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Availability Considerations in the Design of K-DEMO *

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Abstract. A DEMO device has been considered the next step following ITER as a near-term prototypical reactor design that is tritium self-sufficient and produces a limited amount of net electricity. The machine maintenance approach and planned configuration concept plays a major role in establishing the design point. DEMO will also need to show that adequate operating availability can be achieved over a reasonable time period, as a last step before full-scale electricity production. The ability to operate with high availability/reliability plays a key ingredient in defining the DEMO configuration, fostering the need for rapid removal/replacement of limited-life in-vessel components. DEMO pre-conceptual studies are being carried out by South Korea (with US participation) and other countries. The device designs span a range of maintenance approaches from full radial extraction of large in-vessel modules through all TF horizontal openings to vertical maintenance of segmented in-vessel components. Progress made on the S. Korea's K-DEMO design will be provided with emphasis on the design choices identified to promote high availability.

1. Introduction

Earlier papers written [1,2,3] provide the background and overview of the K-DEMO pre-conceptual design and physics scenarios that were investigated in sizing the device. The 6.8-m tokamak is being developed to operate with a staged mission; an early phase planned for PMI and material testing and a later stage planned to generate 200-600 MW electric power with 70% availability. The high availability goal of K-DEMO sets a strong requirement for developing a machine design that supports operating flexibility and ease of maintenance. DEMO design concepts have been developed and studied over the years [4-9] with plans to meet the challenge of high availability. The K-DEMO design incorporates a number of unique features that differentiate it from other DEMO designs currently being considered within the fusion community. The design incorporates: 1) a semi-permanent C-shaped shield structure that supports disruption loads, provide shielding for gaps between sectors and an alignment system used for the installation of plasma components; 2) a plasma sector segmentation approach that subdivides the blanket system into 48 sub-modules (16-inboard, 16-outboard located under each TF coil and 16-outboard modules located between TF coils) sized for a vertical maintenance scheme; 3) sixteen enlarged, high field TF coils incorporating two windings - a high field and low field set to offset the cost of the large TF coil and eliminate coolant pressure drop issues associated with the extended winding length of a single winding and finally 4) a service arrangement that brings blanket services from beneath the device through lower vacuum vessel vertical ports.

The design of the K-DEMO device configuration is still in progress with some component details developed and analyzed [10-12]. In the course of the K-DEMO study blanket details have been developed and configuration features have evolved to reduce component sizes and enhance maintenance operations. The current progress in developing the device configuration is presented in detail in this paper.

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2. Setting the Device Configuration Arrangement

The main features of the K-DEMO tokamak are shown in

Fig. 1. A magnetic fusion device delivering net power with high operating availability will be a complex machine that requires detailed review of design options and operating parameters that set the design point. The vision of the machine maintenance concept itself will impact the machine topology. The K-DEMO device reference point incorporates a double-null (DN) divertor which promotes strong plasma shaping (elongation and triangularity) forcing the divertor X-point inside the vacuum vessel, close to the plasma. The DN option promotes higher plasma performance, improved vertical position control with an accompanying reduced machine size when compared with single-null (SN) designs; however, it brings about engineering issues associated with increased number of divertor components, reduced breeding volume, added maintenance regions and services. A comparison to candidate SN DEMO options will need to be made to evaluate the merits or deficiency of the K-DEMO DN configuration. High availability requires large openings to remove and replace large in-vessel segments. Heating systems, diagnostics, and services that surround a tokamak device will challenge the success of a design with full horizontal maintenance. Limiting horizontal maintenance to four locations results in a stiffer machine structure compared with a full toroidal segmentation option and minimizes auxiliary system interface complications; however, in-vessel toroidal movement of a full sector and developing a large cask system to service the full extracted in-vessel module with an effective interface to the facility and the remote maintenance hot cell will continue to present design challenges.

