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A COMPREHENSIVE DESIGN OF THE UPPER PORT #18 INTERSPACE SUPPORT STRUCTURE FOR THE ITER DIAGNOSTIC PORT

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Abstract

The paper describes the design strategy and results for the ex-vessel components of Upper Port #18 (UP #18) for ITER diagnostics to integrate tenant diagnostics and to ensure overall design considerations. One of the ITER diagnostic ports, UP #18, has three diagnostic systems: 1) Vacuum ultra-violet spectrometer (VUV), which measures and identifies all impurities in the ITER plasma; 2) Neutron activation system (NAS), which measures the first wall neutron fluence; 3) Upper vertical neutron camera (UVNC), the multichannel neutron collimator, which measures the time-resolved neutron emission profile. The ITER diagnostic port is divided into two main areas. One is the integrated port plug, in-vessel component, is equipped with diagnostic first wall (DFW) and diagnostic shield module (DSM) which has a role of neutron shielding and of diagnostic safety. The other area is interspace and port cell which is located at the outside of the vacuum vessel. Interspace support structure (ISS) and port cell support structure (PCSS) are installed in the area. The diagnostic electronics and detectors are also located in this area, away from the plasma, to protect the equipment from nuclear radiation. During the maintenance phase, the shut-down dose rate (SDDR) should be controlled to check the diagnostic status or to replace the diagnostic by hand. The ISS/PCSS structures are mounted on permanent remote handling rails. The ISS/PCSS structures are detached from the rails and each structure is removed with a trolley when maintenance is required. Therefore, the final design of the ISS needs to be done from the perspective of neutron and gamma shielding for the human passage area, structural integrity, cooling performance, and maintainability.

1. INTRODUCTION

ITER has 14 upper port plugs of which are used for the installation of diagnostics. All ITER diagnostic ports are equipped with diagnostic devices that measure plasma phenomena and properties, as well as fusion reactions. The diagnostic ports have a robust design that supports diagnostics safely. Additionally, the ITER tokamak is activated by the fusion reaction and can become contaminated. Therefore, the diagnostic ports must be capable of supporting and protecting the diagnostics in such a harsh environment[1].

The Upper Port #18 (UP#18) has three distinct zones (Port Plug, Interspace and Port Cell) for diagnostic integration, with a dedicated structure in each zone to support the diagnostic components. The structures located in each zone are named as the Port Plug Structure, the Interspace Support Structure (ISS), and the Port Cell Support Structure (PCSS), respectively. The ISS and PCSS are designed to support diagnostic systems in such a way that the structural integrity and performance of each diagnostic system is not degraded under various load conditions. Additionally, supports for diagnostic components on the ISS and PCSS allow the optical elements to be properly aligned with the apertures and compensate for relative movement. Additional blocks are provided to shield critical or sensitive diagnostic elements from neutrons and gamma radiation. These blocks are located on both the ISS and the PCSS.

The primary structure of the ISS/PCSS comprises beams formed from ribs that are bolted to the chassis. The diagnostic components and service components in the interspace are mounted on ISS and the those in the port cell are on PCSS. The main components in the UP #18 interspace are the VUV assembly and the bioshield plug, which are mounted onto the ISS chassis, as well as the gas lines and electric cables, which are mounted on the Port Cell Rails. The main components in the UP #18 port cell are the VUV Detector Box and the UVNC Shielding Cabinet. Once the ISS and PCSS sub-assemblies have been completed, they are transported into the port cells, docked to the port cell rails, and pushed up to their final radial position. Once locked, connections are established between the Port Plug and the ISS, the ISS and the PCSS, and the Port Cell services. As these three zones undergo relative displacement during events such as disruption, seismic activity and baking, flexible connections such as bellows are used to accommodate this displacement. This structure is also intended to support shielding, tenants and services. During the maintenance phase, the ISS and PCSS structures are released from the port cell rails, after which they are each removed with a trolley. Before removing a structure, all links between the ISS and the PCSS must be disconnected. Additional shielding blocks and a shielded cabin structure are provided to protect workers from gamma radiation. In addition, to reduce the Shut Down Dose Rate (SDDR) during maintenance, the ISS/PCSS materials have been selected to be stainless steel with a cobalt content of less than 0.05%. The central bioshield plug contributes to reducing the neutron flux in the main cell and protecting sensitive electronics. The ISS and PCSS designs comply with the RH cask space allocation, enabling the quick and easy removal of structures with mounted diagnostic systems. The designs also need to integrate tenant diagnostics and ensure structural integrity, manufacturability and overall design considerations. To realise all the requirements of this design, neutronic, structural and thermo-hydraulic analyses are carried out using MCNP, ANSYS and CFX software. The following chapters will introduce a design strategy and present the results of the analysis and design.

