Status ARIES-AT Blanket and Divertor Design

The ARIES Team

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ARIES Project Meeting
University of California, San Diego
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UCSD

Presentation Outline

- **Blanket**
  - Geometry and coolant routing
  - Analysis
    - MHD flow considerations
    - Temperature and thermal stress
    - Pressure stress
- **Divertor**
  - Configuration with LiPb as coolant
  - Preliminary flow analysis
- **Future Work**

ARIES-AT Machine and Power Parameters Used for Analysis

Power and Neutronics Parameters

• Fusion Power	1737 MW
• Neutron Power	1390 MW
• Alpha Power	347 MW
• Current Drive Power	41 MW
• Transport Power to Divertor	289 MW
• Fraction of Divertor Power Radiated Back to FW	0.2
• Overall Energy Multiplication	1.1
• Total Thermal Power	1927 MW
• Average FW Surface Heat Flux	0.5 MW/m^2
• Max. FW Surface Heat Flux	0.7 MW/m^2
• Max. Divertor Surf. Heat Flux	5 MW/m^2
• Average Wall Load	4.3 MW/m^2
• Maximum O/B Wall Load	6.1 MW/m^2
• Maximum I/B Wall Load	4.0 MW/m^2

Machine Geometry

• Major Radius	4.8 m
• Minor Radius	1.2 m
• FW Location at O/B Midplane	6 m
• FW Location at Lower O/B	4.8
• I/B FW Location	3.6 m

Toroidal Magnetic Field

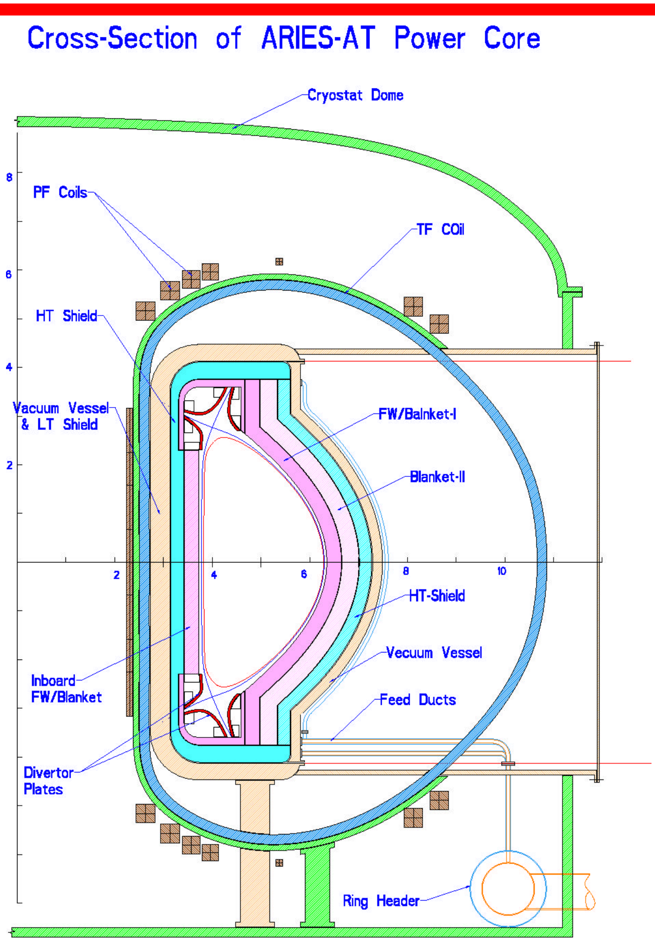
• On-axis Magnetic Field	7.5 T
• Magnetic Field at I/B FW	10 T
• Magnetic Field at O/B FW	6 T

SiC/SiC Properties Used for Design Analysis

(Consistent with SiC/SiC Town Meeting Suggestion)

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

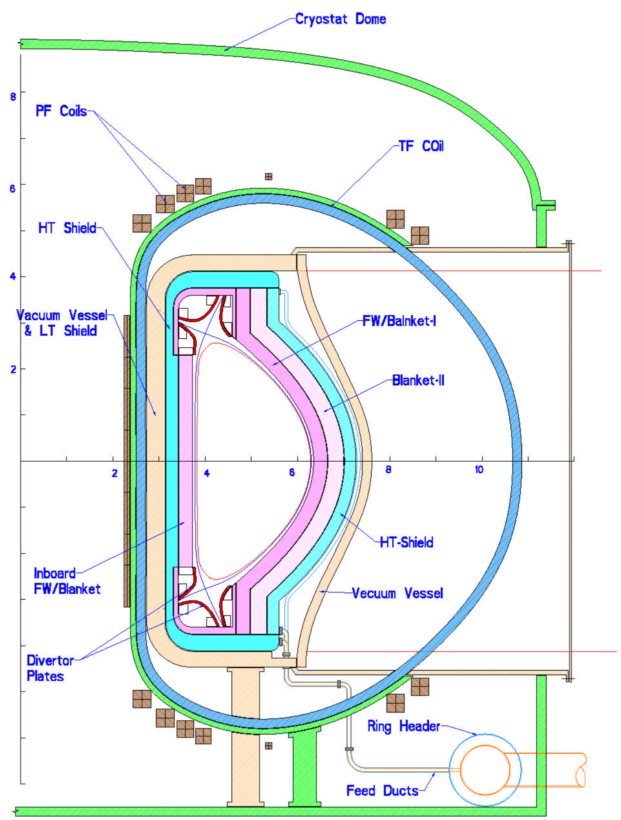
Cross-Section of ARIES-AT Showing Power Core Components and Coolant Routing
(Preliminary)



- **LiPb Coolant**
  - Inlet/Outlet Temperatures 653/1100 °C
  - Inlet Pressure *~2.5 MPa (Divertor-dependent)*
- **Circuit 1 - Lower Divertor + I/B Blkt Region**
  - Thermal Power 535 MW
  - Mass Flow Rate 6500 kg/s
- **Circuit 2 - Upper Divertor + 1st O/B Blkt Region**
  - Thermal Power 1040 MW
  - Mass Flow Rate 12,700 kg/s
- **Circuit 3 - Hot Shield + 2nd O/B Blkt Region**
  - Thermal Power 352 MW
  - Mass Flow Rate 4270 kg/s

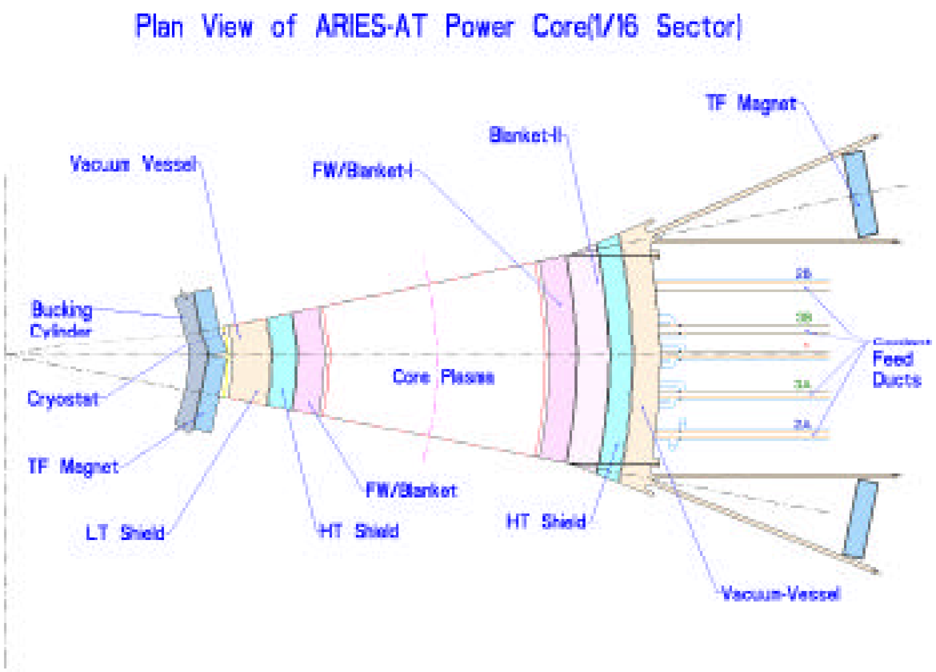
Cross-Section of ARIES-AT Showing Power Core Components and Alternate Coolant Routing

