ARIES-ACT1 SYSTEM CONFIGURATION, ASSEMBLY AND MAINTENANCE

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Abstract

ARIES-ACT1 engineering design efforts were devoted to develop a credible configuration that allows for rapid removal of full power core sectors followed by disassembly in hot cells during maintenance operation. The power core was evolved with the major objective of achieving high performance while maintaining attractive design features, credible configuration and maintenance, and fabrication processes. To achieve high availability and maintainability of a fusion power plant, power core components of a sector, including inboard and outboard FW/blankets, upper and lower divertor and structural ring or high temperature shield were integrated into one replacement unit to minimize time consuming handling inside plasma chamber. Similar to ARIES-AT design, the FW/blanket design was based on Pb-17Li as coolant and breeder, and low activation SiC/SiC as structural material, however the Pb-17Li mass flow rate control, flow path, first wall and blanket cooling channels, coolant access pipes and blanket structural configuration have been revised and improved to provide about the same thermal performance (~58% thermal efficiency) while keeping the MHD pressure drop and pumping power, material temperature and stresses in the acceptable level. Helium-cooled W or W-alloy divertor concepts were developed to accommodate the peak surface heat flux up to ~14 MW/m\textsuperscript{2}, including a smaller size–finger-based, mid-size T-Tube to the larger size of the plate-type divertor concepts which takes advantage of simple configuration, smaller number of plate units and joints to be used in a power plant. The two-zone divertor concept with a combination of the finger-based divertor and the plate-type divertor was selected and integrated to the ARIES-ACT1 power core, and the fingers were used to accommodate the designed peak heat flux of ~13 MW/m\textsuperscript{2} while the plate-type divertor is used for lower heat flux region.

The overall power core configuration and system integration, as well as the definitions of major power core components, such as the FW/blankets, divertor, structural ring, and the vacuum vessel etc., are described in here and main design features are highlighted. Sector maintenance operations have been investigated and motion demonstrations for removing the
power core sectors have been performed by using the state-of-art 3D CAD technology to analyze the clearances and spaces in all directions. Maintenance sequence/procedure of removing the replacement unit from the plasma chamber to the hot cell for exchange and refurbishment is also discussed in this paper.

Keywords: Power plant, power core configuration, system integration, SiC/SiC blanket, W-based divertor, maintenance

1. INTRODUCTION

The ARIES-ACT1 is a 1000 MWe, DT-burning fusion power plant conceptual design based on advanced tokamak and advanced engineering concepts.\textsuperscript{1,2,3} Like ARIES-AT power core,\textsuperscript{4,5} the ARIES-ACT1 utilizes Pb-17Li as breeder and coolant and low activation SiC/SiC composite as structural material with high coolant outlet temperature (~1030 °C) for achieving high power cycle efficiency (~58%) while keeping the blanket structure SiC/SiC temperature below allowable limits (<1000 °C).\textsuperscript{3} Engineering efforts have been mainly focused on developing the ARIES-ACT1 power core configuration and system integration with the overall objectives of achieving high performance, high availability and maintainability while maintaining attractive features, credible maintenance and fabrication processes and reasonable design margins.

Our prior power plant studies including ARIES-RS\textsuperscript{6,7} and ARIES-AT\textsuperscript{8} considered the high availability as one of our major goals to design the power core configuration and components in order to be competitive in the electric generation market. The availability of the power plant has a large impact on the cost of electricity, thus on the attractiveness of the entire power plant because utilities cannot accept frequent shutdowns or extended replacement periods due to the high cost of replacement power. To achieve the goals of the high availability and maintainability, the sector maintaion schemes and maintenance strategy of the ARIES-RS and ARIES-AT with large sector withdrawn between TF coils was adopted in the ARIES-ACT1 configuration design. The entire power core was segmented into 16 sectors, and each sector was integrated together by the inboard and outboard FW/blankets, upper and lower divertor target plates and their structural supports, structural ring and structural ring blocks. All the components were mechanically attached to the structural ring to form a replacement unit. During maintenance operation, the replacement unit would be removed out through the maintenance port horizontally.

The major component designs of the ARIES-AT1 power core described in this paper include: 1. the Li-17Pb SiC/SiC inboard and outboard FW/blanket segments; 2. the Helium-cooled W or W-alloy divertor target plates and their support structure; 3. the Helium-cooled ODS (oxide dispersion-strengthened) steel structural ring or high temperature shield; 4. the Helium-cooled ribbed bainitic FS (3Cr-3WV) VV (vacuum vessel); 5. the water cooled low temperature bainitic FS shield; 6. the upper and lower shield blocks made of bainitic FS at the entrance of the maintenance port; 7. the supra conductor TF and PF coils. With the efforts on making the design improvements, optimizations and adding new elements and features into the design of the ARIES-AT like power core configuration, the ARIES-ACT1 plant design becomes more robust while maintaining the same performance (~58% thermal efficiency) and reasonable engineering design margin. Table 1 is the design comparison of the ARIES-AT and ARIES-ACT1 power core components, and Table 2 summarizes the major parameters of the ARIES-ACT1 tokamak power plant.
In this paper, the overall power core configuration and system integration designs are summarized, and the definitions of in-vessel components and major design features are described. The maintenance strategy and operation sequence/procedure are presented.

Table 1
A comparison of the ARIES-AT and ARIES-ACT-1 power core

<table>
<thead>
<tr>
<th></th>
<th>ARIES-AT</th>
<th>ARIES-ACT-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius</td>
<td>5.5 m</td>
<td>6.25 m</td>
</tr>
<tr>
<td>FW/Blankets</td>
<td>Li-17Pb cooled SiC/SiC structure Blanket inlet pressure=1 MPa</td>
<td>Li-17Pb cooled SiC/SiC structure Blanket inlet pressure=1.95 MPa</td>
</tr>
<tr>
<td></td>
<td>$T_{\text{inlet}}/T_{\text{outlet}}=760/1050 ^\circ \text{C}$</td>
<td>$T_{\text{inlet}}/T_{\text{outlet}}=740/1030 ^\circ \text{C}$</td>
</tr>
<tr>
<td></td>
<td>$T_{\text{max}}(\text{SiC/SiC})=996 ^\circ \text{C}$</td>
<td>$T_{\text{max}}(\text{SiC/SiC})=990 ^\circ \text{C}$</td>
</tr>
<tr>
<td></td>
<td>$\eta_{\text{th}}=58.8%$</td>
<td>$\eta_{\text{th}}=57.9%$</td>
</tr>
<tr>
<td>Structural ring</td>
<td>Li-17Pb cooled SiC/SiC structure and B-FS filler</td>
<td>Helium-cooled ODS steel structure $T_{\text{inlet}}/T_{\text{outlet}}=650/680 ^\circ \text{C}$</td>
</tr>
<tr>
<td>High temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shield</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper/Lower</td>
<td>Li-17Pb cooled SiC/SiC structure with 3.5 mm W coating,</td>
<td>Helium-cooled W-based divertor and ODS steel cartridge</td>
</tr>
<tr>
<td>divertor sectors</td>
<td>$q_{\text{peak}}=5 \text{ MW/m}^2$</td>
<td>$q_{\text{peak}}=\sim 13 \text{ MW/m}^2$</td>
</tr>
<tr>
<td></td>
<td>$T_{\text{inlet}}/T_{\text{outlet}}=650/785 ^\circ \text{C}$</td>
<td>$T_{\text{inlet}}/T_{\text{outlet}}=700/800 ^\circ \text{C}$</td>
</tr>
<tr>
<td>Vacuum vessel</td>
<td>Water-cooled FS structure and WC, operating temperature at ~50$^\circ \text{C}$, 30 cm thick</td>
<td>He-cooled ribbed bainitic FS (3Cr-3WV) structure, operating temperature at ~500$^\circ \text{C}$</td>
</tr>
<tr>
<td>Water-cooled</td>
<td></td>
<td></td>
</tr>
<tr>
<td>shield</td>
<td></td>
<td></td>
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Table 2
Major parameters of the ARIES-ACT1 tokamak power plant

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Aspect ratio</td>
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<tr>
<td>Major radius, m</td>
<td>6.25</td>
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<tr>
<td>Minor plasma radius, m</td>
<td>1.56</td>
</tr>
<tr>
<td>Plasma vertical elongation (x-point)</td>
<td>2.10</td>
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<tr>
<td>Plasma current, MA</td>
<td>10.9</td>
</tr>
<tr>
<td>Toroidal field on axis, T</td>
<td>6.0</td>
</tr>
<tr>
<td>Normalized plasma beta, %</td>
<td>5.75</td>
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<tr>
<td>Average neutron wall load at FW, MW/m$^2$</td>
<td>2.3</td>
</tr>
<tr>
<td>Maximum neutron wall load at FW, MW/m$^2$</td>
<td>3.6</td>
</tr>
<tr>
<td>Fusion power, MW</td>
<td>1813</td>
</tr>
<tr>
<td>Total thermal power, MW</td>
<td>2016</td>
</tr>
<tr>
<td>Net electric power, MW</td>
<td>1000</td>
</tr>
<tr>
<td>Thermal conversion efficiency, %</td>
<td>57.9</td>
</tr>
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</table>
2. PLANT CONFIGURATION

