As part of the ARIES-CS study, the machine configuration design, including the power core components and attachment, the coil supporting structure, the cryostats and the vacuum vessel, is developed in close integration with the chosen port maintenance scheme. This paper summarizes the major features of the configuration design and maintenance of the ARIES-CS power plant.

II. POWER CORE CONFIGURATION DESIGN

The ITER strategy of replacing in-vessel components is based on removal of components from the inside of the vacuum vessel (VV), and remote transfer to a hot cell where the components will be either repaired or replaced. One or more in-vessel transporters with a manipulator arm are mounted on a full circumferential rail deployed inside the vessel (behind the divertor cassettes) in order to perform above operations. However, a rail system for a stellarator is very challenging and may not be practical because of the complex geometry and tight space. Thus, maintenance of the blanket and the divertor modules with an articulated boom, inserted through a small number of maintenance ports, is the preferred approach for ARIES-CS. The main challenges for the power core configuration and assembly procedures include: (1) How can the coil system be supported to react centering forces pulling the coil sets radially towards the centre of the torus, and out-of-plane forces between neighbouring coils? (2) How can the connections between the cold coil system and a support at ambient temperature be designed to carry the total weight of coils and coil structure? (3) How can the weight of hot power core components be transferred to the base structure of the power plant? (4) How can the hot power core components be subdivided into small modules to be extracted through the maintenance ports? (5) Which component should the blanket modules be mechanically attached to? (6) How can the thermal stresses caused by differential thermal expansion of the various components be minimized?

II.A. Power Core Integration and Assembly

Fig. 1 shows the overall layout of the power core configuration of the ARIES-CS compact stellarator power plant. This configuration is based on the NSCX-like coil and plasma shape with three-field periods. The main design parameters are: major radius R=7.75 m, aspect ratio A=4.5, plasma magnetic field B=5.7 T, number of modular coils=18, minimum distance from the mid-coil to plasma=1.3 m, fusion power=2.4 GW, and average neutron wall loading=2.6 MW/m². Key features of the power core configuration include: (1) an internal VV arranged between the breeding/shield zone and the superconducting modular coils; (2) a breeding zone subdivided
into relatively small blanket modules; (3) two maintenance ports per field period for replacement of the blanket and divertor modules; (4) combination of the high temperature shield and the poloidal coolant manifold to form a strong skeleton shell capable of taking the weight of the blanket modules and resting on sliding bearings at the bottom of the cooler VV (to accommodate the differential thermal expansion); (5) use of concentric tubes for all coolant access pipes with sliding seals at the inner tube; (6) operation of the skeleton shell and the outer tubes of all coolant access pipes at nearly uniform temperature to minimize thermal stresses; (7) supply of the coolant in the primary loops through penetrations in the VV located at the geometrical fixed points of the skeleton shell sectors, minimizing the differential thermal expansion between the VV and the coolant access pipes; (8) sealing of these penetrations with bellows, loaded only by the small pressure difference between the plasma chamber and the cryostat atmosphere.

As shown in Fig. 1, the entire coil system is enclosed in a common cryostat since no disassembly of the VV is necessary for the blanket exchange. Thermal insulation between the cold coils/coil structure and the warm VV has to be provided. The cryostat consists of a cylindrical section with reinforcing ribs, and top and bottom sections. It can serve as a vacuum environment to limit thermal loads to the superconducting magnet system and at the same time as a second containment for the tritium in the VV.

II.B. Coil Supporting Structure

The coil system of the ARIES-CS power plant consists of 6 modular coils per field period with only three different coil shapes in the complete coil system because of the twofold mirror symmetry. Conventional design approaches (ITER-like) for the super conducting magnets are adopted in the ARIES-CS coil system. Nb3Sn and JK2LB (Japanese austenitic steel) are utilized as superconducting and coil structure materials, respectively. There are three kinds of forces acting on the coils when the coils are energized: (1) net centering forces pulling each coil set within a field period toward the centre of the torus; (2) out-of-plane forces acting between neighboring coils inside a field period; (3) weight of the cold coil system. The engineering challenge for the design of the complex 3-D coil structure is how the coil system can be supported to react all the forces acting on the coils and satisfy the stress and deformation constraints as well as the machine design requirements (in particular the need for a number of penetrations). To meet this design challenge, a novel design approach for the coil structure is proposed. All the 6 modular coils of one-field period are wound into grooves of a continuous coil supporting shell which is composed of the inter-coil structure, coil strong-back, coil cases and integrated winding packs operating at cryogenic temperature (4K). Fig. 2 shows how the modular coils are supported by a common structural shell.