Cross-Section of ARIES-AT Power Core



Plan View of ARIES-AT Power Core

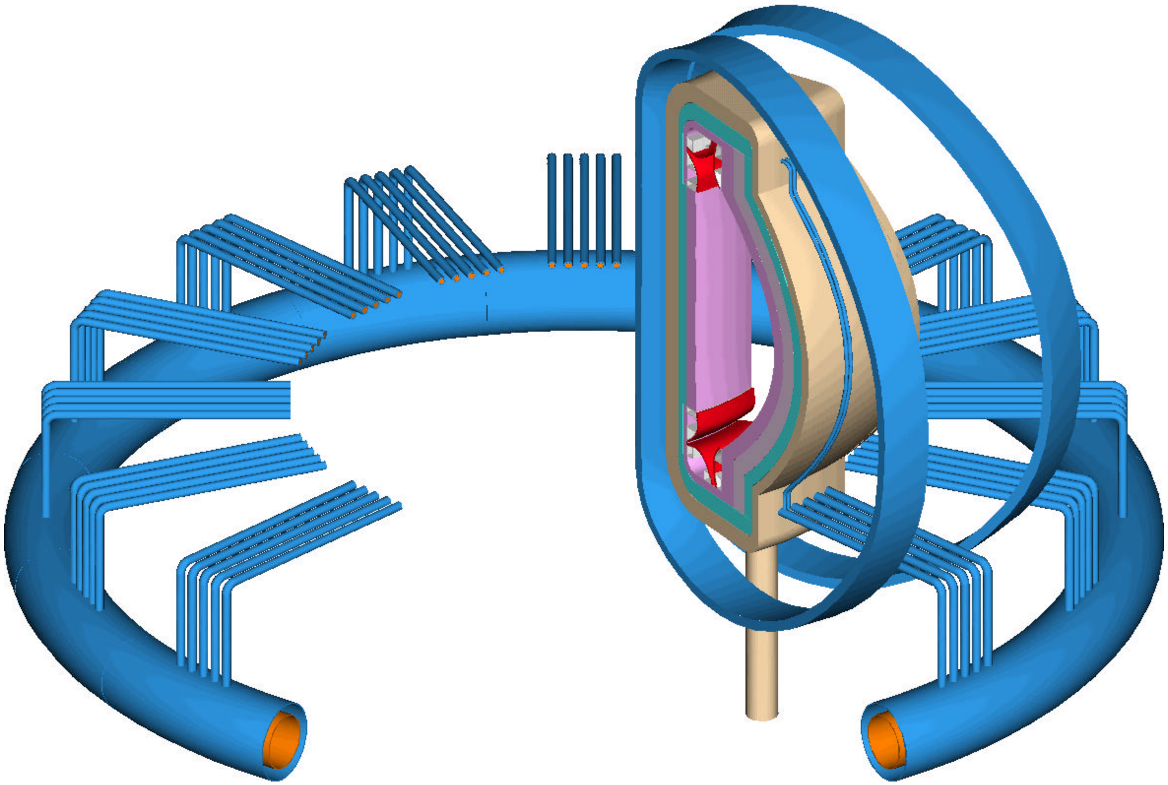
(Preliminary)



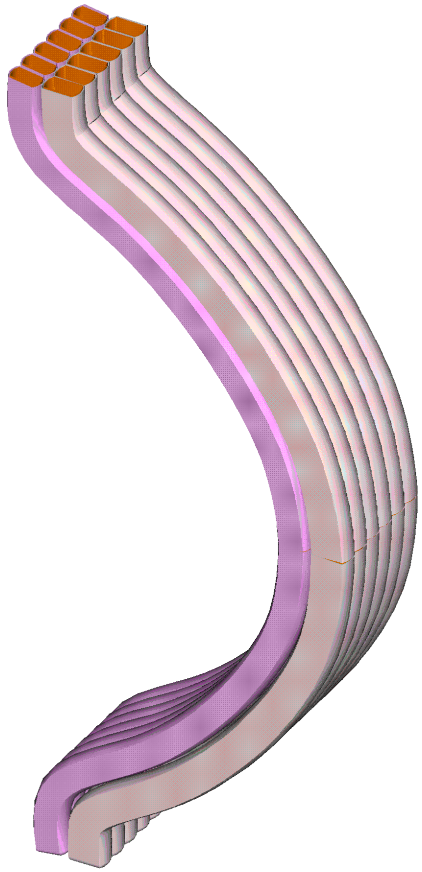
- **Circuit 1 - Lower Divertor + I/B Blkt Region**
  - Thermal Power 535 MW
  - Mass Flow Rate 6500 kg/s
- **Circuit 2A - Upper Divertor + 1st O/B Blkt Region**
  - Thermal Power 587 MW
  - Mass Flow Rate 7168 kg/s
- **Circuit 2B - 1st O/B Blkt Region**
  - Thermal Power 453 MW
  - Mass Flow Rate 5532 kg/s
- **Circuit 3A - I/B Hot Shield + 2nd O/B Blkt Region**
  - Thermal Power 188 MW
  - Mass Flow Rate 2282 kg/s
- **Circuit 3B - O/B Hot Shield + 2nd O/B Blkt Region**
  - Thermal Power 164 MW
  - Mass Flow Rate 1988 kg/s

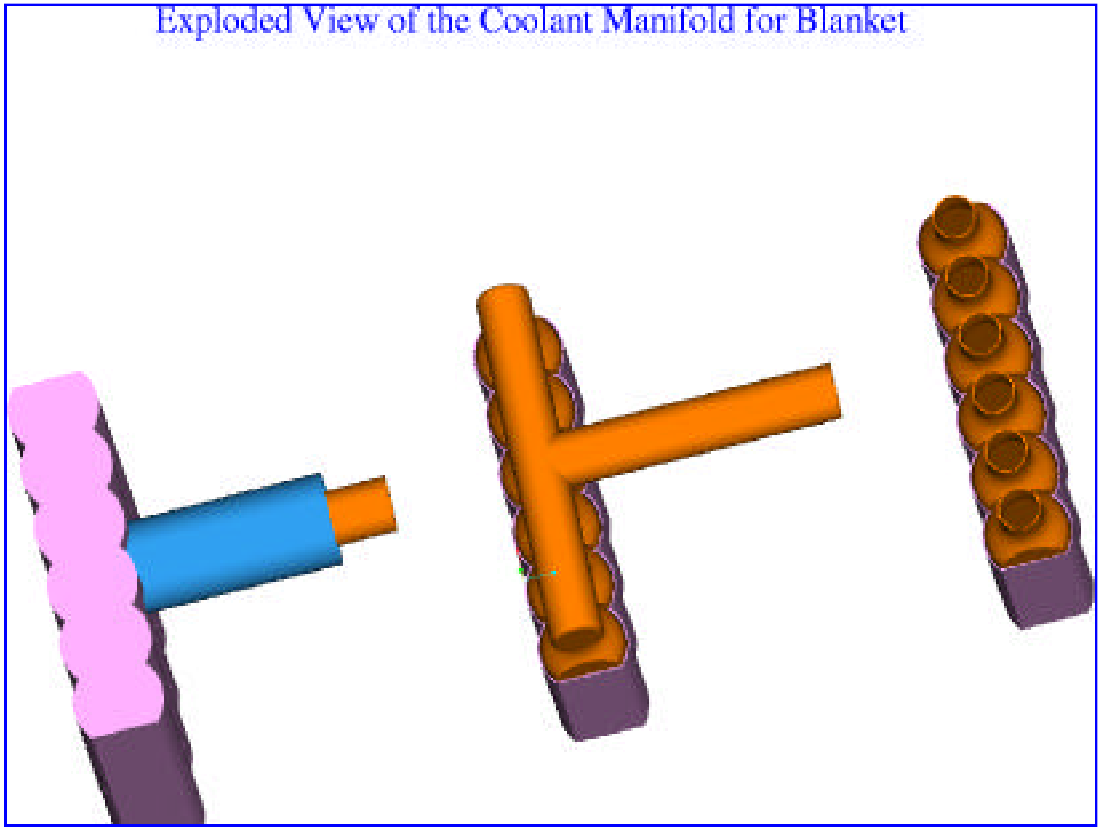
Example Coolant Manifold for ARIES-AT Power Core