2.1 Plant Layout

The ARIES-ACT1 is a 1000 MWe DT-burning fusion power plant conceptual design based on advanced tokamak and advanced engineering concepts. The plant comprises of the tokamak power core, auxiliaries, and supporting plant facilities including a tritium plant, heat transport systems, and electrical power conversion systems. The major components of the tokamak power core are the superconducting TF (toroidal field) coils, superconducting PF (poloidal field) coils, which confine, shape and control the plasma inside an evacuated torus (vacuum vessel). Inside the VV are removable life-limited components, these include the first wall, blankets, divertor and structural ring or high temperature shield. The auxiliary heating and CD (current drive) systems of the ARIES-ACT1 include two low hybrid CD launcher assemblies, one ICRF (Ion Cyclotron Radio Frequency) system and one EC (electron cyclotron) system, and they are capable of delivering a total of ~80 MW power (20 MW for each LHCD launcher, ICRF and EC) to bring the plasma to ignition. The tritium plant processes the torus exhaust, separates the tritium and deuterium, and returns them to the fueling system. Meanwhile the tritium process system also detritiates the heat transport system coolant and the atmosphere in space where potential contamination can occur. The heat transport system includes 9 primary cooling circuits,

- 3 Li-17Pb circuits for cooling the inboard blanket, and the first and second outboard blanket segments.
- 2 Helium circuits for cooling the upper and lower divertor individually, including the W target plates, support structure and divertor local shield behind dome.
- 2 Helium coolant circuits for cooling the structural ring (or high temperature shield), including the inboard and outboard segments.
- 1 Helium coolant circuit for cooling the VV, including 16 U shaped-vessel sectors and 16 maintenance ports and doors.
- 2 Helium coolant circuits for the upper and lower shield blocks at the entrance of the maintenance port.
- 1 water coolant circuit for cooling the low temperature shield.

There is one or three Li-17Pb coolant ring headers for feeding the inboard and outboard blanket segments with the hot Pb-17Li (1030 °C) in the center duct and cold Pb-17Li (740 °C) in the annulus; 1 helium ring header for the divertors with the coolant inlet/outlet temperature of 700/800 °C; 1 Helium ring header for the structural ring with the temperature inlet/outlet temperature of 650/680 °C; 1 Helium ring header for the VV with the inlet/outlet temperature of 400/500 °C. All the coolant ring headers are arranged underneath the ground with hot coolant in the center duct and cold coolant in the annulus.

Like our previous ARIES studies, such as the ARIES-RS, ARIES-AT and the ARIES-CS, major engineering efforts were devoted on the power core configuration design and system integration, and less activities on the plant site and building designs. The ARIES-ACT1 principal buildings are simply summarized:
1. The tokamak building (fusion power core) contains the tokamak power core and its supporting systems. The maintenance access corridor is arranged in all the way around the tokamak building, and all the turbines, heat exchanges and other the energy conversion equipment are arranged on top of the maintenance corridor.

2. The electrical termination building for all the electrical power supplies including the TF and PF coils, LHCD, ICRF and EC launchers, etc., is placed on the west of the tokamak building, and the tritium processing and cryogenics building is located to the east of the tokamak building.

3. The assembly hall used for the tokamak assembly is located on the south of the tokamak building and the laydown hall used for the storage of the largest single item from the tokamak, such as the cryostat dome during major maintenance is located on the north of the tokamak building.

The layout of the ARIES-ACT1 plant is illustrated in Fig. 1 and 2. These layouts just provide a general arrangement of buildings, power core systems, support systems, equipment and facilities. Fig. 1 shows the cross section (west-east direction) of the tokamak building and the arrangement of the overhead bridge crane.

The Fig. 2 shows the cross section (north-south direction) of the tokamak building with the maintenance corridor under the assembly hall and laydown hall.

![Fig. 1. Cross section (west-east direction) of the tokamak building](image-url)
2.2 Power Core Configuration

The ARIES-ACT1 power core design builds upon many features of the ARIES-AT and ARIES-RS. Horizontal removal and replacement a power core sector is a key feature of the ARIES-AT and ARIES-RS plants, and is adopted in the ARIES-ACT1 power core configuration design. The overall power core configuration of the ARIES-ACT1 is illustrated in Fig. 3. The power core consists of the first wall, inboard and outboard blankets, upper and lower divertor target plates and structural support plates, structural ring or high temperature shield, VV with attached maintenance ports, low temperature shield, TF and PF magnets, cryostat and current drive launcher assemblies. The power core systems are major parts of the power plant equipment.

As illustrated in Fig. 4, the entire 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. Fig. 5 is a cross section of the ARIES-ACT1 power core cutting through a power core sector vertically. The plasma is surrounded by the FW, breeding blankets and upper and lower W divertor target plates and divertor structure support plates. The inboard vertical stabilizing shell made of the W with ~ 4 cm thick is embedded into the inboard structural ring (or high temperature shield), and the outboard W stabilizing shell is located between the first and second outboard blanket segment. The W kink stability shell with 1 cm thick and ~4 m poloidal height is also embedded into the second outboard blanket segment.

The structural ring is located immediately outside of the blanket regions and serves as the high temperature and neutron shield to protect the magnets, and it also provides support for the first wall, blankets, and divertor modules. The vacuum vessel is located behind the high temperature shield with additional permanent water-cooled shielding arranged outside the vessel.
Located on the outside of the structural ring are active feedback coils (or “control coil” in Fig. 5) for vertical position control that runs toroidally. These coils are supported by the back of the outboard structural ring. The control coil above the midplane can be removed to up and held by the VV during sector removal. The control coil below the midplane can be removed down to the surface of the bottom VV plate after removing the coolant access pipes under the coil and sliding a hydraulic lift system into the space between the bottom structural ring and VV. Detailed procedures of removing the control coils are discussed in maintenance section. There is a saddle coil mechanically attached to the front surface of the shield block for each power core sector. This saddle coil can be removed together with the shield block during maintenance. The 16 TF coils are enlarged to allow withdrawal of complete sectors between these magnets. The PF coils on the outside of the TF magnets are placed higher and lower than normal for allowing to remove entire power core sector. As illustrated in Fig. 5, there are 7 spare PF coils laying down on the cryostat for quick exchanges, if there is any PF coil below the midplane failure.
Fig. 4. A top view of the ARIES-ACT1 fusion power core

Fig. 5. Cross-section of ARIES-ACT1 power core
2.3 Design Description

The major engineering design efforts have been devoted on the system integration and design of the ARIES-ACT1 power core components, and the new design features and improvements are described and highlighted as following:

1. The ARIES-AT blanket design, cooling circuits, flow paths and coolant access pipes have been revised and optimized with the major objective to achieve high performance (~58% thermal efficiency) while keeping attractive design features, feasible fabrication and reasonable design margin on operating temperature and stress limits. The main incentive for re-designing the power core was to avoid complicate 3D MHD issues in the LM manifolds distributing the LM flow into the parallel poloidal ducts. The inboard blanket segment composes of 8 identical modules, and each module has two centric ducts and inner duct with ribs manufactured together as one piece to form annular and center ducts. The outboard blanket is segmented into two regions, the first outboard segment and the second outboard segment, and they are mechanically connected together by bolt systems or keys. There are 16 identical blanket modules for each outboard blanket segment, and each outboard module composes of a concentric outer duct and a center duct and manufactured as one piece from top to bottom, and they are brazed together as one blanket segment. The coolant Pb-17Li enters into the annulus from the bottom of the blanket module through its individual coolant access pipe, which connects the blanket module to the ring header underneath of the power core in order to make identical flow condition. After a fast upwards flow in the annular ring to the upper divertor region, the Pb-17Li makes a U-bend and flows into the center duct down to the coolant access pipe at the bottom.

2. The Pb-17Li cooled SiC/SiC divertor design of the ARIES-AT has been replaced by one of the Helium-cooled W-based divertor concepts, including the finger-based divertor, T-Tube, plate-type and two-zone divertor which is combination of the fingers and plate-type divertors. The two-zone divertor has been selected and integrated into the ARIES-ACT1 power core for handling the peak surface heat flux of ~13 MW/m² and an average surface heat flux of ~3.5 MW/m². The finger-based divertor, which is capable of handling a surface heat flux up to ~14 MW/m², was applied in the high heat flux zone and the plate-type divertor which is capable of removing the surface heat flux up to ~9 MW/m² was adopted in the low heat flux region. All the W target plates (~6 cm thick) are supported by the structure plate made of the ODS steel and connected by strong adjustable screw-type attachment, which is similar to the divertor attachment design of the ARIES-RS.6,7,12

3. The structural ring (or high temperature shield) of the ARIES-AT power plant utilized the SiC/SiC composite as the structural material and cooled by the Pb-17Lb as the temperature and neutron shielding for protecting the magnets.5 This component has been revised by using the He-cooled ODS steel structure in order to get rid of the Li-17Pb coolant flowing in the high magnet field causing 3D MHD effects. The most composition of the structural ring is the ODS steel and it is strong to support all the blankets and divertor. The inboard and outboard structural ring made of the ODS are bolted to the SiC/SiC layered structural ring block to form a closed ring in the poloidal direction to support the vertical load of the blankets and divertor, and plasma disruption load.

