ARIES-AT BLANKET AND DIVERTOR

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ABSTRACT

This paper summarizes the results of the design study of the ARIES-AT blanket and divertor, which have been developed with the overall objective of achieving high performance while maintaining attractive safety features, credible maintenance and fabrication processes, and reasonable design margins as an indication of reliability.

I. INTRODUCTION

The ARIES-AT power plant was evolved to assess and highlight the benefit of advanced technologies and of new physics understanding & modeling capabilities on the performance of advanced tokamak power plants[1]. Figure 1 shows the ARIES-AT power core and Table 1 summarizes the typical geometry and power parameters of the reactor, emerging from the parametric system studies[2].

Table 1 Typical ARIES-AT Parameters

Major/Minor Radii	5.2/1.3 m
On-Axis Magnetic Field	5.9 T
Fusion Power	1719 MW
Blanket Energy Multiplic. Factor	1.1
Maximum Thermal Power	1897 MW
Average Neutron Wall Load	3.2 MW/m^2
Outboard/Inboard Max. Wall Load	4.8/3.1 MW/m^2

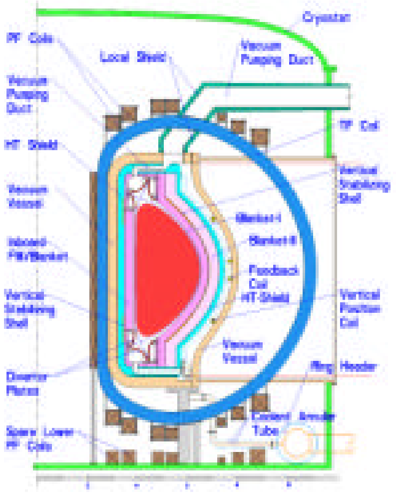

Fig. 1 ARIES-AT Power Core (radial dimension in m)

The blanket and divertor designs utilize Pb-17Li as breeder and coolant and low-activation SiC_f/SiC composite as structural material. The Pb-17Li operating temperature is optimized to provide high power cycle efficiency while maintaining the SiC_f/SiC temperature under reasonable limits. The Brayton cycle offers the best near-term possibility of power conversion with high efficiency and is utilized[3]. The Pb-17Li exiting the blanket is routed through a heat exchanger where it raises the cycle He temperature to 1050°C, resulting in a high cycle efficiency of about 58.5%.

II. MATERIAL CONSIDERATIONS

Use of SiC_f/SiC as a structural material is attractive since it enables operation at high temperature and its low decay heat facilitates the accommodation of loss-of-coolant and loss-of-flow events without serious consequences to the in-reactor structure[4,5]. However, there are some key issues influencing its attractiveness, including: thermal conductivity; operating temperature limits; maximum allowable stress limits; lifetime parameters; and fabrication and joining procedures. These issues were addressed in detail in presentations and discussions at the January 2000 International Town Meeting on SiC_f/SiC Design and Material Issues for Fusion Systems and in a related publication[6,7]. The SiC_f/SiC parameters and properties used in the ARIES-AT analysis are consistent with the suggestion from this meeting and are summarized in Table 2.

III. BLANKET DESIGN AND ANALYSIS

For waste minimization and cost saving reasons, the blanket is subdivided radially into two zones, as shown in Figure 1: a replaceable first zone in the inboard and outboard, and a life of plant second zone in the outboard. To simplify the cooling system and minimize the number of coolants, the Pb-17Li is used to cool the blanket in-series with the divertor or hot shield regions. Annular coolant manifolds are used to feed the in-reactor components, with the lower temperature inlet flow in the outer channel and the higher temperature outlet flow in the inner channel. In this way any effect of the high SiC/Pb-17Li interface temperature on the manifold inner wall would only result in a leak to the manifold outer channel, which would not be of major consequence. However, the structural integrity of the configuration would be ensured by the low temperature outer channel.

As illustrated in Figure 2, each blanket segment consist of a number of modular annular boxes through which the Pb-17Li flows in two poloidal passes. Positioning ribs are attached to the inner annular wall forming a free floating assembly inside the outer wall. These ribs divide the annular region into a number of channels through which the coolant first flows at high-velocity to keep the outer walls cooled. The coolant then makes a U-turn and flows very slowly as a second pass through the large inner channel from which the Pb-17Li exits at high temperature. This flow scheme enables operating Pb-17Li at a high outlet temperature (1100°C) while maintaining the blanket SiC_f/SiC composite and SiC/PbLi interface at a lower temperature (~1000°C). The first wall consists of a 4-mm SiC_f/SiC structural wall on which a 1-mm CVD SiC armor layer is deposited.

