Design Study of Vacuum Vessel Concepts for COMPASS-U Tokamak


Abstract—COMPASS upgrade (COMPASS-U) is a high-magnetic field, medium-sized tokamak with high-temperature (<500 °C) operation. The scientific program is aimed to address the topics of plasma exhaust, liquid metals, enhanced confinement modes, and edge plasma physics. The plasma current is up to 2 MA and the toroidal magnetic field is up to 5 T. Therefore, plasma disruptions can produce large electromagnetic forces on the vacuum vessel (VV) and other conducting structures. This article presents the study of different VV design concepts, which were considered during the COMPASS-U conceptual design phase. This article describes the electromagnetic forces exerted during plasma disruption, high-temperature operation requirements, and other design constraints. INCONEL 625 is selected as a reference material for VVs. FE simulations of the 45° sector of the vacuum vessel were carried out for various load combinations. This article summarizes the wall thickness optimization that limits the vessel deformation and minimizes the stress in the shell. The results are broken down into different categories of stress according to the ASME code and compared with material limits.

Index Terms—COMPASS-U, coupled field analysis, plasma disruption, vacuum vessel (VV).

I. INTRODUCTION

THE COMPASS upgrade (COMPASS-U) project received funding at the beginning of 2018, and subsequently the conceptual phase of the design was started at the Institute of Plasma Physics, Czech Academy of Sciences. The COMPASS-U tokamak is a new, compact, medium-sized tokamak with a high magnetic field and high-temperature operation. It aimed to address the key challenges related to the plasma exhaust, liquid metal divertor, enhanced confinement modes, and edge plasma physics that are important for the next-step devices [1]. The general parameters and basic dimensions of COMPASS-U are listed in Table I.

Table I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius (R)</td>
<td>0.894 m</td>
</tr>
<tr>
<td>Minor radius (a)</td>
<td>0.27 m</td>
</tr>
<tr>
<td>Magnetic Field at center (Bt)</td>
<td>5 T</td>
</tr>
<tr>
<td>Plasma Current (Ip)</td>
<td>2 MA</td>
</tr>
<tr>
<td>Flat top time (tflat-top)</td>
<td>~2 s</td>
</tr>
<tr>
<td>Triangularity (θ)</td>
<td>0.5</td>
</tr>
<tr>
<td>Elongation (κ)</td>
<td>1.8</td>
</tr>
<tr>
<td>Plasma volume (V Plasma)</td>
<td>~2 m³</td>
</tr>
<tr>
<td>Vessel Temperature (T_vessel)</td>
<td>&lt;500 °C</td>
</tr>
</tbody>
</table>

The COMPASS-U plasma is designed to operate with a 2-MA plasma current and 5-T toroidal magnetic field, hence strong eddy currents can be induced in the vacuum vessel (VV) and other surrounding passive structures during plasma disruption. The interaction of the induced current with the toroidal magnetic field generates large electromagnetic forces on the systems. The COMPASS-U VV design is mainly based on the electromagnetic forces produced during plasma disruption events and several FE simulations were carried out for different load combinations to ensure its structural integrity. Fig. 1 illustrates the initial design and general arrangement of the components for COMPASS-U, where toroidal field (TF) coils are supported by a heavy support structure inside the cryostat. The VV system is positioned inside of the TF coils. The TF coils are designed with demountable sliding joints for assembly and maintenance reasons similarly to the C-mode [2], [3]. The poloidal field (PF) coils and central solenoids (CSs) are placed between the TF coils and the VV. All the components are tightly organized in the available space leaving not much space for major changes in the vicinity.

II. VACUUM VESSEL

The COMPASS-U VV system includes the main vessel, port extensions, and its support connecting it to the support structure. The VV has to provide a first confinement barrier, high quality vacuum, high toroidal resistance, a reliable structural boundary for the lifetime of the machine, and remove heat from the in-vessel component. The VV has to support the in-vessel components and withstand design loads, high normal and off-normal electromagnetic forces, and thermal loads.

