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ABSTRACT

DEMO should be as close as possible to a future fusion power plant, produce electricity and have a high level of availability. In the current Concept Design phase, the design is to be further elaborated and industry is to be increasingly involved as a partner in the development. An essential component will be the vacuum vessel (VV), which has to fulfil many tasks. It serves as a first confinement barrier and houses in-vessel components (IVCs) that are necessary for operation. The VV has numerous openings - the ports. These are closed during DEMO operation by so-called port closure plates (PCPs). All handling of the PCPs and IVCs, as well as inspection throughout the operational phase, must be done through remote maintenance tools and without the presence of personnel. Within the framework of qualified partners from industry the fastening and sealing of the PCPs is studied. Many requirements are associated with the technical implementation. As the development of DEMO is still in an early phase, the present goal is not yet the development to a high degree of maturity. Instead the review of established industrial solutions regarding their suitability to DEMO as well as the identification of adapted solutions with more attractive features for the DEMO application are aimed for. In this paper, the background as well as the status of this task is explained.

1. Introduction

The development of EU DEMO (referred to as DEMO in the remainder of this document) entered the Concept Design (CD) phase in 2021. One of the goals is the synthesis and analysis of variants for different components. It is also an aspect to examine the applicability of solution concepts with regard to the boundary conditions and requirements.

2. Organisation of development work

The technical research and development (R&D) is organized within dedicated work packages (WPs) most of which are located in research units. With the start of the CD phase, integration work is structured by system design leads in the Fusion Technology Department (FTD) or in the WPs. This approach should further facilitate the close cooperation of the integration of the different systems [1].

The roadmap of the fusion programme [2] envisages that DEMO will not be conceived by research units alone. Industry is to gradually become a driving force in fusion development. Therefore, industry is to be intensively involved early. Aim of the current framework programme (FP9) is also to use the experience of industry and to involve it through targeted tasks.

3. DEMO

DEMO is to be orientated towards the operating conditions of a future fusion power plant to generate electricity. High availability is also to be achieved by minimising the time required for planned and unplanned maintenance.

3.1. Vacuum vessel

The vacuum vessel (VV) is a central component of a fusion power plant in many respects [3]. Amongst other tasks, it provides the necessary high vacuum environment (<1E-5 Pa) for the fusion plasma and

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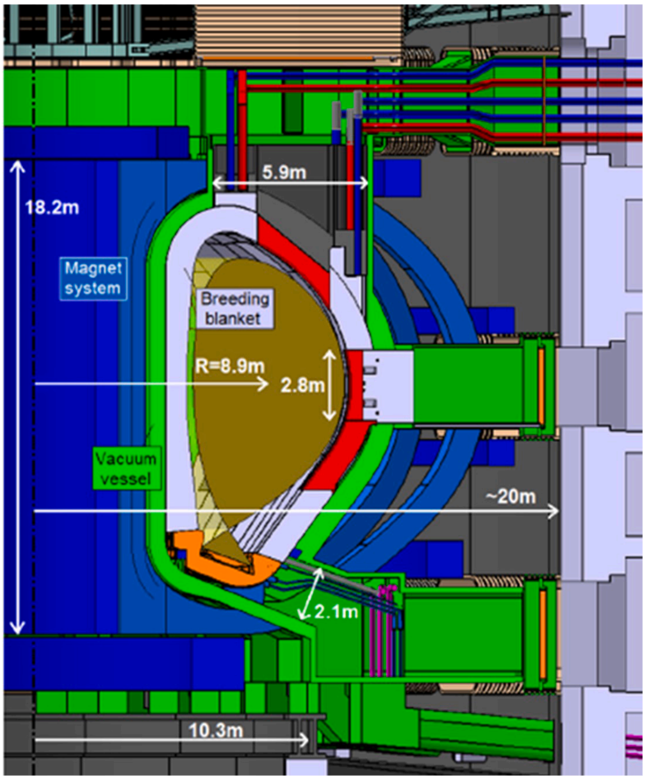

Fig. 1. DEMO VV (green) with upper, equatorial and lower ports, IVCs BB (grey), divertor (orange) and limiters (red) and some size indications.

must therefore have the appropriate tightness. Furthermore, it serves as a first confinement barrier for the activated dust and the tritium. It is therefore subject to nuclear regulation and, as nuclear pressure equipment, must be designed to withstand an internal pressure of 0.2 MPa.