Table 2 SiC_f/SiC properties assumed in this study[6]

Density	~3200 kg/m^3
Density Factor	0.95
Young's Modulus	~200-300 GPa
Poisson's ratio	0.16-0.18
Thermal Expansion Coefficient	4 ppm/°C
Thermal Cond. through Thickness	~20 W/m-K
Maximum Combined Stress	~190 MPa
Max. Operating Temperaturre	~1000 °C
Max. SiC/LiPb Interface Temp.	~1000°C
Max. SiC Burnup	~3%

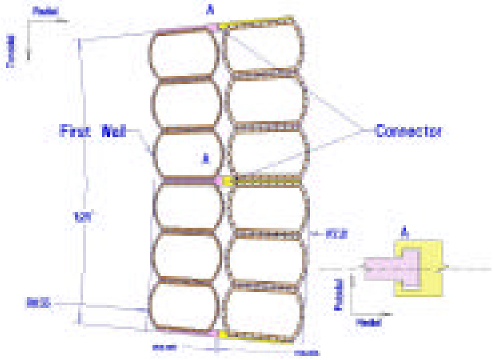

Fig. 2 Cross-Section of ARIES-AT Outboard Blanket Segment (all dimensions in cm)

Detailed 3-D neutronics analyses of the power core were performed yielding a tritium breeding ratio of 1.1 and the energy multiplication and wall loading values shown in Table 1[8]. The volumetric heat generation profiles from these analyses were used in subsequent thermalinvestigations. Of the three blanket regions, the first outboard region is subjected to the highest heat loads. A typical module in an outboard segment cooled in series with the upper divertor was the focus of the thermal analyses which are described below and whose results are summarized in Table 3.

For these analyses, the plasma heat flux profile was estimated by considering bremstrahlung, line and synchotron radiations, with average/peak values[2] of 0.26/0.34 MW/m^2. The analysis assumes no radiation to the first wall from the 256 MW transport power to

Table 3 Summary of Typical ARIES-AT Blanket Parameters (as represented by first outboard region)

Pb-17Li Coolant	
Power Core Inlet/Outlet Temperature	654/1100°C
Pb-17Li Blanket Inlet Pres./Pres.Drop	1/0.25 MPa
Total Pb-17Li Mass Flow Rate	22,700 kg/s
Outboard Blanket Region I	
No. of Sectors/Segments	16/32
No. of Modules per O/B Segment	6
Module Poloidal and Radial Dimens.	6.8, 0.3 m
Module Average Toroidal Dimension	0.19 m
FW SiC_f/SiC and CVD SiC Thick.	4+1 mm
First Wall Annular Channel Thickness	4 mm
Pb-17Li Inlet Temp. to O/B Blanket I	764°C
Flow Rate per module in O/B Blkt I	76 kg/s
Ave. Vel. in FW and Inner Channel	4.2, 0.11 m/s
First Wall Channel Re	3.9 x 10^5
First Wall Channel Transverse Ha	4340
MHD Turbulent Transition Re	2.2 x 10^6
First Wall MHD Pressure Drop	0.19 MPa
Max. SiC_f/SiC and CVD SiC Temp.	996, 1009°C
Max. Pb-17Li/SiC Interface Temp.	994 °C

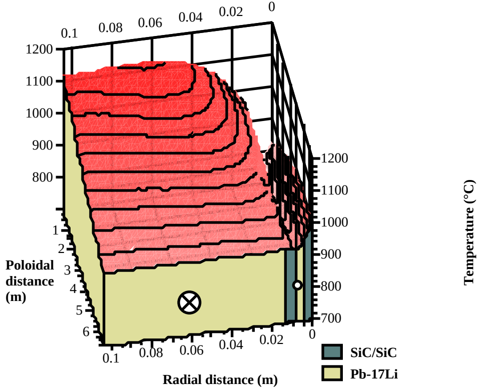

Fig. 3 Temperature Distribution in Blanket Module of First Outboard Region

the divertor. The design can be re-optimized if such radiation becomes appreciable under future physics scenarios.