4. The water-cooled thicker VV of the ARIES-AT has been replaced by the Helium-cooled thinner bainitic FS vessel design. The VV is designed as a container for a high vacuum
and all radioactive products in the vessel generated by irradiation. It also serves as a first barrier in case of pressurization by the in-vessel coolant leaks or ruptures and provides a water-free tritium barrier with low inventory. The VV of the ARIES-ACT1 has been revised as a ribbed-structure to take normal operation, gravity and disruption loads, and the whole vacuum system including divertor pumping ducts for the upper and lower divertors, vacuum pumping ring headers, and vacuum ducts which are connected to the cryo-pumps, and all the maintenance ports has the lifetime-of-plant. The 3Cr-3WV bainitic FS has been chosen as the VV material to eliminate the need for post-weld heat treatment of the vessel and to avoid the relatively high activation of austenitic steels. The entire VV system is illustrated in Fig. 6. The VV operates in the temperature range of ~400 to 500°C in order to minimize the tritium/impurity migration to the VV. The size and shape of the VV main chamber and maintenance ports are defined based on the requirements of the sector maintenance withdrawn through the ports horizontally, integration of the overall power core and primary stress iteration. As shown in the cross-section of the power core (see Fig. 5), the vertical weight of the entire sector is supported by the VV, and the weight of each sector is transferred to a vertical support pillar through the water-cooled low temperature shield made of the bainitic steel also. There is only one vacuum door located at the outer end of the port for each sector. The vacuum door is bolted to the door flange with the structural support coming from the bolts, and seal-welded for vacuum tightness. Detailed design, performance analysis and optimization of the VV design are described in Ref. [13].

Fig. 6. Cut-away view of the vacuum vessel
5. The water-cooled low temperature shield is arranged outside the VV to reduce radiation dose to all the coils. However, the ARIES-AT design integrated the VV and low temperature shield into one single component with functions of both the VV and shield. The ACT1 outer shield will run at room temperature and provide a good heat sink and cool the afterheat by natural convection during power plant accidents. This shield is also made of the bainitic FS and it is a lifetime-of-plant component which composes of an inboard U-shaped segment and an outboard frame-shaped segment with a large opening for the maintenance port. The outboard frame-shaped shield segment is mechanically attached to the U-shaped shield by bolts. The low temperature shield will stay in the power core during the maintenance operation.

6. The upper and lower shield blocks, as shown in the cross-section of the power core, are located at the entrance of the maintenance port for protection of the TF magnets and the port walls. The shield-blocks utilize the same structural material as the low temperature shield; however, they are cooled by the Helium and operate in the same temperature range as the VV (~500°C). The weight of the upper shield block is ~115 tons and supported by the bottom shield block. 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 penetrate through the lower shield block, and need to be removed together with the lower shield block after cutting the brazing blocks, disconnecting and removing the mainfolding pipes at the port and the upper shield block. The detailed steps of cutting and removing the blocks and coolant access pipes are described in maintenance section. There are a few pumping slots at the top and bottom ends of the shield blocks for the vacuum pumping.

7. There are 16 superconductor TF coils, 7 pair superconductor PF coils, and the 16 maintenance ports arranged between TF coils for the sector maintenance. Each power core sector has its own horizontal maintenance port allowing replacement of entire sector without opening the cryostat or disassembling other components such as the coil system. The TF coils have to be designed to have sufficient spaces and clearances for the sector withdraw the maintenance ports. All PF coils are shifted towards top and bottom to allow withdrawal of the sectors. The similar design approach was also proposed in the ARIES-RS and ARIES-AT power plant studies.

2.4 Removable Power Core Unit

All the in-vessel components have a limited lifetime, and require replacement in certain intervals. Our ARIES plant design philosophy is to integrate all the in-vessel components into replacement units to minimize the number of the coolant access pipe connections and time-consuming 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. 7 illustrates one of the 16 replacement units. The blankets, divertor, and structural ring or high temperature shield form an integral unit within each sector. 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 radial-poloidal direction, composed of the inboard and outboard FW/blankets, divertor target plates, divertor structure support, structural ring and layered structural ring block. These rings have sufficient structure to provide enough mechanical strength for the entire power core sectors.
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 vertical loads of the unit are transferred to and supported by the vertical pillar. The connections between the structural ring and attached components must maintain a constant distance in the radial direction, but differential thermal expansion in the poloidal and toroidal directions is possible without causing large thermal stresses. No welds are used between the components of different lifetime classes, thus allowing easy disassembly in the hot cell and reuse of the components not at the end of their lifetime.

Fig. 7. The replacement unit of the ACT1 power core

3. BLANKET

3.1 Overall Concept
The ARIES-ACT1 breeding blanket is derived from the ARIES-AT blanket concept. It utilizes the Pb-17Li as the breeder and coolant, and the low-activation SiC/SiC composite as the structure material. The blanket uses a concentric duct design in which the coolant passes through an outer annular region before turning 180° at the top of the power core to return through the central duct. On the first pass, the coolant velocity along the first wall is high in order to allow effective removal of surface heating. The coolant velocity is much lower in the large central duct, where most of the neutron heating is deposited. The major objective of the blanket design is to solve some remain design issues and concerns of the ARIES-AT, for example, the blanket coolant access pipes, access pipes cutting/reconnecting, and Pb-17Li flow path and mass flow rate control to cool the first wall and blankets effectively, reduce the 3D MHD pressure drop and effects, and achieve the high performance (~58% thermal efficiency) while maintaining attractive design features, feasible fabrication, credible maintenance schemes and reasonable design margin on the operating temperature and stress limits. The first wall and blanket operating parameters were listed in Table II. The bulk average outlet temperature is allowed to exceed the structure temperature limit because the annular channel arrangement cools the SiC/SiC with inlet coolant. The flow in each of the three blanket segments is tailored to the local surface and volumetric heating in order to maintain the same bulk coolant temperatures. Only worst-case peak values are presented in the table. 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. The ASME code 3 Sm limits (Section-III) cannot be directly applied to ceramic composite when a traditional FEM analysis is used to analyze the stresses. It was suggested by the International Town Meeting on SiC/SiC Design and Material Issues for Fusion System that the combined primary and thermal stresses should be less than 190 MPa as a conservative first order approximation.

MHD considerations, heat transfer and MHD pressure drop calculations were ever described by Tillack. Extensive thermo-mechanical analyses and design iteration have been performed by using ANSYS Workbench in order to optimize the geometry and dimensions to provide the blanket design with reasonable margins on the temperature and stress limits to reduce the SiC/SiC volume fraction which will benefit tritium breeding. The major results are presented at separate paper.

3.2 Blanket Design

Each blanket sector is composed of three blanket segments – one inboard and two outboard segments. Each segment consists of a number of small identical modules containing two concentric ducts manufactured as one piece to form annular and center ducts. The Pb-17Li enters into the annulus from the bottom of the blanket coolant access pipes, flows up and runs behind and above the upper divertor region, then makes a 180 degree U-bend and returns to the ring header through the center ducts. Fig. 8 illustrates the cross section of the inboard blanket segment at midplane, and Fig. 9 shows the cross section of two outboard blanket segments at midplane.
Fig. 8. Cross section of the inboard blanket at the midplane

Fig. 9. Cross section of the outboard blanket at the mid-plane
The two outboard blanket segments are connected together by mechanical connectors (keys and bolts) at each side of the blanket. 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. Results of the pressure and MHD pressure drop indicate that the total pressure at the FW annular ducts of the blanket is \( \sim 1.95 \) MPa and \( 1.65 \) MPa at the center duct.¹⁷ 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 modules for each blanket segment to provide a design with reasonable margins on the temperature and stress limits while reducing the SiC/SiC structural volume fraction of the blanket which will benefit the blanket tritium breeding. Compared to the ARIES-AT blanket design, one significant improvement of the ARIES-ACT1 blanket is that all the ribs of the center ducts and annular ducts are manufactured together as one single stiff blanket module for accommodating a high pressure up to \( \sim 2 \) MPa while the center duct of the ARIES-AT blanket module is free-floating to the outer duct and enable handling the pressure of \( \sim 1 \) MPa. A number of identical modules are brazed together to form one blanket segment.

There are 8 identical blanket modules brazed together to form one the inboard blanket segment, 6 inner modules with pressure balance on both sides and 2 outer modules without the pressure balance on the outer side walls. As illustrated in Fig. 8, the outer side walls of the outer modules are enforced by increasing the thickness of the outer side walls and the number of the ribs. The thickness of the front, back and side walls, ribs as well as the distance between the 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.⁵,¹⁷ The same design approaches are applied to define the configuration, dimensions and composition of the first and second outboard blanket segments. There are 16 identical modules for each outboard blanket segment, 14 inner modules and 2 outer modules. Like the outer modules of the inboard blanket, the outer side walls of the outer modules without the pressure balance coming from each side of the wall have to be enforced by increasing the thickness of the outer side walls and number of the ribs as shown in Fig. 9.

### 3.3 Cooling Configuration

#### 3.3.1 Normal cooling schemes

The most difficult issues for the ARIES-ACT1 blanket concept is the design of the Pb-17Li coolant access pipes because there are difficult questions involved on the large impact of 3D MHD phenomena on the flow distribution and the MHD pressure drop. In previous ARIES-AT blanket design there was always a sudden transition from a big access duct into a number of smaller parallel ducts. With presently available analysis tools it is not possible to ensure equal flow distribution in the up to 16 parallel poloidal ducts of the outboard blanket segment after such a sudden step from one duct into a large number of parallel ducts.

In the cooling systems of the ARIES-ACT1 power core, there are 3 Pb-17Li circuits for cooling the inboard blanket segment, the first and second outboard blanket segments individually. The major advantage of the 3 cooling circuits for the blankets is to have each of the blanket poloidal ducts in all three segments fed individually from the ring header outside the VV in order to ensure identical flow rates in all parallel ducts. In addition, the mass flow rates flowing into each blanket segment can be adjustable during overpower or downpower operation, in this way,
the temperature of the blanket segments can be manageable to meet the maximum and minimum temperature limits.

