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Engineering Aspects on the Development of a Reactor Concept for DEMO

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Abstract
On the way to the first commercial nuclear fusion reactor DEMO conceptual studies addressing the design of the in-vessel components, namely the breeding blankets, the helium supply unit or manifold and the hot ring shield, are underway. Of particular importance is the development of an appropriate concept to integrate these components into the reactor. As part of the European DEMO effort different blanket concepts and segmentation have been investigated. The Helium Cooled Pebble Bed (HCPB) as well as the Helium Cooled Lithium Lead (HCLL) blanket concept are quite advanced and no matter what type of blanket is favored the so-called vertical Multi Module Segment (MMS) integration concept has been identified to be promising. An advantageous handling of the MMS can be expected if blanket and manifold constitute vertical non-permanent segments to be installed and dismantled with remote handling tools through the upper port of the reactor. The present report gives an overview of the integration of the Helium Cooled Pebble Bed blanket into the reactor. The MMS concept is applied. The required mechanical attachments need to be flexible to compensate different thermal expansions, but also need to withstand the loads during normal as well as off-normal operating conditions, e.g. plasma disruptions. A possible design is introduced and certain engineering aspects are highlighted. Implications of the chosen maintenance concept on blanket integration are briefly described to provide a complete picture.

1. Introduction

On the way to the first commercial nuclear fusion reactor DEMO conceptual studies addressing the design of the in-vessel components, namely the breeding blankets, the helium supply unit or manifold and the hot ring shield, are underway. Of particular importance is the development of an appropriate concept to integrate these components into the reactor. The technical feasibility needs to be demonstrated. Pressure loads and thermal loads under normal as well as off-normal conditions and also electro magnetic (EM) loads in case of plasma disruption need to be considered.

The present report gives an overview of the integration of Helium Cooled Pebble Bed (HCPB) blankets into a DEMO device in which the Multi Module Segments (MMS) concept is applied. Discussions about the most appropriate assumptions considering unit size, technology, and mode of operation for a fusion reactor are by far not concluded. Nevertheless, main plant parameters need to be defined to allow focus on relevant engineering aspects. The assumed layout is less ambitious than Model C from the EU Power Plant Conceptual Studies (PPCS) [1]. While maintaining the size of the device it is envisaged to produce a net electric power of only 1.0 GW. This conceptual single null DEMO device for steady state operation is based on Model AB technology and a major radius of 7.5m [2, 3].

The required mechanical attachments to integrate the blankets into the reactor need to be flexible to compensate different thermal expansions, but also need to withstand the loads during normal as well as off-normal operating conditions. The present report introduces a possible integration concept and highlights certain engineering aspects of the design. With respect to the current state of development, implications of the chosen maintenance concept on blanket integration are briefly described, to provide a complete picture.

2. Integration Concept

As part of the European DEMO effort different blanket concepts and segmentation have been investigated. The Helium Cooled Pebble Bed (HCPB) [4, 5] as well as the Helium Cooled Lithium Lead (HCLL) [3, 6] blanket concepts are quite advanced and no matter what type of blanket is favored the so-called vertical 'Multi-Module-Segment' (MMS) integration concept has been identified to be promising. An advantageous handling of the MMS can be expected if blanket and manifold constitute vertical non-permanent segments to be installed and dismantled with remote handling (RH) tools through the upper port of the reactor [7]. The segmentation in toroidal direction is determined by the acceptable total weight of the segments and the size and number of the employed maintenance ports.

The present concept proposes to attach the MMS to the self- supporting Hot Ring Shield (HRS), whereas the HRS is supported by the Vacuum Vessel (VV) by flexible bending bars. Figure 1 illustrates the integration concept and the required mechanical connections. There will be a strong temperature difference between the hot plasma facing first-wall of the blanket and the water cooled VV. It is intended to cope with this temperature difference, which inevitably induces thermal stresses, in a way that the total temperature difference is suitably distributed between the different in-vessel components [8].