The preliminary design of the main vessel is derived upon electromagnetic forces exerted during plasma disruption, high...
temperature operation, and spatial constraints. The general arrangement of the VV system and its basic shape are shown in Fig. 2. The main vessel is 1.55 m in height, the inner radius is 0.52 m, and the outer radius is 1.33 m. The thickness of the shell varies from 25 to 50 mm for the first iteration of design concept.

The vessel is a single-wall structure with a “D”-shaped cross-section and flat top and bottom. The design is kept simple to reduce the fabrication complexity and to lower the cost. The top and bottom corners of the vessel are strengthened by corner ribs. The vessel has totally 64 port openings by 16 equatorial ports, 16 upper horizontal ports, 16 lower horizontal ports, 8 upper vertical ports, and 8 lower vertical ports. Every alternative equatorial port has a bigger opening (500 x 350 mm) for the purpose of component maintenance and manual access. The upper and lower horizontal ports vary from 0° through ∼15° to 60° for diagnostic access to the divertor, X-point, and plasma center. The VV is supported vertically by flexible plate supports at eight toroidal locations in-between each lower vertical ports.

INCONEL 625 is selected as a reference material for the VV. Compared with SS-304L, SS-316LN, Ti6Al4V, and Nitronic 50, Inconel 625 has good mechanical strength at high temperatures (500 °C), high electrical resistance (∼50% more resistive than SS), and achievable fabrication characteristics. Table II shows the main parameters of the VV.

### III. VESSEL DESIGN AND CONCEPTS

Several concepts were considered and checked for the vessel sizing and available space. A combined approach of theoretical calculations and simulations has been used to confirm the shape and shell concept of the vessel. Initial simulations had shown very high vertical forces in the top and bottom parts of the vessel, hence three different shell concepts were studied by approximation of simply supported beam calculations:

1) vessel wall with internal ribs (T-beam);
2) double walled vessel with ribs (I-beam); and
3) single walled shell (rectangle beam).

A vessel sector was divided and simplified as abovementioned beam sections and compared against stress calculations. Different loads from deadweight and in-vessel component weight, atmospheric pressure, and focused electromagnetic loads (refer to Section IV-A) were considered for the calculations. The design calculations were carried out for different shell thicknesses, number of ribs, rib thicknesses, and rib widths. Tight spatial constraints are applicable on total shell thickness and maximum outer dimensions of VV design due to the position of the divertor on the inside and PF coils on the outside of the vessel. The design of the vessel evolves mainly from early consideration of the machine cross section. Hence, there is only 65 mm of space available for shell design at the top and bottom sides of the vessel. Fig. 3 shows the results of calculation and its comparison for different shell thicknesses and rib heights. Considering the spatial constraints, fabrication complexity, and cost, the single wall concept with varying wall thickness (top/bottom = 50 mm, HFS = 25 mm, LFS = 40 mm) was selected for further FE verifications.

The corner in the vessel between the inner cylinder and the top/bottom plate is the weakest portion of the vessel, which is supported by 20-mm thick, ten corner ribs (five top + five bottom) per sector. Initial simulation shows that about 11-MN vertical force is exerted on the vessel during the vertical displacement event (VDE). The thickness of the VV wall is primarily determined by the need to resist plasma disruption forces.
IV. FE Verification of Preliminary Concept

The model of disruptions used in the conceptual design of the COMPASS-U VV is based on a simplified engineering approach, which provides a basis for primary quantification of the electromagnetic forces experienced by the vessel during the plasma disruption [4]. FE electromagnetic simulations are carried out considering the worst possible plasma disruption parameters, and the calculated forces are then transferred to mechanical analysis.

Two different 3-D FE models of 45° sector are prepared for the simulations, where the first model is simplified and includes only a vessel with an equatorial port stub and a flexible plate support, and the second model includes a vessel with all port openings, passive stabilizing plates (PSPs) supported on the VV, and a flexible plate support.