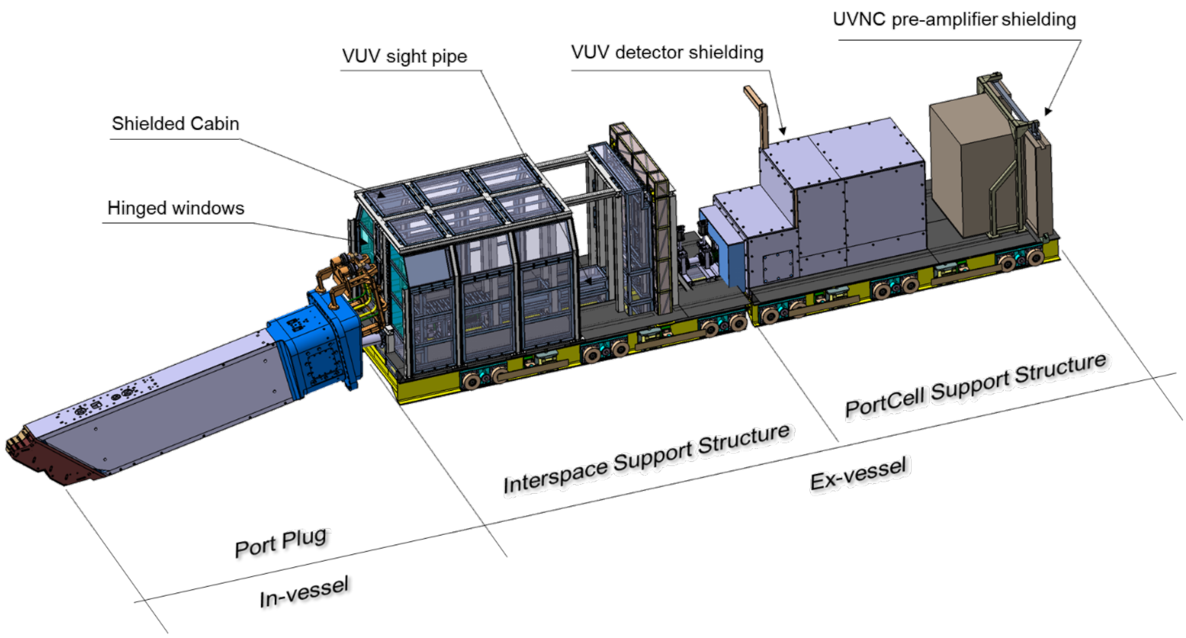

FIG. 1. Upper Port #18 Overall Configuration.

2. DESIGN STRATEGY

FIG. 1 shows the overall configuration of UP #18. FIG. 2 shows the final design of the UP #18 ISS/PCSS structure. The VUV detector shielding and the UVNC preamplifier shielding are installed on the PCSS. The VUV sight pipe is routed through the ISS to provide the an optical path between the port plug and the port cell equipment. To meet the ITER SDDR requirements of 100 μSv/hr after 10^6 seconds from shutdown in the interspace area, a shielded cabin concept has been adopted for the UP #18 ISS. Borated heavy concrete panels will be installed on the ISS frame. The human passage is fully shielded to minimise SDDR. This provides access to the interior of the shielded cabin for maintenance and diagnostics. The front-hinged windows can be opened to access the port plug components. These can be opened separately to minimise occupational radiation exposure when handling the port closure plate components. Removable shield blocks are installed around the pipe for VUV bellows and sight pipe maintenance. The weight is less than 15 kg and can be lifted by hand. Detailed views are shown in *FIG. 3*

In the port cell area, the level of SDDR is very low due to the presence of a bio-shield wall. Therefore, a shielded cabin structure for human access is not necessary. However, since the electronics used for the VUV and UVNC are sensitive to neutron flux and gamma radiation, each system has thick shielding. The shielding structure provides appropriate windows and doors for accessing the electronic devices, and these can be removed during maintenance if necessary.