The three blanket cooling circuits of the ARIES-ACT1 include:

a) the 1\textsuperscript{st} Pb-17Li circuit for the inboard blanket segment with the total thermal power of 308 MW, including both nuclear heating and FW surface heating, and the total mass flow rate of ~5740 kg/s;

b) the 2\textsuperscript{nd} Pb-17Li circuit for the first outboard blanket segment with the total thermal power of 833 MW and total flow rate of ~15530 kg/s;

c) the 3\textsuperscript{rd} Pb-17Li circuit for the second outboard blanket segment with the total thermal power of 273 MW and total flow rate of ~5090 kg/s.

Fig. 10 shows that all three inboard and outboard blanket segments connected to the Pb-17Li ring header through a number of coolant access pipes penetrating the lower shield block and maintenance port. Fig. 11 illustrates the Li-17Pb circuit 1 and flow paths of the inboard blanket segment, and the second Pb-17Li circuit for cooling the first outboard blanket segment is shown in Fig. 12. The third Pb-17Li circuit which is the same as the circuit 2 is not shown.

Fig 10. A sector showing all Pb-17Li coolant access pipes connected to the ring header
As shown in Fig. 11, the inboard blanket segment consists of 8 identical blanket modules with annular and center ducts. All the 8 inboard blanket modules are individually connected to one larger ring header underneath of the reactor core by 8 coolant access pipes. All the coolant access pipes are concentric pipes with the same configuration as the blanket module, but little smaller flow cross-section in the center ducts.

![Diagram](image)

**Fig. 11.** Circuit 1: Pb-17Li flow path through the inboard FW and blanket segment

The Pb-17Li enters the annulus with ~740 °C cooling the first wall, side and back walls and making a 180 degree bend at the top of the divertor region and flows out the blanket segment through the center duct with the temperature of ~1030 °C. With this design principle, each blanket module has identical coolant flow rate and the same thermal condition. This flow scheme enables operating the Pb-17Li at high outlet temperature (~1030 °C) while maintaining composite SiC/SiC and SiC/Pb-17Li interface at a lower temperature (~960 °C). The detailed results of the heat transfer and MHD analysis are presented in a separate paper. For the two outboard blanket segments, the same design approach as the inboard blanket segment is used. Each outboard blanket segment consists of 16 identical blanket modules and each blanket module is connected to the ring header through one coolant access pipe individually. Fig. 12 illustrates the flow path of the first outboard blanket segment; the second outboard blanket segment has the same flow path.
Fig. 12. Circuit 2- Pb-17Li flow path through the first outboard blanket segment

3.3.2 Sector with CD launchers

Heating and CD (current drive) systems are not baseline designs of our ARIES-ACT1 power plant study. ITER heating and CD systems\(^{18,19,20}\) will directly be adopted in the ARIES-ACT1 power core in order to investigate system integration and opening issues, and the impacts on the cooling scheme of the outboard blanket segments. To sustain steady-state operation of the ARIES-ACT1, three heating and CD launcher systems are proposed for delivering total power of \(~80~\text{MW}\) to the plasma,\(^9\) including two LHCD, one ICRF and one EC launchers, and each launcher provides 20 MW. The ITER ICRF launcher design has a 24-strap array and 8 coaxial transmission lines to be connected to the power supply, and the launch block has dimensions of 1.9 m (tor.) \(\times\) 2.4 m (pol.) including frame structural support and cooling manifold. In the design of the ARIES-ACT1 power core, the ICRF launcher was proposed to be installed at the midplane in one of the 16 torus sectors. Two LHCD launchers would be installed in the same sector centered at \(~50\) degree poloidally above the ICRF launcher in order to avoid conflicting to the W stabilizing shells which are located above and below the midplane and between the first and second blanket segments. Each of them is basically a block with the dimensions \(~1.475~\text{m}~\text{(tor.)} \times 1.075~\text{m}~\text{(pol.)}\) including surrounding structural frame and cooling channels, and the area of waveguide is \(~1.0~\text{m}^2\). The high power RF generators are connected to the launcher by means of the MTL (main transmission lines) and there are 24 MTLs for the ITER LHCD system. The EC launcher was proposed to be installed in the same sector centered at \(~50\) degree poloidally below the midplane. The opening of the FW area for the EC launcher installation is roughly the same as the LHCD launcher \(~1.59~\text{m}^2\). Fig. 13 shows the sector with all the launchers installed.

The toroidal width of the outboard blanket segment which composed of 16 identical small modules is \(~3.2~\text{m}\) at the midplane, and each module is \(~0.2~\text{m}~\text{width}\) in the toroidal direction. As the first design approach, the dimensions of the ITER ICRF launcher has to be revised in
order to get agreement between the launcher and blanket dimensions and fitting inside blanket coolant channels:

- toroidal width: 2.4 m in order to cover 12 of the 16 outboard blanket modules.
- poloidal height: 1.9 m.
- radial thickness 0.8 m (identical to the total thickness of the outboard blankets).

Fig. 13. A power core sector with installation of the launcher systems

The configuration of the ICRF launcher in ARIES-ACT1 is completely the same as in ITER, but just turns the launcher with a 90 degree in order to fit the ARIES-ACT1 outboard blanket configuration and cooling scheme. There are two LHCD launchers installed above the ICRF system in the same sector in parallel and 14 of the 16 blanket modules need to be cut with the opening dimensions of 1.3 m (tor.) x 1.22 m (pol.) for each launcher. Therefore, the dimensions of the ITER ICRF launcher have to be slightly revised in order to install the two launchers in the same sector. The same opening at the FW is needed for the installation of the EC launcher. Fig. 14 illustrates a backview of the outboard blanket modules, which have been cut for installation of the launcher system. An ODS steel wedge is installed between LHCD and ICRF launchers and between the ICRF and EC launchers because of difficulty to feed the Pb-17Li. The wedges are cooled by the same coolant as the launchers.

The basic idea of the cooling scheme for the sector with the LHCD, ICRF and EC launcher system installation is illustrated in Fig. 15.
Fig. 14. A 3D isometric view of showing the blanket with the installation of the launchers.

Fig. 15. Cooling scheme of the blanket segment with launcher installed.
The coolant temperature rise in the different blanket modules should be made identical to the coolant in the “normal” modules by adjusting the flow rate corresponding to the heat generated in the modules. In the outer 4 blanket modules (2 for each outboard blanket segment) at the sides of the LHCD launchers, the flow rate is identical to the flow rates in the normal sectors. The flow rates in all other blanket modules must be adjusted based on their heat generation while maintaining the same coolant temperature rise. For all the modules below the launchers, the Pb-17Li coolant will be fed from bottom manifold which consists of 16 concentric access pipes and all the pipes are connected to the 16 blanket modules at one end and to the ring header at another end. Therefore, each module has its coolant access pipe in order to distribute the flow rate. There are 28 blanket modules (14 for each outboard blanket segment) above the LHCD launchers and they will be cooled from top Pb-17Li manifolding pipes which consist of 28 concentric access pipes (not shown in Fig. 14). The mass flow rate in the blanket modules must be adjusted to maintain the same coolant temperature rise as the normal blanket modules. All the top coolant access pipes will be connected to the ring header at the bottom.

3.4 Blanket Manifolds

3.4.1 Manifold design

The most difficult issues for the ARIES-ACT1 blanket concept is the design of the LM (liquid metal) manifolds because there are difficult questions involved on the large impact of 3D MHD phenomena on the flow distribution and the MHD pressure drop. In the ARIES-AT study, all the blanket modules were connected directly to a concentric toroidal manifold and fed by only one radial access pipe per sector.\textsuperscript{5} This geometry, however, caused very complicated 3D MHD problems which could result in considerable largely different flow rates in the modules of a sector and may also cause problems of cooling the first wall and blankets. Since no MHD tools are available for the analysis of these problems, it was decided to avoid such 3D MHD issues by modifying the design of the coolant manifolds.

Fig. 16. A Y-shaped manifold concept for ACT1 blanket
Previous ideas for an improved manifold design for the ARIES-ACT1 power plant focused on a merging of the 8 coolant access pipes for the IB segment (or 16 for each outboard blanket segment) up to only one main access pipe per blanket segment. Many cuttings and joinings inside the reactor during maintenance should be minimized with this concept. A Y-shaped pipe connection between two pipes was proposed, as illustrated in Fig. 16, which keeps the symmetry between two module pipes for an equal mass flow distribution, and which keeps the MHD pressure drop low. A study about the use of Y-shaped pipe connections for the manifold structure of a blanket changing from 8 (inboard blanket segment) or 16 (for each outboard blanket) pipes into just one main access pipe has been made with main focus on fabrication and assembling issues. It has been emerged as very difficult to fabricate and maintain. Especially the merging point within the piece of the Y-shape has been pointed out to be difficult to merge together keeping all the ribs in the annular gap.

Instead of the Y-shape pipe connection, the latest concept for the ACT1 manifold prefers to feed each single module direct from the main Pb-17Li ring header without any merging of pipes. All blanket module pipes will be guided straight out down to the main Pb-17Li ring header pipes without any pipe joining inside the reactor, which means much less effort concerning fabrication issues and is also an improvement concerning MHD effects. To avoid a cutting and joining of all these pipes inside the reactor, a brazing block is installed at the closest point of these pipes outside of and close to the structural ring after assembling all of the sector parts together. A brazing block consists of two halves, where on each end all 40 access pipes are connected. With these brazing blocks only the outside of one brazing block has to be connected or cut during maintenance to get the two halves with still attaches pipes on each end. Small leaks between parallel channels can be tolerated within the block, because all parallel channels share nearly the same coolant conditions. These brazing blocks serves as pipe connections and have been placed several times between blankets and main PbLi ring header.