Inside the VV, there are numerous in-vessel components (IVCs). These include the 80 segments of the breeding blanket (BB) system [4], the 48 divertor cassettes [5] and first wall protection limiters [6]. In addition, several diagnostics, heating systems and parts of the gas inlet and vacuum systems [7] are required for the operation of the plasma (see Fig. 1). All these IVCs are subject to natural wear and tear and particular ones will require scheduled replacement. For the installation, maintenance, and replacement of these IVCs, access ports are implemented at various levels of the VV.

3.2. Port ambient conditions

The VV and its ports are located inside the cryostat very close to the plasma of a fusion device. Thus, they are exposed to harsh conditions and must reliably withstand them. These are essentially determined by:

- High heat loads
- Magnetic field [8]
- Neutron irradiation [9]
- Tritium environment [10]
- Various pressure cycles, also due to potential accident scenarios [11]

Many of these ambient conditions are influenced by the design of DEMO and are being investigated in ongoing tasks. It is expected that these requirements will become increasingly converged within the CD phase, but until then only preliminary numerical values can be used.

3.3. DEMO operation and maintenance

The operation and maintenance concept for DEMO is currently in the early stages of development. However, it is already clear that because of the large dimensions and weights, but also because of the activation of the components, all work must take place with the help of remote maintenance (RM) tools. In principle, it would be desirable if access through one port could also be used to carry out maintenance work at other locations, so that as few ports as possible have to be opened [12]. However, this requires very complex kinematics inside the VV. Therefore, it must be assumed that rather many of the ports must be used for maintenance.

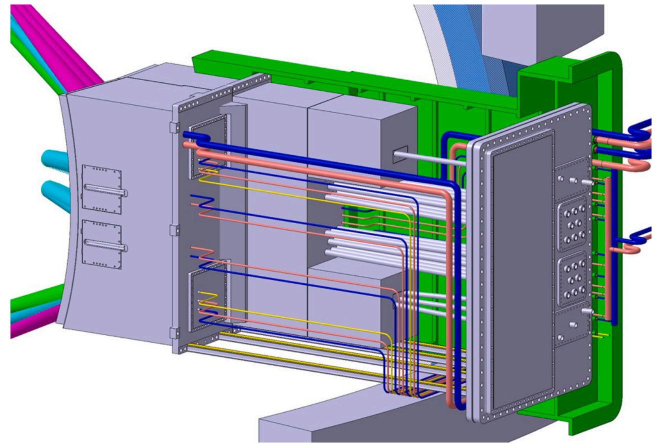

Fig. 2. DEMO PP of EC launcher and the associated PCP.

3.4. Application of ITER solutions

Wherever it seems reasonable and technically feasible, the possible use of solutions developed for ITER will be considered in the development of DEMO. However, in areas where the operating conditions or the design of DEMO is too different, this is not always appropriate.

In ITER, the installation of plasma diagnostics and auxiliary heating front-end systems in the ports [13] of the upper and equatorial levels is foreseen in so-called port plugs (PPs) [14,15]. These PPs are designed as cantilevers. The structural connection between PP and VV is made at their end by bolting. The vacuum-tight seal is only created after this installation by one of two specially developed sealing solutions:

a) The (bolted) double flange [16] is a kind of frame consisting of an additional flange on the VV side and a flange on the PP side that are connected with a somewhat elastic sheet metal bend. A double spring-loaded C-ring seal with intermediate vacuum between seals this frame to the VV and to the PP.
b) With the (welded) lip seal [17], the sealing of the PP to the VV is realized by welding one sheet metal strip on the PP side and one on the VV side.

Both of these sealing solutions ensure that the sealing element is not damaged during the difficult assembly of the PP. Furthermore, small movements of the PP in relation to the VV affect the seal less. However, both solutions rely on the use of numerous bolted connections to fix the PP to the VV. In addition, bolted connections are necessary to fasten clamps that reliably prevent deformation of the lip seal in case of internal overpressure in the VV. Even more bolts are needed for fastening the double flange.