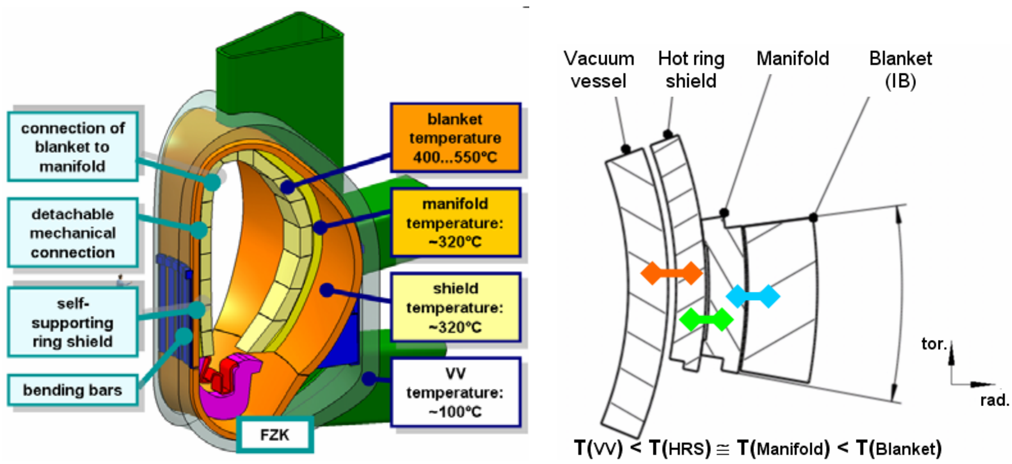

Figure 1: Principle of the integration concept (left) and required mechanical connections (right).

On the plasma side the cooling configuration of the blanket will have to ensure that 550°C are not exceeded. Otherwise the material properties of the envisaged materials such as the low activation steel EUROFER are not sufficient to achieve a reliable design. The inlet temperature of the coolant Helium is 300°C which allows tempering the manifold which supplies the blanket modules with the cooling fluid and the HRS to approximately the same temperature value. The water cooled VV will be operated at a temperature level of about 100°C. This means that only the connections between blanket module and manifold as well as the connections between the supporting HRS and the VV have to be able to compensate the expected temperature differences. In contrast, the connection between the MMS and the HRS can be designed for a more or less uniform temperature level, which certainly facilitates reliable integration and support of the large MMS.

Although some implications due to the hydraulic connections considering for example purge gas in the case of the HCPB or Lead Lithium pipes in the case of the HCLL might have to be expected, the integration concept at hand is not necessarily restricted to one single blanket concept but rather aims to be applicable to different blanket designs. Nevertheless, at Forschungszentrum Karlsruhe the development of the blanket concept employing ceramic breeder material- the HCPB blanket- has been promoted since many years [4, 5, 9, 10]. Based on this continuous long-term development, the present contribution is focused on engineering aspects of the integration of the HCPB blanket into a conceptual DEMO fusion reactor. The design of an attachment system is influenced by the chosen maintenance concept. To provide a complete picture of the reactor concept, a very brief description is given in the following.

Implications of Maintenance Concept The chosen maintenance concept employs vertical ports for inserting and removing the MMS. It is assumed that only a limited number of ports are opened for maintenance which is reasonable considering the high expenditure to open the ports. This is also advantageous since it is reasonable, if magnet technology allows doing so, to adjust a limited number of ports to particular maintenance requirements, especially in terms of size. But this also implies the following major consequences: (1) The RH attachment of the MMS to the HRS has to be realized under restricted geometric conditions and limited access from inside the vessel. (2) The MMS need to be transported inside the vessel, which requires the design of an appropriate rail system and/or toroidal mover. (3) The use of in-bore tools for cutting and welding of the cooling pipes is suggestive. It is important to note that a complete reactor concept has to address all of these issues and can only hold if technical feasibility is demonstrated for all of them. These issues are not treated explicitly in the present text, but information going into some detail is given elsewhere [11, 12]. To date a positive general statement considering feasibility and expected maintenance time- a decisive criterion for a maintenance scheme- can be given.

