Overall Power Core Configuration and System Integration for ARIES-ACT1 Fusion Power Plant

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ARIES-ACT1 power plant has been designed and configured to allow for rapid removal of the full power core sectors followed by disassembly in the hot cells during maintenance operation. To achieve high availability and maintainablity of the fusion power plant, the power core components of a sector, including the inboard and outboard FW/blankets, upper and lower divertor, high temperature shield were integrated into one replacement unit to minimizing time comsuming handling inside plasma chamber. In this paper, the overall power core configuration and system integration, as well as the definition of the major power core components are described and the main design features are highlighted.

I. INTRODUCTION

The ARIES-ACT1 is a 1000 MWe, DT-burning fusion power plant conceptual design based on an advanced tokamak and advanced engineering concepts with major radius R=6.25 m and aspect ratio of 4.[1,2] Like ARIES-AT power core,[3] the ARIES-ACT1 utlizes Pb-17Li as breeder and coolant and low activation SiC/SiC composite as structural material with high coolant outlet teperature (~1030˚C) for high power cycle efficiency (~58%) while keeping the blanket structure SiC/SiC temperature below allowable limits (<1000 ˚C).[2] Engineering efforts have been mainly focused on: 1. re-design the Pb-17Li coolant circuits and flow paths cooling the FW and blankets to minimize and reduce 3D MHD effects; 2. re-examine and optimize the inboard and outboard blanket module designs for accommdating higher pressure and pressure drop; 3. replace the Pb-17Li cooled SiC/SiC divertor design of the ARIES-AT by a He-cooled W-based divertor design capable of handling a surface heat flux up to ~14 MW/m^2;[4, 5] 4. replace the Pb-17Li cooled SiC/SiC HT (high temperature) shields by utlizing the He-cooled ODS (oxide dispersion-strengthened) steel structural ring (or HT shield), 5. arrange all coolant access pipes connecting the power core sectors to the ring headers through maintenance ports; 6. re-examine requirements and design of the VV (vacuum vessel) for a fusion power plant; 7. re-explore the ARIES sector maintenance schemes. With adding all new elements and features into the ARIES-AT like power core, the ARIES-ACT1 design becomes more robust while maintaining the same performace.

In this paper, the overall power core configuration and system integration designs are summarized, and the definition of the in-vessel components and major design features are described.

II. POWER CORE INTEGRATION AND ASSEMBY

The overall layout of the ARIES-ACT1 fusion power core is illustrated in Fig. 1. The power core is subdivided into 16 sectors with 16 maintenance ports arranged between TF coils. Each power core sector has its own horizontal maintenance port, allowing replacement of the entire sector without opening cryostat or disassembly other components such as the coil system. The VV is designed as a container for a high vacuum, T-inventory and all radioactive products in the vessel generated by irradiation, and it also serves as a first barrier in case of pressurization by the in-vessel coolant leaks or ruptures. The in-vessel components include the inboard FW/blanket, divertor target plates and structure, outboard FW/blankets, and SR (structural ring). All the in-vessel components are attached to the SR made of the ODS steel. The SR is also subdivided into 16 sectors and supported at the bottom only by the VV. The major functions and design features of the power core components are described in following:

1. The ARIES-ACT1 blanket is similar to the ARIES-AT which utilizes the Pb-17Li as the coolant and breeder, and the low activation SiC/SiC composite as the structural material. However, the Pb-17Li circuits

and flow paths cooling the FW and blankets of the ACT1 were redesigned to minimize and reduce 3D MHD effects. All the blankets enable operating the Pb-17Li at high inlet and outlet temperature (740/1030 ˚C) for high power cycle efficiency (~58%) while maintaining the temperature of the SiC/SiC structure below the allowable limits (~1000 ˚C).

2. The He-cooled W-based plate-type divertor is selected from our ARIES W-based divertor designs[4, 5] and integrated into the ARIES-ACT1 power core for handling the peak-time average heat flux about ~10.6 MW/m^2. The minimum and maximum operating temperature of the W structure in all divertor target plates is in the range of 800 to 1300 ˚C.
3. The HT shield is a closed ring along the poloidal direction, and all the in-vessel components are mechanically attached to the ring, therefore, the ring provides a structural support for the sector. The ODS steel is considered as the structure material cooled by the He and operated in the temperature range between 600 and 700 ˚C in order to minimize thermal stresses between the blanket and shield.
4. The VV is designed to be a ribbed-structure to take normal operation, gravity and disruption loads. Unlike the ARIES-AT water cooling VV, the ARIES-ACT1-type VV is cooled by the helium and operated at the temperature of ~400 to 500 ˚C in order to minimize the tritium/impurity migration to the VV.[6]
5. The water cooled shield is arranged around the VV to reduce radiation dose to all the coils. This shield will run at room temperature and provide a good heat sink and cool the afterheat by natural convection during power plant accidents.
6. The TF coils are designed to have sufficient spaces and clearances for all the components and maintenance ports. All PF coils are shifted towards top and bottom to allow for withdrawal of the sectors.