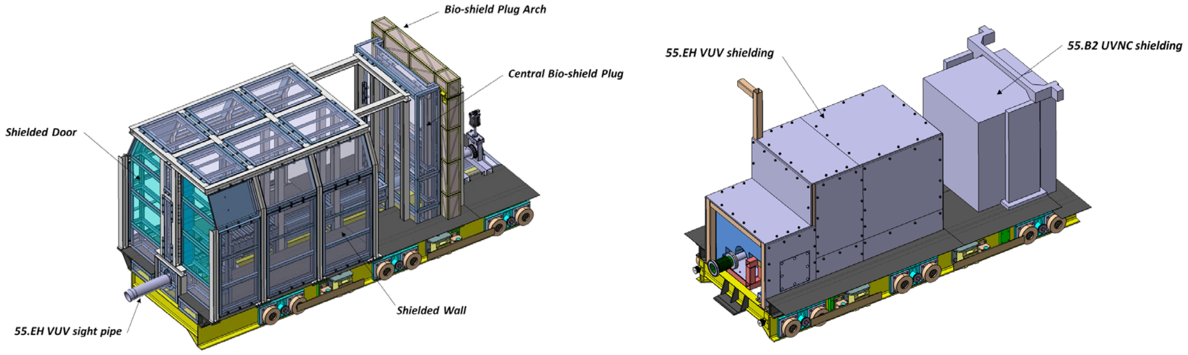

FIG. 2. Upper Port #18 ISS and PCSS

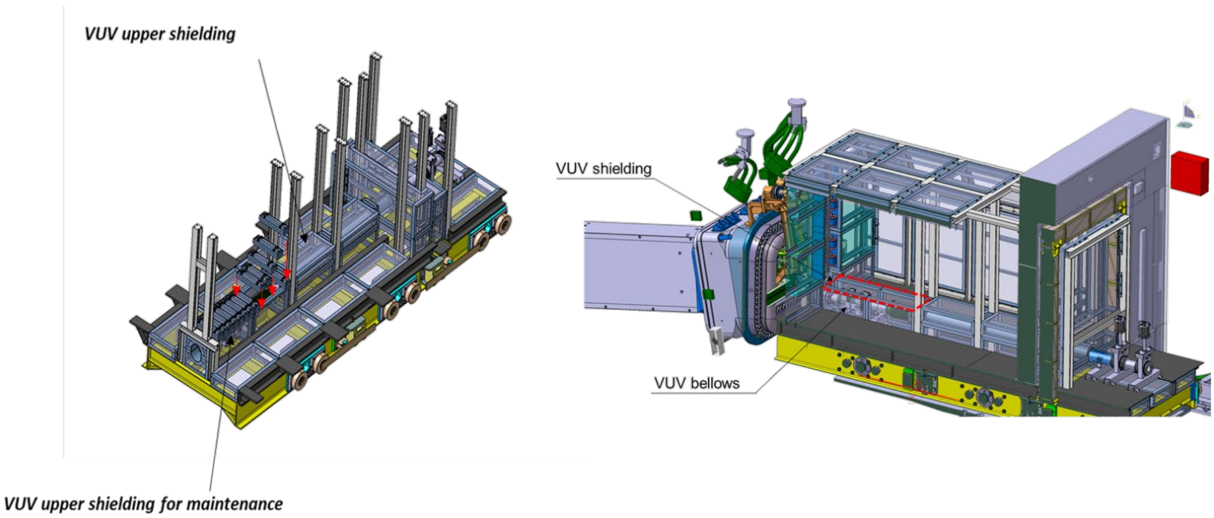

FIG. 3. Removable shielding for VUV maintenance

3. NEUTRONICS ANALYSIS

A neutronic analysis was conducted to estimate the SDDR at the human passage inside the shielded cabin. The neutron source employed in this study was a standard plasma source with a fusion power of 500 MW, as described in the MCNP ITER C model. Neutron analysis was conducted using D1S-UNED v3.1.4 with the FENDL 3.1 cross-section library. In this particular analysis, the SRC-UNED code was utilised due to the fact that the neutronics analysis was conducted by generating the surface source for efficient calculation. The distance from the plasma core to Interspace and Port Cell is quite long. This means that more time is needed for the calculation because of the PP structure's heavy shielding effect. Thus, Interspace and Port Cell neutronics analysis was conducted using a surface source technique. The surface sources for Interspace and Port Cell calculation were generated using the 'SSW' option in SRC-UNED on a cylindrical surface with a radius of x=991 cm and x=1,470 cm. The source particle history for the surface source is 5.0×10^{10} and the saved particle tracks are 1.4×10^{5}. The variance reduction for the whole C-model was applied to generate a more exact surface source. In the SDDR calculation, the ITER SA2 scenario was used for the purpose of determining the history of neutron irradiation, with a cooling time of 10^{6} seconds. The region in which the SDDR was calculated is situated behind the front shielding in the shielding cabin, and is designated as the maintenance region. The target SDDR is set at 100 µSv/hr in the interspace 12 days after machine shutdown and 10 µSv/hr in the port cell 24 hours after machine shutdown [2].