Layout of Coolant Manifold for ARIES-AT Power Core

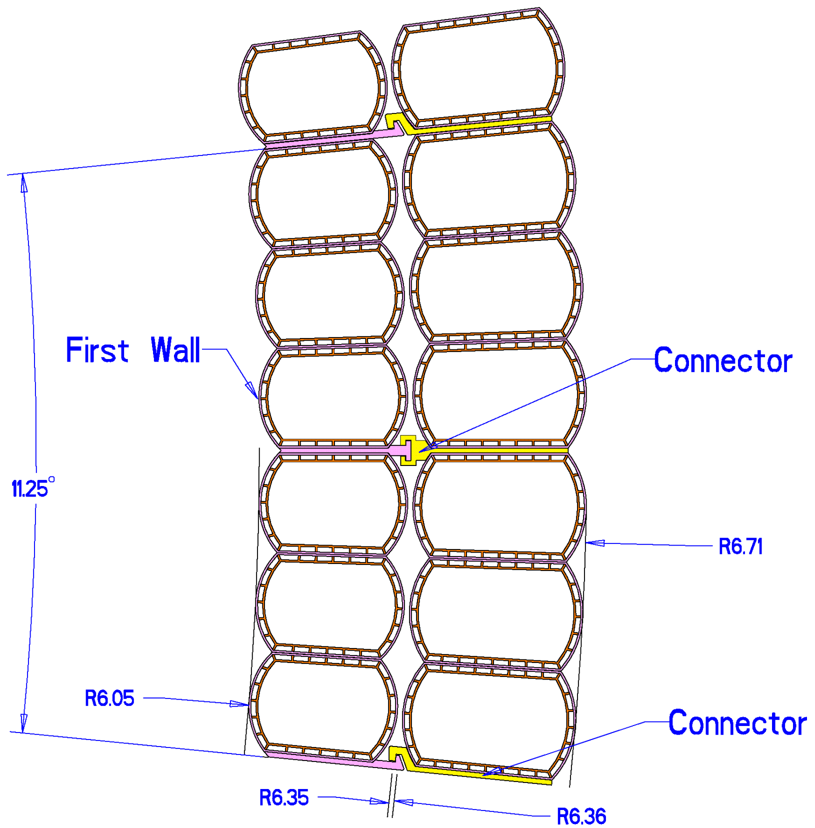


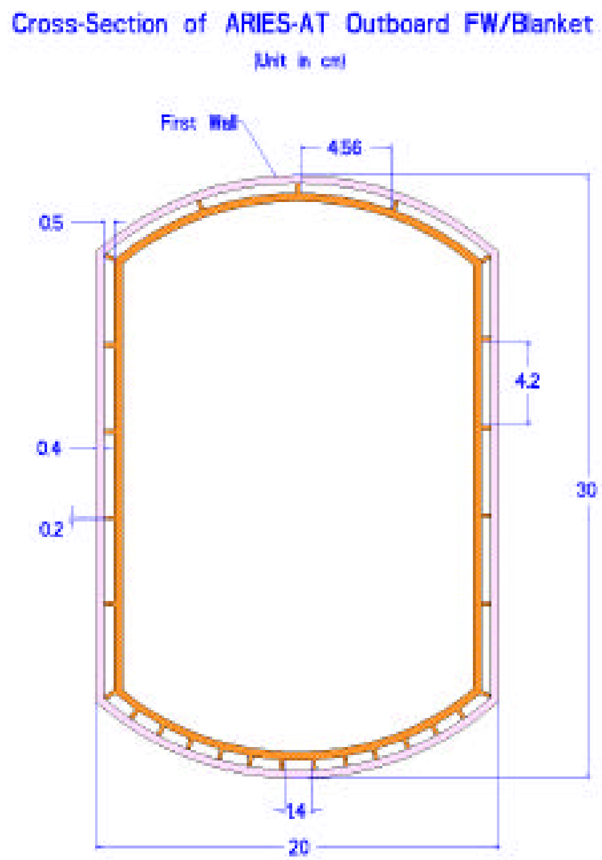
ARIES-AT Outboard Blanket Segment Configuration



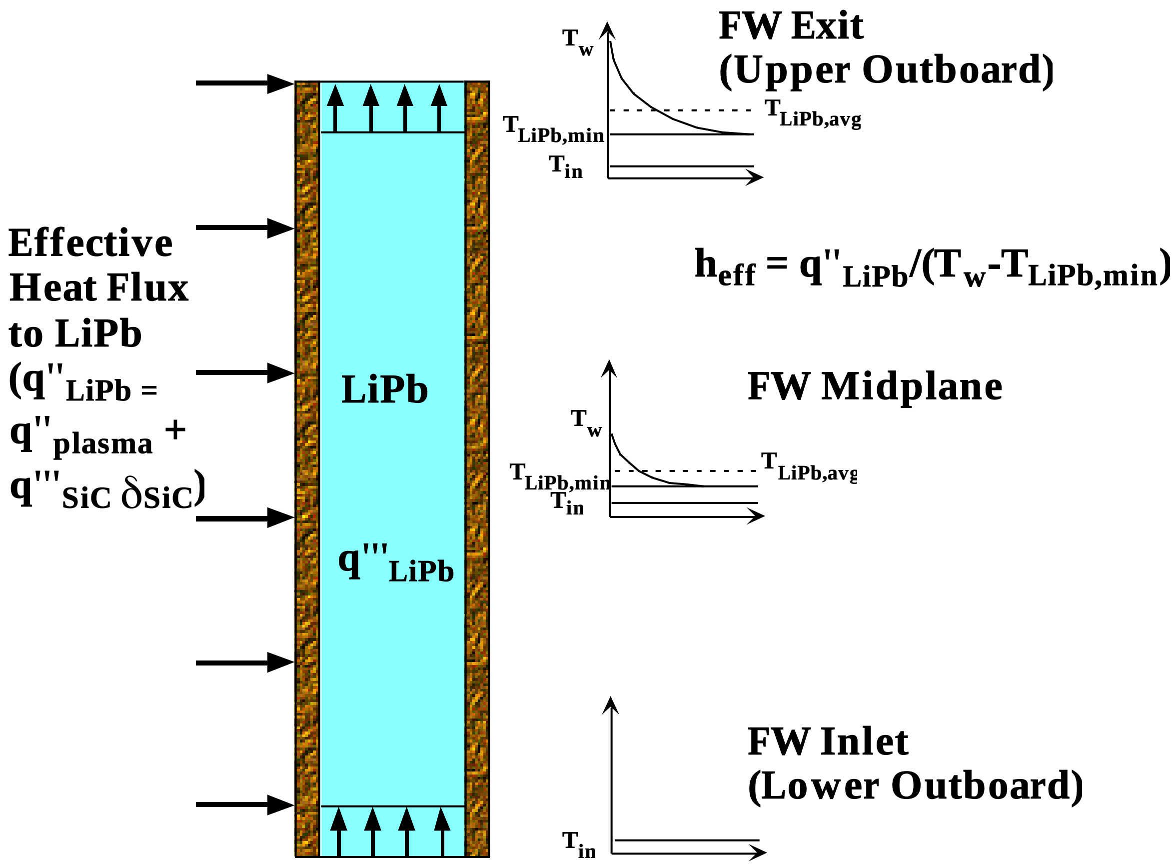


Cross-Section of ARIES-AT Outboard Blanket





LiPb Temperature Distribution in FW Poloidal Channel under MHD-Laminarization Effect