3. Blanket Concept

Breeding blankets are key components of fusion power plants and determine to a large degree their attractiveness. Besides the obvious challenge to extract the thermal power from the fusion reactor most efficiently, breeding blankets need to provide an adequate margin of tritium self-sufficiency and appropriate shielding with a limited radial build of the blanket.

A major improvement of the blanket design was possible since the MMS concept was introduced. The MMS concept offers flexibility to the designer particularly with regards to module size without compromising in terms of maintenance time [7, 12]. The new HCPB blanket design adapted to the MMS concept is based on the Large Module design applied in the PPCS Model B [4]. The HCPB blanket concept comprises a modular design with breeder units stacked between steel plates. The reduced number of breeder units with only two breeder units placed on top of each other in poloidal direction allow simplifying the manifold design and reducing the pressure losses in manifold, cooling channels and first wall. The cooling plates serve as heat sink and also can provide the required stiffness for the pressurized blanket box. Figure 2 shows the assembly of the blanket module with breeder units and L-shaped stiffening structure. The solid pebble bed breeder unit employs ternary Lithium Orthosilicate ceramic (Li_4SiO_4) as breeder material, Beryllium as neutron multiplier and the low activation ferritic-martensitic steel EUROFER as structural material. The coolant, also for the thermally high loaded first wall, is Helium at 8 MPa. The inlet temperature is 300°C; the foreseen outlet temperature is 500°C. The main advantage of the solid breeder blankets is the good compatibility between breeder material, structural material and coolant while comprising a very good neutronic performance resulting in a sufficient Tritium breeding ratio [13]. The major drawbacks are the limits in power density due to the relatively low thermal conductivity of the ceramic breeder pebble beds [14] and the limits on blanket lifetime caused by irradiation damages in the ceramic breeder Beryllium. Tritium inventory in the ceramic breeder blanket region is a concern for safety reasons, but seems to diminish over the years with improvements of data bases and modeling tools [15].

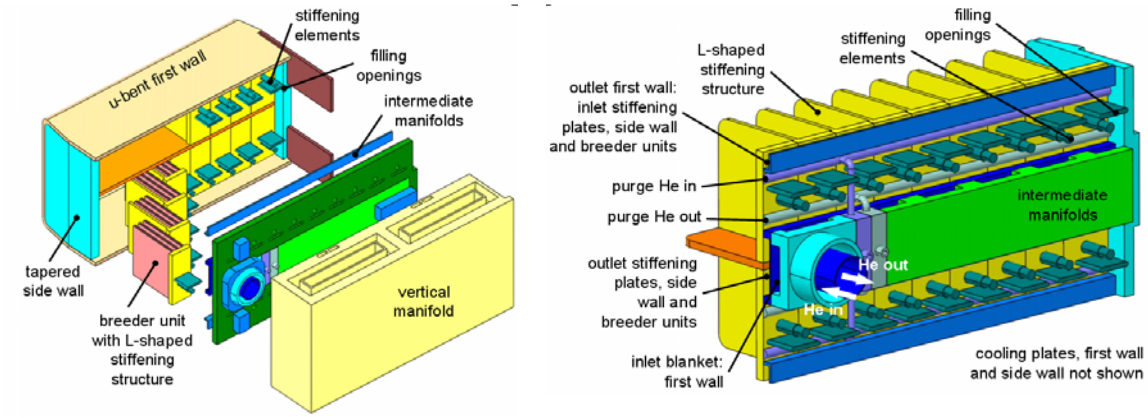

Figure 2: Exploded view of HCPB blanket (left) and assembly drawing with flow scheme (right).

The following sections deal with the engineering challenge to integrate the HCPB blanket module into a conceptual fusion reactor with the help of a mechanical attachment system.