FIG. 4 shows the SDDR distribution of Interspace. It shows that the SDDR is less than 100 µSv/h which meets the ITER requirement. The flux and SDDR were calculated in Interspace and Port Cell. The SDDR in the maintenance for VUV double bellows in Interspace are 42.5 µSv/hr and 42.1 µSv/hr.

FIG. 5 show the neutron flux distribution in Port Cell area of UP #18. The neutron streaming is observed in a gap between the bio-shield and the bio-shield shielding. The neutron streaming is also observed within the bio-shield plug. The maximum neutron flux in the Port Cell is 10^{6} n/cm^{2}/sec, and the neutron flux is decreased as the distance from the bio-shield increases.

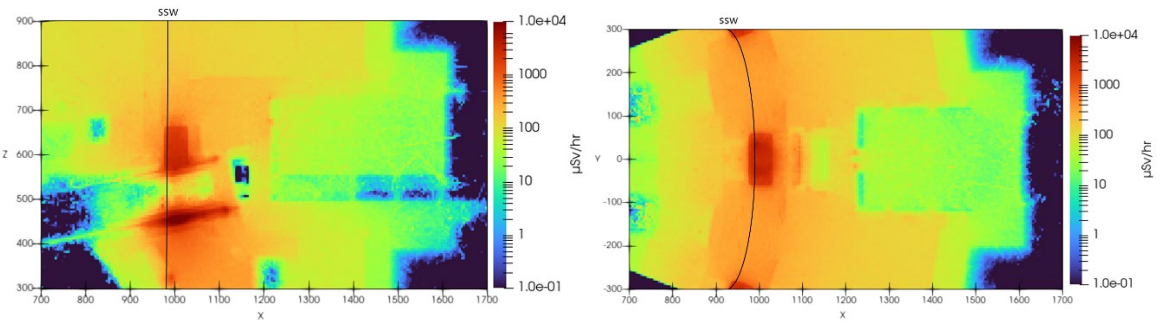

FIG. 4. SDDR in Interspace area

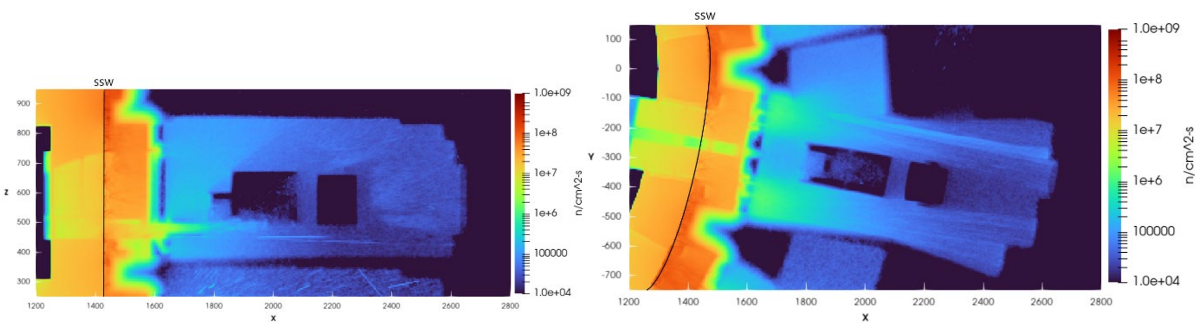

FIG. 5. Neutron flux in Port Cell area

4. FLUID ANALYSIS

CFD analysis has been performed to estimate the thermal–hydraulic characteristics in the Interspace area, including mean velocity, total pressure, temperature, heat flux and wall heat transfer coefficient. The considered loads are the flow rate and the temperature at inlet face. Two thermal–hydraulic analyses were performed, and all cases were assumed to be steady state and turbulent with single phase. In this paper, two different inlet conditions of cooled air are considered.