4. Scope of industry task

The current DEMO foresees a different design for the PPs. In respect to ITER they are expected to be much shorter and are mechanically attached more balanced and further inside the port to the VV. The vacuum tight sealing is done at the rear end of the port with an independent port closure plate (PCP). In DEMO operation, these PCPs are subject to the same technical and regulatory requirements as the VV.

This separation of PP and PCP reduces the requirements for the seal in some respects. In addition, other design solutions may be possible, which could be further relaxing RM efforts. As an example, Fig. 2 shows the DEMO PP of the electron cyclotron (EC) launcher of the plasma heating system [18,19] and the PCP.

Bolted connections have several specific properties. Firstly, the loosening and tightening of many bolts is always time-consuming. Additionally, these connections can seize and make necessary unpredictable, laborious repairs.

The basic idea behind this task is the search and rudimentary development of other solutions for the fastening and sealing of the PCPs.

4.1. Breakdown of task

Considering a new design of the PCP from scratch results in very many degrees of freedom. At the same time, the close interaction of the individual components has to become clearer.

The following is a rudimentary description of the possible areas in which initial considerations suggest potential success. For this purpose, a conscious attempt has been made to split the overall topic as much as possible in a meaningful way.

4.2. Fastening solutions of PCP

4.2.1. Fixation of PCP by bolts

Different types of bolted connections are often used in mechanical engineering to join components together in a detachable manner. This makes it possible to create a frictional connection. The force generated can also be used to compress a seal between the components to such an extent that the components are tightly joined together. Many things play a role in the use of bolted connections. amongst other things, the mechanical design of the flange pairs is important because of their rigidity against mechanical deformation and the possibility of reducing the number of bolts required. However, the selection of suitable materials and material pairings are also important. Unsuitable combinations can lead to cold welding and thread galling. Thus, the development of procedures for repair is also crucial.

4.2.2. Fixation of PCP by means other than bolts

Many technical topics require a quick opening of components otherwise tightly sealed. Depending on the requirements for vacuum tightness, there are many different technical implementations. Examples of this are bulkhead doors for submarines or ships, nuclear doors, doors for vaults, or space applications. The force required for a stable connection can be generated by mechanical or hydraulic actuation or also by a well-planned welded connection. Here, too, the solution can be designed with regard to pure fastening of the PCP or simultaneous pressing of a seal. There are also various commercial solutions of clamping or chain flanges [20].

With regard to the required compression pressure of metallic gaskets, the limiting size and the cross-sectional geometry are of particular interest.

4.2.3. Separated sealing and PCP mechanical fixation

Section 3.4 has already described the ITER solutions for sealing the vessel closures. An investigation into the basic advantages and disadvantages of a design in which the seal is separated from the PCP attachment could improve this decision-making process.

4.2.4. Combined sealing and PCP mechanical fixation

The combination of fastening a vessel closure with simultaneous sealing by pressing a seal in between is a widespread technical solution. In the field of vacuum technology with the required low leakage rates, many requirements are associated with this. The investigation of these could provide important suggestions for future design.

4.3. Sealing solutions

In the already long history of vacuum techniques [21], many varieties of technical solutions for vacuum-tight sealing have been developed. However, most of them play a minor role in the modern world. Only a limited number of now almost standardised solutions have been able to hold their own.

In general, as with the solutions for ITER, a distinction can be made between permanent and semi-permanent, demountable seals.

4.3.1. Welded / permanent seals

A hermetic seal can be created with welded joints. If such a seal is made in accordance with the rules, it represents a very reliable and long-lasting seal. Many technological solutions have to be developed in regard of the execution of the welding, the inspection before commissioning, the monitoring during operation and the re-opening.

