High performance blanket for ARIES-AT power plant

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Abstract

The ARIES-AT blanket has been developed with the overall objective of achieving high performance while maintaining attractive safety features, simple design geometry, credible maintenance and fabrication processes, and reasonable design margins as an indication of reliability. The design is based on Pb–17Li as breeder and coolant and SiCf/SiC composite as structural material. This paper summarizes the results of the design study of this blanket. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The ARIES-AT power plant was evolved to assess and highlight the benefit of advanced technologies and of new physics understanding and modeling capabilities on the performance of advanced tokamak power plants [1]. Fig. 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].

The blanket design utilizes Pb–17Li as breeder and coolant, and SiCf/SiC composite as structural material. SiCf/SiC is attractive based on its high temperature compatibility and its low decay heat. However, there are some key issues influencing its attractiveness, including: thermal conductivity; parameters limiting the temperature of operation, such as swelling under irradiation and compatibility with the liquid metal; 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 SiCf/SiC Design and Material Issues for Fusion Systems and in a related publication [3,4]. The SiCf/SiC parameters and properties used in the ARIES–AT analysis are consistent with the suggestion from this meeting and are summarized in Table 2.
Table 2

<table>
<thead>
<tr>
<th>SiCf/SiC properties and parameters assumed in this study [3,4]</th>
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<tbody>
<tr>
<td>Density (kg/m³) 3200</td>
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<td>Density factor 0.95</td>
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<tr>
<td>Young’s modulus (GPa) 200–300</td>
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<td>Poisson’s ratio 0.16–0.18</td>
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<td>Thermal expansion coefficient (ppm/°C) 4</td>
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<td>Thermal conductivity through thickness (W/m K) 20</td>
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<td>Maximum allowable combined stress (MPa) 190</td>
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<tr>
<td>Maximum allowable operating temperature (°C) 1000</td>
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<tr>
<td>Maximum allowable SiC/LiPb interface temperature (°C) 1000</td>
</tr>
<tr>
<td>Maximum allowable SiC burnup (%) 3</td>
</tr>
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</table>

The energy from the high temperature Pb–17Li exiting the blanket is transferred to the cycle He through a heat exchanger. The Brayton cycle considered is described in Refs. [5,6]. Its main parameters include: a lowest He cycle temperature of 35 °C; a turbine efficiency of 93%; a compressor efficiency of 90%; a recuperator effectiveness of 96%; and a He fractional pressure drop of 0.025 in the out-of-vessel cycle. The maximum He cycle temperature is 1050 °C, resulting in a high cycle efficiency of about 58.5%.

2. Configuration

For waste minimization and cost saving reasons, the blanket is subdivided radially into two zones, as shown in Fig. 1: a replaceable first zone in the inboard and outboard (see Ref. [7] for a discussion of maintenance method), 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 as well as the divertor and hot shield regions.

As illustrated in Fig. 2, the blanket design is modular, each module consisting of a simple annular box 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-ve-
locity 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/SiC composite and SiC/Pb–17Li interface at a lower temperature (~1000 °C). The first wall consists of a 4-mm SiC/SiC structural wall on which a 1-mm CVD SiC armor layer is deposited.

As a reliability measure, minimization of the number and length of brazes was a major factor in evolving the fabrication procedure for the blanket which only requires three radial/toroidal coolant-containment brazes per module [3].

3. Analysis

Detailed 3D 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 thermal investigations. 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 bremsstrahlung radiation, line radiation and synchotron radiation with average and peak values of 0.26 and 0.34 MW/m², respectively [2].

3.1. Thermal-hydraulic analysis

Even though the SiC/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. Fig. 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/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.

3.2. Stress analysis

Stress analyses were performed for both the module outer and inner walls. 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. There are six modules per outboard segment as shown in Fig. 3. 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. A tapered configuration (with a maximum thickness of ~ 2 cm) is preferred to reduce the SiC volume fraction and benefit tritium breeding, while maintaining a reasonable maximum pressure stress, σp, of 85 MPa. At the first wall, σp is 60 MPa. The inner shell is designed to withstand the difference between blanket inlet and outlet Pb–17Li pressures (~ 0.25 MPa) and the corresponding σp is 116 MPa for a 8-mm thick lateral inner wall. For all these cases, the combined pressure + thermal stresses are well within the 190 MPa limit, the first wall design even providing for the accommodation of plasma heat fluxes at least twice as high as the design values. These comfortable margins can be considered as a measure of reliability.

3.3. Safety analysis

The activation, decay heat, and waste disposal analyses performed in support of the ARIES-AT design are described in Ref. [9]. The decay heat results were used to perform 2D safety analyses of the power core which showed that the low decay heat of SiC enables accommodation of any loss-of-coolant or loss-of-flow scenarios without serious consequences to the blanket structure [10].

4. Conclusions

The ARIES-AT blanket utilizes high temperature Pb–17Li as breeder and coolant and low-activation SiC/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 design is based on a simple annular box design 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 SiCf/SiC material. They include development of low-cost high-quality material and joining methods and characterization of key SiCf/SiC properties and parameters at high temperature and under irradiation, in particular thermal conductivity, temperature limits (based on both strength degradation and compatibility with Pb–17Li), and lifetime.

Acknowledgements

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