For both solid and fluid regions, conduction and convection are accounted for, whereas radiation is not included in heat transfer. In order to maintain an optimal temperature within the inner region of the ISS, a flow rate of 3,500 m^3/h of cooled air is supplied. The flow within the ISS was assumed to be in a steady-state, single-phase, and turbulent condition. To numerically simulate turbulence, the k–ω SST model with a wall function was used. For the baking condition, the walls of the water circuit carrying heated water were set to 240 °C, and the building temperature was maintained at 35 °C. The flow rate of cooled air is 3,500 m3/h, thus enabling the internal structures of the ISS to be maintained at a temperature suitable for protecting the equipment.

In the first case, the opening at the side bio-shield door was designated as the inlet, with cooled air at 28 °C being supplied at a flow rate of 3,500 m^3/h. The cooled air flows through the ISS, absorbing heat, and is discharged through the remaining surfaces, which were assigned an opening boundary condition with a static pressure of 0 Pa. As illustrated in FIG. 6, the temperature distribution ranges from 28 °C to 240 °C within the solid and fluid domains, and the three-dimensional streamline results originate from the inlet. High-temperature regions have been observed in proximity to the chimney interface, the water circuits carrying heated water, and the area around the VUV. The transfer of heat to lower-temperature regions occurs primarily through conduction in solids and convection in fluids. The streamline color is indicative of the temperature distribution. The ISS structure is designed to allow cooled air to enter from the sides. The incoming air flows around the main frame and moves towards the port area, where the temperature primarily increases. The air is then discharged through the outlets, with the hotter air mostly exiting downward through the space around the rail. The complex structure of the ISS gives rise to intricate internal flows, which in turn generate a multitude of vortices.

In the second case, the opening at the bottom of the bio-shield plugs were designated as inlets, with cooled air at 28 °C being supplied at a flow rate of 3,500 m^3/h. In a similar manner, air flows through the ISS and is discharged through the remaining surfaces. As illustrated in *FIG. 7* the temperature distribution ranges from 28 °C to 240 °C within the solid and fluid domains, and the three-dimensional streamline results originate from the inlet. High-temperature regions have been identified in the vicinity of the chimney interface, the water circuits carrying heated water, and the area around the VUV. Heat transfer primarily occurs to lower-temperature regions through conduction in solids and convection in fluids. The streamline colour represents the temperature distribution. Cooled air enters the lower part of the ISS and moves towards the port area along the space around the rail and chassis. The temperature primarily rises around the ports prior to being discharged through the outlets. Given the complexity of the ISS structure, the internal flow exhibits intricate patterns, generating numerous vortices.

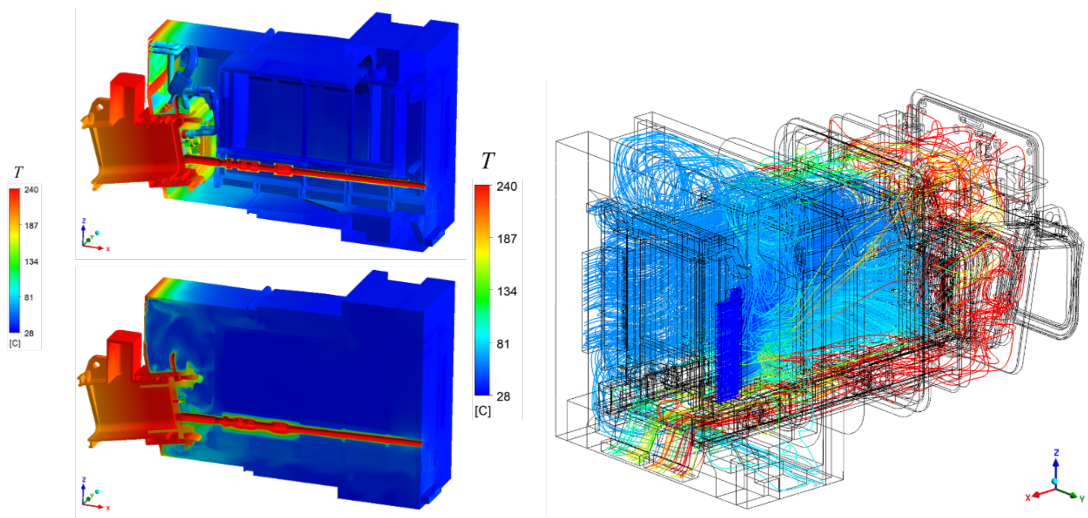

FIG. 6. Temperature distributions and streamline (Case 1)

