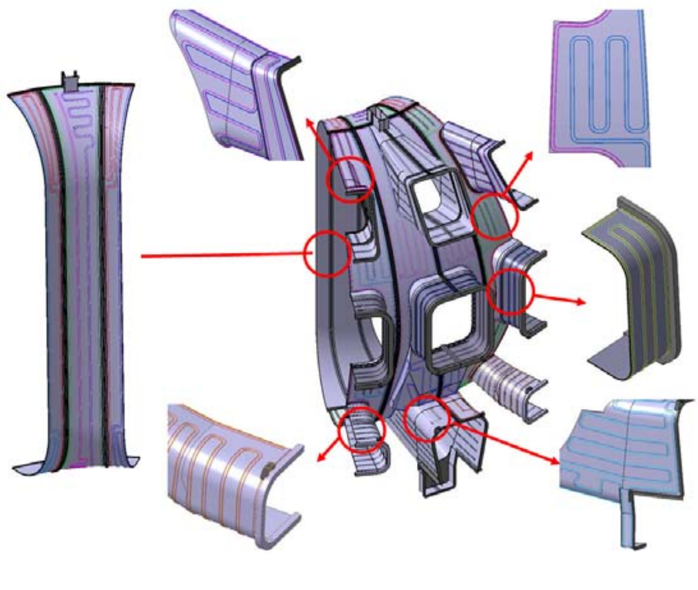


FIG. 3. Cooling line layout for ITER vacuum vessel thermal Shield.

The full 3D CATIA models are generated for VVTS and ECTS with the designed cooling tube layout. Figure 3 shows the 40 degree sector models of VVTS describing detailed tube tracing.

3. Supporting Analysis

3.1 Structural Analysis

Both Global and local analysis have been performed to verify structural stability for the ITER thermal shield. Global analysis focuses on the determination of displacement and primary stress intensity as well as reaction force in the inboard/outboard support. Local analysis intends to check stress level in the TS joint using ANSYS sub-modeling procedure [6]. The main loads on the TS are gravitational, seismic, electromagnetic forces and TF coil out-of-plane deformation. Structural analysis was conducted for each load applied on the TS and load combinations were also considered to verify the new design.

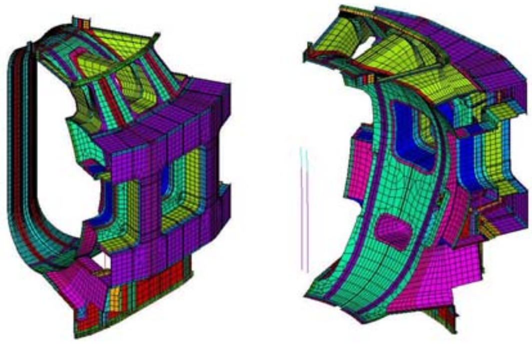


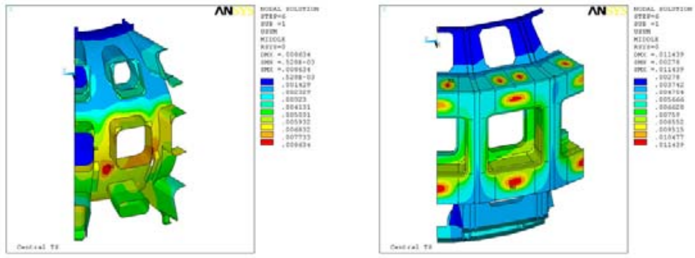
FIG. 4. FE model of equatorial thermal shield.

Global FE model corresponds to the 40˚ sector of the regular equatorial TS as shown in Figure 4. ANSYS cyclic symmetric condition is applied for the cyclic symmetry boundary. Inboard upper/lower strip and outboard support are described by bar element to fix displacement of ETS. In the FE model, joints are modeled by layers which have orthotropic properties [6]. Pre tension load, which is 2/3 of the yield strength, was applied in the bolt for all joints.

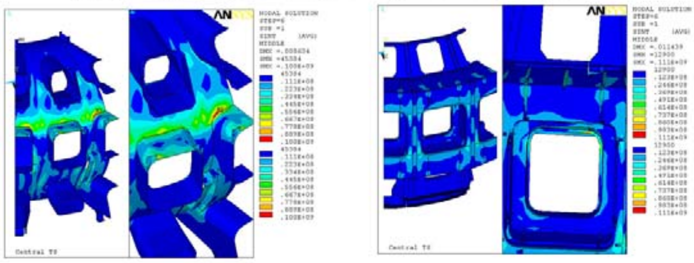
For the consideration of the dead weight only, gravity acceleration g (9.81 m/s^2) is applied and 2 mm upward adjustment of the inboard support has been modeled. Structural analysis considering EM load especially CPD-II and SDVDE-III regime is performed. All degree of freedom for the inboard and outboard support is fixed. Additionally, a coefficient of dynamic amplification factor 2 and toroidal peaking factor 1.5 has been applied to the results of static analysis. Seismic analysis of the ETS under SL-2 has been conducted. Tri-axial acceleration value of 3.0g for vertical direction, 1.5g for x and y direction is applied. In the TF displacement, the maximum toroidal rotation of TF Coil of 0.3˚ and out-of-plane displacement of 21 mm is applied for the conservative purpose [1].