![Fig. 1. ARIES-CS power core configuration](image1)

The VV is internal to the coils and serves as an additional shield for the protection of the coils from neutron and gamma irradiation. No disassembling and re-welding of the VV are required for the blanket maintenance. Provisions for cutting and re-welding of the VV have to be made only for the very unlikely case that coils have to be replaced or the VV itself fails. Considering the non-uniform shape and size of the modular coils, the VV for the ARIES-CS with three-field periods is assembled from six sectors. The assembly welds are arranged at the largest cross-section (at 0°) and the smallest cross-section (at 60°). This allows sliding the VV sector into the coils of a field period in the toroidal direction. The breeding blankets are attached to a shell composed of shielding and coolant manifold which is supported by the VV through sliding bearings.

![Fig. 2. Coil supporting shell](image2)

There are three field period coil support structures, each of which contains six winding packs. The three structures are bolted together to form a strong and continuous structural element. All the magnetic forces...
inside a field period are reacted by the coil supporting shell with the exception of the centering force which is reacted by hoop stress in the coil supporting shells bolted to form a closed coil supporting structure. Fig. 3 shows a bird view of the coil supporting assembly with main penetrations/openings and coil supporting legs.

![Diagram of coil supporting assembly](image)

Fig. 3. Full-field period supporting assembly

The weight of the coils and coil structure rests on the warm foundation via three long legs per field-period with high thermal resistance in order to keep the heat ingress into the cold system to tolerable limits. Details on the coil structure design and structural stress analysis can be found in Ref. [5].

II.C. Hot Core and Blanket Attachment Design

The hot core is composed of the first wall, the breeding blanket, the shield and the coolant manifold. The basic idea is to combine the high temperature shield and the poloidal coolant manifold together to form a strong skeleton shell continuous in the poloidal direction but subdivided in the toroidal direction into three sectors (one per field period). This hot skeleton shell rests on sliding bearings located at the bottom of the cooler VV, and can freely move relative to the VV. The skeleton shells operate at nearly uniform temperature in order to minimize differential thermal expansions and thermal stresses. The blanket modules are mechanically attached to the shell and can float with it relative to the VV. Fig. 4 shows the hot core components, illustrating blanket module attachment to the shell.

![Diagram of blanket attachment](image)

Fig. 4. Illustration of blanket integration and attachment with shield and manifold.

II.D. Attachment of the Divertor Plate

The divertor plates have to be exchanged through the same maintenance ports as the blanket modules. There are 8 divertor plates per field period, and each plate has average dimensions of 3.25 m (tor.) x 1.0 m (pol.). Each divertor plate is attached to the VV through the coolant access pipe, which serves both as coolant supply/return pipe and as support, as illustrated in Fig. 5.

![Diagram of divertor attachment](image)

Fig. 5. Cross-section of the divertor attachment
There are 24 divertor plates and divertor access pipes which penetrate the breeding blanket modules, the hot shielding ring, the coolant manifold, the VV and the coil structure for connection to the outside concentric coolant supply/return pipe running toroidally outside the coil. During maintenance, a closure flange is first opened. The shield ring, shield block and inner tube, which are structurally connected, can then be removed as a single unit, and in-bore tools inserted for pipe cutting/re-welding. Fig. 6 shows the divertor attachment integrated to the power core configuration.

![Fig. 6. Layout of the divertor plates and access pipes (at 10° toroidal location)](image)

There are a total 24 openings through the blanket/shield and manifold for vacuum pumping. Like ARIES-RS design, the vacuum pumping ducts are placed behind the divertor regions for efficient exhaust. Radial channels then direct the gas to single set of cryopumps at the bottom of machine. The vacuum pumping ducts are rectangular shape with dimensions of 0.42 m (pol.) x 1.2 m (tor.). Neutron streaming is a major concern in the divertor regions. Shielding blocks and rings inside the divertor access tubes, and behind and around penetrations are used in order to protect the magnet and make the VV and the blanket manifold lifetime components, as illustrated in Figs. 5 and 6.

