HIGH PERFORMANCE BLANKET FOR ARIES-AT POWER PLANT

PRE-PRINT

A. R. Raffray[1], L. El-Guebaly[2], S. Gordeev[3], S. Malang[3], E. Mogahed[2], F. Najmabadi[1], I. Sviatoslavsky[2], D. K. Sze[4], M. S. Tillack[1], X. Wang[1], and the ARIES Team

[1]University of California, San Diego, 460 EBU-II, La Jolla, CA 92093-0417, USA
[2]University of Wisconsin, Fusion Technology Institute, 1500 Engineering Drive, Madison, WI 53706-1687, USA
[3]Forschungszentrum Karlsruhe, Postfach 3640, D-76021 Karlsruhe, Germany
[4]Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439, USA

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 SiC_f/SiC composite as structural material. This paper describes the results of the design study of this blanket including a discussion of the major SiC_f/SiC composite parameters and properties influencing the design, and a description of the design configuration, analysis results and reference operating parameters.

1. 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]. The design builds on over a decade of experience and effort by the ARIES team in advanced power plant design [e.g. 2,3] and reflects the overall benefit from high-β operation, high temperature superconducting magnet, high power cycle efficiency, and low-cost advanced manufacturing techniques. 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 [4].

The blanket design utilizes 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.

2. Power Cycle

The Brayton cycle offers the best near-term possibility of power conversion with high efficiency and is chosen to maximize the potential gain from high temperature operation of the Pb-17Li which after exiting the blanket is routed through a heat exchanger with the cycle He as secondary fluid. The Brayton cycle considered is described in Refs.[5,6]. It includes three-stage compression with two intercoolers and a high efficiency recuperator. Its main parameters are set under the assumption of state of the art components and/or with modest and reasonable extrapolation and are as follows:

- Lowest He temperature in the cycle (heat sink) = 35 °C
- Turbine efficiency = 93%; Compressor efficiency = 90%

- Recuperator effectiveness = 96%
- He fractional pressure drop in out-of-vessel cycle = 0.025 (this would probably require a He pressure of about 15-20 MPa)

The maximum He cycle temperature is 1050°C, resulting in a high cycle efficiency of about 58.5%.

3. Material Consideration

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 (LOCA) and loss-of-flow (LOFA) events. 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 SiC_f/SiC Design and Material Issues for Fusion Systems and in a related publication [7,8]. 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.

4. Configuration

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 as well as the divertor and hot shield regions. The coolant is fed through an annular ring header surrounding the power core from which it is routed to each of 16 reactor sectors through the following five sub-circuits: (1) series flow through the lower divertor and inboard blanket region; (2) series flow through the upper divertor and one segment of the first outer blanket region; (3) flow through the second segment of the first outer blanket region; (4) series flow through the inboard hot shield region and first segment of the second outer blanket region ; and (5) series flow through the outboard hot shield region and second segment of the second outer blanket region.

As illustrated in Figures 2 and 3, the blanket design is modular and consists 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-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.

5. Analysis

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 [9]. 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 bremstrahlung radiation, line radiation and synchotron radiation with average and peak values of 0.26 MW/m^2 and 0.34 MW/m^2, respectively [4]. Radiation to the first wall from the 256 MW transport power to the divertor has not been fully evaluated yet and was not included. As results from the final divertor edge physics calculations become available, the thermal analyses will be updated accordingly for final blanket design optimization.

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 4 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 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. For example, Figure 5 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 5, 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.

Safety Analysis**:** The activation, decay heat, and waste disposal analyses performed in support of the ARIES-AT design are described in Ref. [10]. The decay heat results were used to perform 2-D safety analyses of the power core which showed that the low decay heat of SiC enables accommodation of any LOCA or LOFA scenarios without serious consequences to the blanket structure [11].

6. Manifold

Annular Pb-17Li coolant manifolds are used to feed the blanket, 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.

7. Fabrication and Maintenance

As a reliability measure, minimization of the number and length of brazes was a major factor in evolving the fabrication procedure for the blanket. The proposed fabrication scheme requires three radial/toroidal coolant-containment brazes per module, as illustrated by the following fabrication steps for an outboard segment consisting of 6 modules:

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. Inserting the free-floating inner separation wall in each half module;
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.