Fig. 17 shows the lower part of an ARIES-ACT1 power core sector containing the blanket segments, blanket coolant concentric pipes, structural ring blocks, divertor target plates, divertor structural support and inboard/outboard structural ring segments. The blanket coolant access pipes connect the blanket module of the inboard, the first and second outboard blanket segments to the main Pb-17Li ring header which is not shown in the figure. The inboard blanket segment consists of 8 separate modules and they are identical. Each of the outboard blanket segments has 16 small identical modules. As illustrated in Fig. 17, all 40 Pb-17Li access pipes of one blanket sector are embedded in the layered manifolding structure-ring block (shown with transparency) made of the same material as the blankets. All of these single layers are bolted together to one structural-ring block, which fills the empty spaces among the coolant access pipes for neutron shielding as well as closes the gap of the structural ring between the inboard and outboard segments to keep the function of the structural ring. The blanket modules itself consist of two concentric SiC/SiC pipes with intermediate fins. At the outer end of the manifolding structure a brazing block is brazed to the 40 coolant access pipes (8 for the inboard blanket and 16 for each of the outboard blanket segments). All the blanket coolant access pipes and brazing blocks are made of the SiC/SiC composite, and they are replaced together with the blanket segments.
3.4.2 Blanket fabrication

The fabrication of the SiC/SiC concentric ducts is really difficult task. The inboard blanket segment consists of 8 identical blanket modules and two half of SiC/SiC structural blocks, where the coolant access pipes are embedded. With today’s fabrication technologies a fabrication of two concentric circular pipes with intermediate fins is possible, as shown in Fig. 18, actively cooled ceramic matrix composite thrustcells of NASA.²¹
It is assumed that the ARIES-ACT1 blankets with a similar inner structure can be fabricated. Fig. 19 shows the fabrication steps of the inboard blanket segment. With a total length of about ~12.4 m for one inboard blanket module as well as different 3D shapes and cross-sections along the length, the module has to be fabricated in several pieces and brazed together to form an entire module, as shown in Fig. 19-1. Possible pieces could contain points with the same or similar inner structure like the long straight pipe, the diminution of the pipe or the two bends. After fabricating all of the 8 identical modules, they are brazed together to form one inboard blanket segment (see Fig. 19-2) and will be embedded into two half shells of the structural ring block layer made of the SiC/SiC, which will be bolted together afterwards (see Fig. 19-3). Both half shells of the structural ring block have to contain the diminution and the channels of 8 modules. The fabrication steps of the outboard blanket segments are similar to the inboard blanket segment. After preparing all three blanket segments, they will be bolted together to the structural ring block.

Fig. 19. Fabrication steps of the IB blanket, 1. a single blanket module with full length; 2. an inboard blanket segment with 8 modules brazed together; 3. all coolant access pipes embedded into two half shells of the structural ring block layer

3.5 Attachments

Our basic design principle for the ARIES-ACT1 power core is to transfer all forces including gravity, disruption forces and forces caused by the coolant pressures to the structural ring from
where they are transferred to the VV only in the bottom region of the torus. Since the blanket segments (SiC/SiC-composite) and structural ring (ODS steel) have different thermal and irradiation induced expansion, the mechanical fix point of this connection has to be arranged close to the bottom region where all the coolant access pipes are located too. The connections between the structural ring and the attached elements must be designed to maintain a constant distance in the radial direction, but differential thermal expansion in the poloidal and toroidal direction is accommodated without large thermal stresses. These connections have to be designed to transfer the gravity and plasma disruption forces. A system of bolts, sliding joints, and shear keys has to be utilized, and welding should be avoided in order to disassembly the replace unit easily in the hot cell.

As shown in Fig. 9, the T-shaped attachment connectors were designed to connect the first and second outboard blanket segments and maintain ~5 cm as constant distance between them. The two blanket segments are structurally attached to the midplane point with self-contained, retracted connectors in the two sidewalls of the blanket segments. Similar attachment connectors are used above and below the midplane which will allow differential expansion of the blanket sector.

Similar attachment systems are used with joints on one side to the blanket and on the other side to the structural ring, allowing differential thermal expansion between the blanket and structural ring, but no movement in the radial direction. Theses attachment systems can be disconnected in the hot cell for blanket replacement.

3.6 Connection of W Stabilizing Shells

The vertical stabilizing shells are 4 cm thick tungsten plates arranged between the two outboard blanket segments. They are arranged in the top and bottom region of the outboard blanket segments and have ~1 m in the poloidal direction. These plates are not actively cooled but radiate their heat on both surfaces to the blankets.

In order to obtain the function of a ring around the torus closed in the toroidal direction, the plate is given a U-shape with radial extensions reaching from the blanket FW up to the structural ring outside the blankets. There are bridges necessary in the region of the structural ring with a high electrical conductance in order to obtain the function of closed ring in the toroidal direction. This means those bridges must have a conductance comparable to the 4 cm thick tungsten plate. Possible design solutions for the bridges achieving such a goal include:

a) Inserting a conducting block into the ~2 cm wide gap between the radial extensions of the shell in the area of the structural ring, and to ensure high electrical conductances between the shell and the block inserted. This would be ideal for the electrical connection, but would require a really difficult maintenance operation (~20 cm thick steel structural ring, 4 cm thick W-shell, brazing temperature > 700 °C).

b) Inserting a wedge-shaped conducting block into the gap between the two sectors, and ensuring sufficiently high electrical conductance by applying mechanically high contact pressure between the block and the structural rings of the two neighboring sectors. Such a high conduct pressure can be obtained with strong screws operated from the inside of the maintenance ports.

As illustrated in Fig. 20, the second design approach is adopted in the ARIES-ACT1 for the toroidal electrical connection of the vertical stabilizing shells, and the following details for such a bridge are proposed:
i. Making the contact surface area at least 3 times as large as the cross section of the tungsten shell, this means at least 12 cm in radial direction.

ii. Using W or WC as material for the wedge-shaped block in order to combine high electrical conductance, allowable high temperature operation, and excellent neutron shielding to minimize gap streaming.

iii. Coating the block with a soft and highly electrical conductive layer, for example 0.5 to 1 mm thick Cu.

The ARIES-ACT1 power core has been designed with independent sectors with individual structural rings closed in the poloidal direction but 2 cm wide gaps between the neighboring sectors to facilitate easy replacement in horizontal direction and unrestricted differential expansion between the replacement unit and VV. For this reason, the structural ring is connected at the bottom only with the VV, and transfers all forces (caused by gravity, disruptions, coolant pressures) in this region only. The replacement units are allowed to expand freely in the poloidal, toroidal and radial direction. By installation of bridges between neighboring sectors for providing electrical conductance for the stabilizing shells, the structural rings of the sectors can still expand in the toroidal direction because such a ring closed in the toroidal direction can grow in its diameter without any interference with the VV. Therefore, the bridges will not cause a new problem for expansion, but in the opposite, they provide additional strength against disruption forces which could overturn moments to the sectors.

Fig. 20 Toroidal electrical connection of the vertical stabilizing shells
4. DIVEROR

4.1 Divertor Design

A number of advanced He-cooled W-alloy divertor concepts have been proposed and developed for the ARIES-ACT, including the large-scale plate-type divertor (100 cm poloidal x 20 cm toroidal),\textsuperscript{22-25} the mid-size T-tube (1.5 cm in diameter and 10 cm long along toroidal),\textsuperscript{26,27} the EU-like finger (2.0 cm in diameter for thimble),\textsuperscript{28,29} and integrated plate/finger concept.\textsuperscript{30} All diverter designs utilize the W as sacrificial armor, 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. The main distinction is the use of either linear “slot” jets or an array of circular jets, and the means of feeding and manifolding the He coolant. For the finger and T-tube designs, pure (non-structural) W armor is castellated and brazed onto the W-alloy substrate in order to provide additional resistance to plasma erosion and transients. The main design improvement based on the EU-like finger concept includes, 1. avoiding the transition joints between the W fingers and the steel manifolds, 2. adding the cylindrical ring for double containment in critical region for decreasing the potential for high pressurized helium leaks, 3. increasing the size of finger by ~33% to reduce the number of finger units used in the power plant.\textsuperscript{29} For the plate-type divertor, the front plate itself is castellated to create an armor zone. We assume the armor can operate up to 2/3 the melting point of W, because it does not carry loads. In all cases, a transition joint is located outside the high heat flux region, where the W-alloy heat sink is bonded to steel coolant supply lines through an intermediate Ta layer to accommodate differential stress.\textsuperscript{31}