4. Attachment System

As indicated in Figure 1 several mechanical connections need to be designed. Coming from the plasma side the blanket module has to be mounted onto the MMS. The MMS has to be attached to the HRS, where remote handling for scheduled maintenance inside the vessel is a requirement. Furthermore, the self supporting HRS has to be supported by the VV.

Attachment of Blanket Module to Manifold Requirements for the design are a blanket layout and attachment system suitable to withstand the expected loading during normal and off-normal operation and to facilitate maintenance, fabrication and reliable manufacturing. In this regard it is a major advantage of the MMS concept that the blankets do not have to be replaced inside the vacuum vessel.

Coming from four square meters first wall surface in the Large Module concept the module front surface area was reduced to two square meters in order to reduce the electromagnetic loads [16]. As detailed in [17] the module's aspect ratio has influence on the expected EM loads. As a consequence the reference blanket module is two meters wide (toroidal) and one meter high (poloidal). Considering basic scaling laws for the EM loads and possible geometric configurations to place the attachment's lever arms, an optimized configuration was defined. Thus, each individual blanket module is connected to the strong vertical manifold structure by use of a flexible attachment system. The fix point of the expected thermal deformation and the hydraulic connection are located at coinciding position. Its shift to the side of the module helps to determine the preferential direction of thermal expansions and enables its predictability. Furthermore, the attachment comprises bending plates- welded between the blanket module and the manifold- at the far end from the fix point to compensate thermal expansions and shear keys to withstand the torque loads from EM forces. Figure 3 shows the arrangement of the module on the MMS, an assembly drawing, and the connecting elements. The stress calculation by means of finite element analysis (FEA), considering normal operating conditions as there are thermal and pressure loads as well as considering off-normal operating conditions are promising and demonstrate the feasibility of such an attachment. For more details please refer to [17].

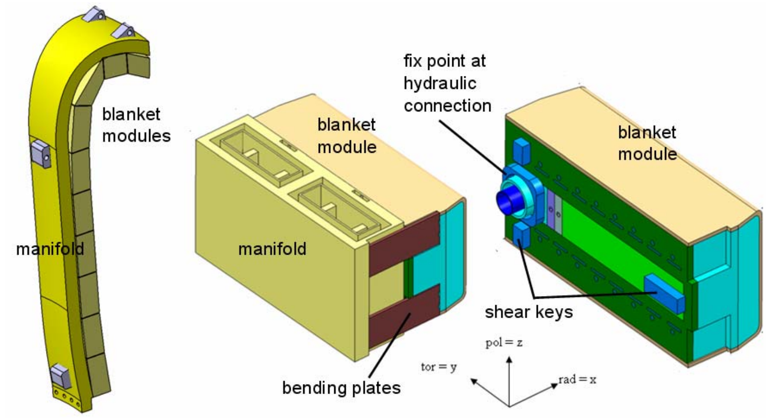

Figure 3: Inboard MMS with blanket modules (left), assembly drawing (middle) and detailed view of connecting elements (right).

Attachment of Multi Module Segment to Hot Ring Shield The MMS are supported by the HRS. It is a conceptual advantage that the permanent self supported shield structure can be operated at the same temperature as the MMS manifold structure. Thus relative thermal expansions are of minor importance and a design of an attachment relying on shear keys with low clearances and bolts is possible. The attachment comprises upper, middle and lower shear keys. Their shape is not only determined by the load cases to be considered, but also by kinematics. The reason for this is, as explained in Figure 4, that the MMS have to be inserted under restricted geometric conditions due to limited in-vessel design space. After the toroidal transportation by a RH machine located in the divertor region the MMS have to be inserted by vertical and rotational movement. The upper shear key can serve as block. After insertion the attachment is locked by bolts at the lower end of the MMS where access is facilitated.

