DESIGN AND ANALYSIS OF ARIES-ACT SiC BLANKET

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ARIES-AT: SiC Composite Blankets

- Attractive design features:
  - The ARIES-AT blanket design utilizes LiPb as breeder and coolant, low-activation SiC/SiC composite as structural material.
  - High power core efficiency (~60%) is achieved by high LiPb outlet temperature (~1,100°C) while maintaining SiC structure temperature below 1,000°C.
  - Simple design and simple manufacturing technique.
  - Very low afterheat.
  - LiPb-cooled SiC composite divertor is capable of 5 MW/m² of heat load.
  - LiPb-cooled inboard and outboard shield.
**Objective:** Achieving high performance (~58% efficiency) while maintaining attractive design features, feasible fabrication, credible maintenance scheme and reasonable design margins on the temperature (1000°C) and stress limits (190 MPa) and TBR.

**Major changes and improvements:**
- Straight IB FW & blanket, and the OB-I and OB-II blanket with one curvature for easy fabrication
- Avoiding or reducing 3D MHD pressure drops in the coolant routings, turns, manifolds and access pipes (the manifolds design in underway)
- He-cooled divertors (plate-type, T-tube, finger divertor) are capable of removing heat flux in the range of 8 to 13 MW/m²
- He-cooled both inboard and outboard shield
Structural Design Options and Optimizations of the ARIES-ACT Blankets

- Each SCLL blanket modules must accommodate a hydrostatic pressure of \(~0.8\) MPa (\(~8\) m high) and MHD pressure drops through the blanket.
- Design iterations have been made to optimize the dimensions to provide the blanket design with reasonable margins on the stress limits and reduce the SiC volume fraction which will benefit tritium breeding.

A: reinforced inner ducts with toroidal ribs, ribs of the inner ducts are free-floating.

B: ribs of the inner ducts brazed to the outer ducts

C: ribs of the inner ducts not connected to the outer ducts (free-floating, ARIES-AT like)
Scope Structural Analyses

Stress limits for using in FEM analysis:
- Conventional stress limits ($3 S_m$) can not be directly applied to ceramics.
- A total combined stress of 190 MPa was recommended by the ARIES Town Meeting, and the stress limit was applied in the ARIES-AT study.
- Either the pressure stress or thermal stress should not exceed the limit of \( \approx 190 \text{ MPa} \).
- For our design, we try to maintain the primary stress < 100 MPa.

![Graph showing stress limits and pressure drop](image)

- **A**: Inner duct with a toroidal reinforced rib
- **B**: ribs of the inner tube brazed to the outer duct
- **C**: ribs of the inner tube not connected to the outer duct (free-floating, ARIES-AT like)
- Design option-B will be considered as the reference design

- Ribs of the inner duct are fully connected to the outer duct, and assumed the \( \Delta P_{\text{MHD}} = \approx 0.2 \text{ MPa} \).
- Minimum number of the modules per sector may be reduced to 8 for total pressure of 1 MPa.
- Less number of the blanket module means a larger size of the module (smaller SiC volumetric friction).
Mark made the calculations of the pressure drops including 3D MHD drops in the inlet/outlet manifold, and turns.*

The results indicate that the pressure and pressure drops of the ARIES-AT blanket were underestimated.

The bottom section of the IB will be simulated first, and the entire IB module will be simulated next.
Inboard Blanket Design

- The design of the inboard blanket must accommodate a coolant pressure up to 1.95 MPa at the inlet (annular) and a pressure of 1.65 MPa at the exit of the IB blanket (center).

- The pressure stress will be affected by the size of the module, FW&BW curvature, wall thickness, rib thickness and rib spacing.