In our previous studies on Helium-cooled W-based divertor for the fusion power plant, including all the plate-type, T-tube, finger and integrated finger/plate concepts, the most important design goal is to accommodate the surface heat flux (of the order of 10 MW/m\textsuperscript{2}) while meeting three main design limits, (a) the minimum operating temperature of the W-structure must be higher than 700 °C in order to avoid embrittlement under neutron irradiation; (b) the maximum operating temperature of the W structure must be maintained below the recrystallization temperature (~1300 °C); and (c) the required pumping power for the divertor coolant should be less than about ~10% of the heat extracted from the divertor in order not to have an excessive impact on plant net efficiency. Based on these design limits, the maximum allowable heat flux that remains under 3S\textsubscript{m} stress limits of the ASME code were determined to be ~13 MW/m\textsuperscript{2} for the finger design, ~11 MW/m\textsuperscript{2} for the T-tube and ~9 MW/m\textsuperscript{2} for the plate concept, respectively. Recent studies on helium-cooled W-based divertors have shown that the allowable heat flux can be increased by ~20% if yielding by plastic strain is allowed. However, since fracture toughness of the W alloy is reduced by low temperature irradiation, the lower operating temperature limit must probably be raised to ~800 °C to avoid embrittlement of the W structure material.\textsuperscript{32} To achieve this, the helium exit temperature must be raised to a range of 750-800 °C comparing current EU finger cooling conditions of the inlet temperature 600 °C and outlet temperature 700 °C. Such a higher helium exit temperature certainly will require a reduction in the maximum allowable heat flux in order to keep the maximum temperature of the W structure under the upper operating temperature limit of 1300 °C. An advanced ODS steel (such as 12CrYWTi)\textsuperscript{33} could be one option for the manifold, functioning only as the cartridge for such high cooling temperature without any structural strength requirement. Ta can be an alternate material for the manifold because of its high operating temperature. The thermo-fluid and thermo-mechanical results\textsuperscript{17} indicate that the maximum allowable heat flux for the plate concept
is ~9 MW/m$^2$ for the coolant exit temperature of 800 °C, ~20% reduction. For the finger concept, the maximum allowable heat flux would be dropped from 15 to 14 MW/m$^2$ if the lower operating temperature of the W structure were raised to 800 °C, roughly ~7% reduction. The results of the parametric study for the T-tube concept indicate that the maximum allowable heat flux would be reduced from ~13 to ~11 MW/m$^2$, roughly ~15% reduction of the allowable heat flux.

Our divertor studies show clearly that the finger design removes a greater incident heat flux with a lower pumping power penalty, but it does that with considerably increased complexity. The characteristic scale length of finger divertor elements is of the order of 2.0 cm; approximately ½ million fingers would be needed to cover all divertor targets of a 1000 MW plant. On the other hand, performance results and design iterations also clearly demonstrate that the plate divertor becomes increasingly challenging when the heat flux exceeds 10 MW/m$^2$. The integrated plate/finger concept is particularly useful in these cases, since the more complex fingers can be used only in locations where the anticipated heat flux is above 10 MW/m$^2$. Fig. 21 shows the divertor concepts of the plate, revised finger and integrated finger/plate conceptual design.

![Diagram showing divertor concepts](image)

a. the plate-type divertor
The divertor of the ARIES-ACT1 consists of three target plates (inner, outer and dome) plus the mechanical support structures and manifold. The strike points for the edge plasma occur on the inner and outer plates, close to the pumping ducts. Plasma exhaust is evacuated behind the dome, which allows adequate space for conductance to the inner and outer slots. Fig. 22 shows the layout of the lower divertor region. In order to provide adequate slot length for the divertor plasma solution on the inboard side the inboard blanket thickness is reduced behind the divertor, which is possible due to the lower neutron flux at this location.
Fig. 22. A 3D view of the lower divertor region

Fig. 23. Layout of divertor pumping ducts
The detailed divertor operating parameters were listed in Table IV. 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 \( \sim 48 \) cm, and \( \sim 76 \) 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.

Fig. 23 illustrates the W divertor integrated into the ACT1 power core with divertor pumping ducts arranged at the top and bottom and connected the vacuum ring header. There are 3 divertor vacuum pumping slots penetrating through the divertor support structure and manifolding region at the bottom without affecting the Pb-17Li coolant access pipes and cooling schemes. The same design approach is proposed to design the upper divertor pumping slots penetrating through the upper divertor region without affecting the cooling schemes of the divertor and blanket.

4.2 Cooling Configurations

In all Helium-cooled W-based divertor concepts, the coolant flows in the poloidal direction in parallel channels. The surface heat flux, cooling condition, and temperatures are equal in these parallel channels. The Helium enters at one side of the plate and leaves at the other side. The heat flux into the plate is low at the channel inlet, rises to a maximum value, and drops again in the direction to the exit. Inside the channels there is an inlet manifold with decreasing cross section, and an outlet manifold with increasing cross section, as illustrated in Fig. 24.

![Fig. 24. Manifolding and access pipe of the divertor](image)

With this arrangement, the helium velocity in both the inlet and outlet manifold remains constant over the entire length of the plate, and the height of the entire channel is constant over the length. Since most of the pressure drop occurs at locations where the coolant leaves the inlet manifold (the nozzles), the coolant pressure remains fairly constant over the length of both manifolds. This means the pressure drop in the nozzles generating the cooling jets is constant over the length of the plate. The pressure drop in the nozzle can be estimated by an equation:

\[
\Delta P = 0.5 \rho v^2
\]

Since the pressure drop \( \Delta P \) and the coolant density \( \rho \) remain constant over the length of the plate, the jet velocity \( v \) will be constant over the entire plate. It is desirable to avoid mixing of helium with different temperatures. Therefore we suggest keeping the difference between the helium inlet and outlet temperature constant over the length of the channel. To achieve this, the local
coolant mass flow rate must be adjusted to the local divertor heat flux, requiring the ratio of the mass flow rate to the surface heat flux to be constant. As the jet velocity is constant over the length of the plate, the flow cross sections (in cm$^2$ per cm plate length) must be adjusted to the local divertor heat flux, and the ratio of the local cross-sectional area of the nozzles to the cross-sectional area of the nozzles at the location of maximum heat flux must be the same as the ratio of the local heat flux to the maximum heat flux:

$$\frac{S_{\text{nozzle at local}}}{S_{\text{nozzle at max}}} = \frac{q''_{\text{local}}}{q''_{\text{max}}}$$

$S_{\text{nozzle}}$: Cross-sectional area of the nozzles
$q'':$ surface heat flux

For the plate concept, since the slot should not become too small for practical reasons, the alternative would be to replace a continuous slot by an interrupted slot with a ratio of:

$$\frac{L_{\text{slot at local}}}{L_{\text{slot at max}}} = \frac{q''_{\text{local}}}{q''_{\text{max}}}$$

$L_{\text{slot}}$: length of the slot

The same design method would be applied in the finger concept (cylindrical jets). If the nozzle diameter becomes too small for practical reasons, we could keep the nozzle diameter constant and decrease the number of nozzles in the same ratio as the local heat flux decreases.

### 4.3 Attachments

The divertor target plates are made of ~6.0 cm thick W or W-alloy with ~ 2 cm wide (toroidal) cooling channels at the plasma facing side. Our intention is to separate the divertor target plates from the replacement units in the hot cell when the divertor plates and their structural support (ODS steel) reach the life-time. All target plates have to be attached to the structural support made of the ODS steel and meet the requirements: 1. the W target plates must be precisely aligned; 2. the target plates must allow differential expansion without causing large thermal stresses; 3. the attachment must withstand the gravity of the plates and support structure, and large disruptive forces, 4. the target plates must be replaceable from/within the hot cell without cutting/rewelding highly irradiated parts. To meet these requirements, strong adjustable screw-type attachments were designed in ARIES-RS plant study $^6,^7,^{12}$ to connect the W target plates to the divertor structural support. The similar screw-type attachments will be used in the ARIES-ACT1 divertor sector for the mechanical connections and alignment of the W target plates and reaction of the plasma disruption forces. These screw-type attachments are threaded and hollow bolts with opposing threads on either end which are flexible enough to allow for differential thermal expansion between the W target plates and support structure without excessive and large bending stresses. The bolts can be made of the ODS steel which is the same material as the support structure and each bolt has a hexagonal hole on the end which attaches to the support structure. The W target plates are aligned by turning the bolts with a hex wrench from the outside of the support structure. The number, location and orientation of the bolts will be determined by the plasma disruption forces.
5. STRUCTURAL RING

The most composition of the structural ring is the ODS steel and it is cooled by Helium. The structural ring is designed to operate at high temperature of ~ 680°C to minimize the temperature difference between the SiC/SiC blanket and structural ring and to reduce the thermal stresses. For our ARIES-RS and ARIES-AT studies, the structural ring is a closed ring along a radial-poloidal direction, and all the in-vessel components, including the inboard FW and blanket, the first and second outboard blankets, and the upper and lower divertor target plates and their structural support plates are mechanically attached to the continuous ring, which is capable of withstanding large loads caused by gravity of inside components and disruption forces. Besides supporting the in-vessel components and providing mechanical strength to the sectors, the structural ring helps to shield the permanent components and captures a significant amount of energy at high temperature for power conversion.

The structural ring is also subdivided into 16 sectors and supported at the bottom only by the VV and transfer the weight and loads to the vertical pillar. The main function of the structural ring is to ensure the structural stability of the in-vessels components and take plasma disruption loads as well as to carry the weight of the blankets and divertors. Unlike the ARIES-RS and ARIES-AT power plants, the structural ring of the ARIES-ACT1 consists of an inboard segment and an outboard segment made of the ODS steel, as well as a layered structural ring block, where the coolant access pipes of the blankets are embedded. The structural ring block is made of SiC/SiC to resist the high temperature up to 1000°C within the blanket and manifolding area and will be passively cooled by the embedded coolant access pipes. No separate cooling system for these layers is necessary. To avoid a weakening of the structural ring by guiding the blanket and divertor coolant access pipes outwards through the structural ring in its full module size, the size of the coolant access pipes has been decreased before guided through it. The penetration of the structural ring includes 16 coolant access pipes for the first outboard blanket segment, 16 coolant access pipes for the second outboard blanket segment and 8 pipes for the inboard blanket as well as 2 Helium concentric access pipes for the upper and lower divertor segments. The Pb-17Li velocity within the penetration area is about ~1 m/s to avoid a high MHD pressure drop within these pipes, and ~100 m/s is assumed for the Helium in the Helium access pipes. A detailed calculation of the maximum possible penetration size for the structural ring may be needed as soon as operational loads as EM loads are available. Occurring thermal stresses between the two used materials ODS-steel and SiC/SiC are absorbed by the connecting bolts. There are no analysis results in current study.