As with ITER, vertical installation will be used to assemble DEMO – setting the stage for a vertical maintenance concept. The building space above the device is set by machine assembly requirements. Taking advantage of this space and using the tooling needed to assemble the device to also maintain the machine components provides valuable design incentives. The K-DEMO device incorporates a vertical maintenance design that differs from the EU single-null, multi-module vertical arrangement approach [7]. The EU concept has relatively close fitting TF coils sized to allow 32-inboard and 32-outboard segments to be extracted through 16-vertical ports. The K-DEMO concept uses a different in-vessel

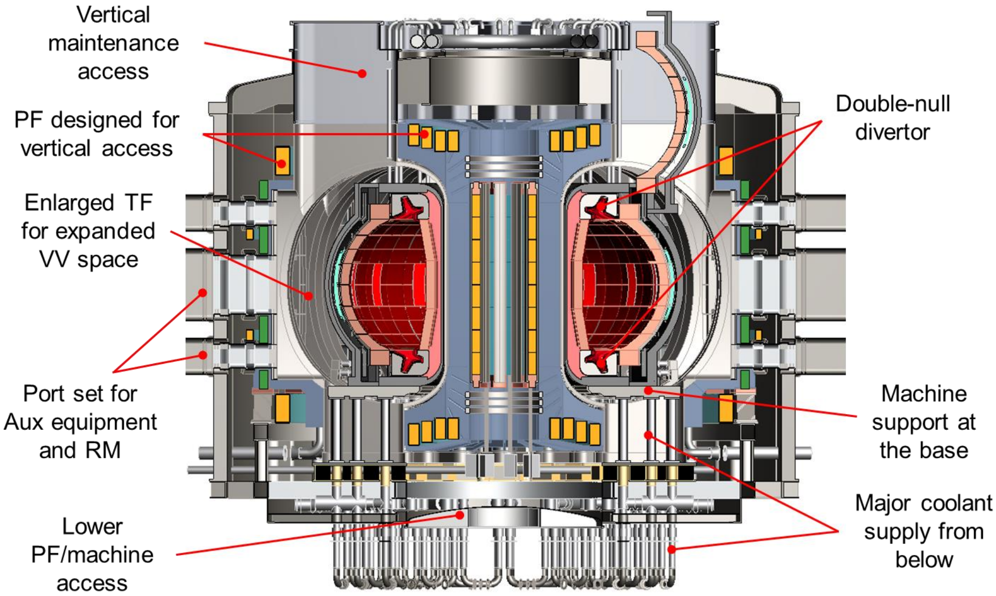

Fig. 1. K-DEMO device core design features

segmentation scheme. Blanket modules are subdivided into 16 inboard modules and 32 outboard modules. To allow radial space for the vertical extraction of larger blanket modules the TF coils are enlarged in a design that incorporates a two-conductor, low field / high field windings, sized to reduce overall TF coil costs. To enhance alignment, provide labyrinth gap shielding and method for supporting disruption loads, a semi-permanent inboard shield/support structure with ties to the outboard blanket back wall structure is being developed. The design adds a small amount to the inner build dimension but potentially can improve support, maintenance and alignment conditions. A lower machine support system includes a machine support structure that integrates basement coolant supplies, with potential improvement in interface efficiencies.

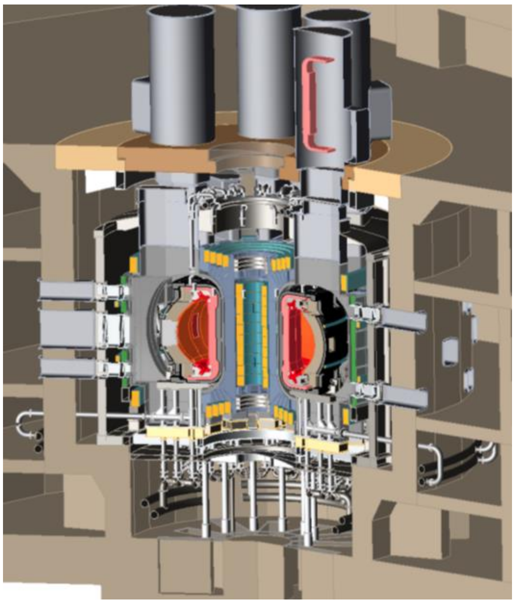

Fig. 2 Test Cell accommodates vertical maintenance

A test cell built to assemble the device accommodates the vertical maintenance scheme planned to replace half of the blanket modules simultaneously (see Figure 2). The rapid removal and replacement of limited-life in-vessel components is a necessary condition for high availability.