Thermal-Hydraulic Analysis: Even though the SiC_f/SiC provides insulated walls thereby minimizing MHD effects, the analysis conservatively assumes MHD-laminarized flow of the Pb-17Li in the blanket and heat transfer by conduction only. The temperature profile through the blanket was estimated by a moving coordinate analysis which follows the Pb-17Li flow through the first-pass annular wall channel and then through the second-pass large inner channel. The annular wall rib spacing is used as MHD flow control to achieve a higher flow rate through the first wall (with larger toroidal spacing) than through the side and back walls. For example, having three channels in the module first wall and thirteen in the back wall allows for a high velocity of 4.2 m/s in the first wall channels and a lower velocity of 0.66 m/s in the back wall channel for the same MHD pressure drop. The second poloidal pass of the Pb-17Li through the large inner channel is much slower with an average velocity of 0.11 m/s. Figure 3 illustrates the results for a typical outboard module. Even though the average outlet Pb-17Li temperature is 1100°C, this design results in a maximum SiC temperature at the first wall (radial distance=0) of 1009°C, a maximum SiC_f/SiC temperature of 996°C, and a maximum blanket SiC/Pb-17Li interface temperature at the inner channel wall of 994°C, which satisfy the maximum temperature limits shown in Table 2. The corresponding blanket pressure drop is about 0.25 MPa.

Stress Analysis: Stress analyses were performed both on the module outer and inner shells. A 1-MPa inlet pressure is assumed for the coolant which adequately accounts for both the pressure drop through the blanket (~0.25 MPa) and the hydrostatic pressure due to the ~6 m Pb-17Li (~0.5 MPa) column. The outer wall is designed to withstand this pressure while the inner wall is designed to withstand the difference between blanket inlet and outlet pressures (0.25 MPa). There are six modules per outboard segment as shown in Figure 2. These modules are brazed to one another and the side walls of all the inner modules are pressure balanced. However, the side walls of the outer modules must be reinforced to accommodate the 1 MPa coolant pressure. For example, Figure 4 shows that the maximum side wall pressure stress is 85 MPa for a 2-cm thick side wall. The side wall can be tapered radially by tailoring the thickness to maintain a uniform stress. This would reduce the SiC volume fraction and benefit tritium breeding. In addition, the thermal stress at this location is small and the sum of the pressure and thermal stresses is well within the 190 MPa limit. This margin can be considered as a measure of reliability and provides some flexibility if the final blanket design optimization shows that further reductions of the SiC volume fraction are needed for better tritium breeding. From Figure 4, the pressure stress at the first wall is quite low, ~60 MPa. The corresponding thermal stress, as obtained from a 3-D thermal stress analysis, is 114 MPa resulting in a combined stress of 174 MPa still well within the 190 MPa limit

A stress analysis of the inner wall was also performed. For a 8-mm lateral inner wall under a 0.25 MPa differential Pb-17Li pressure, the maximum stress is 116 MPa, again well within the maximum allowable stress. In addition, the maximum pressure differential of ~0.25 MPa occurs at the lower poloidal location. The inner wall thickness could be tapered down to ~5 mm at the upper poloidal location if needed to minimize the SiC volume fraction.

IV. DIVERTOR DESIGN AND ANALYSIS

Consistent with physics calculations for ARIES-RS[9], the maximum design heat load on the divertor is moderate (5 MW/m^2) and allows the use of Pb-17Li as coolant, thus providing the advantage of minimizing the number of coolants, simplifying the cooling system design and maintaining relatively low pressure in the in-reactor components. In case future R&D does not confirm the heat transfer performance of the proposed concept, back-up options exist, including the He-cooled W porous media concept used and analyzed for the ARIES-ST design[10], evaporative cooling with Li and plasma-facing LiSn liquid jets.