Maintenance methods have been investigated which allow for end-of-life replacement of individual components. These are discussed in detail in Ref [12].

8. Conclusions

The ARIES-AT blanket utilizes 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 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 SiC_f/SiC material. They include development of low-cost high-quality material and joining methods and characterization of key SiC_f/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.

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Tables

Table 1 Typical ARIES-AT Machine and Power Parameters

Machine Geometry	
Major Radius	5.2 m
Minor Radius	1.3 m
On-Axis Magnetic Field	5.9 T
Power Parameters	
Fusion Power	1719 MW
Neutron Power	1375 MW
Alpha Power	344 MW
Blanket Multiplication Factor	1.1
Maximum Thermal Power	1897 MW
Average Neutron Wall Load	3.2 MW/m^2
Outboard Maximum Wall Load	4.8 MW/m^2
Inboard Maximum Wall Load	3.1 MW/m^2

Table 2 SiC_f/SiC properties and parameters assumed in this study [7]

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 Conductivity through Thickness	~20 W/m-K
Maximum Allowable Combined Stress	~190 MPa
Max. Allowable Operating Temperature	~1000 °C
Max. Allowable SiC/LiPb Interface Temp.	~1000°C
Maximum Allowable SiC Burnup	~3%

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 Pressure/Pressure Drop	1/0.25 MPa
Total Pb-17Li Mass Flow Rate	22,700 kg/s
Outboard Blanket Region I	
Number of Sectors/Segments	16/32
Number of Modules per Outboard Segment	6
Module Poloidal and Ave. Toroidal Dimensions	6.8, 0.19m
Average Module Toroidal Dimension	0.19 m
First Wall SiC_f/SiC and CVD SiC Thicknesses	4+1 mm
First Wall Annular Channel Thickness	4 mm
Pb-17Li Inlet Temp. to Outboard Blanket Region I	764°C
Mass Flow Rate per module in O/B Blkt Region I	76 kg/s
Average Pb-17Li Vel. in FW and Inner Channel	4.2, 0.11 m/s
First Wall Channel Re	3.9×10^5
First Wall Channel Transverse Ha	4340
MHD Turbulent Transition Re	2.2×10^6
First Wall MHD Pressure Drop	0.19 MPa
Maximum SiC_f/SiC and CVD SiC Temperatures	996, 1009°C
Maximum Pb-17Li/SiC Interface Temperature	994 °C