3. Evolution of the K-DEMO Design

In a re-evaluation of some early configuration features, design changes were identified that offer improvements in maintenance operations and the reduction in size of some components. One change undertaken was the reshaping of the vacuum vessel (VV). The original VV took on a conformal design shaped by circular arcs that followed a close offset of the TF coil inner bore with the outer section spaced not far from the inner surface of the TF outer leg. The VV shape was altered to include a vertically straight outer section and horizontal sections on the top and bottom of the VV. To provide space to further compact the VV, the geometry of the inboard semi-permanent support system was altered to allow reshaping of the VV at the inboard section to move it closer to the divertor. Figure 3 illustrates the change in the VV, moving from the baseline VV (highlighted in red) with a conformal TF shape to a more compact vacuum vessel with straightened segments at the outboard and top/bottom regions. This change in shape will allow a reduction in the TF geometry or redistribution of the space being allocated to the divertor or blanket services.

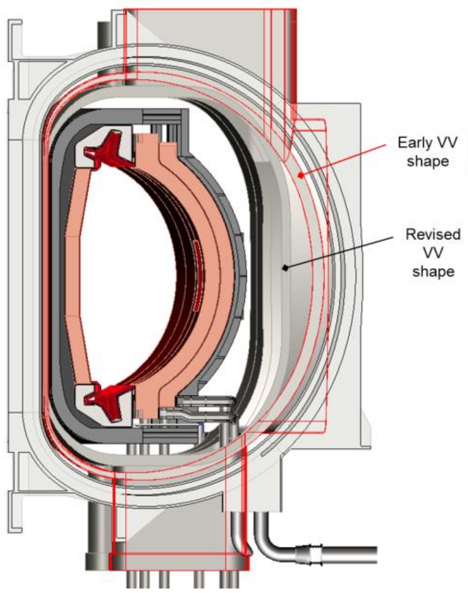

Fig. 3 Revised VV geometry

The blanket segmentation approach and divertor geometry has gone through some changes from the initial design. The radial extent of the outer divertor section was reduced to provide more outboard blanket coverage to enhance the tritium breeding ratio (TBR). Developing a TBR>1 requires maximization of blanket coverage, which is especially challenging in the case of a double-null divertor configuration. It was found that the outer section of the divertor reference divertor design had a radial extent that was farther than needed. This space was eliminated and given to extend the coverage of the outer blanket. To improve uniformity in the blanket design the outer blankets was changed to constant 11.25° segmentation split. Where neutral beam heating is introduced with tangential alignment, a pair of unique adjacent blanket segment would be defined that accommodate angled midplane