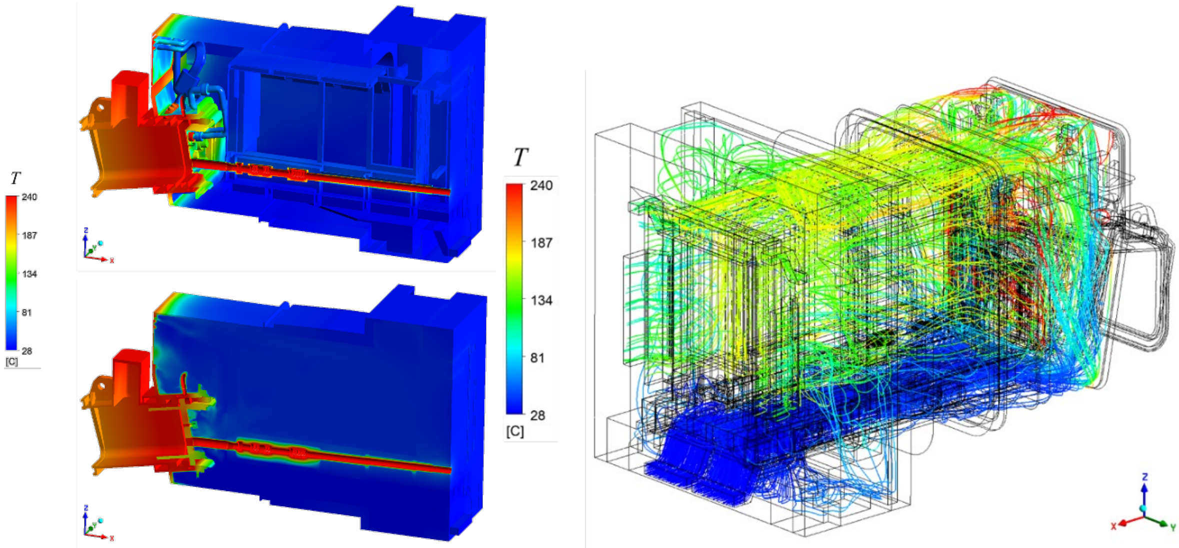

FIG. 7. Temperature distributions and streamline (Case 2)

An analytical calculation for heat energy was performed and compared to the CFD results for verification. The main results are summarized as below:

TABLE 1. Thermal-hydraulic analysis result

	Total pressure drop	Total heat transferred	Outlet temperature	ISS temperature
Case 1	55.5 Pa	7,330 W	34.3 °C	33 °C
Case 2	26.4 Pa	12,205 W	42 °C	38.3 °C

5. ELECTROMAGNETIC ANALYSIS

In order to calculate the electromagnetic load on the ISS/PCSS, a detailed analysis has been performed. The subsequent results are displayed under the VDE UP 36ms scenario (Upward Fast Vertical Disruption Event with linear 36ms current decay), representing the worst disruption scenario. Forces and torques for each component are calculated at the barycentre. The primary EM load components are vertical force. The maximum EM force is 7.8kN in the vertical direction.