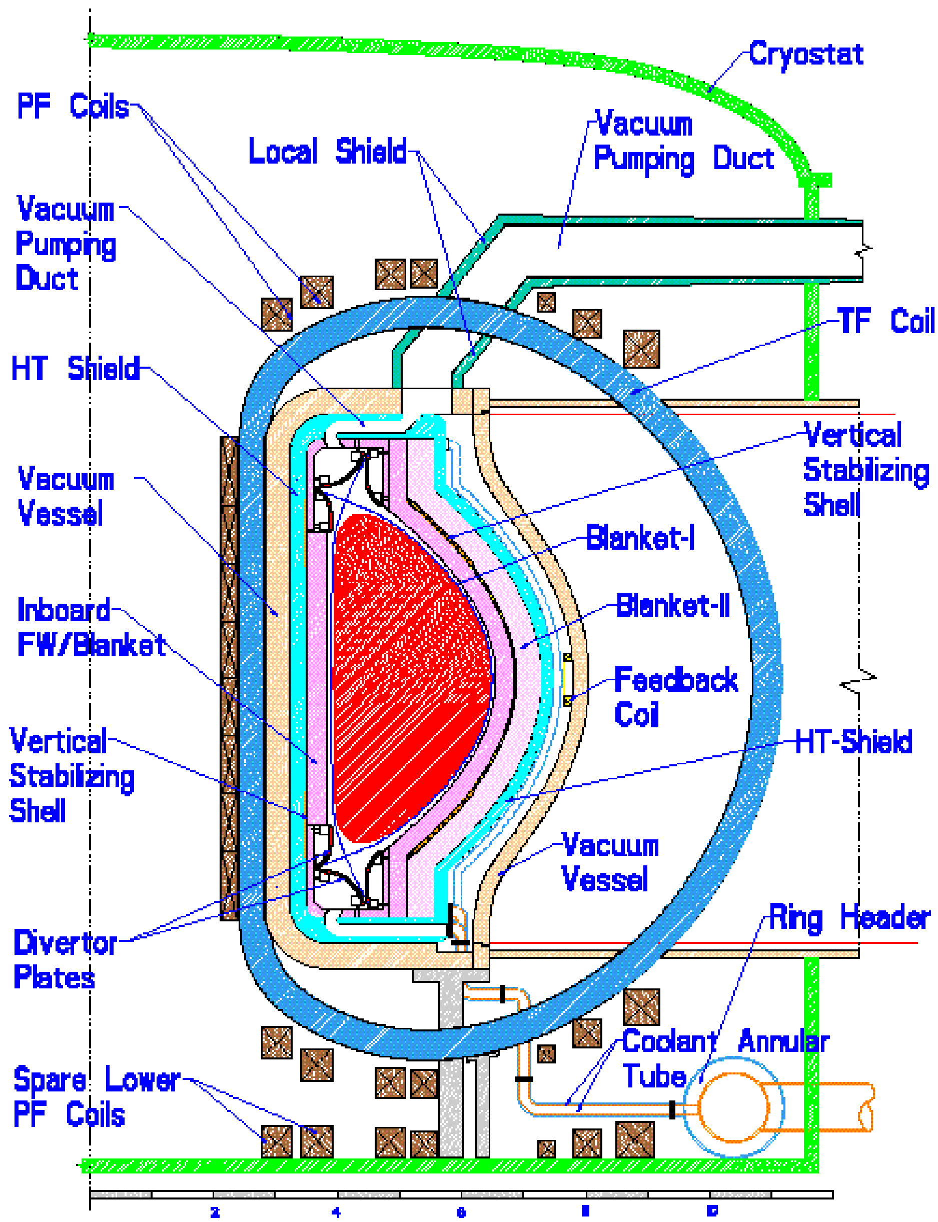

Figure 1. ARIES-AT Power Core (radial dimension in m)

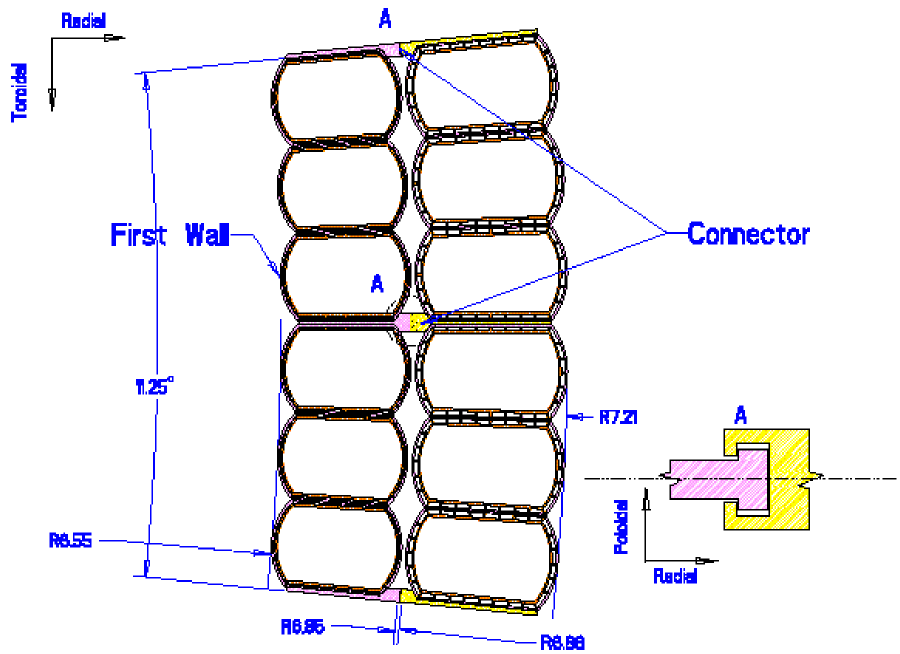

Figure 2. Cross-Section of ARIES-AT Outboard Blanket Segment (all dimensions in cm)