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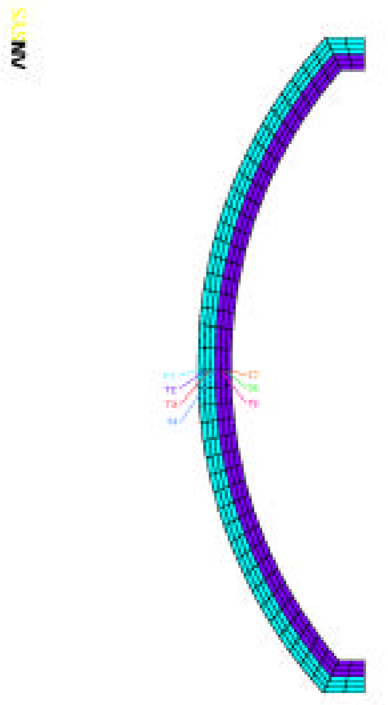
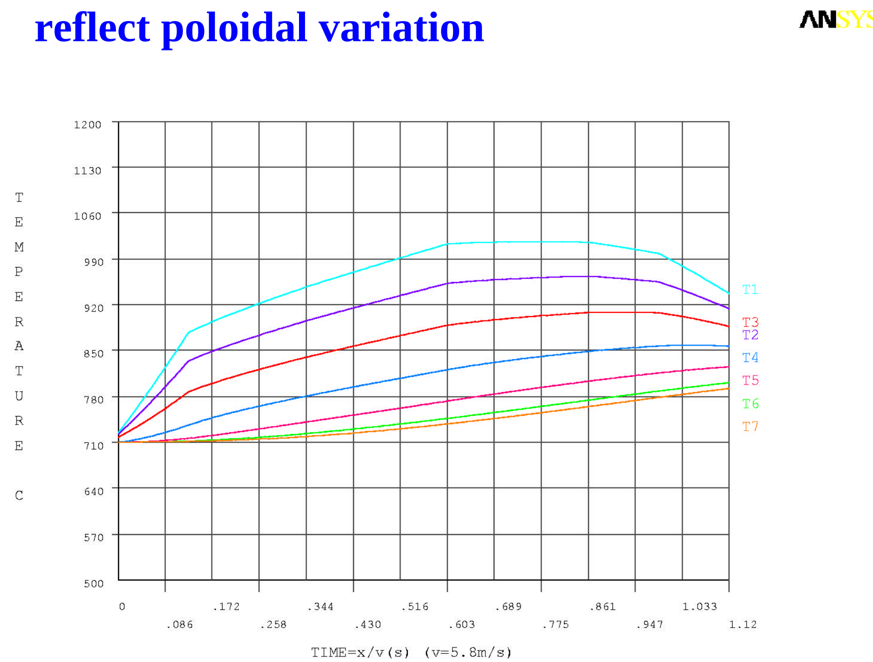
2-D Moving Coordinate Analysis of FW



Toroidal-Radial Plan View of Blanket Outboard Region 1

- **Transient analysis of 2-D FW geometry over LiPb residence time to simulate 3-D situation under the assumption of conduction only in LiPb**
- **Heat flux and heat generation varied over time to reflect poloidal variation**



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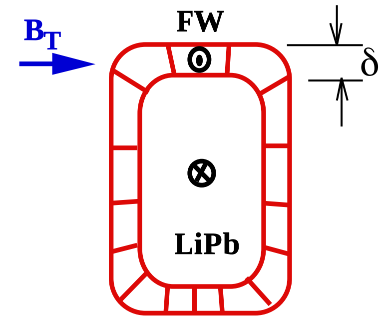
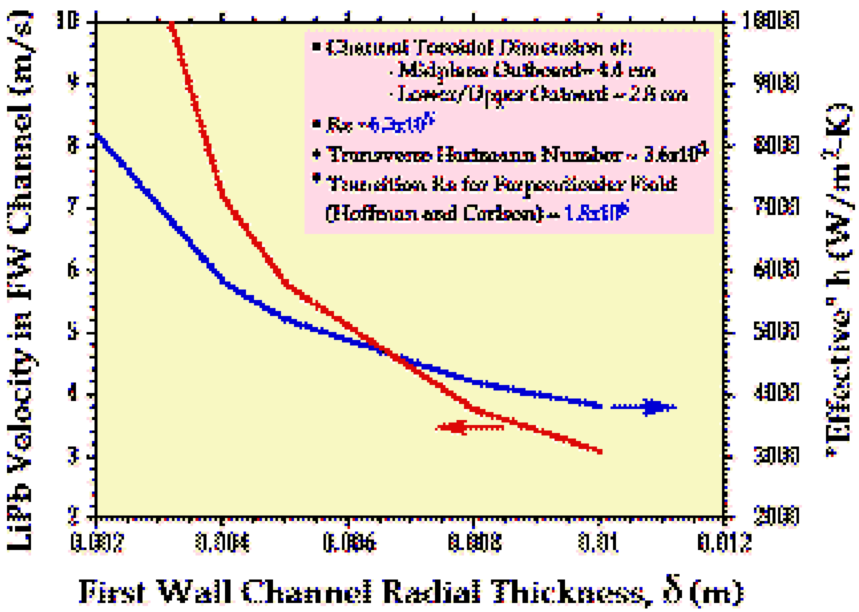
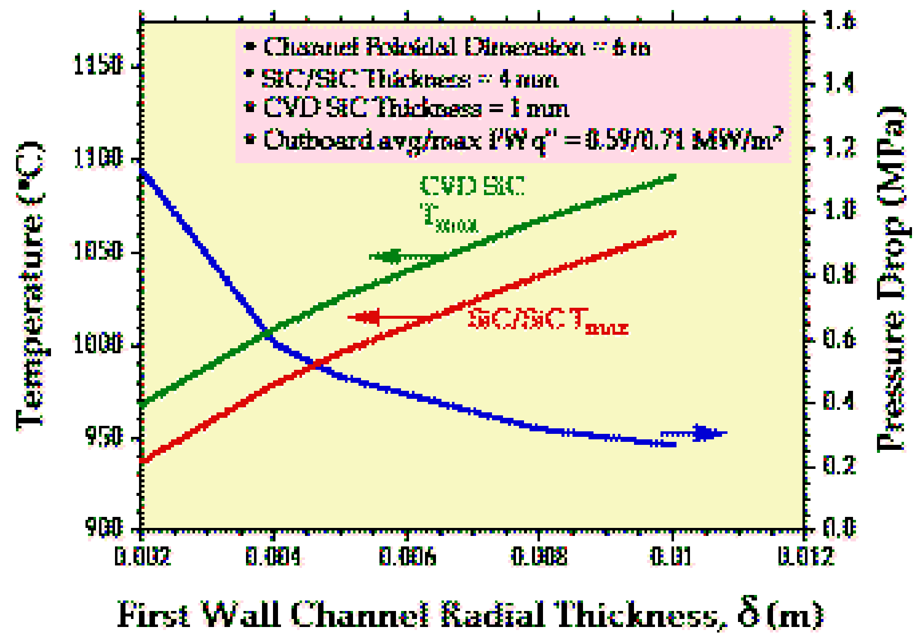
Flow and Thermal Parameters for LiPb-Cooled FW of Outboard Region 1 as a Function of FW Channel Thickness