There is only one vacuum door located at the end of the port for each sector, as illustrated in Fig. 2. The vacuum door is bolted to the door flange with structural support coming from the bolts, and seal-welded for vacuum tightness. The He-cooled ODS steel shield blocks inside the port are arranged for protecting the TF coils. A saddle coil is attached to the upper shield block and will be removed together with the shield block during the maintenance. All coolant access pipes will penetrate through the lower shield block, and will be removed together with the pipes for withdrawal of the sectors.

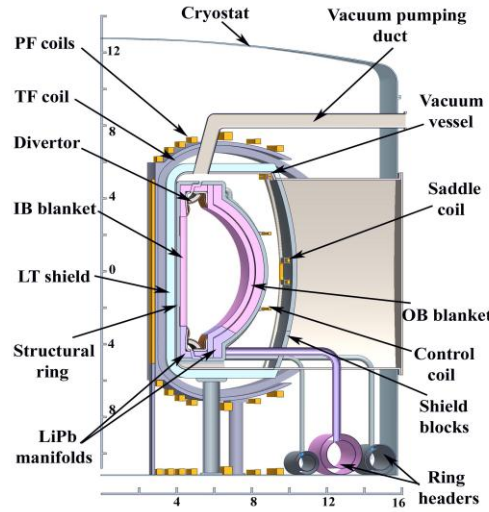

Fig. 1. Cross-section of ARIES-ACT1 power core

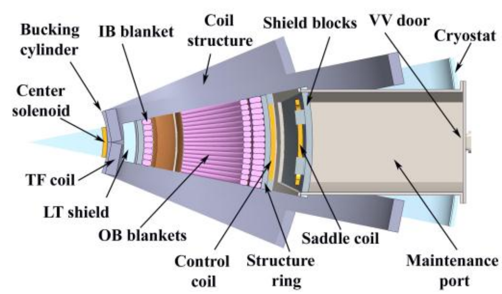

Fig. 2. Top view of ARIES-ACT1 power core

All the in-vessel components have a limited lifetime, and require replacement in certain intervals. Our ARIES design philosophy is to integrate all the in-vessel components into the replacement units to minimize the number of the coolant access pipe connections and time-consuming of handling inside the plasma chamber. The integrated replacement units can be inserted and withdrawn by a straight movement in the radial direction during installation and maintenance. Fig. 3 illustrates one of the 16 replacement units. All power core components are subdivided into different radial zones in order to maximize the useful lifetime of the components as well as minimize the waste stream. The replacement units are rings closed in the poloidal direction, composed of the inboard and outboard FW/blankets, divertor target plates, divertor structure support. These rings have sufficient structure to provide enough mechanical strength for the entire power core sector. The replacement units are supported at the bottom only by the VV, and can expand freely in all the directions without interaction with the

VV. The connections between the SR and the attached components must maintain a constant distance in the radial direction, but differential thermal expansion in the poloidal and toroidal direction is possible without causing large thermal expansion. No welds are used between the components of different lifetime classes, thus allowing for easy disassembly in the hot cell and reuse of the components not at the end of their lifetime.

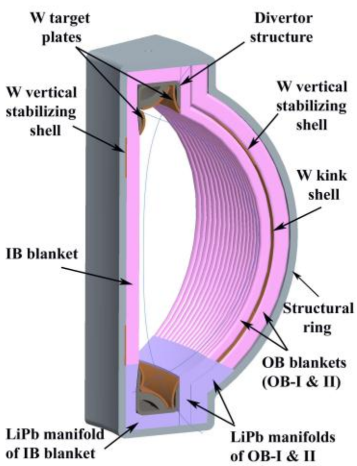

Fig. 3. The replacement unit of the ACT1 power core

III. BLANKET MECHANICAL DESIGN AND DIVERTOR INTEGRATION

The ARIES-ACT1 blanket design utilizes Pb-Li as the breeder and coolant, and the low-activation SiC/SiC composite as the structure material. The major objective of the blankets is to achieve high performance while maintaining attractive design features, feasible fabrication, credible maintenance schemes and reasonable design margin on the operating temperature and stress limits. The maximum SiC/SiC temperature limit (<~1000 ˚C) is set to avoid the void swelling regime, and the minimum temperature (> 600 ˚C) is based on the minimum thermal conductivity requirement.[3, 7] Conventional ASME code cannot be directly applied to ceramic composite when traditional FEM analysis is used to analyze the stresses. It was suggested that the combined primary and thermal stresses should be less than 190 MPa as a conservative first order approximation.[3]