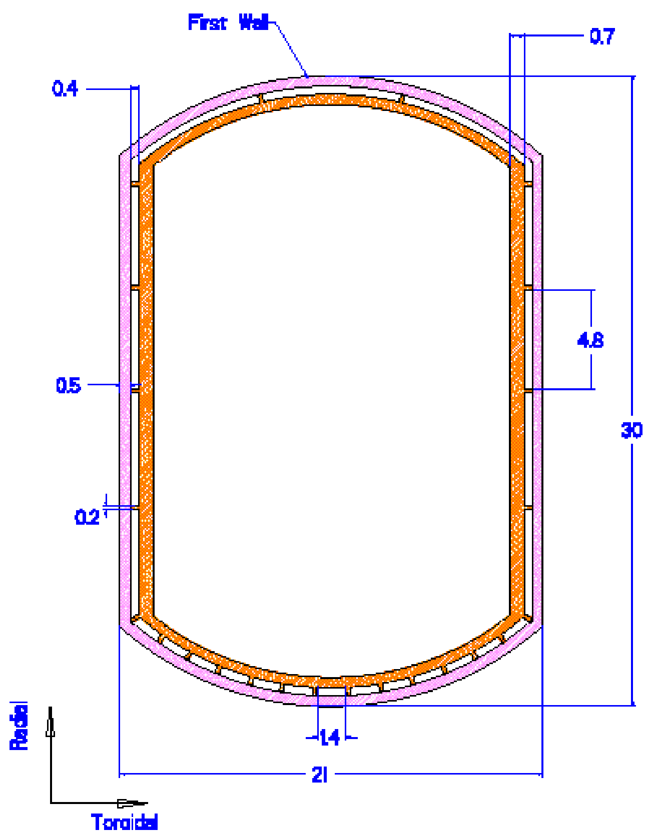

Figure 3. Cross-Section of ARIES-AT Blanket Module in First Outboard Region (radial dimension in m)