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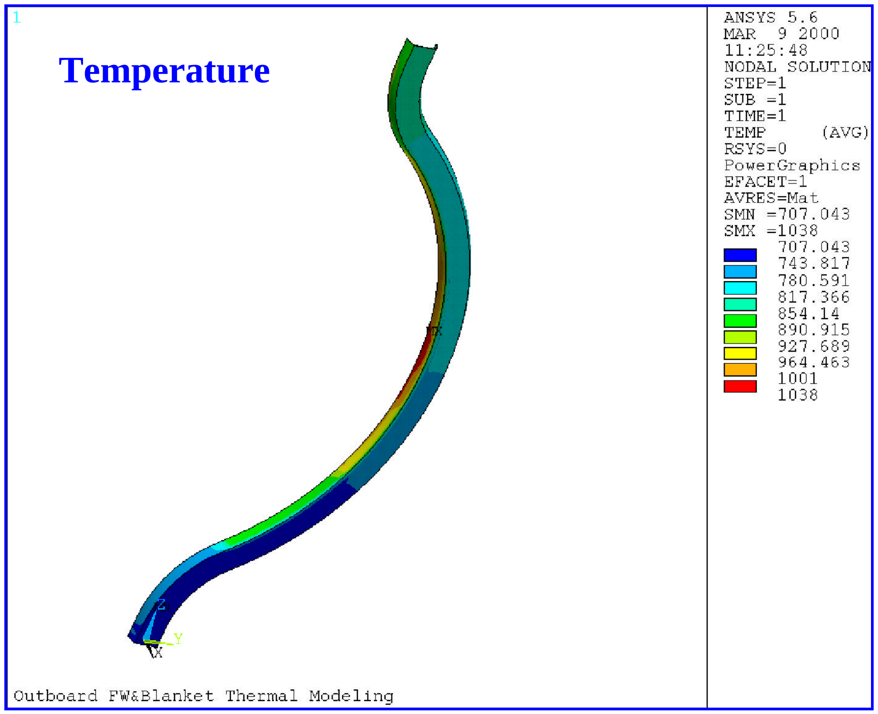
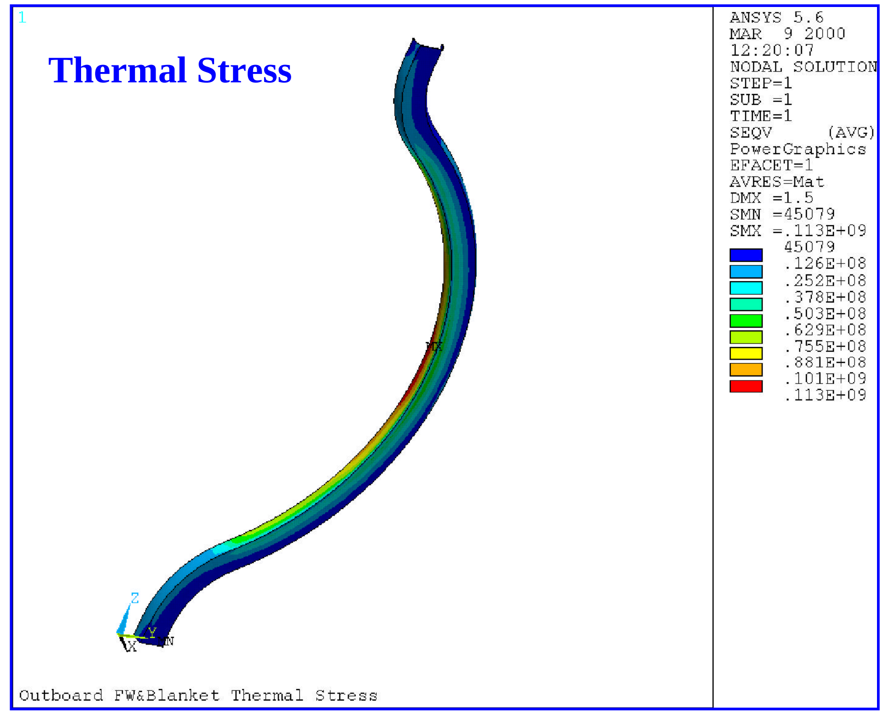
3-D Thermal Analysis of Toroidal Half of Outboard Blanket Region 1





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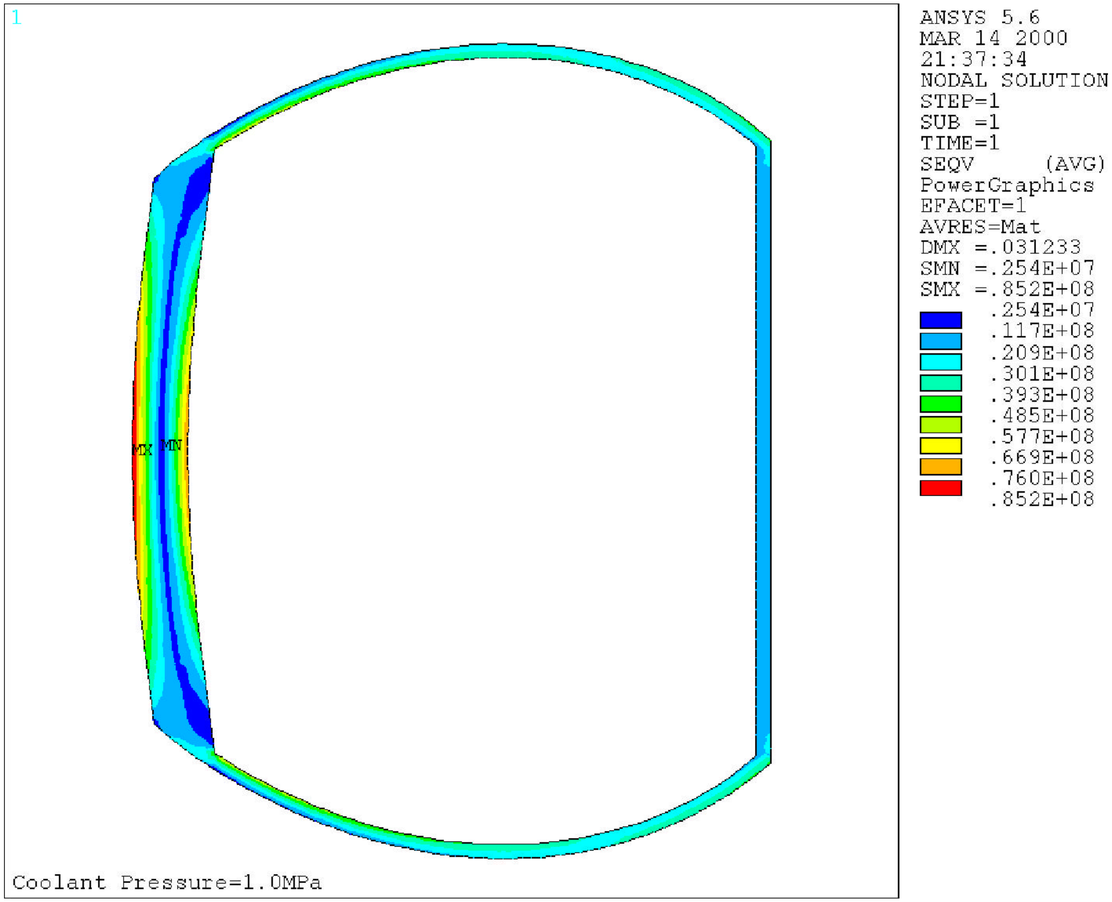
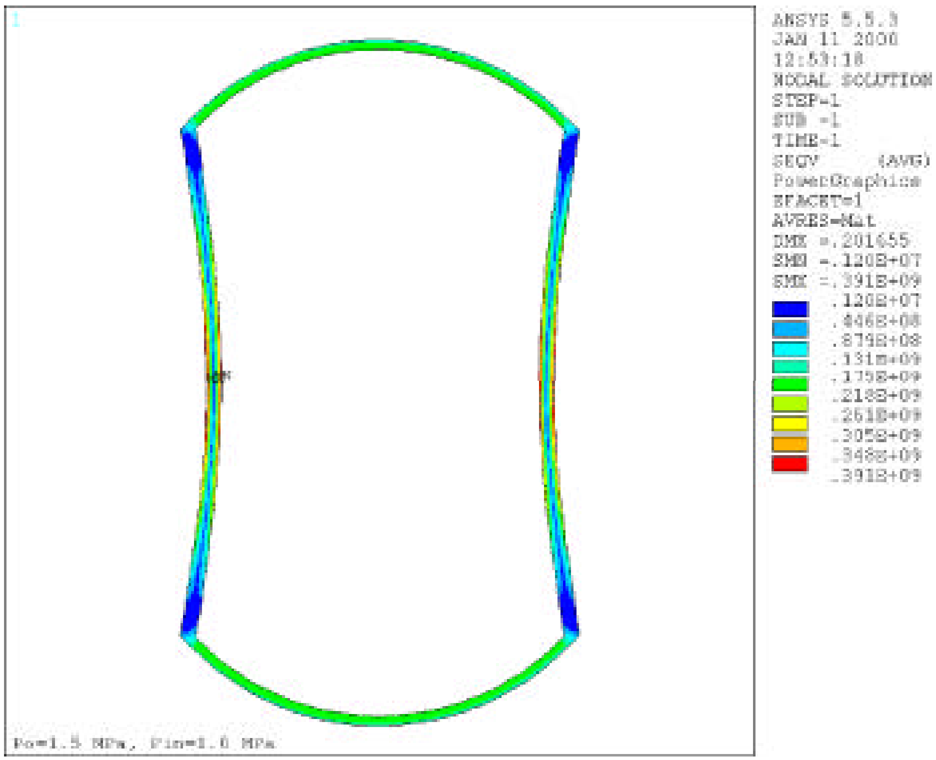
Pressure Stress Analysis of Outer Shell of Blanket Module at Segment End