Pb-17Li has a relatively low thermal conductivity and tends to offer limited heat removal performance in particular in the presence of a magnetic

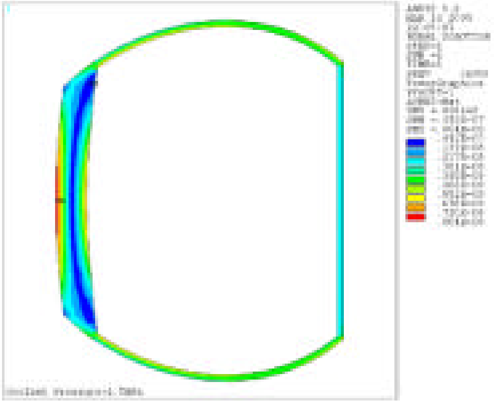

Fig. 4 Stress Analysis of Blanket Module Outer Wall

field. In order to accommodate MHD effects, the proposed design:

- Minimizes the interaction parameter (<1) which represents the ratio of MHD to inertial forces;
- Directs the flow in the high heat flux region parallel to the toroidal magnetic field; and
- Minimizes the Pb-17Li flow path and residence time in the high heat flux region

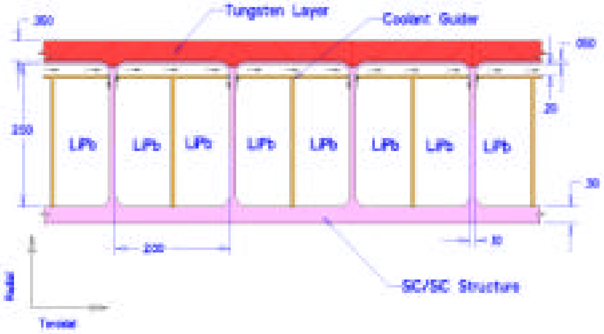

Figure 5 Cross-section of outer divertor plate
(all dimensions in cm)

The design is illustrated in Figure 5 and the key parameters summarized in Table 4. As shown in Fig. 5, the divertor plate consists of a number of 2-cm x 2.5-cm SiC_f/SiC poloidal channels. The front SiC_f/SiC wall is very thin (0.5 mm) in order to maintain the maximum temperature and combined stress limits to <1000°C, and <190 MPa, respectively. A 3.5-mm plasma facing layer of W is bonded to the thin SiC_f/SiC to provide additional structure to accommodate the 1.8-MPa Pb-17Li pressure and to provide sacrificial armor (≈1mm). In each channel a T-shaped flow separator is inserted. The Pb-17Li flows poloidally through one half of the channel which acts as an inlet header. The flow is then forced to the PFC region through small holes at one side of the channel. The flow through these small holes is inertial with an interaction parameter <1. The Pb-17Li then flows toroidally to cool the high heat flux region through a very short flow path (2 cm). It is then routed back to the other side of the poloidal channel serving as outlet header. The Pb-17Li velocity through the toroidal PFC channel can be adjusted by changing the channel dimension or by increasing the number of toroidal passes through a plate. The reference design uses a 2-mm channel and 2-pass flow resulting in a 0.35 m/s toroidal channel velocity and a 0.06 s residence time.

The 2-D moving coordinate method was used for the flow analysis under the conservative assumption of MHD-laminarized flow in the toroidal channel. Figure 6 shows the typical results for a mid-life case with an inlet Pb-17Li temperature of 653°C, a W thickness of 3 mm, a SiC_f/SiC first wall thickness of 0.5 mm, a Pb-17Li channel thickness of 2 mm, a SiC_f/SiC inner wall thickness of 0.5 mm, a Pb-17Li velocity of 0.35 m/s and a surface heat flux of 5 MW/m^2. The maximum W temperature is ≈1150°C, and the maximum SiC_f/SiC temperature is ≈950°C.

Table 4 Summary of Typical Divertor Plate Parameters

Poloidal Dimension (Outer/Inner)	1.5/1.0 m
Divertor Channel Toroidal Pitch	2.1 cm
Divertor Channel Radial Dimension	3.2 cm
No. of Div. Channels (Outer/Inner)	1316/1167
SiC_f/SiC Plasma-Side Thickness	0.5 mm
Tungsten Thickness.	3-3.5 mm
PFC Channel Thickness	2 mm
No. of Toroidal Passes	2
Outer Div. Channel V (Lower/Upper)	0.35/0.42 m/s
Pb-17Li Inlet Temp. (Outer/Inner)	653/719 °C
Pressure Drop (Lower/Upper)	0.55/0.7 MPa
Max. SiC_f/SiC Temp. (Lower/Upper)	950/930 °C
Max. Tungsten Temp.(Lower/Upper)	1180/1150 °C
W Pressure +Thermal Stress	~35+50 MPa
SiC_f/SiC Pressure +Thermal Stress	~35+160 MPa
Toroidal Dimen. Of Inlet/Outlet Slots	1 mm
Vel. in Inlet/Outlet Slots	0.9-1.8 m/s
Interact.Parameter in Inlet/Outlet Slots	0.46-0.73