A. Plasma Disruption Loads and Electromagnetic Modeling

The transient analysis of the plasma disruption is used to calculate induced eddy currents in the vessel, which interact with the TF and PF and its time derivative to impose $J \times B$ forces on the vessel model

$$\vec{f} = \vec{j} \times (\vec{B}_{\text{int}} + \vec{B}_{\text{ext}})$$

where

- $\vec{j}$ is the induced current density;
- $\vec{B}_{\text{int}}$ is the magnetic field from the plasma and currents induced in the vessel; and
- $\vec{B}_{\text{ext}}$ is the magnetic field from TF, PF, and CS coils.

The FIESTA code is used to calculate 13 representative plasma equilibria for the magnetic field from TF, PF, and CS coil currents [5]. The ANSYS Maxwell [6] code is used to simulate plasma disruption forces. The FEM, non-self-consistent disruption model includes the following cases.

1) **Current Quench (CQ):** A single, toroidal current filament with a linear decrease of current from 2 MA to 0 A in 0.2-ms time. The timescale of CQ is presumed on the calculation and the available CQ rate data for runaway electrons dominated plasma disruption in the COMPASS tokamak [7], [8]. Investigated for four plasma positions (top/bottom/centre/HFS).

2) **Thermal Quench (TQ):** Linear decrease of the -150-mWb, diamagnetic flux in 0.1 ms induces poloidal current in the vessel. Similar poloidal current is calculated during the CQ, when the 50-mWb paramagnetic flux induces the current.

3) **VDE:** Multiple toroidal current filament moves from the vessel center to the top/bottom of the VV wall with the prescribed evolution of position in 1-ms time.

4) **Halo Current:** Up to 75% of the pre-disruptive plasma current for the toroidal peaking factor equal to one.

The calculation of the forces during each case continues by combining the cases into the worst possible combination. Each disruption contribution is taken as a separate one, and consequently the contributions are combined. Several simulations were carried out to find the worst possible (upper bound) EM load combinations on the VV. The body force density taken for the time instant of the maximal induced current is exported to mechanical stress analysis. Table III shows a comparison of eddy currents in both mentioned models.

B. Mechanical Analysis and Results

In addition to the electromagnetic forces, the vessel is subjected to atmospheric pressure, deadweight, and thermal loads. The vessel will work up to 500 °C during the plasma operation. Preliminary FE verification using non-linear elastic analysis is carried out for the assessment of vessel stresses with the following boundary conditions.

1) Simulations of a vessel model without a PSP. It includes the applied uniform temperature of 300 °C, self-weight, IN-VV component weight, cyclic symmetry, and model fixed at the end of the flexible support (three plates).

2) Simulations of a vessel model with a PSP. It includes the applied uniform temperature of 500 °C, self-weight, IN-VV component weight, PSP supported on the vessel, cyclic symmetry, and model fixed at the end of the flexible support (seven plates).

The thermal deformation results show that the vessel deforms 5.2 mm radially and 5.6 mm vertically at 300 °C and 9.5 mm radially and 10 mm vertically at 500 °C. The results are broken down into different categories of stress and verified against material limits considering ASME BPVC Sec 8 Div 1 standards. Fig. 4 shows the results and a comparison of the total deformation and equivalent stress contour for the CQ, top plasma, without PSP; CQ, top plasma, with PSP; VDE, down, without PSP; and VDE, down, with PSP scenarios.
TABLE III
INDUCED EDDY CURRENT IN THE VESSEL AND PSP

<table>
<thead>
<tr>
<th>Component</th>
<th>Current Quench</th>
<th>VDE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Eddy Current [kA]</td>
<td>Eddy Current [kA]</td>
</tr>
<tr>
<td></td>
<td>With PSP</td>
<td>W/o PSP</td>
</tr>
<tr>
<td>VV</td>
<td>740</td>
<td>1 990</td>
</tr>
<tr>
<td>PSP, TOP</td>
<td>1174</td>
<td>-</td>
</tr>
<tr>
<td>PSP, BOT</td>
<td>115</td>
<td>-</td>
</tr>
</tbody>
</table>