One argument for the structural ring block layers was an easy way to include shielding material as well as a simple replacement at the end of their lifetime at once. The single layers of the structural ring block are bolted together. The coolant access pipes of the blankets are embedded inside these blocks. The massive structural ring block is also the support point for occurring loads as pressure loads, gravity loads as well as thermal stresses. Other than in previous designs the structural ring block in the present design has also adopted the function of a shielding block. This means a shortened lifetime of the structural ring block compare to the rest of the structural ring, which has about 20 years lifetime, consisting of ODS material. By introducing the single layers, they can easily be replaced with and at the end of the blanket lifetime after 3-4 years.
6. MAINTENANCE STRATEGY AND OPERATION

6.1 Maintenance Strategy

The power core maintenance philosophy of the ARIES-ACT1 is the same as the ARIES-RS and ARIES-AT power plants, 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 and refurbishment?

The following design principles have been selected for the ARIES-ACT1 power core configuration and system integration in order to achieve the design goals:

a. Self-cooled Pb-17Li blankets with the SiC-composites as the structural material.

b. Structural ring/HT shield made of the ODS-steel with the Helium cooling designed for an operating time up to ~ 20 years, not re-weldable after a few FPY’s.

c. Thin Helium-cooled VV made of ~ 3 % Cr bainitic steel, and operated at 400-500 °C, not re-weldable in the inboard region.

d. Water cooled low temperature shields made of the bainitic steel arranged outside the VV.

e. Replacement unit composed of the inboard blanket segment, the first and second outboard blanket segments, structural ring/HT shield, upper and lower divertor targets and their structural support.

f. All concentric coolant access pipes penetrating the VV in the area of the maintenance ports and to be connected to the replacement unit and ring header.

g. For each of the 3 blanket segments (inboard, the first and second blanket segments), the Pb-17Li coolant access pipes distributing the Pb-17Li flow from a single concentric pipe to each parallel blanket module of the segment (for example 16 outboard blanket modules in each outboard blanket segment) are integral parts of the blanket segments to be replaced together with the blankets.

One important design approach of the ARIES-ACT1 configuration is to minimize the impact of the blanket replacement on the overall availability of the plant. The anticipated life time of the Pb-17Li SiC/SiC blanket is about ~4 years and the structural ring has a lifetime of ~20 years for the inboard region, and considerably longer for the outboard region. This leads to the question, in which time intervals the replacement units (sectors) have to be replaced by new or refurbished ones. In order to minimize the down-time for such an operation, it is mandatory to have spare units available, and to refurbish the used ones during the operation of the plant. If all the 16 sectors of a plant are replaced at the same time (for example in 4 year intervals), we would need 16 spare units, and for a minimized down time the tools and man power for a considerable number of parallel replacement operation.

In order to avoid these large costing factors, it is suggested to plan the blanket replacement in a similar way as the fuel rod replacement in a Pressurized Water reactor (PWR). The fuel rods in such a plant have a life time of ~3 years, and each year one third of the rods are replaced. These replacement operations are synchronized with other maintenance operations of the entire plant which requires in general a yearly down time in any case. If we adapt this method for our fusion plant, we can exchange a quarter of the power core sectors every year, and this requires 4 spare
units only. It looks feasible to perform the replacement of these four sectors in parallel. A similar maintenance strategy was adopted in the ARIES-AT.\(^8\)

In the time between two replacement operations, the four sectors can be refurbished with new blanket segments, new divertor target plates, and, if required, with new parts of the structural ring.

### 6.2 Rail System Design

There are 16 replacement units located inside of the VV. Each removable unit weighs approximately ~162 metric tons. These replacement units must be aligned inside the plasma chamber within a few millimeters for proper function. A rail system similar to the ARIES-RS which was used in the installation and maintenance study\(^6\) is proposed for the alignment of the power core sector, and sector removal and support during the installation and maintenance operation. As illustrated in Figure 25, the entire power core sector is supported by the T-shaped attachments between the bottom of the structural ring and the VV. There are wide gaps in the wedge allowing the precise alignment of the sector in all directions.

![A 3D view of the T-shaped attachments](image1)

**a. A 3D view of the T-shaped attachments**

![Cross-section of the rail system](image2)

**b. Cross-section of the rail system**

*Fig. 25. T-shaped attachments and rail system (1/16 sector)*
The rail system with a hydraulic lift sub-system, which consists of three or more vertical pistons, is inserted into the space between the bottom of the structural ring and the VV. The entire sector is supported by the rail system for the vertical and horizontal alignment during installation. After the alignment is made, these grooves of the T-shaped attachment 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 can be withdrawn.

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 ~162 tons. The rail system needs to be inserted into the space between the bottom plate of the structural ring and VV for the sector replacement after removing all the coolant access pipes and shield blocks during the maintenance operation. 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 cask. As a next step, the new sector which is already contained in the cask 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.

6.3 Maintenance Operation

6.3.1 Maintenance equipment

The total weight of the replacement unit is about ~162 tons, and ~115 tons for the upper shield block. A transporter or extractor must be able to lift the upper shield block (115 tons), vacuum vessel door (~28.2 tons) and the bio-shield blocks before the replacement unit removal. The bio-shield, VV door and shield blocks are the lifetime-of-plant components, and will be removed and relocated in the storage room for re-use. The transporter also must have other functions such as tools for cutting the sealing welds of the VV door, cutting/disconnecting all the SiC/SiC brazing block pairs and ODS steel access pipes, and unbolting/disconnecting the components for disassembling the blanket segments and divertor for the refurbishment and disposal.

6.3.2 Cutting/Connection the access pipes

There are 9 coolant circuits to be connected to each power core sector by the coolant access pipes and all the coolant access pipes are designed to be concentric pipes with the cold coolant in the annulus and the hot coolant in the center duct. The replacement of the sector requires cutting/re-connection most of these coolant access pipes and removing them in order to allow for the rail system to be inserted through the maintenance port for the sector removal. The manifold access pipes include:

a. 8 Pb-17Li access pipes for the inboard blanket segment.

b. 16 Pb-17Li access pipes for the first outboard blanket segment.

c. 16 Pb-17Li access pipes for the second outboard blanket segment.

d. 2 Helium access pipes for the divertor segments (upper and lower divertor plates and their structure support).

e. 2 Helium access pipes for the structural ring (inboard and outboard structural ring segments).

f. 2 Helium access pipes for the upper and lower shield blocks.
All the access pipes to the sector are guided to the structural ring close to its bottom plate which is the mechanical fix-point of the entire power core sector. To reduce the number of cutting and joining of pipes inside the reactor the connection of the PbLi access pipes per sector for the inboard, first and second outboard blanket segments has been combined in one brazing block. All 40 coolant access pipes of the blanket modules consisting of two concentric pipes with intermediated fins are brazed to a half of brazing block and will be connected or cut during maintenance with a counter piece of brazing block half with already attached pipes on each end. These brazing blocks serve as pipe connections and have been placed several times between blankets and main PbLi ring header. Only the outer pipe is brazed to such a half of block with an axial extension to achieve an overlapping. Thereby, same levels of brazing and pipe connection are avoided. Both concentric pipes are designed with different assembly levels at the end of the inner and other pipe and chamfers for easier assembling and to decrease possible cross-flows between the concentric pipes. Brazing the brazing block onto the coolant access pipes happens outside of the reactor after bolting the inboard and outboard blocks together. After installation of one sector inside the reactor a similar counter piece brazing block with pipes going to the main access pipe will be brazed to the counter piece of the blanket brazing block, where the pipes going to the main ring header are attached. There is only the brazing or cutting line around this block, which needs to be done inside the reactor for maintenance. Inside the brazing block, the high-pressure inlet still can leak into the low-pressure outlet channels. But this is a problem regardless of the manifold design. Even a single concentric pipe will be difficult to braze between the inner and outer pipe at the connections points. Some additional design work is needed to fully describe how to ensure acceptable leakage rates. Fig. 26 shows a simplified sketch of the brazing block.

![Fig. 26. A Simplified sketch of SiC/SiC brazing block](image-url)
Fig. 27. Cross-section of showing cutting locations of the blanket coolant access pipes

Fig. 27 shows the flow path and brazing blocks of the blanket coolant access pipes during the maintenance operation. During maintenance the brazing blocks, which are placed close to the bottom of the port (Brazing block 4), where all the coolant access pipes are guided through the door of the vacuum vessel down to the main Pb-17Li ring header, and the brazing block at the outside of the lower shielding block (Brazing block 3) has to be cut. The pipe structure with halves of the brazing blocks on each side can then be removed. Afterwards, the rail system used for maintenance can be placed and the upper part of the shielding block can be removed. The brazing block inside of the shielding block (Brazing block 2) is now accessible and can be cut. After removal of the lower shielding block also the brazing block close to the structural ring (Brazing block 1) is accessible and can be cut.

The sector is now free to remove. All other dis-/assembling steps for the blanket structure can be done outside of the reactor with a better accessibility in the hot cells.