Pressure Stress Analysis of Inner Shell of Blanket Module



- **Maximum Differential Pressure Stress on Blanket Module Inner Shell ~ 0.5 MPa**
- **Thermal stress is too high for original thickness of 5mm**
- **Solution**
  - **Increase thickness**
  - **Add rib for same thickness**

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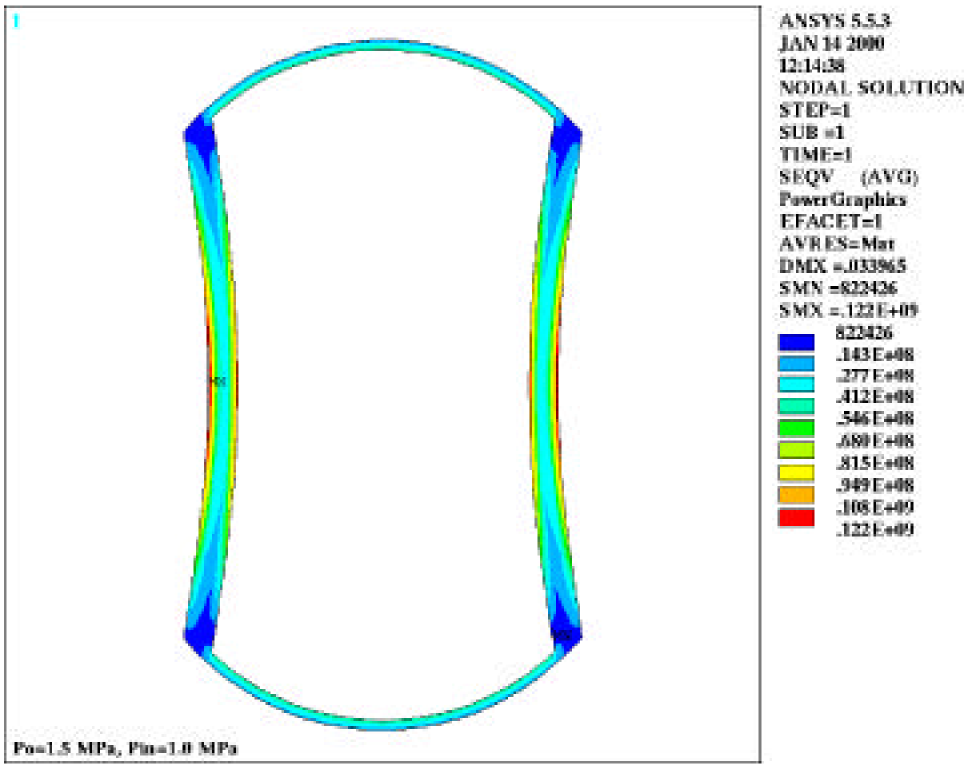
Increasing Inner Shell Thickness to Accommodate Pressure Stress

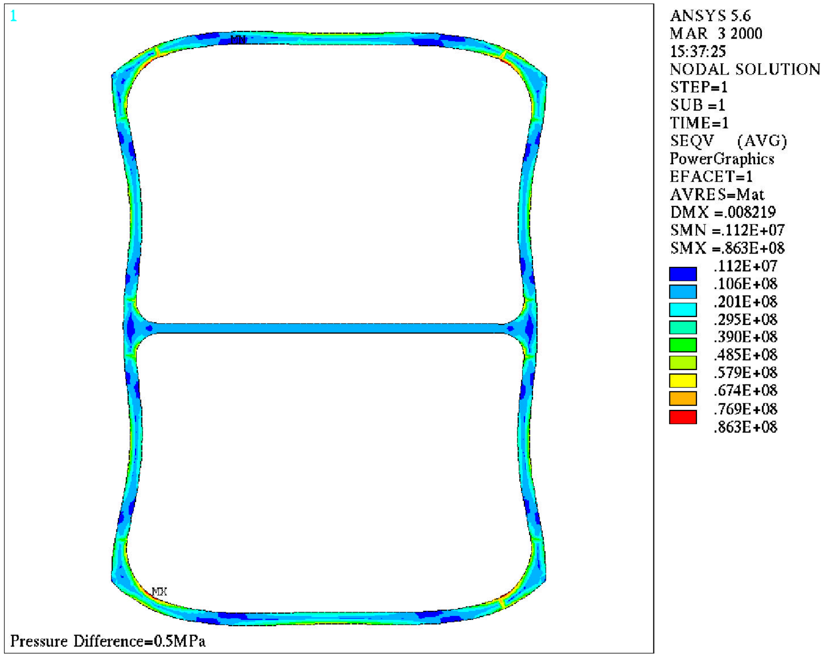


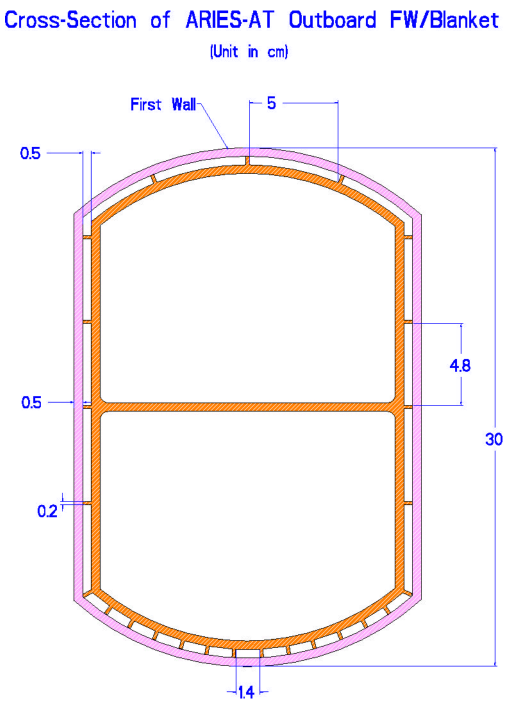
- **Maximum pressure stress is 122 MPa for 1.5-cm thickness**
- **Thermal Stress probably small**
- **Effect on TBR**
- **Thickness can be poloidally tapered to account for local pressure differential value**