III. HORIZONTAL MAINTENANCE PORTS

A modular replacement scheme through a small number of designated maintenance ports is selected for ARIES-CS. There are three main maintenance ports arranged horizontally at toroidal locations of 0°, 120° and 360°, where larger space is available and where the stress in the coil structure is small.

The internal size of each port is 3.85 m high and 1.85 m wide. In addition, there are three ECH ports (1.54 m high and 1.52 m wide), each arranged on the outer region of the power core at a toroidal location of 35° from the main maintenance port. These ports also serve as auxiliary maintenance ports to help with the operation of hardware and tools during maintenance. All the ports are extensions of the VV, bridging the distance between the VV and the outer surface of the cryostat. The usual design of such ports incorporates two closure doors, one at the VV and the second one at the outside of the cryostat to avoid any spread of radioactivity during blanket replacement. Fig. 7 shows a plane view cutting through the mid-plane of the power core illustrating the major maintenance ports and the ECH/Aux. ports. On the ECH maintenance it is different in that the ECH module extends from the plasma back into the fixed chamber outside the bioshield. The VV port extends all the way into the maintenance room during operation. The ECH launcher tube has at least two vacuum windows between the plasma and the ECH gyrotron chamber. More detailed descriptions about the ECH launcher design and maintenance can be found in Ref. [7].

![Fig. 7. Maintenance ports at the torus mid-plane](image)

IV. MODULAR MAINTENANCE SCHEME

For module maintenance through ports, only the blanket module has to be moved through the opening of a port with an articulated boom. The VV is internal to the coils and serves as an additional shield for the protection of the coils from neutron and gamma irradiation. No disassembling and re-welding of the VV are required for blanket maintenance.

The blanket module replacement is based on cutting/re-welding of the outer tube of the coolant concentric pipes. Each blanket module is connected to the poloidal manifolds through two concentric coolant access pipes, one for helium and one for Pb-17Li. These pipes have to be cut/re-welded for every blanket exchange, but only the outer pipe has to be cut because there are sliding seals at the inner pipe to allow for differential thermal
expansion and the replacement without cutting/re-welding of the inner tube. An important criterion for the design of such coolant access pipes is to maintain the helium concentration in the steel at the location of an assembly weld to < 1 appm. To ensure this, the assembly weld of the blanket module is arranged at the interface between shield and poloidal coolant manifolds. Shielding rings are installed inside the coolant access pipes to shield against any neutron streaming through the large helium duct. Orbital welding heads are proposed for cutting and re-welding of such complicated tubes.

An annular access space is created by removing shielding blocks and rings, following removal of an adjacent module, starting from the port module. These removable shielding blocks are made of WC, and which will radiate their volumetric heat to the cooler surroundings. However, this cutting/re-welding from the outside can be done only at a location close to the blanket module. At this location, the He-generation at the end of the module lifetime exceed the given limit of 1 appm He. Therefore a second cut is required at the shield/manifold interface, using in-bore tools. This means that the short tube between the locations of the first and the second cuts has to be exchanged together with the blanket module in order to have steel without helium impurities at the location of the two welds, as illustrated in Fig. 8.

Fig. 8. Side view of the coolant access pipes

V. CONCLUSIONS

The ARIES-CS compact stellarator power core configuration is designed based on the NSCX-like coil and plasma shape, and a port maintenance scheme is selected for both blanket and divertor module exchanges. The innovative features of the ARIES-CS power core configuration and maintenance design approach include: (1) winding all the coils of a field period into grooves in a common supporting shell and bolting the three coil supporting shells together to form a strong ring; (2) attaching the blanket modules to the strong skeleton shell composed of the shield and the blanket coolant manifold, and operating these rings at nearly uniform temperature; (3) cutting/re-welding the outer tube of the concentric blanket coolant access pipes with orbital tools, (4) using sliding seals at the inner tube of the concentric blanket coolant access pipes; (5) cutting/re-welding the access pipe of the divertor attachment from the outside of the VV and the magnets; (6) using shielding blocks and rings inside the helium access pipes to reduce neutron streaming in order to meet the helium generation limit at the locations of assembly welds < 1 appm; and (7) exchanging the blanket and divertor modules through horizontal ports with articulated booms.

All these measures result in the potential for a reliable operation and a reasonable down time for blanket replacement. The design principle of the hot power core developed in the frame of this compact stellarator power plant study could be applicable to tokamak power plants also.

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