4.3.2. De-mountable seals

4.3.2.1. Gasket seals. There are unavoidable tolerances and roughness on the surface of flange couplings. Gaskets fill the resulting gap to a certain extent and thereby reduce the leakage rate. To achieve enough deformation of the gasket, sufficiently high contact forces are required. In addition, many other influencing factors must be taken into account in order to select a suitable pairing of flange and gasket. In addition, cold-welding and cleaning are key for reliable application.

4.3.2.2. Liquid and elastomer seals. In a liquid seal, material in the liquid phase is used to fill the gaps between the connected parts [22]. Mercury, which is liquid under DEMO operating conditions, can be used for this. This material is also intended as the operating medium in the DEMO vacuum pump. Therefore, the handling has to be considered anyway [23]. Alternatively, materials can be used that are already solid under normal operating conditions and are only liquid during application.

Elastomer seals are generally widely used for vacuum assemblies. However, the areas of application differ in many respects from those of metallic seals. Nevertheless, it might be helpful to investigate the possibility of using elastomeric seals in the sealing of the PCP.

4.4. Further topics

In many respects it is important, to investigate the influence of the given environmental conditions on the materials used. There is expected cold welding [24], which would cause several issues with removing the components from each other and cleaning the surfaces for the preparation of the next combination. The influence of neutron irradiation and fatigue may limit the quality of the tightness. As the development of PCP seals progresses, there are likely to be further issues that need to be addressed.

DEMO commissioning is likely to follow a stepwise approach, as envisaged for ITER. This might have the consequence that different PCPs and seals are used for each step. It would therefore be advantageous if these could be exchanged for a better seal easily.

5. Objectives and methodology

In the previous section, possible topics for industrial participation are roughly outlined. As can already be seen from the previous description, within the industry tasks the focus should not yet be on the development of detailed technical solutions. This would entail the great risk that a complete new development would be necessary if assumed design parameters would change. The goal is, together with experienced

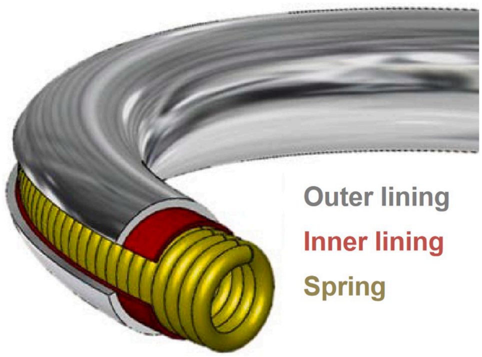

Fig. 3. Sketch of a spring-loaded C-ring gasket (courtesy Technetics).

companies in the field of the corresponding task, a joint elaboration and definition of the relevant boundary conditions as a basis for a deeper mutual understanding and problem awareness.

The following aspects should be considered:

- The first step should be to research existing technologies and compile them in a kind of catalogue.
- Application of a robust, established, industrial solution could reduce risks compared to completely new developments.
- The total time required to open and close the PCP shall be considered as a criterion.
- All activities must be able to be performed without personnel access.
- A possible uniform design for the PCPs, at least within one level, also simplifies the development of the RM tools and the approval process.
- The technologies should be described in particular with regard to their limitations and capabilities and be evaluated according to a quality or performance number.
- Design drafts can contribute to a better understanding of the assessment. They also allow for better identification of technical and technological gaps.

6. Industry contracting

One of the leading manufacturers and designers of sealing and component solutions has already been contracted under the frame of EUROfusion industry collaboration. Technetics was chosen for its decades of experience in a wide range of applications, from nuclear and fusion to space applications. Currently, the task for the following years is being formulated in detail. As a first step, the creation of a kind of user guide is foreseen. This should provide a better understanding of the challenges, levels and mechanisms of a sealing technology and should contain especially for the promising concept of a spring-loaded C-ring seal (see Fig. 3 for illustration), key points, typology, mechanical characterisation and simulations. Furthermore, summarizing the portfolio of seals used in ITER and a comparison of the ITER and DEMO situation is planned.

In a next step, solutions with regard to service life, RM-friendliness, easy monitoring, compact design or other aspects like cleaning of sealing surfaces are to be presented in more detail. As far as possible at this time, also material ability in regard of DEMO environmental conditions will be examined. These should consider magnetic field, neutron irradiation and meeting the licensing and legal requirements imposed by the tritium environment.