III.1. FW and Blanket Module Design and Optimization

The blanket sector is composed of a number of small identical modules. Each blanket module has two concentric ducts brazed together to form an anualer and center ducts. The Pb-17Li enters into the annular from the bottom of the blanket, flows up and runs behind and above the upper divertor region. The Fig. 4 illustrates one section of the outboard blanket modules composed of two outboard blanket regions (OB-I and OB-II) connected together by mechanical connectors (keys and bolts). The blanket modules must accommodate a hydrostatic pressure (considering the total height of the power core, heat exchanger and coolant ring header underneath the reactor) and the MHD pressure drops through the blanket and manifolds. The total pressure at the FW annular ducts of the blanket is ~1.95 MPa and 1.65 MPa at the center ducts. The details of the Pb-17Li flow control in the FW and blankets, manifolds design and MHD pressure drop calculations are separately presented in these proceedings.[2] Design iterations have been made to determine and optimize all the parameters of the blanket modules including curvature of the FW, thickness of the FW, width and depth of the coolant flow channels, number of the ribs, and number of the module for each blanket sector to provide a design with reasonable margins on the temperature and stress limits while reducing the SiC volume fraction of the blanket which will benefit the blanket tritium breeding. Comparing to the ARIES-AT blanket design, one significant improvement of the ARIES-ACT1 blanket is that all the ribs of the center ducts are brazed to the outer ducts together to form a stiff blanket module for accommodating a high pressure up to 2 MPa while the center duct of the ARIES-AT blanket module is free-floating to the outer duct and enable handling the pressure of ~1 MPa. A number of identical modules are brazed together into one blanket sector.

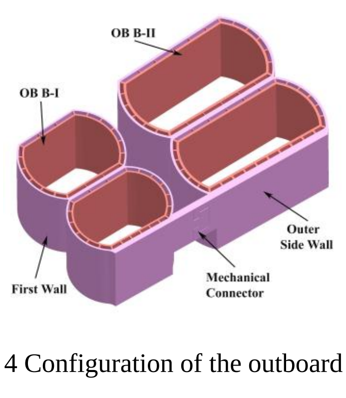

Fig. 4 Configuration of the outboard blanket

There are 8 blanket modules brazed together to form one blanket sector for the inboard blanket, and 6 inner modules with pressure balance on both sides and 2 outer modules without the pressure balance on the outer side walls. All the thickness of the front, back and side walls, ribs, distance between ribs are determined and optimized by the primary stress calculations, then verified by heat transfer and thermo-mechanical analyses. Results indicate that the temperature and stress limits are satisfied. The same approaches are applied to define the configuration, dimensions and composition of the OB-I and OB-II. There are 16 modules for each outboard blanket sector, 14 inner modules and 2 outer modules. The outer side walls of the outer modules without the pressure balance have to be enforced by increasing the thickness of the outer side walls and number of the ribs.

III.2. Divertor Integration

A number of advanced He-cooled W-alloy divertor concepts have been proposed and developed for fusion power plant applications under the ARIES program, including the large-scale plate-type divertor, the mid-size T-tube and smaller-scale finger concept.[4, 5] All diveror designs utilize the W as sacrificial armor, the W or W-alloy as the main divertor structural material and advanced ODS steel as the coolant access tubes and cartridges. Both pin-fins and impinging jet cooling schemes have been considered to enhance heat transfer in the high heat flux zone. Based on the design limits from the W minimum/maximum operating temperature, pumping power for the divertor cooling system, and plastic strain or 3Sm stress limits, the he-cooled W-based divertor can possibly accommodate the surface heat flux up to 14 MW/m^2.[4] Results from edge plasma physics modeling indicate that the peak-time average heat flux is about ~10.6 MW/m^2, therefore, the plate-type divertor concept is selected for the ARIES-ACT1 power core in order to take the advantages of the larger size and less divertor units for the power plant. Fig. 5 illustrates the W divertor integrated into the ACT1 power core. Each target plate was configured with one curvature in order to allow the cartridges to be inserted into the cooling channels. The inboard divertor target to the X-point length is ~48 cm, and ~76 cm for the outboard target and the divertor design criteria from the edge plasma physics are satisfied. The divertor plates with all the support structure have the same lifetime as the FW and blankets and need to be replaced together with the FW and blankets. More details of the W divertor applied in the ACT1 power core including design parameters and coolant routing are discussed in other paper of this proceedings.[2]