- **The dimensions of the inboard blanket are defined based on design iterations:**

  - Total number of the blanket modules per sector=8 (12 modules for the ARIES-AT).
  - The fluid thickness in the FW, SW and BW annular=10 mm (4 mm for the ARIES-AT)*
  - The number of the sub-ducts=18
  - Wall thickness of the outer and inner ducts=5 mm
  - Rib thickness at the front and back wall=4 mm (2 mm for the ARIES-AT)
  - Rib thickness on the two side walls=2 mm
  - Diameter of the curvature for the FW and BW=35 cm
Primary Stress of the IB Blanket

Max local stress = ~88 MPa

Design limits: combined primary and secondary stresses should be less than ~190 MPa

- Maximum local stress is located at the 4 corners of ribs.
- The stress in most regions of the FW, BW and SWs is less than ~50 MPa.

(Deformed displacement is scaled by 35)
Total deformation = 0.4 mm
There are 8 modules per IB blanket sector (16 in total), and 6 inner modules and 2 side modules. These modules are brazed to one another and all the side walls of the inner modules are pressure balanced.

The outer walls of the outer modules must be reinforced to accommodate ~2.0 MPa pressure.

The parameters and dimensions of the outer module are defined based on the design iterations.

The local primary stress occurs at the corners of the inner duct (~103 MPa) for a 2 cm thick side wall, and the stress at the most region is < 60 MPa.
Configuration and Parameters for the OB Blanket-I

- The 3D MHD pressure drops of the OB blankets will be lower than IB blanket.
- However, the same pressure and pressure drops as the IB blanket are assumed:
  \[ P_{\text{inlet}} = 1.95 \text{ MPa}, \ P_{\text{outlet}} = 1.65 \text{ MPa} \ (\text{accounting for hydrostatic pressure and MHD pressure drop}) \]
- The OB blanket radial width is 30 cm (strawman ARIES-ACT 1b)
- Parameters and dimensions of the OB blanket are defined after design iterations:
  - Total number of the blanket modules per sector=12
  - Total number of the sub-ducts=18
  - The wall thickness of the outer/inner ducts=5 mm
  - The fluid thickness in the annular= 10 mm (4 mm for the ARIES-AT)
  - Rib thickness in the front and back=4 mm
  - Rib thickness on both sides=2 mm
  - Diameter of the curvature for the FW and back wall=30 cm

(New OB-I design for ~2 MPa)

(AT design for 1 MPa)
Primary Stress Results of the OB Blanket-I

- Maximum local stress is located at the corners of ribs and it is ~71 MPa.
- The stress in most regions of the FW, BW and SWs is less than ~55 MPa.

(Deformed displacement is scaled by 30)
Total deformation=0.7 mm
The same pressure and pressure drops are assumed for the OB-II:

\[ P_{\text{inlet}} = 1.95 \text{ MPa}, \ P_{\text{outlet}} = 1.65 \text{ MPa} \]
(accounting for hydrostatic pressure and MHD pressure drop).

The OB blanket radial width is 45 cm (strawman ARIES-ACT 1b)

Parameters and dimensions of the OB blanket are defined after design iterations:

- Total number of the blanket modules per sector = 12
- Total number of the sub-ducts = 24
- The wall thickness of the outer/inner ducts = 7 mm
- Rib thickness at 4 corners = 6 mm
- Rib thickness on both sides = 2 mm
- The fluid thickness at the annular = 10 mm
- Diameter of the curvature for the FW and back wall = 45 cm
Maximum local stress is located at the 4 corners of the inner duct, it is ~80 MPa.

The stress in most regions of the FW, BW and SWs is less than ~53 MPa.