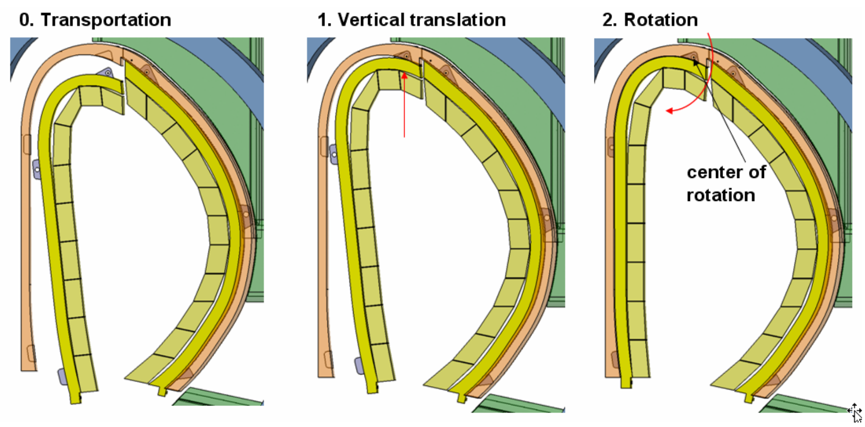

Figure 4: Sequence for insertion an inboard MMS into the supporting HRS.

Basic dimensioning of the joining elements, assuming different normal (gravity load) as well as off-normal load cases (EM loads), determined the design. As shown in Figure 5, FEA was employed to verify the design. Deformation as well as stress distribution was calculated and the revealed stresses were well beyond the relevant design limits.

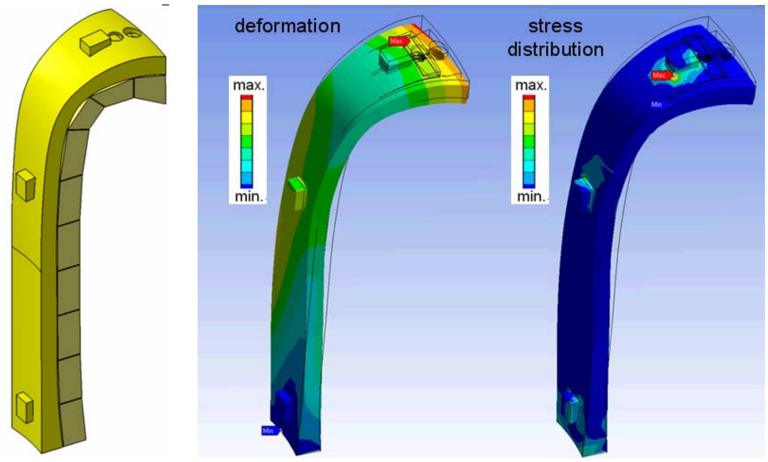

Figure 5: CAD model of inboard MMS (left) and results of FE calculations with simplified model.

As mentioned already, the MMS is supported by the HRS. Therefore, the structure of the HRS needs to cope with the localized loads from the shear keys of the MMS and also needs to provide enough global stiffness to transfer the loads to the VV. At the same time sufficient shielding has to be provided and the radial build should be limited.

Design of Hot Ring Shield The principle build up of the HRS is illustrated in Figure 6. It is designed as a permanent self supporting structure. The structural material is steel; tungsten carbide (TC) is foreseen as shielding material. It is composed as a strong "steel box" with increased stiffness from strengthening ribs and inserts for shear key support. Since the HRS has to be cooled by Helium (up to 5% of the fusion power is generated in the shield) a sufficient gas flow has to be assured. Due to this the ribs are provided with openings and stapled TC plate packages allow the flow of coolant. Furthermore, the shield needs to be segmented to allow assembly inside the vessel and insertion of the HRS segments through the ports. The segments are connected by dedicated bolts for RH reasons. These removable locking devices are tolerant regarding possible misalignment of the large and heavy segments.