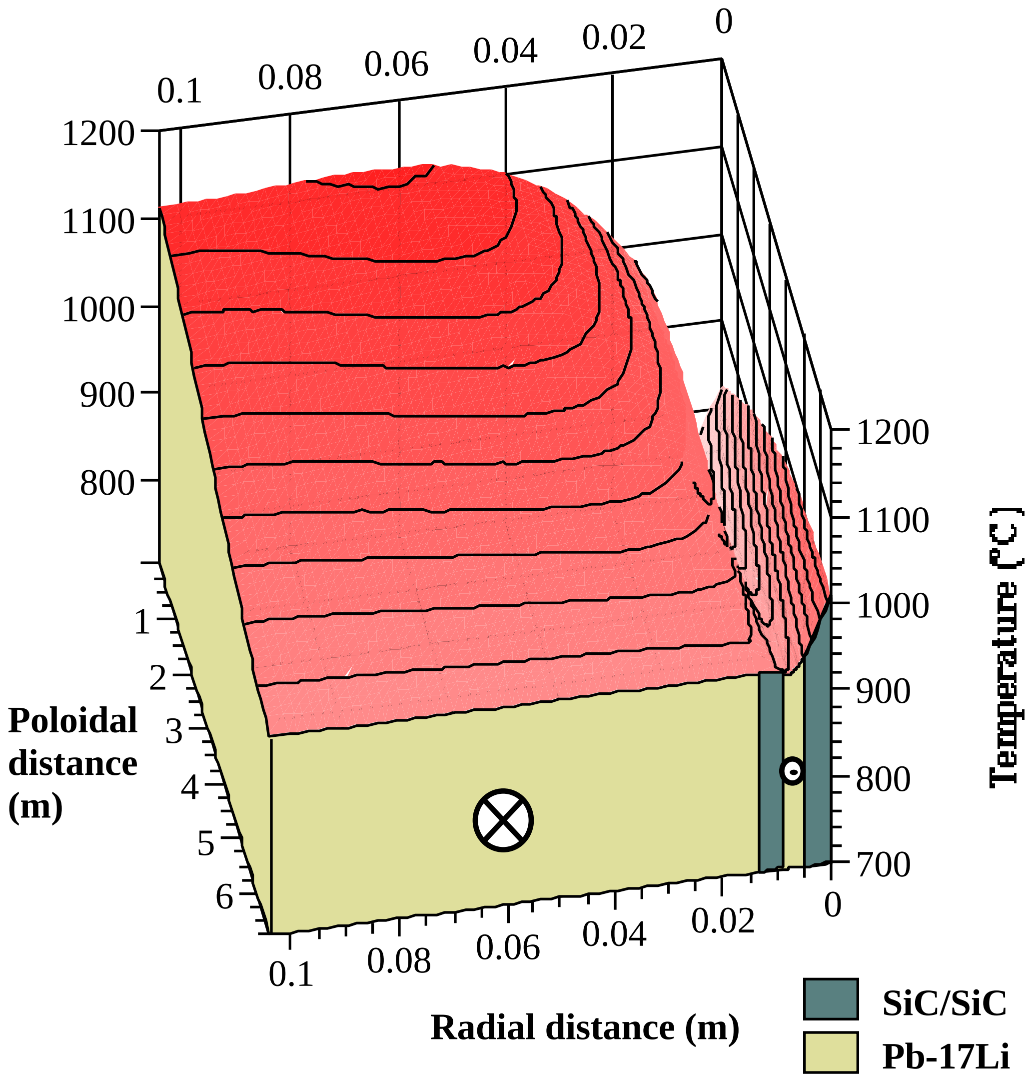

Figure 4. Temperature Distribution in Blanket Module of First Outboard Region

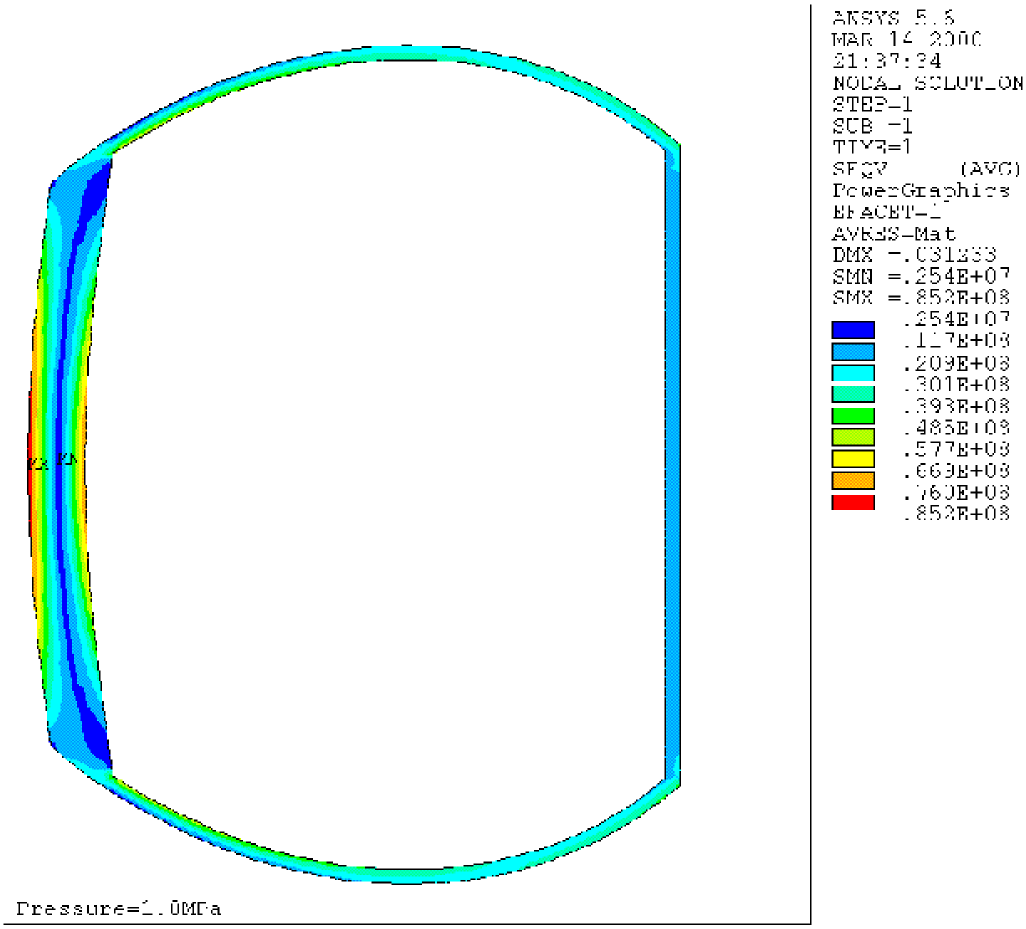

Figure 5. Stress Analysis of Blanket Module Outer Wall