Adding Rib to Inner Shell as an Alternative Option Increasing to Accommodate Pressure Stress

- **Maximum pressure stress is low, 86 MPa**
- **Minimal Effect on TBR**

- **Add complexity to manufacturing**
- **Rib must be cooled**
- **Familiar look!**





Divertor Design Considerations

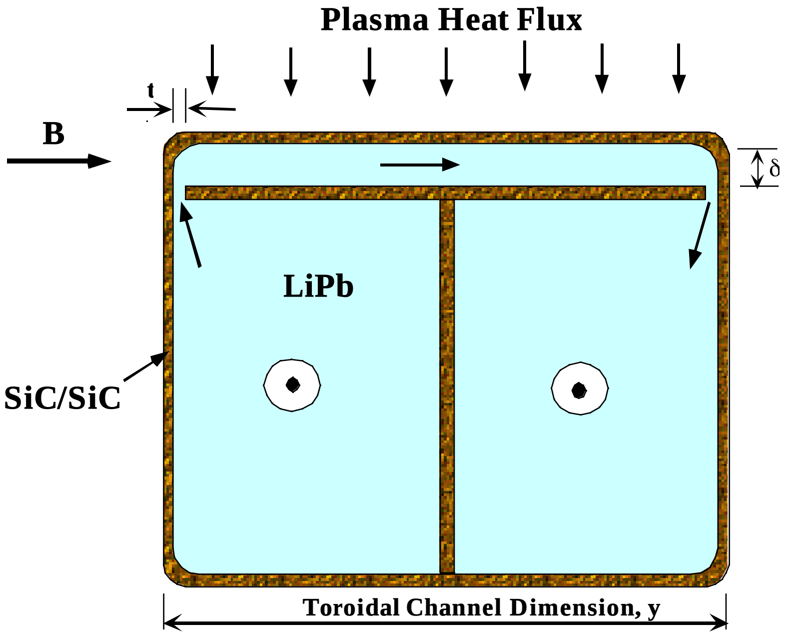
- **Compatibility with Blanket Configuration and Coolant**

- **Structural Material**
  - SiC/SiC thickness < 1mm
    (σ_{th} ~ 235 MPa and ΔT_{SiC} = 250°C for q''= 5 MW/m^2)
  - W with thin SiC insert with or without structural function

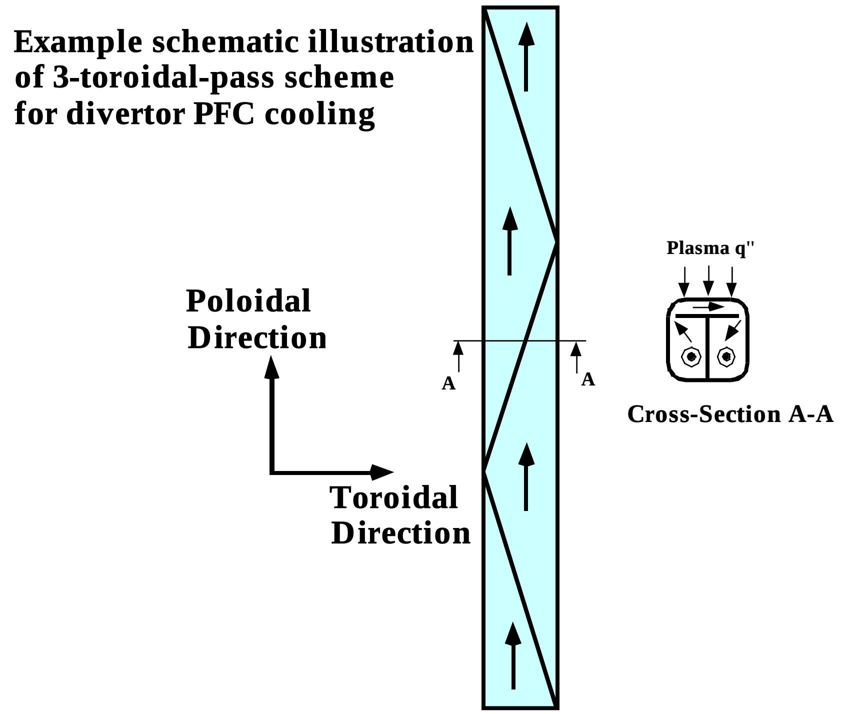
- **Possible Concepts**
  - Dry Wall
    – LiPb as coolant (Preferable to avoid in-reactor high pressure He but needs innovative scheme because of poor heat transfer removal capabilities)
    – Porous W HX concept with He coolant as in ARIES-ST
    – Phase-change liquid metal (Li)
  - Liquid Wall (Sn-Li)

LiPb Cooling Scheme for ARIES-AT Divertor

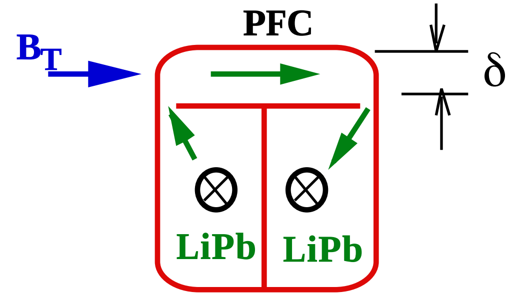
LiPb Poloidal/Toroidal Flow for ARIES-AT Divertor