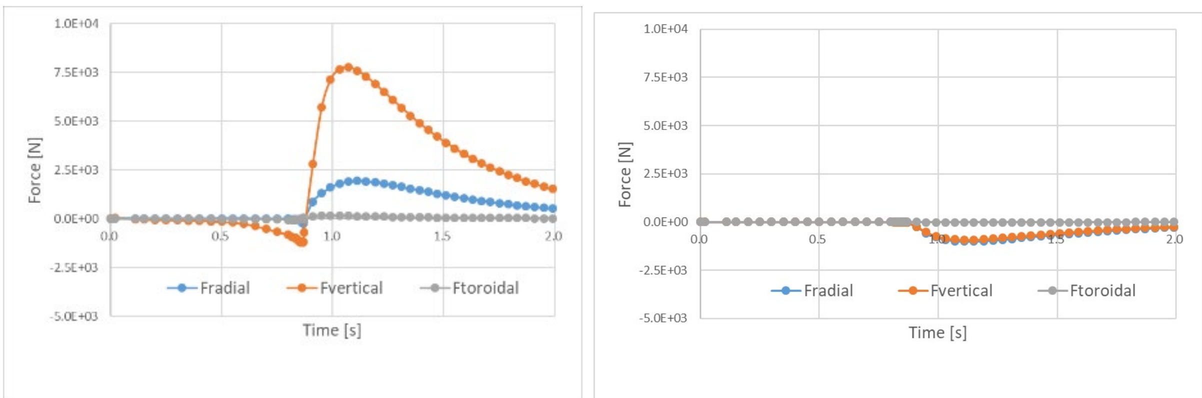

FIG. 8. EM load on ISS and PCSS

6. STRUCTURE ANALYSIS

The structural analysis presented in this paper aims to assess the structural evaluation of the shielded cabin with ISS. This evaluation was carried out in accordance with the RCC-MR (2007) code. The integrity of structures using the H-beam meets the design allowable stress under the ITER's severe load conditions.