In a foreseen further step, engineering considerations will be made for the design of the various PCPs. This involves in particular the generation and application of the contact pressure by e.g. mechanical or hydraulic means. The variants synthesised are to be qualified with regard to their suitability for the application of RM methods.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

[1] G. Federici, et al., The EU DEMO staged design approach in the pre-concept design phase, Fusion Eng. Des. 173 (2021), 112959.
[2] A.J. Donné, et al., Roadmap towards fusion electricity, J. Fusion Energy 38 (2019) 503–505.
[3] C. Bachmann, et al., Containment structures and port configurations, Fusion Eng. Des 174 (2022), 112966.
[4] G. Federici, et al., An overview of the EU breeding blanket design strategy as an integral part, Fusion Eng. Des 141 (2019) 30–42.
[5] U. Bonavolontà, et al., EU-DEMO divertor: Cassette design and PFCs integration at pre-conceptual stage, Fusion Eng. Des. 159 (2020), 111784.
[6] J.H. You, et al., Limiters for DEMO wall protection: Initial design concepts & technology options, Fusion Eng. Des. 174 (2022), 112988.
[7] Chr. Day, et al., The pre-concept design of the DEMO tritium, matter injection and vacuum systems, Fusion Eng. Des. 179 (2022), 113139.
[8] V. Corato, et al., The DEMO magnet system – Status and future challenges, Fusion Eng. Des 174 (2022) 11297.
[9] M.R. Gilbert, et al., Scoping of material response under DEMO neutron irradiation: Comparison with fission and influence of nuclear library selection, Fusion Eng. Des. 125 (2017) 299–306.
[10] G. Caruso, et al., DEMO – The main achievements of the pre – concept phase of the safety, Fusion Eng. Des. 176 (2022), 113025.
[11] T. Haertl, et al., Rationale for the selection of the operating temperature of the DEMO vacuum vessel, Fusion Eng. Des. 146 (2019) 1096–1099.
[12] O. Crofts, et al., EU DEMO remote maintenance system development during the pre-concept design phase, Fusion Eng. Des. 179 (2022), 113121.
[13] Yu. Utin, et al., Final design and start of manufacture of the ITER vacuum vessel ports, in: IEEE 25th Symposium on Fusion Engineering, 2013, pp. 1–6.
[14] F. Josseaume, et al., Development and qualification of the ITER port plug handling process, Fusion Eng. Des. 136 (2018) 902–907.
[15] V.S. Udintsev, et al., Final design of the generic equatorial port plug structure for ITER diagnostic systems, Fusion Eng. Des. 96 (97) (2015) 993–997.
[16] J.-P. Martins, et al., Study of ITER equatorial port plug handling system and vacuum sealing interface, Fusion Eng. Des. 84 (2009) 1268–1275.
[17] B. Levesy, et al., ITER lip seal welding and cutting developments, Fusion Eng. Des. 98 (99) (2015) 1528–1531.
[18] T. Franke, et al., Integration concept of an electron cyclotron system in DEMO, Fusion Eng. Des. 168 (2021), 112653.
[19] P. Spaeh, et al., Design progress of structural components of the EU DEMO EC equatorial launcher, in: Proceedings of the 32nd SOFT conference, Dubrovnik, HR, 2022.
[20] M. Mapes, et al., Summary of quick disconnect vacuum flanges, J. Vacuum Sci. Technol. A 19 (2001) 1693.
[21] A. Roth, Vacuum Sealing Techniques, Springer, 1994.
[22] D.M. Mattox, A short history: vacuum sealing-grease, oils, cements, elastomers, and metals, svc bulletin I fall/winter (2016).
[23] T. Giegerich, et al., Preliminary configuration of the torus vacuum pumping system installed in the DEMO lower port, Fusion Eng. Des.146 Part B (2019) 2180–2183.
[24] A. Merstallinger, Influence of coatings and alloying on cold welding due to impact and fretting, in: Proc. 9th European Space Symposium on Material in a space Environment, Noordwijk, NL, ESTEC, 2003.