ITER Upper Port Plug handling cask system assessment and design proposals

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\textbf{A B S T R A C T}

The current design of the ITER cask for Upper Port Plugs has been evaluated. Careful reduction of the number of mechanical degrees of freedom is an opportunity to relax the tolerances in the design, resulting in cost reduction and reliability increase. A new kinematical design for the tractor module has a higher stiffness to weight ratio, reduces actuator forces by a factor four and minimizes cross-talk between lift and rotation motion. Non-cantilevered handling is recommended to reduce wheel loads on the tractor by a factor six and to simplify guidance. At the system level the tubular guide (TG) is proposed, a semi-permanent 3.5 m long tube which is an extension of the Upper Port. Cask docking is simplified and the risk of the cask tilting is prevented. Redesigning the system concept is recommended and the TG looks promising. Since a system level redesign impacts the external interfaces, overall feasibility has to be investigated.

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\section{1. Introduction}

The cask and plug remote handling systems (CPRHS) for ITER shall provide the means for remote transfer of in-vessel components and remote handling equipment between the hot cell facility (HCF) and the vacuum vessel (VV) through dedicated galleries and lift in the ITER buildings [1]. During docking, the CPRHS for Upper Port Plugs (UPP’s) interfaces with the building, the docking flange, the dock flange and the plug flange.

The current design assumptions lead to a five modules solution to fulfil the requirements on containment, exchange and transportation (Fig. 1). This results in a complex design with relatively long force loops. Mechanical features in the present design may result in lack of accuracy, position hysteresis, and unnecessary wear and jamming, which could affect the system’s reliability, availability and safety [2].

In this paper the CPRHS latest design is assessed. In Section 2 the functional requirements are listed. It is shown that tolerances in the design can be relaxed by systematic reduction of the number of degrees of freedom (DoF), resulting in cost optimization and reliability increase. Section 3 shows the most important examples of these design issues together with suggestions for improvements. Finally, in Section 4, the most important results are summarized in the form of conclusions leading to a motivation to select specific design solutions.

\section{2. Functional requirements}

\subsection{2.1. Functions}

The CPRHS’ functions are (i) confinement, (ii) transfer and (iii) plug handover. For these, the following modules are foreseen: the cask envelope, the air transport system (ATS) and handover tooling (Table 1).

\subsection{2.2. Performance}

The transfer of the cask from the hot cell facility to the vacuum vessel is remotely controlled and self-propelled by the ATS. The current design features a double seal door (DSD), which is a system of two stacked doors, for the prevention of contamination-spreading during (un)docking. The handover tooling handles a load of 20 ton within the tight Upper Port clearance; the design must feature a high stiffness-to-weight ratio and use a small number of actuators.

\section{2.3. Constraints}

The baseline cask properties are listed in Table 2. The Upper Port Plugs are mounted cantilevered with a bolted flange at the
Fig. 1. Side view of baseline cask in the port cell with the vacuum vessel at the left side of the figure.

Table 1

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confinement</td>
<td>(Un)dock cask volume to VV or HCF.</td>
</tr>
<tr>
<td>Transfer</td>
<td>Split/join volume of the cask and the VV/HCF.</td>
</tr>
<tr>
<td>Handover</td>
<td>Transfer by the ATS from HCF to VV.</td>
</tr>
<tr>
<td></td>
<td>(De)connect handover tool with UPP.</td>
</tr>
<tr>
<td></td>
<td>(De)connect handover tool with VV/HCF.</td>
</tr>
<tr>
<td></td>
<td>(De) mount UPP from VV.</td>
</tr>
<tr>
<td></td>
<td>Linear motion UPP (two directions) VV/HCF.</td>
</tr>
<tr>
<td></td>
<td>(De)Connect to service connector at VV/HCF.</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPP Mass</td>
<td>20 ton</td>
</tr>
<tr>
<td>Dimensions (L x W x H)</td>
<td>6000 mm × 800 mm × 1200 mm</td>
</tr>
<tr>
<td>Position CoG</td>
<td>3900 mm from flange</td>
</tr>
<tr>
<td>Port cell Distance docking flange – concrete floor</td>
<td>3.52 m</td>
</tr>
<tr>
<td>Cask Maximum (loaded) weight</td>
<td>100 ton</td>
</tr>
<tr>
<td>L x W x H</td>
<td>8500 mm × 3650 mm × 2620 mm</td>
</tr>
</tbody>
</table>

distal side of the Port. A vacuum seal is applied next to the flange. The clearance between the UPP and the port wall is 20 mm (40 mm between bottom and floor). The baseline handover tooling handles the UPP in cantilever under 11 degrees. This implies a gravity force of 0.2 MN and a moment at the flange of 0.75 MNm. In between the docking flange and the building is the port duct, a vulnerable flexible bellows structure to allow expansion of the vessel. For manufacturing inaccuracy and for hysteresis, a maximum allowable deviation of only 10 mm and 0.1° in all directions is assumed from the port cell and baseline cask dimensions [3].