Maximum total deformation is ~0.8 mm.
INBOARD BLANKET THERMAL ANALYSIS*  
— METHODOLOGY AND ASSUMPTIONS —

\[ u(x) \frac{\partial e(x,z)}{\partial z} = k \frac{\partial^2 T(x,z)}{\partial x^2} + Q(x) \]

\[ \frac{de}{dt} = k \frac{\partial^2 T}{\partial x^2} + Q - u \frac{\partial e}{\partial z} = 0 \]

- A FORTRAN program was written using finite difference method.
- This was needed because ANSYS can’t handle user-defined velocities.
- 2D poloidal/radial grid .
- 5.3-m module length, 35 cm depth, 5-mm SiC walls (k=20 W/m-K).
- 10-mm FW cooling channel with \( <v_{fw}> = 2.66 \) m/s.
- 10-mm SW cooling channel with \( <v_{fw}> = 0.266 \) m/s (to reduce \( \Delta T, \sigma_{th} \)).
- \( q'' \) profile from ARIES-AT \( (20e^{-5.74x}) \). \( q'' = 0.2 \) MW/m\(^2\) (uniform).

* "Power core performance parameter (SCLL),” presented by Mark at ARIES Group Meeting, 6 February 2010.
Temperature Profiles of the IB for Thermal Stress*

- Temperature limits are met (<1000 °C on all solid walls)
- Front-to-back module temperature differences are modest, ~100 °C at the bottom and ~130 °C at the top
- η~58% (~1% penalty due to stagnated FW coolant)
- The thermal stress of the bottom and top sections will be simulated first.

* “Power core performance parameter (SCLL)” presented by Mark at ARIES Group Meeting, 6 February 2012.
Initial Results of Thermal Stress for the Inboard Blanket

B.Cs:
1. Free expansion, and allowing for free bending
2. Free expansion, bending suppressed

On the bottom of IB blanket:
- Local $\sigma_{th} = 91$ MPa ($\sim 128$ MPa for B.C. 2)
- Most region $\sigma_{th} < \sim 60$ MPa ($\sim 70$ MPa for B.C. 2)

On the top of IB blanket:
- Local $\sigma_{th} = 118$ MPa ($\sim 158$ MPa for B.C. 2)
- Most region $\sigma_{th} < \sim 90$ MPa ($\sim 101$ MPa for B.C. 2)

- Need a full 3-dimensional primary and thermal stress analyses considering non-uniform heat flux and pressure profiles.
Possible Fabrication Procedure for the Inboard Blanket

1. Manufacturing separate SiC/SiC inner duct with ribs and outer duct;
2. Inserting the inner duct into the outer duct and brazing (or not brazing) the inner ribs to the outer duct;
3. Forming the blanket sector by brazing all 8 modules together;
4. Brazing the end cap at the top and bottom;
5. Brazing an access pipe.
Possible Fabrication Procedures for the OB Blanket

1. Manufacturing separate SiC/SiC inner duct with ribs and two half outer ducts (1-a and 1-b),
2. Sliding the two halves outer ducts into the inner duct, and brazing the two half outer ducts in the middle, and brazing the inner ribs to the outer duct;
3. Forming a sector by brazing the all 12 ducts together;
4. Brazing the top and bottom caps;
5. Mechanically Connecting the OB-I and OB-II together.
Blanket Maintenance: Sector Maintenance Scheme

Front view: (vertical cutting through half the sector)

Top view: (cutting through middle plane)

ARIES-AT blanket maintenance
The SCLL blankets have been designed and optimized with objective of achieving high performance (~58% efficiency) while maintaining attractive features, feasible fabrication process, credible maintenance scheme and reasonable design margin on the temperature, and stresses. The blanket design will be updated when the final radial build is available.

A full 3D primary and thermal stress analyses including an entire height of the blankets with non-uniform heat flux and pressure profiles may be needed when the final redial build is available in order to verify whether the design stress limit (~190 MPa) is satisfied.

Detail design of the manifolds and access pipes for the SCLL blankets are underway.
SiC/SiC Composite Joint Techniques (extra viewgraph)

- SiC/SiC composite joints using **brazing** technique*
- Brazing material, Si-16Ti (melting temperature ~1330 °C)
- Brazing material, Si-18Cr (melting temperature ~1305 °C)
- Strength at the brazing joints could be as strong as the base material

- Or using silicone resin to join them together at 1200 °C

*B. Riccardi et al, *J. of Nuclear Materials*