Three load combinations expected as worst cases are applied in order to evaluate the load combination effect on the ETS. The first load combination is refers to SL-1+Disr. I+DW. The second load combination refers to the SL-1+VDE II+DW+F.Disch. And third load combination refers to the SL-1+Disr. II+DW+F.Disch [1]. The maximum stress was occurred in the third load combination and the results are shown in Figure 5 and table I. The results show that maximum stress is within allowable limits.

Maximum mutual displacement of joint flange is obtained for local joints models from post processing global results of load combination. The global flange displacements are become boundary conditions for local joints model in sub-modeling approach. Table II show the result of sub-assembly joint under the load combination. The results show that maximum stress is within allowable limits.



(a) Total displacement of VVTS and CTS under Load Combination



(b) Membrane stress of VVTS and CTS under Load Combination

FIG. 5. Results of structural analysis for equatorial thermal shield under load combination.

TABLE I: STRESS EVALUATION FOR LOAD COMBINATION

Load Combination	**Location**	**Category**	**Stress Intensity [MPa]**	**Allowable Stress [MPa]**
SL-1+Disr. II +DW+F.Disch	VVTS	P_m	63	175
		P_L+P_m	161	263
	ECTS	P_m	41	175
		P_L+P_m	225	263
Pm : membrane stress, PL+Pm : membrane+bending stress				

TABLE II: STRESS EVALUATION OF SUB-ASSEMBLY JOINT FOR LOAD COMBINATION

Load Combination	**Location**	**Category**	**Stress Intensity [MPa]**	**Allowable Stress [MPa]**
SL-1+Disr. II +DW+F.Disch	Joint	P_m	26.6	175
		P_L+P_m	162	263
	Bolt	P_m	398	444
		P_L+P_m	419	666

3.2 Thermal Analysis

The layout of the cooling tube tracing is important in order to satisfy the heat load criteria for the TS. the The cooling tube is to be welded on the TS surface in zigzag pattern, hence, the distance between the adjacent tubes is one of the major parameters for the TS design. The maximum cooling tube distance for each parts of TS is determined by satisfying the overall heat load design condition. We conducted thermal analysis of a simplified 3D model as shown in Figure 6.

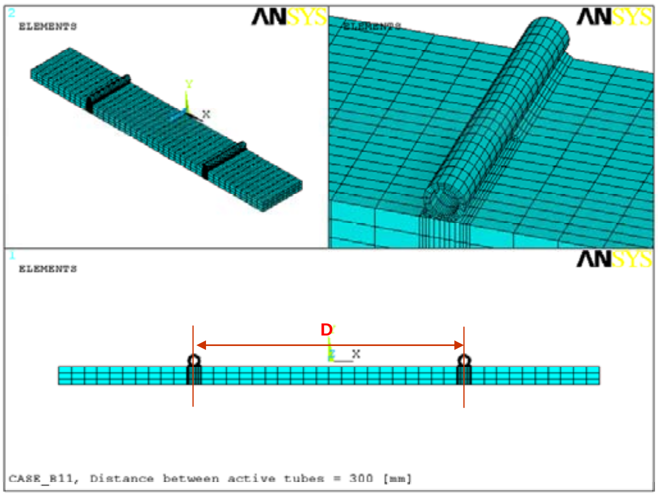


FIG. 6. Simplified FE model for thermal anslysis.

In this model, two boundary conditions are applied. At the TS surface facing VV, there is radiation heat flux from the VV hot surface. Convection heat transfer coefficient is assigned along the inner surface of the cooling tube where gaseous helium flows in. The boundary conditions and operating temperatures are summarized in Table III for two operating conditions, plasma operation stat (POS) and baking operation status (BOS) [7].

TABLE III: CONDITIONS FOR THE THERMAL ANALYSIS

Operation state		**POS**	**BOS**
VV temperature [°C]		120	200
Emissivity	**TS panel**	0.05	
	Joint/flange	0.06	
GHe inlet temperature [K]		80	80
GHe outlet temperature [K]		100	121
Heat flux from VV [W/m^2]		71.1	137.0
Heat transfer coefficient [W/m^2/K]	**Inboard**	739.1	777.5
	Outboard	1293.7	1364.0
	Port	575.1	604.1

Figure 7 shows the temperature profiles along the tube side surface when the tube distance is 500 mm at BOS condition. Maximum surface temperature position is approximately located at the center region between the tubes. From the temperature contour obtained by FE numerical simulation, the radiant heat load can be calculated.