3. Assessment baseline and design proposals

Current design assumptions have led to the transfer cask system design proposal with five modules (ATS, pallet, cask envelope, ramp and tractor). In addition, the system features three docking interfaces in the port cell (port cell floor, docking interface, plug flange). As a consequence, the docking concept results in a significant number of DoFs. Theoretically, a 12 DoF system can be explained at least, where 6 DoF are used for the transfer between VV and HCF and 6 DoF for the handover at both interfaces. The tractor actuates 2 DoF. Also, long force loops are used (introduced forces are transmitted to the solid world via a rather long detour). These issues may result in lack of accuracy, position hysteresis, unnecessary wear and jamming.

3.1. Docking cask in port cell

The baseline system is aligned and docked first to the building after which the heavy cask envelope translates into the tight clearance budgeted port duct without structural guidance or support on the front of the cask. The bellows are vulnerable. An additional risk is that, due to the overhanging center of gravity (CoG), the cask could drop into the gap (0.2 m from front pallet feet). The introduction of forces perpendicular to a face far from edges causes a low stiffness, as is the case with the docking pins on the front face of the baseline design. Because of this, the front plate is too thick (mass 2 ton) and the CoG is brought even more forward. Due to the low vertical stiffness, the seal between cask and port can be damaged. Furthermore, a force loop is created by the rack and pinion in the rear end of the pallet (pushing the vessel and building apart). This leads to an unpredictable force-distribution on the seal’s circumference [4].

Direct alignment to the docking interface could simplify the docking operation. For this, a tubular guide (TG) is newly proposed: a (semi-permanent) extra tube mounted in the port duct on the port extension with internal rails, see also Fig. 2 or 3. The cask would dock to the TG docking flange. This has several advantages over the current system. The cask cannot drop into the gap between the floor and the vessel in case of a material/equipment failure. The service connector (SC), which provides energy and data for the handover, could be integrated on the same flange. The alignment of the handover mechanism is improved due to the accurate alignment of the internal rails in the extended tube. Furthermore, stiffness is increased in the load take over from vessel to the mechanism. The ‘closed box’ design of the cask envelope with trapezoidal sidewalls is a lightweight design with high stiffness, provided that proper loading conditions are applied. Introducing forces perpendicular to a face far from edges causes a low stiffness, as is the case with the docking pins on the front face of the baseline cask.

Fig. 2. Docking operation of the alternative cask to the TG.
The TG cask docks by hanging a hook on the upper side of TG flange while a docking pin provides the lateral alignment (Fig. 2). The cask is lowered gravity-assisted until the two faces are 6 DoF aligned. For transfer the cask is placed horizontally, and for docking it can be elevated 11° and aligned in 6 DoF. Note that this elevation would exceed the authorized envelope, possibly affecting the routing of pipes in the port cell. The ATS provides 3 DoF in the horizontal plane and the remaining degrees of freedom (\(z \sim 100 \text{ mm}, \varphi \sim 1°, \psi \sim 11°\)) are provided by a mechanism (Fig. 3) with three linear actuators (spindles) and two triangles to make the system statically determined. The tractor translates over sets of rails in the cask (7 m) that continues in the TG (3 m). The gap of 300 mm because of the DSD is bridged by rotating rail extensions in the cask envelope. A spindle with the motor placed outside the cask envelope drives a carriage. A canned rotor ensures the confinement. The carriage sets a chain in motion which is on the bottom fixed to the cask and on the upper side to the tractor. The translation of 5 m of the carriage causes a 10 m translation of the tractor.

A compromise between the guidance/docking concept of the TG and the baseline would be the placement of rails on the bottom of the port duct. The rails would be aligned to the docking interface and are not resting on the port cell floor during Tokamak operation. This concept shares the advantages with the TG of simplified alignment by the guidance, directly orientating to the VV interface and the safer operation in the Duct. An extra function could be that the rails are used for handling of all kinds of port cell equipment.

### 3.2. Tractor module

The analysis of the current design is as follows. The forces introduced do not point at the nodes of the kinematical model of the baseline design (Fig. 4). E.g., the actuators for the rotation motion are mounted on an arm which is connected to an I-beam which is loaded in the direction with the lowest torsional stiffness. The element connecting the bottom of the gripper to the tractor frame has to transmit a pushing force. A flat plate here is an unfortunate choice in view of buckling. The actuators for lift and rotation show considerable crosstalk. The use of a lever could lower the requirements on the actuators and should improve stiffness (bulk modulus of steel is around 100 times higher than water or oil). An extra remark is that it is desirable to use the hydraulic cylinders for push forces only. The mentioned problems conclude towards the assessment of the current design that it is a complex, low stiffness/high weight design, which is negatively influencing UPP handling.