6.3.3 Motion of the removable power core unit

Removing the entire replacement unit from the plasma chamber through the port to the hot cell for exchanges requires certain space margins or clearances for the movement. The size and geometry of the port are defined based on the maximum toroidal width of the replacement unit and its height. Motion demonstrations for removing the replacement units from the plasma chamber have been performed by using 3D CAD technology to analyze the clearances and spaces in all directions. Fig. 28 illustrates the replacement unit moving through the entrance of the maintenance port and shows the clearance at the top, and Fig. 29 shows the space margin on two sides of the unit.
Fig. 28. An elevation view of showing the sector movement and space margin at the top.

Fig. 29. A plan view (cutting through the midplane) of showing the movement and space margin on the side walls of the port.
6.3.4 Maintenance procedure/sequence

The main in-vessel components of the ARIES-ACT1 plant to be maintained/replaced at the end of life-time include:

a. Divertor target plates and their supporting structure and manifold.
b. Inboard and outboard blanket segments including their coolant access pipes.
c. Structural ring.
d. LHCD, ICRF and EC launcher systems.

The lifetime-of-plant components, such as the TF and PF coil system, the low temperature shield and vacuum vessel will be stayed in the original places during the maintenance operation. The maintenance approach of the ARIES-ACT1 plant is to transfer the power core sectors to the hot cell for the sector exchanges and refurbishment. A transfer cask or flask with a double door (one at the cask, 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 replacement.

The major maintenance sequence and procedure for the replacement of power core sectors are described as follows:

a. Loading the two rail systems and a new or refurbished replacement unit (1 sector) into the transfer cask, shifting this cask to the maintenance door, attaching the cask to the flange of the port, and opening and removing the bio-shield door and VV door.
b. Transporting the removed bio-shield door (life-time of the plant) and VV door (the life-time of the plant) to the storage room for re-use.

Fig. 30. Cross-section of showing removed upper shield block
c. Cutting the two pairs of the SiC/SiC brazing blocks located at the inside of the maintenance port (Brazing Block 3 and 4, as illustrated in Fig.27) and removing the access pipes for moving clearance. Fig. 30 shows the upper shield block is removed in the straight along the radial direction.

d. Disconnecting the coolant lines of the shield blocks, removing the upper shield block together with the saddle coil (the life-time component) inside the port and transporting it to the storage room for re-use.

e. Cutting the SiC/SiC brazing block 1 and 2 (see Fig. 27) at the inside of the shield blocks and removing lower shield block together with penetrated coolant access pipes as well as coolant pipes for the lower shield block and divertor (not shown), as illustrated in Fig. 30.

f. Transporting the cut coolant access pipes and shield block to the storage room for re-use.

g. Unlocking the upper stabilizing control coil from its support structure and removing it up to the VV, and the coil will be held by the VV.

h. Cutting and removing the divertor vacuum pumping duct between the bottom plate of structural ring and VV to allow the first rail system to be inserted.

i. Cutting/Disconnecting all other Helium access pipes to the divertor sectors and structural rings and transporting them to the hot cell.

j. Installing the first rail system (~4 m long) into the space between the bottom plate of the structural ring and VV.

k. Unlocking the lower stabilizing control coil from its supporting structure and removing it down to the top surface of the VV.

l. Installing the second rail system (~8 m long) along all the way through the port to bridge to the first rail system for the sector removal, see Fig. 31.

Fig. 31. The steps of installing the two rail systems
m. Using the hydraulic lift system of the first rail system to support the entire sector and melting the special alloy in the grooves of the T-shaped attachment between the bottom of the replacement unit and the VV.

n. Pulling the replacement unit outwards in horizontal direction into the transfer cask and replacing the used replacement unit by the new/refurbished one from the transfer cask and installing it back to the plasma chamber.

o. Using the hydraulic lift system to support the new/refurbished sector for the horizontal and vertical alignment during the installation.

p. Freezing the T-shaped attachment grooves by filling with a suitable liquid metal (possibly a Cu-alloy) and fixed in this position and withdrawing the two rail system.

q. Re-installing the lower shield block and re-connecting all the brazing blocks by rebrazing each pair of the counter blocks, and reconnecting all the Helium access pipes.

r. Re-installing the upper shield block back and re-connecting its coolant line.

s. Closing the double doors of the maintenance port, disconnecting the cask from the port-flange, and transporting it into the hot cell.

t. Disassembling the blanket segments to be replaced from the replacement unit, and installing the new blanket segments in the hot cell. The coolant access pipes of blanket segments are an integral part of the replacement unit and are replaced together with unit.

6.3.5 Disassembling procedures in hot cell

The sectors removed from the tokamak machine will be transported from the power core through the maintenance corridor to the hot cell for repair or disposal by the transfer casks. The repair and maintenance equipment in the hot cell are operated mainly by remote control because the hot cell systems provide space and facilities for highly radioactive and contaminated in-vessel components. The hot cell building is located at east-side of the tokamak building and is connected to the tokamak building by the maintenance corridor. A previously refurbished sector can immediately be reinstalled back into the sector to speed the maintenance of the power core and lessen the plant downtime. This is similar to the design approach utilized in the ARIES-AT maintenance. After the power core is refurbished according to the maintenance schedule, the removed replacement units can be refurbished in the hot cells while the power plant is operating.

The replacement unit composed of the inboard blanket segment, the first and second outboard blanket segments, upper and lower W divertor target plates and their structural support plates, and inboard and outboard structural ring need to be disassembled in the hot cells. The structural ring has the life-time of ~20 years, and need to be replaced only one time during the life-time of the plant. All the components inside of the structural ring need to be replaced at their end of the life-time.

Within the hot cells the Helium access pipes for the divertors, which is embedded between two structural ring block layers, have to be removed by cutting and moving them straight out. The bolted divertor segments can then be removed from the structural ring block. After installation of a supporting structure for the structural ring as well as for the blankets the bolts between the inboard and outboard structural ring segments and the structural ring block can be loosened as seen in Fig. 32. The structural ring block with the manifolds and blankets is then free to maintain.
After disassembling the inboard and outboard structural ring the three blanket segments still remained together because the single layers of the structural ring block are still bolted together as seen in Fig. 33, therefore, the blanket structure has to be cut and unbolted. The first step of disassembling the inboard, first and second outboard blanket segments is to cut the brazing block from the coolant access pipes, then unbolt the bolts between the single layers. As illustrated in Fig. 34, the three structure layers of the three blanket segments are free to remove from each other. For a new or refurbished sector, the assembly procedures follow a reversed sequence.

Fig. 33. Disassembling the blanket structures by unbolting the bolts
Fig. 34. Disassembled blanket segments, a. the inboard blanket segment, b. the first outboard blanket segment, c. the second outboard blanket segment.

6.3.6 Removing LHCD and ICRF launchers

The launcher systems including the ICRF, LHCD and EC have the same life-time as the SiC/SiC blankets and need to be replaced at the end of their life-time. There is only one power core sector with the launcher assemblies installed. Unlike the ITER and ARIES-CS, the launcher systems have been designed to be removed together with the replacement unit and disassembled them in the hot cell. As illustrated in Figs. 13-14, the two LHCD launchers and the EC launcher are installed above and below the ICRF launch and centered at 50 degree, and the launcher assemblies do not penetrate through the structural ring in order to maintain its mechanical strength and stability to support entire blanket and divertor and take the plasma disruption load. Only the coaxial transmission lines (24 for each of the LHCD launcher, 8 for the ICRF and 8 for the EC launcher) of the launchers penetrate through the structural ring, upper shield block, vacuum vessel door and bio-shield block to connect to the RF power generators located at the outside of the bio-shield. Surrounding the coaxial transmission lines are local shields made of the
FS steel with thickness of ~50 cm. The sequence and procedure of the removing the sector with
the launchers are almost the same as the regular replacement units, except some extra steps are
needed before the pulling the sector with installation of the launchers out. The first extra step is
to remove all the local shields surrounding the coaxial transmission lines, and then disconnect
and remove the transmission lines. With the two extra operation steps, the upper shield block and
the sector with installation of the launchers can be removed as the regular replacement units.

7. CONCLUSIONS

The overall configuration and system integration of the ARIES-ACT1 have been made based
on the ARIES-AT plant, and the major improvements on the designs of the power core
components including the Pb-17Li cooled FW/blanks, coolant flow path and mass flow rate
control, blanket coolant access pipes, Helium-cooled W-based divertor, structural ring segments,
water-cooled low temperature shield and rib-based VV are highlighted. The engineering
performance analyses\textsuperscript{17} indicate that with all the engineering efforts on making the design
improvements and optimizations, and adding new elements and features into the ARIES-AT
like power core configuration design, the ARIES-ACT1 plant design becomes more robust while
maintaining the same performance (~58% thermal efficiency) and more design margins.
Maintenance strategy and maintenance operating sequence/procedure of removing the
replacement unit from the plasma chamber to the hot cell for exchange and refurbishment are
described in this paper. As a conceptual design of a future fusion power plant, there are design
issues and uncertainties existent as a result of the limited existing database and extrapolations
that count for anticipated future progress. Many of the engineering challenges relate to
fabrication and materials behavior. The design issues and R&D needs of the ARIES-ACT1
power core design were addressed and discussed by Tillack.\textsuperscript{3,34} These issues have been identified
in previous studies, and already are the subject of ongoing R&D programs.

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FG02-04ER54757.
REFERENCES

1. F. NAJMABADI et al., “Overview of the ARIES-ACT-1 Advanced Tokamak, Advanced Technology Power Plant Study,” these issues.


9. C. KESSEL et al., “Physics Basis for an Advanced Tokamak Power Plant,” these issues.