By comparing the calculated heat load to the magnet with the reference design heat load, we can determine the distance between the adjacent cooling tubes.

The total heat load from the thermal shield to the magnet is within the requirement in case that the distance between cooling pipes is less than 500 mm in the inboard and 350 mm in the outboard.

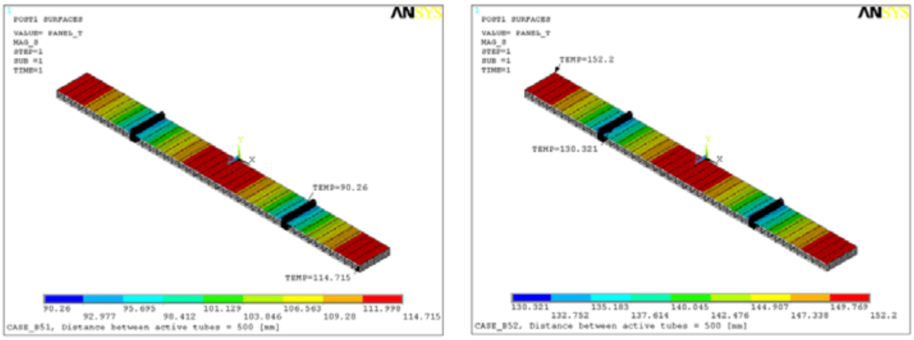


FIG. 7. Temperature distribution as the results of 3D simple model analysis .

The cooling tube distance is obtained for different parts of the thermal shield from the analysis results from 3D simple model. The layouts of the cooling tube are designed based on the tube distance as shown in Figure 3. 3D full model analysis is performed to verify the design layouts of inboard, outboard and CTS panel sections.

The helium temperature in the cooling tube are analyzed by modeling the helium as the Fluid116 which is an one dimensional coupled thermal-fluid pipe element in ANSYS. Heat transfer coefficient is applied to couple the helium and the tube surface temperatures. The mass flow rate and inlet/outlet temperatures are also assigned to the fluid element.

Figure 8 shows the temperature contours from FE simulation for POS conditions. Table IV shows that the heat loads to the magnet from the 3D full analysis are smaller than those from the 3D simple analysis.

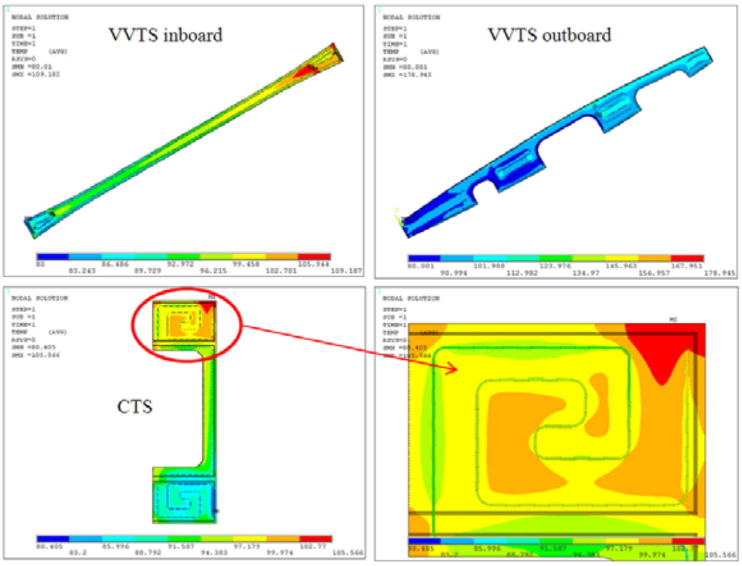


FIG. 8. Temperature distribution as the results of 3D full model analysis.

TABLE IV: RESULTS OF THE 3D FULL MODEL ANALYSIS

Analysis type		**Heat load to magnet [W]**		
		3D full model	**3D simple model**	**Heat load margin [%]**
Inboard	**POS**	2.0	2.3	12.8
	BOS	3.5	4.8	38.5
Outboard	**POS**	3.5	3.5	0.0
	BOS	6.3	6.5	4.4
CTS	**POS/BOS**	2.0	2.5	26.0

4. Summary

The detailed design of joints and cooling panels for the ITER Thermal Shield was conducted taking into consideration manufacturing and assembly. Maximum stress values of the design are shown to be within allowable limits and the calculated heat load is below the reference value. The analyses reported in this paper are based on the current load conditions to verify the design of ITER TS. The final design and analysis will be performed in near future based on new load conditions.

Acknowledgment

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