TABLE IV
CALCULATION RESULTS OF THE FLEXIBLE PLATE SUPPORT

<table>
<thead>
<tr>
<th>Opt: 1: 70<em>20</em>1000 mm</th>
<th>Allowable</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.s of plates: 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bending stress</td>
<td>410 MPa</td>
<td>97 MPa</td>
</tr>
<tr>
<td>Buckling (P_e)</td>
<td>1375000 N</td>
<td>1820234 N (Factor = 1.3)</td>
</tr>
<tr>
<td>Opt: 2: 170<em>20</em>1000 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No.s of plates: 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bending stress</td>
<td>410 MPa</td>
<td>97 MPa</td>
</tr>
<tr>
<td>Buckling (P_e)</td>
<td>1375000 N</td>
<td>4247212 N (Factor = 3.1)</td>
</tr>
</tbody>
</table>

The results show that the stresses are localized mainly in the corner ribs and top and bottom plates of the vessel. Stresses in the model with PSP has peak stresses at the location of the PSP support in the VV plate and not distributed over the plate. For some of the scenarios, stresses are above the material limits in corner ribs. The overstressed areas can be minimised with local strengthening, and this will be done during the detailed design of the vessel. The results depict that the presence of PSP inside the vessel will reduce the electromagnetic load on the vessel, which will allow optimization of the vessel shell thickness.

V. CONCEPT FOR VV SUPPORT

The COMPASS-U VV has to resist the vertical forces up to 11 MN, which can occur during the fast-transient events. Furthermore, the support has to accommodate movement during the thermal expansion. The flexible plate support is proposed, similar to the KSTAR, JT-60SA, ITER, and HT-7U [9]–[12] tokamak. It will provide support for vertical and toroidal forces and accommodate the radial movement (6.5 mm at 500 °C and 0.89-m radius) during thermal expansion. There will be a total of eight supports placed toroidally, each containing seven flexible plates of 100 × 20 mm c/s and 1.24-m length. The preliminary theoretical calculations are carried out for the stresses and bucking. The calculations are based on the following formulas [7] and results are given in Table IV:

\[
\begin{align*}
    y &= \frac{FL^2(1 - v^2)}{Ebh^3} \\
    \sigma_{\text{max}} &= y_{\text{baking}} \frac{3Eh}{L^2(1 - v^2)} \\
    F_B &= \frac{bh^3\pi^3E}{3(1 - v^2)L^2} 
\end{align*}
\]

where

- \(L\) length of the spring plate;
- \(b\) width of the spring plate;
- \(h\) thickness of the spring plate;
- \(V\) Poisson ratio;
- \(E\) Young’s modulus;

Fig. 4. Results and comparison of total deformation and equivalent stress contour for (a) CQ, top plasma, without PSP, (b) CQ, top plasma, with PSP, (c) VDE, down, without PSP, and (d) VDE, down, with PSP.
The results show that both the proposed designs are safe as the calculated critical load is higher than the applicable vertical load, but as per ASME standards [13], the second proposal is more suitable where the buckling factor is higher than 3. The design will be supported by the analysis in the further stage of the design process.

VI. CONCLUSION

The design study of VV concepts for COMPASS-U was carried out and a single-wall, D-shaped VV from Inconel 625 is proposed. Electromagnetic load cases are studied and the worst possible disruption scenarios are simulated. The simulations were performed for the VV with and without the PSP. The results of the preliminary FE simulations show that about 60% of total eddy current induced during disruption is induced in the PSP, which lowers the stress in the vessel and gives possibility to optimize the vessel wall thickness. The design of the PSP support is important to distribute loads on the vessel wall. Further detailed design will be carried out with suggested changes and a more detailed electromagnetic model.

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REFERENCES