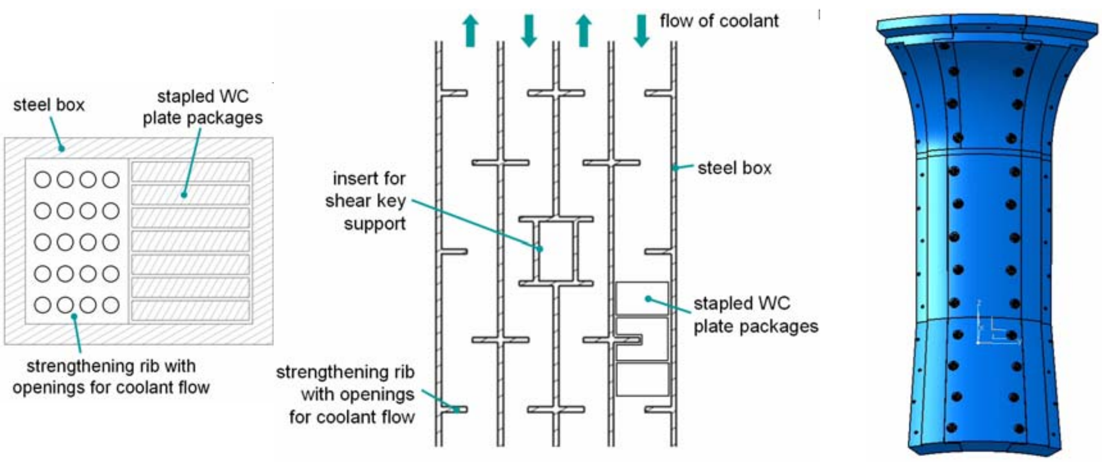

Figure 6: Principle build up of the HRS in the radial-toroidal plane (left), principle configuration in the poloidal-toroidal plane (middle) and conceptual design of HRS segments (left).

The global shield structure is toroidally closed and can expand fairly unconstraint during heat up within the vacuum vessel. Exemplary results of FEA for reasons of evaluating the design can be seen in Figure 7. It shows the deformation of the HRS due to temperature loading (left) and the stress distribution at inboard (middle). Details of the stress distribution in the region of the shear keys that was calculated for the most severe load case considering EM loads can be seen on the right side of Figure 7. The results are promising, revealing acceptable stresses and even show the potential of reducing the amount of steel of the current design. This would improve the shielding capacity while maintaining the same radial build.

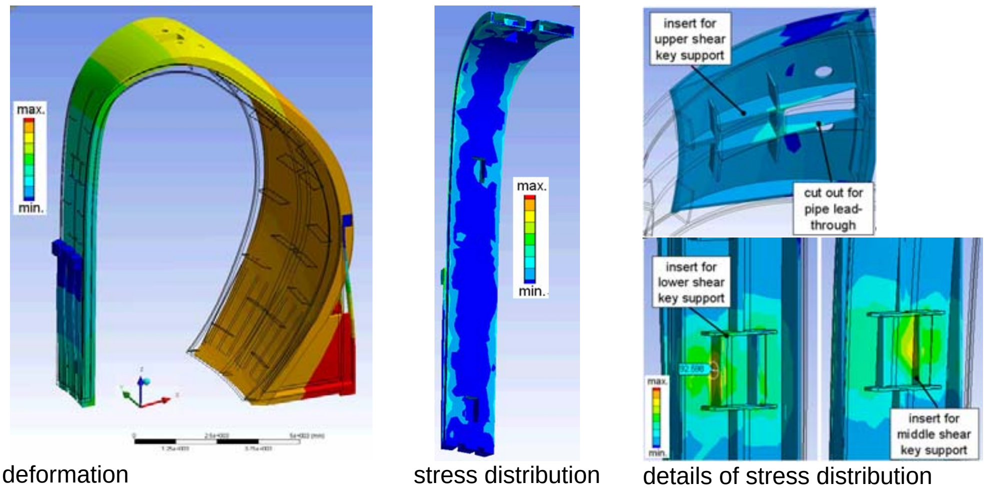

Figure 7: Results of FE calculations of the HRS: Deformation (left), stress distribution (view from plasma to inboard, middle) and details at shear key positions (right).