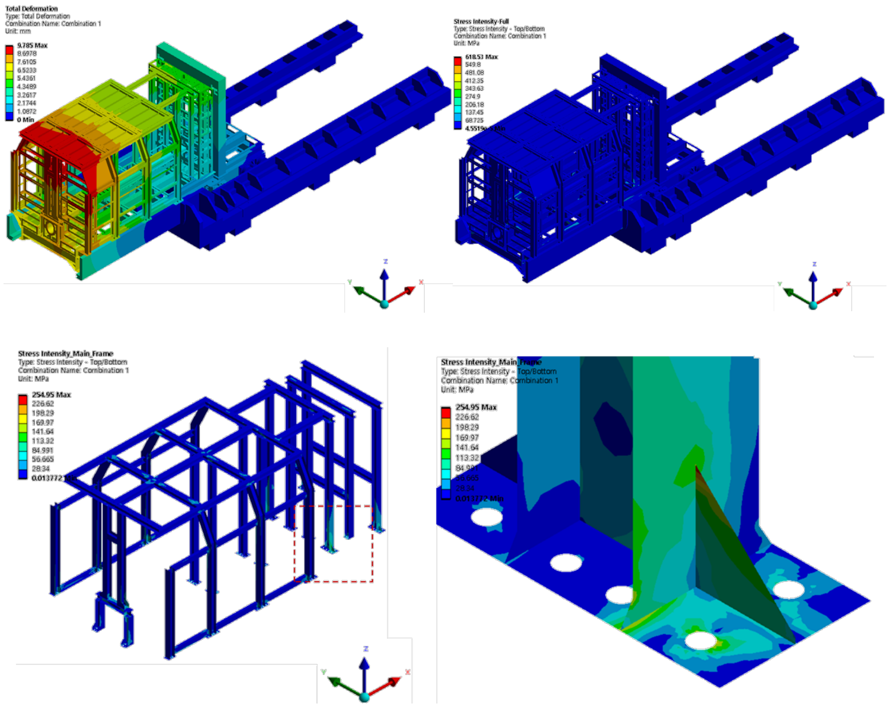

FIG. 9. EM load on ISS and PCSS

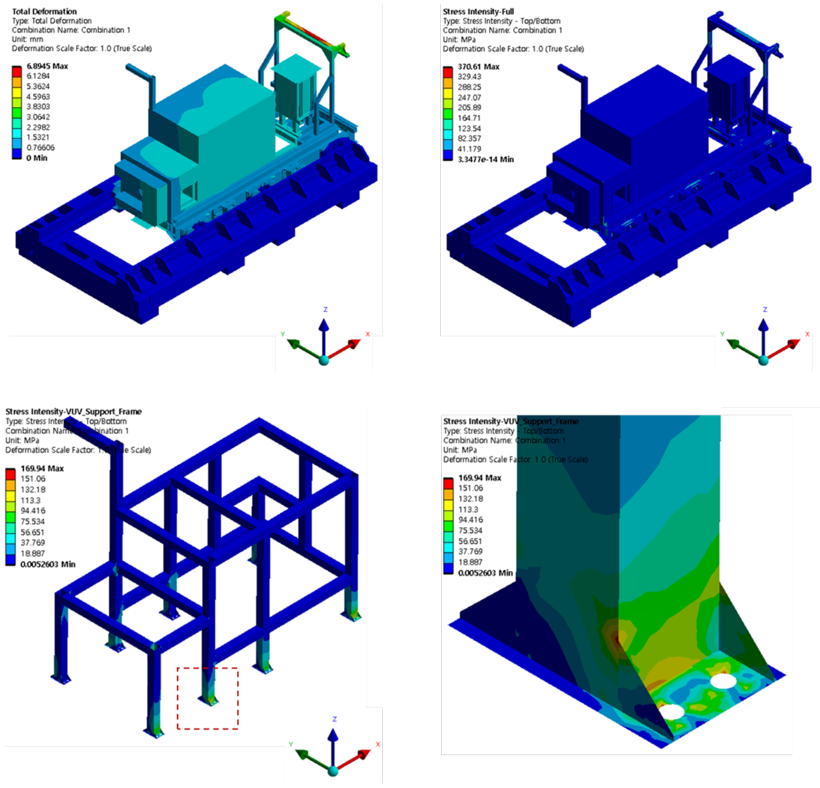

FIG. 10. EM load on ISS and PCSS

The finite element model of ISS and PCSS is analysed for the loads and load combinations provided by ITER. The model needed for this analysis has to be linear, so a linear version of the model has been created. The structure has been evaluated for excessive deformation. An elastic analysis has been performed in accordance with RCC-MR. It is applied that the Newmark load combination scheme and the signs of the accelerations to solve 16 load combinations. The worst combination of loads was then analysed to find the most stresses on the structure. This was used to assess P-type damage. The structure is also checked to ensure it is stable. The assessment criteria for this type of analysis are as follows: firstly, the solution must demonstrate convergence; secondly, it must be able to withstand magnified loads in equilibrium; and thirdly, it must not form any plastic hinges.

7. MAINTENANCE

As illustrated in FIG. 11, the implementation of the maintenance corridor in the Interspace and Port Cell zone is demonstrated. In order to gain access to the diagnostic components during maintenance operations, it may be necessary to remove the ISS shielding panels. It is evident that the shielding panels have been permanently installed on the ISS frame. It is, therefore, the case that the front hinged doors (aqua blue windows in FIG. 11) are being designed to open during the port plug maintenance. In order to minimise the occupational radiation exposure, it is possible to open the doors separately. In the event of the closure plate being opened, it is possible for a human to access the side, even in the case of wearing an air suit. Human access corridors have been implemented on both sides of the ISS for the purposes of maintenance and inspection. With the exception of particular locations, the width of the corridors is 900 mm. The minimum width of corridors is 885 mm at floor level, with obstacles overhead.

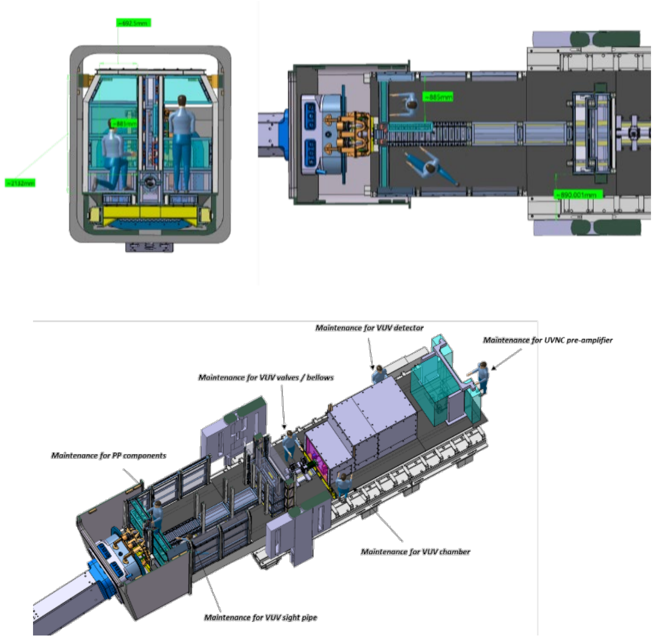

FIG. 11. Schematic implementation of the maintenance corridor in the Interspace in UP#18

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REFERENCES

[1] Pak, S., et al. Final design of the generic upper port plug structure for ITER diagnostic systems, Fusion Engineering and Design, 102 (2016)

[2] Hong, S., Kim, J., Shim, H., Cheon, M., Pak, S., Shut-down dose rate analysis for final design of shielding tent in port interspace of ITER UP#18, Fusion Engineering and Design, 196 (2023).