A new kinematical structure is proposed (Fig. 5) to improve these issues while keeping the same design guidelines as for the previous tractor, i.e. 2 DoF. The new gripper can, if necessary, apply large forces to loosen the plug due to the leverage action of the knee-hinge. Hereeto, a node is added in the middle of an element and an actuator is placed perpendicular to this node. Because of this actuator forces are reduced by a factor four compared to the previous tractor design. The gripper is positioned above and as close to the front wheels as possible. For the lifting operation there is a linear guidance in the lower nodal point. The sliding block is given a certain length to reduce contact stresses and wedging. Rotation and lift motions are less interfering. The gripper has a more compact shape. The object hangs on the upper side (horizontal force) and rests on the bottom (horizontal and vertical component). To provide extra stiffness in angular directions transverse and diagonal beams are added.

### 3.3. Cantilevered UPP handling

The previous design assumption was to handle the UPP cantilevered. The length to section ratio of the UPP of 6 is particular suitable for non-cantilevered handling. Adding a support on the front of the UPP compensates for the large moment forces introduced on the hand-over tooling and can reduce wheel loads by a factor six [5]. Hertzian contact stresses on the tractor wheels are decreased and the demands on the stiffness of the tractor/UPP combination to control the tip deflections are decreased. Furthermore, the alignment of the UPP can be simplified with a front guidance. A small sideways deviation of the tractor causes less deflection of the plug tip. Concepts with front support (two sets of wheels) already have been implemented [6]. It is recommended to design the front support as robust and simple as possible, e.g., ceramic skids instead of wheels. The gap crossing strategy with the two sets of wheels seems critically dimensioned regarding small deviations. The rotating rail extensions mentioned before could provide a solution for this.

### 3.4. Pallet module

Four height adjustable feet are positioned at the corners of the pallet to control \(z\), \(\varphi\) and \(\psi\). Because the feet only have 1 DoF, the feet slip over the floor with an angular adjustment of the Pallet (\(\varphi\) or \(\psi\)) causing high tension and friction. This leads to hysteresis and uncontrolled motion. The cask envelope is guided by five pairs of wheels in the pallet. These can slide in lateral direction. The front three pairs are actuated by 6 hydraulic cylinders to adjust \(y\) and \(\theta\), the rear two pairs are preloaded by springs. When the cask envelope is returning from the extended position, these are not inline, this holds especially for the wheels without flanges on the sides. A rack-and-pinion on the rear side of the pallet actuates the cask envelope in \(x\). These construction-related kinematical shortcomings have negative consequences for the handling of the cask envelope during the docking phase. A new concept for the wheels is suggested inspired on train bogies. Two linear actuators actuate two bogies in lateral direction (Fig. 6) to adjust the cask envelope in \(y\) and \(\theta\). The bogies can rotate around \(\theta\) freely. The advantages compared to the current system are that the wheels now have the same orientation as the rails. By using pairs, wedging over the rails is reduced. Finally, the number of actuators is reduced (two actuators for two DoF).

### 3.5. Service connector

Before docking to the port extension flange, the pallet docks to the service connector. After this, the fine alignments in \(z\), \(\varphi\) and
ψ are done. The docking pins and service connector must allow these movements. It would be better to have a removable flexible connector extension inserted and held in the service connector, which can accommodate the motions required for port docking and which can be removed for service while the actual port connector is rigid and maintenance free.

4. Conclusion

4.1. Trade-off rationale

A number of the previous design subsystem improvements are suggested (new tractor, pallet bogie, non-cantilevered handling, flexible service connector, optimized cask envelope). However, the overall system will still be fundamentally flawed. The biggest issues are: (i) the docking strategy with the initial alignment to the building instead of the vessel, (ii) extending the heavy cask envelope into the vulnerable port duct, and (iii) those tasks fulfilled by a complex system featuring five modules with a superfluous number of DoF. Validation tests on the design can be done with e.g. finite element analysis, but it is expected that performance will meet the safety standards marginally. Therefore, it is suggested to further investigate a full system redesign of the CPRHS system, up to and including the external interfaces, as these are drivers for the system performance. To make progress with the biggest flaws like the cantilevered translation in the duct of the cask envelope, another system concept like the tubular guide is recommended. However, this requires new design solutions and has impact on the PBS. The integration issues are assessed in the next paragraph to distillate realistic proposals.

4.2. Integration issues

For the tubular guide solution, the most important interface changes are needed. The space allocation in time changes for the CPRHS system. The new cask can be designed within the old cask volume envelope, but the tubular guide itself claims volume in the port duct, also during Tokamak operation. The TG changes loading conditions on the VV, the docking interface changes and the contaminated volume is increased. Furthermore, there are unsolved design issues like the disassembling of the UPP pipes, which is still an undeveloped terrain (also for the baseline). The rails-in-duct concept is a compromise by leaving the baseline cask largely intact, but still keeping the advantages of passive guidance and increased stiffness during take over. We suggest investigating the feasibility of these redesigns on these external interfaces, and then the mentioned design suggestions give sufficient motivation and pre-work to elaborate a (safer) remote handling concept. The modular design suggestions of the tractor and non-cantilevered handling are recommended by all means.

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References