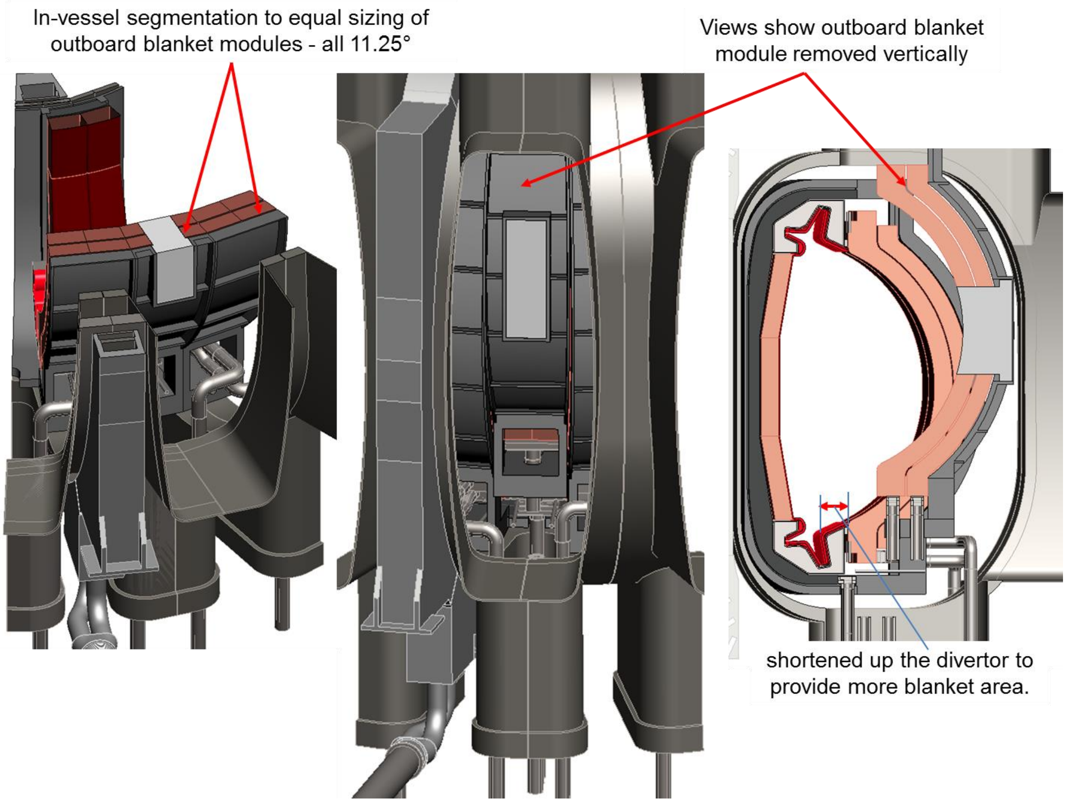

Fig. 4 In-vessel segmentation and geometry alterations

port openings. Figure 4 illustrates the revisions made in the port segmentation and geometry changes in the divertor and outboard blanket. Also shown is the vertical removal of an outboard blanket module.

One major change in the K-DEMO configuration was the elimination of the option to remove the divertor modules independent of the removal of any other component. The early K-DEMO arrangement left a large opening at the bottom and top of blankets located between TF coils allowing a divertor segment to be move radially out (for lower divertors) or on top of the blanket (for upper divertors). This arrangement impacted the ability to achieve a TBR >1 when the blankets are foreshortened at all locations. To maximize the TBR the divertor removal is accomplished by first removing the blanket segment located between TF coils; modules removed with a straight vertical lift. An alternate option to be evaluated is to selectively locate foreshortened blanket modules at a few locations around the device to allow independent removal of divertor modules.

4. Blanket Arrangement Details

The general arrangement of the blanket system and their services is being developed with the goal of identifying a concept that can support different blanket designs. Two blanket concepts have been evaluated with an emphasis on expected blanket services details. Services for the K-DEMO baseline water cooled solid breeding blanket and an alternate dual-coolant lead-lithium (DCLL) blanket have been developed. The design under evaluation is an approach that locates all blanket services at the bottom of the device. A large number of individual piping lines will emanate from individual blankets for both a DCLL and solid breeding blanket designs. Rather than bringing individual lines into the vacuum vessel a manifold service arrangement has been developed, depicted in the local details shown in Figure 5. A reentrant piping system brings in water (for the solid breeder case) through ten individual channels located on the outer pipe. A machined manifold is used to redirect the