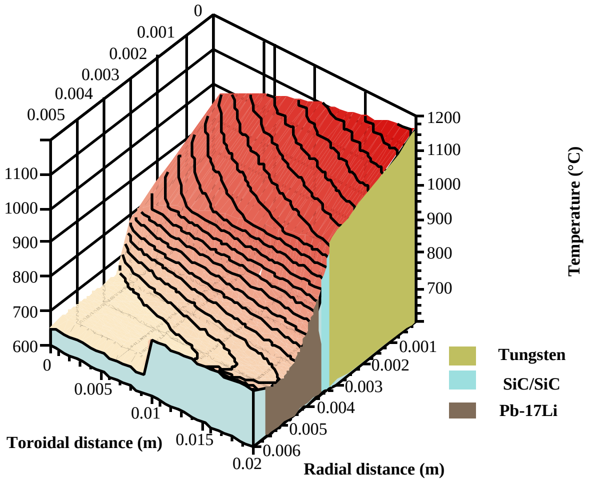

Fig. 6 Temperature distribution in outer divertor PFC channel assuming MHD-laminarized Pb-17Li flow

The resulting Pb-17Li pressure drop through the divertor based on the proposed flow configuration is estimated at about 0.7 MPa. This is significantly larger than the blanket pressure drop. To minimize pressure stresses in the piping and blanket system, the Pb-17Li in the inlet manifold is kept at 1.1 MPa. The Pb-17Li is then pressurized to 1.8 MPa just before flowing though the divertor by means of an E-M pump making use of the existing toroidal magnetic field. The outlet flow from the divertor then rejoins the blanket inlet manifold at about 1.1 MPa.

Based on the results from the detailed 3-D stress analysis performed for the ARIES-ST divertor[10], the current divertor plate design provides for free movement at one poloidal end to accommodate poloidal expansion and minimize the stress in the high heat flux region. Detailed stress analysis of the divertor indicates that the combined primary+secondary stress are within the 190 MPa limit for SiC_f/SiC. The major divertor design parameters are summarized in Table 4.

V. FABRICATION AND MAINTENANCE

As a reliability measure, minimization of the number and length of brazes was a major factor in evolving fabrication procedures. The proposed fabrication scheme of the blanket only requires three radial/toroidal coolant-containment brazes per module, as illustrated by the following fabrication steps for a 6-module outboard segment: 1) Manufacturing separate halves of the SiC_f/SiC poloidal module by SiC_f weaving and SiC Chemical Vapor Infiltration (CVI) or polymer process; 2) Sliding the outer half modules over the inner separation wall; 3) Brazing the two half modules together at the midplane; 4) Brazing the module end cap; 5) Forming a segment by brazing six modules together (this is a joint which is not in contact with the coolant); and 6) Brazing the annular manifold connections to one end of the segment.

The divertor fabrication scheme can be summarized as follows:1) Manufacture separate SiC_f/SiC toroidal halves of the divertor plate by SiC_f weaving and SiC CVI or polymer process; maintain constant channel toroidal dimensions but tapered side wall thicknesses to account for torus geometry; 2) Insert the inner SiC_f/SiC separation wall in each channel; 3) Braze the two toroidal halves of the divertor plate together; 4) Braze the end cap and manifold on each end; and 5) Bond the W layer to the SiC_f/SiC front wall by plasma spray.

Maintenance methods have been investigated which allow for end-of-life replacement of individual components[11].

VI. CONCLUSIONS

The ARIES-AT in-reactor components utilize high temperature Pb-17Li as breeder and coolant and low-activation SiC_f/SiC composite as structural material. High power cycle efficiency (~58.5%) is achieved while the in-reactor material limits are accommodated by the design. The blanket and divertor designs are based on a simple geometry with a credible fabrication procedure which minimizes the coolant containing joints and enhances reliability. Comfortable stress limit margins are maintained as an additional reliability measure. Key issues requiring R&D attention are mostly linked with the SiC_f/SiC material, and the MHD effects in particular for the divertor.

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