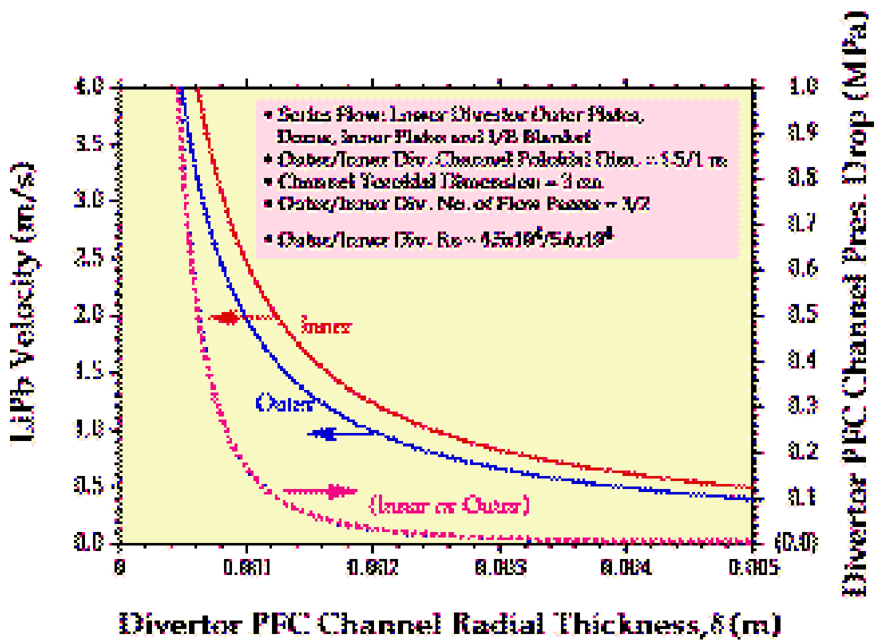


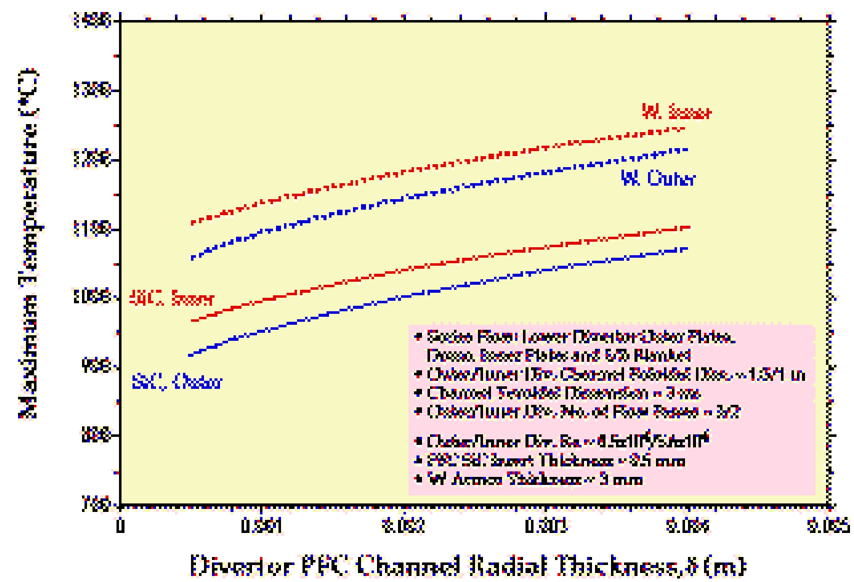
LiPb Poloidal Flow in ARIES-AT Divertor Header



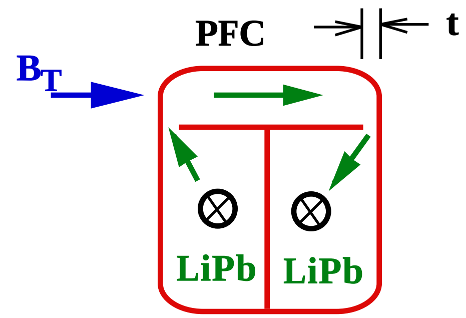
Flow and Thermal Parameters for LiPb-Cooled Divertor PFC as a Function of PFC Channel Thickness



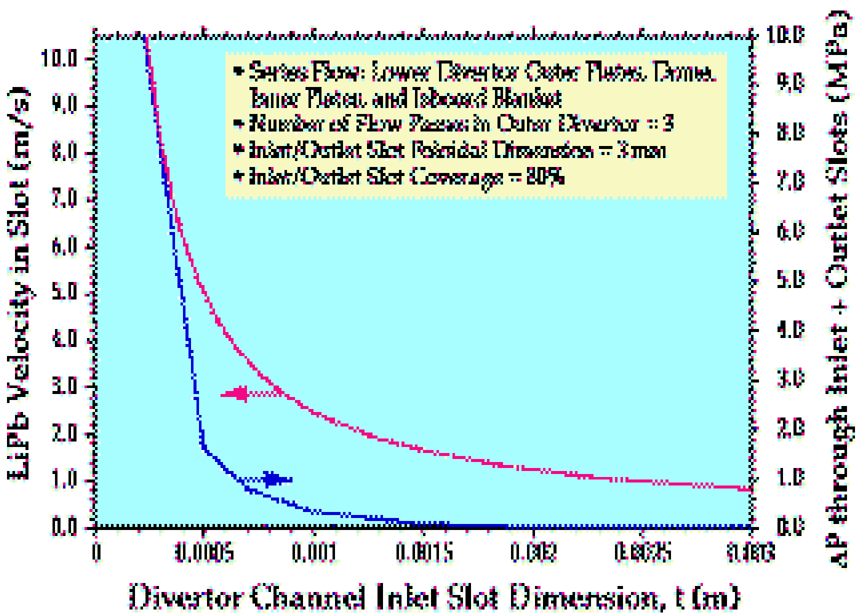


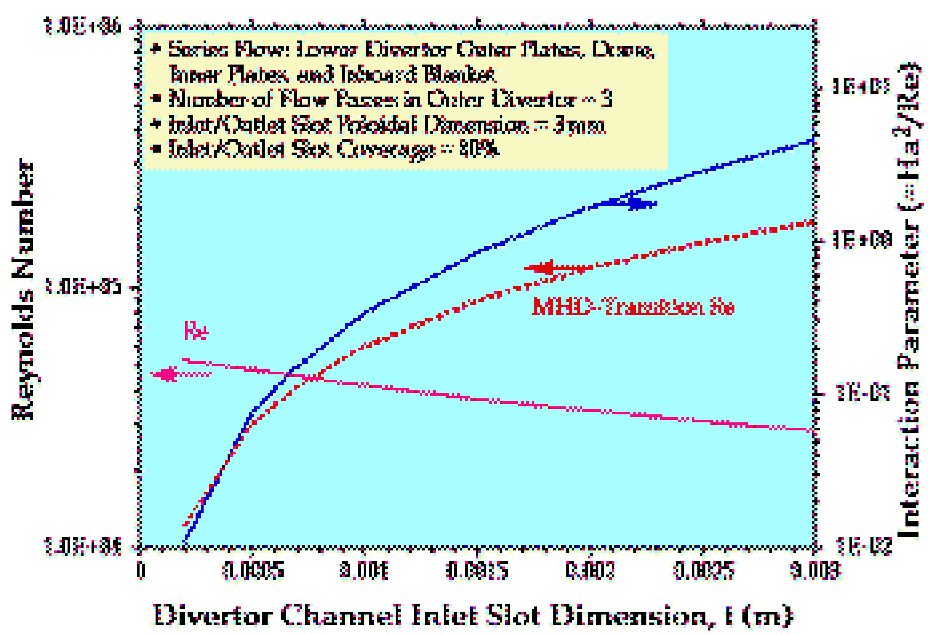


Velocity, ΔP, Re, and Interaction Parameter as a Function of Divertor Channel Inlet/Outlet Slot Dimension



- **High inertia regime (low interaction parameter) to overcome MHD-induced slanted velocity profile**





Typical Blanket and Divertor Parameters for Example Design Point

Blanket Outboard Region 1	
No. of Segments	32
No. of Modules per Segment	6
Module Poloidal Dimension	6 m
Avg. Module Toroidal Dimen.	0.18 m
FW SiC/SiC Thickness	4 mm
FW CVD SiC Thickness	1 mm
FW Annular Channel Thickness	5 mm
Avg. LiPb Velocity in FW	5.8 m/s
FW Channel Re	6.2×10^5
FW Channel Transverse Ha	3540
MHD Turbulent Transition Re	1.8×10^6
FW MHD Pressure Drop	0.49 MPa
Maximum SiC/SiC Temp.	997°C
Maximum CVD SiC Temp. (°C)	1030 °C

Lower Outer/Inner Divertor	
Poloidal Dimension	1.5/1.0 m
Divertor Channel Toroidal Dimension	3.8 cm
Divertor Channel Radial Dimension	3.75 cm
Number of Divertor Channels	744/595
SiC Insert Thickness	0.5 mm
W Thickness	3 mm
PFC Channel Thickness	2 mm
Number of Toroidal Passes	3/2
Velocity in PFC Channel	1/ 1.2 m/s
Maximum SiC Temperature	1000/1040°C
Maximum W Temperature	1150/1180°C
W (1-D) Thermal Stress	162 MPa
Toroidal Dimension of Inlet and Outlet Slot	1 mm
Vel. in Inlet & Outlet Slot to PFC Channel	2.5/3.1 m/s
Interaction Parameter in Inlet/Outlet Slot	0.34/0.42
Pressure Drop	0.47/0.5 MPa

Future Work Includes:

- **Converge on coolant routing scheme**
- **Converge of maintenance scheme**
- **Tabulated list of parameters (LiPb volume and mass in different components, etc..)**
- **Blanket fabrication flow diagram**
- **Power cycle: Better characterization of heat exchanger**
- **Divertor**
  - **Recommend using LiPb as reference coolant and He as back-up option**
    - Inlet and toroidal flow in PFC channel under low interaction parameter must be verifiedby detailed MHD analysis and testing
  - **Detailed thermal and stress analysis**