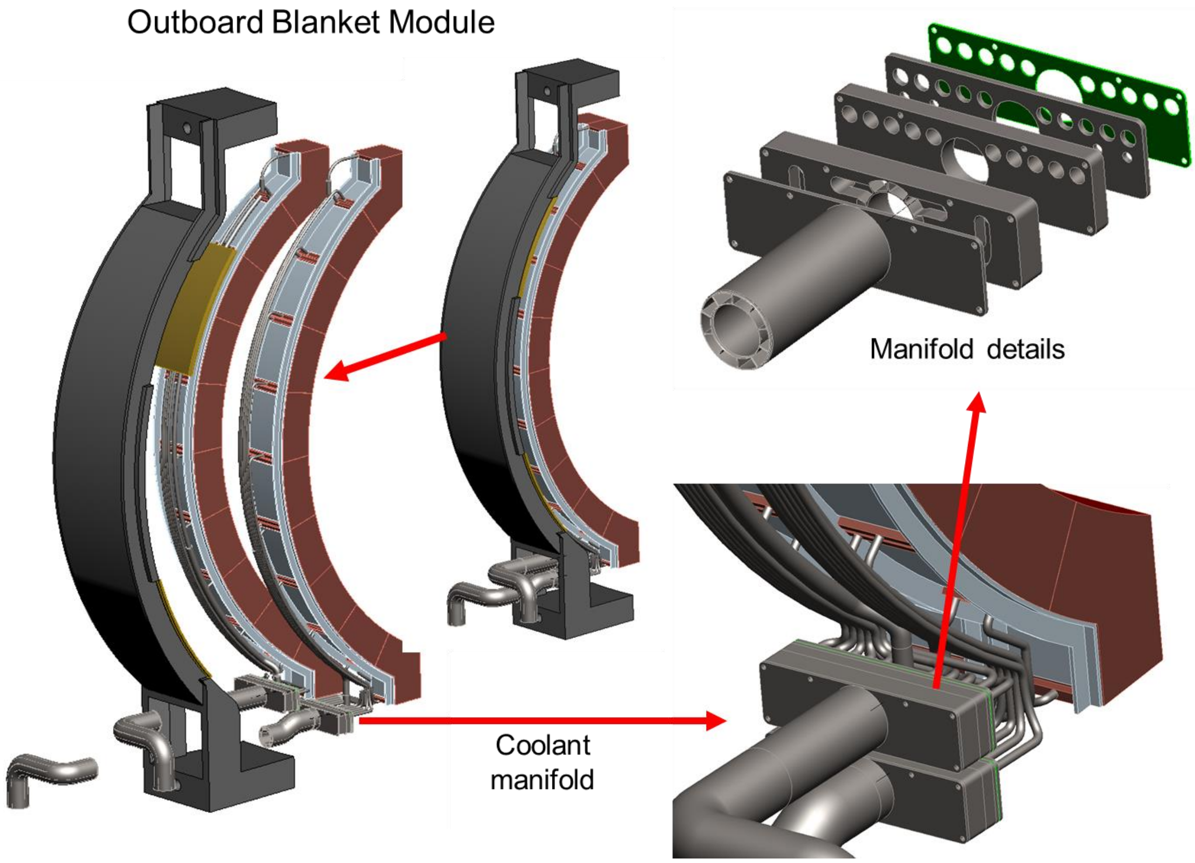

Fig. 5 Typical piping connections to the outboard blanket

flow to ten horizontal pipe feeds that will interface with individual tubes to carry the coolant to ten blanket segments. A common return line brings the coolant back down to feed the center pipe of the coolant supply that emanates from the lower vacuum vessel port. Figure 6 shows a section cut at the base of the device where the coolant lines interface with the divertor and blanket. Even with the collection of individual pipes into common feeds, there will be six large blanket supply lines passing through a lower vacuum vessel port. Also included will be blanket helium and lower divertor pipes – implying that pipe service details still need to be developed.

5. Conclusions

Defining a successful concept depends on assessing tradeoffs among some very fundamental machine design choices and evaluating a range of concepts in sufficient detail to assure that a feasible solution can be defined that meets the project mission and cost objectives. The K-DEMO vertical maintenance design is showing promise in defining concepts that enhances high availability. When all DEMO design concepts have been developed to a level of majority a comparative assessment needs to be made between the different design approaches.

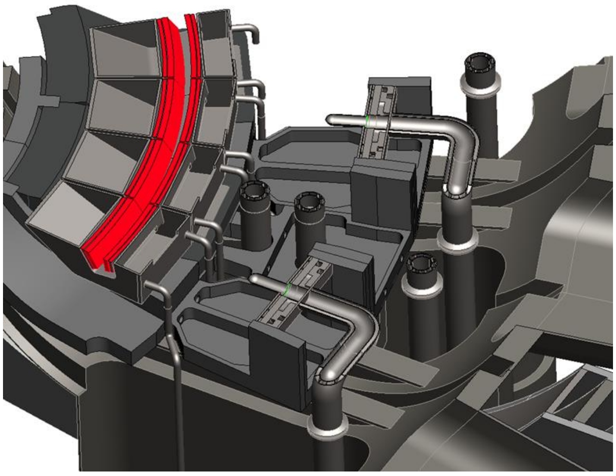

Fig. 6 Local section cut showing piping interfaces with the divertor and blanket system

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