Attachment of Hot Ring Shield to the Vacuum Vessel by Bending Bars The principle dimensions of the bending bars are determined by the weight to be supported and the thermal deformation to be tolerated. Considering the relevant acceptable stresses, the weight determines the cross section of the bars and the length of the bars (bending) is determined by the anticipated deformation due to thermal expansions. Figure 8 shows results from FEA. It shows the calculated deformation and the related stress distribution including gravity loads from the HRS and the MMS. The stresses are permissible and prove the feasibility of such a bending bar attachment.

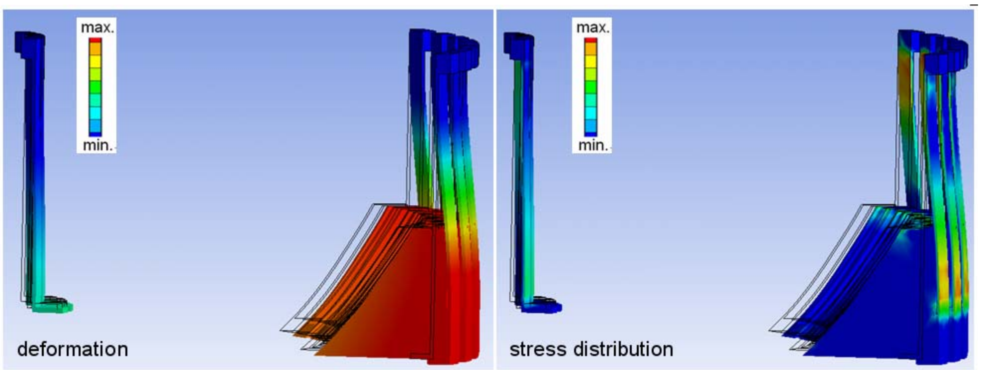

Figure 8: Results from FEA of the bending bars.

It profits from the toroidal closed structure of the HRS that ensures nearly pure tensile load from the weight and also leads to a compensation of the EM loads. Therefore, EM loads do not have to be considered. Additionally, employing the HRS as the supporting structure leads to a reduced power density by neutron flux in the bars and, since also the contact temperature in this region is maximal 300°C, performed calculations imply that cooling is not required. Furthermore, the circumferential arrangement of the bending bars is adaptable to account for requirements of equatorial ports.

5. Summary and Outlook

Important engineering aspects on the development of a reactor concept for DEMO have been discussed. Focus has been on the (blanket) attachment system whose design could be facilitated by employing an appropriate integration and- of equal importance- maintenance concept. Evaluation by means of FEA revealed promising results that suggest the feasibility of the system. Integration of the HCPB blanket has been studied but the results are not necessarily limited to this blanket type. The blanket modules are linked to the MMS by appropriately combining welded connections, flexible elements, and shear keys. It profits from the MMS concept which means that this connection does not have to be handled inside the vessel. The MMS itself are attached to the permanent HRS structure by tensioning the segments with bolts. Shear keys take the expected loads. It is a conceptual advantage that this attachment has to cope with only minor temperature differences between HRS and MMS. RH with limited access from inside the vessel seems to be feasible. The attachment between the HRS and the VV has to cope with different thermal expansions due to existing temperature differences. The suggested solution comprises bending bars that are capable to withstand the expected loads. The concept benefits from the toroidally closed supporting HRS structure. Due to this EM loads are compensated. The design of a HRS providing sufficient stiffness and sufficient shielding is a challenge but a promising design and its positive assessment has been presented.

It is evident that further work will be necessary. Not only to adapt to possibly changed DEMO plant parameters and requirements in the future but also to develop more detailed design solutions, the related fabrication and manufacturing procedures, ingenious cooling schemes, and appropriate maintenance scenarios to allow for final judgments on the feasibility of the overall reactor concept. Nevertheless, a certain stage of development has been reached that allows concluding that the development of the presented attachment system- a major engineering challenge requiring reliability under harsh environmental and loading conditions- is on a promising path.

Acknowledgments
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