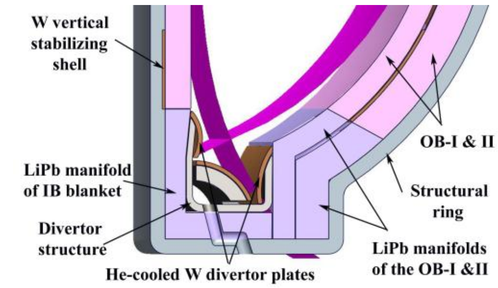

Fig.5. Cross-section of the W divertor region

IV. MAINTENANCE FEATURES

The power core maintenance philosophy of the ARIES-ACT1 is the same as the ARIES-RS and ARIES-AT power plants,[8, 9, 10] and one of the important design goals is to achieve high availability and maintainability. To achieve the goals, key questions for the power core engineering designs are: 1. where (or how) should the coolant access pipes be connected/disconnected to the sector? 2. how should the power core sector be precisely aligned into the plasma chamber, supported and removed during the installation and maintenance? 3. how should the power core sector be extracted from the plasma chamber and transferred to the hot cell for exchanges?

There are 7 access pipes to be connected to each power core sector and all the access pipes are concentric pipes with the cold coolant in the annular and the hot coolant in the center ducts:

1. Three PbLi access pipes for one inboard and two outboard blankets (the OB-I and OB-II).
2. Two helium access pipes for the upper and lower divertor plates and their structure support.
3. Two helium access pipes for the inboard and outboard SR.

All the coolant access pipes to the sector are connected to the SR close to its bottom plate which is the mechanical fix-point of the entire power core sector. The replacement of the sector requires cutting/re-connection of all these access pipes and removing all the pipes in order to allow for a rail system to be inserted through the maintenance port for the sector removal. The rail system proposed in the ARIES-RS maintenance study[8] is used in the ARIES-ACT1 for the power core sector alignment, and sector removal and support. As illustrated in Fig. 6, the entire power core sector is supported by the T-shaped attachments between the bottom of the SR and the VV. There are wide gaps in the wedge allowing the precise alignment of the sector in all directions. The rail system with two or three vertical pistons is inserted into the space between the bottom of the SR and the VV, and the entire sector is supported by the rail system for the vertical and horizontal alignment during the installation. After the alignment these grooves have to be filled with a suitable liquid metal (probably a Cu-alloy), and fixed in this position by freezing the T-shaped attachment grooves, and the rail system is withdrawn.

The maintenance approach is to transfer the power core sectors to the hot cell for the sector exchanges. A transfer flask or cask with a double door (one at the flask, the other one at the port) system can be docked to the maintenance port to avoid any spread of radioactivity (Tritium, dust) during the sector replacements. After the shield blocks, saddle coil, control coils and all access pipes are removed, the rail system will be moved from the flask into the port and the space between the SR of the sector and the VV. At the top of the rail system, there is a low friction Teflon plate installed capable to carry the entire weight of the sector in the order of ~200 tons. Using the rail system, the sector is supported by pressurizing the pistons, and separated from the VV by melting the metal inside the T-shaped attachment grooves. Then, the sector can be pulled in a straight way out the plasma chamber into the maintenance port and further into the transfer flask. As a next step, the new sector which is already contained in the flask will be moved into the plasma chamber in reverse order, and the sector can be installed and aligned with the help of the hydraulic lifting system.

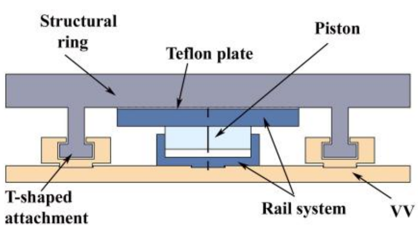

Fig. 6 Cross-section of T-shaped attachments and rail system (1/16 sector)

Motion demonstrations for removing the power core sectors have been performed by using 3D CAD technology to analyze the clearances and spaces in all directions.

V. SUMMARY

The overall configuration and system integration of the ARIES-ACT1 are designed and the main design features and maintenance scheme are presented in this paper. The design issues and R&D needs of the ACT1 power core design, the SiS/SiC blanket and W-based divertor are separately discussed in this proceedings.[2]

ACKNOWLEDGMENTS

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