ARIES-AT Blanket and Divertor Design
(The Final Stretch)

The ARIES Team

Presented by

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ARIES Project Meeting
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June 19-21, 2000

Presentation Outline

- **Blanket**
  - Geometry and coolant routing
  - Update analysis and parameters based on 3/10/00 strawman
  - New analysis
    - 2-D moving coordinate thermal analysis
    - Pressure stress in inner SiC/SiC separation wall
- **Manifolding**
  - Thermo-fluid analysis
- **Divertor**
  - Configuration with LiPb as coolant
  - Thermal and stress analysis
  - Fabrication
- **Summary**

ARIES-AT Machine and Power Parameters from 3/10/00 Strawman

Power and Neutronics Parameters

• Fusion Power	1719 MW
• Neutron Power	1375 MW
• Alpha Power	344 MW
• Current Drive Power	25 MW
• Transport Power to Divertor	256 MW
• Fraction of Divertor Power Radiated Back to FW	TBD
• Overall Energy Multiplication	1.1
• Total Thermal Power	1897 MW
• Average FW Surface Heat Flux	0.26 MW/m^2
• Max. FW Surface Heat Flux	0.34 MW/m^2
• Max. Divertor Surf. Heat Flux	5 MW/m^2
• Average Wall Load	3.2 MW/m^2
• Maximum O/B Wall Load	4.8 MW/m^2
• Maximum I/B Wall Load	3.1 MW/m^2

Machine Geometry

• Major Radius	5.2 m
• Minor Radius	1.3 m
• FW Location at O/B Midplane	6.5 m
• FW Location at Lower O/B	4.9
• I/B FW Location	3.9 m

Toroidal Magnetic Field

• On-axis Magnetic Field	5.9 T
• Magnetic Field at I/B FW	7.9 T
• Magnetic Field at O/B FW	4.7 T

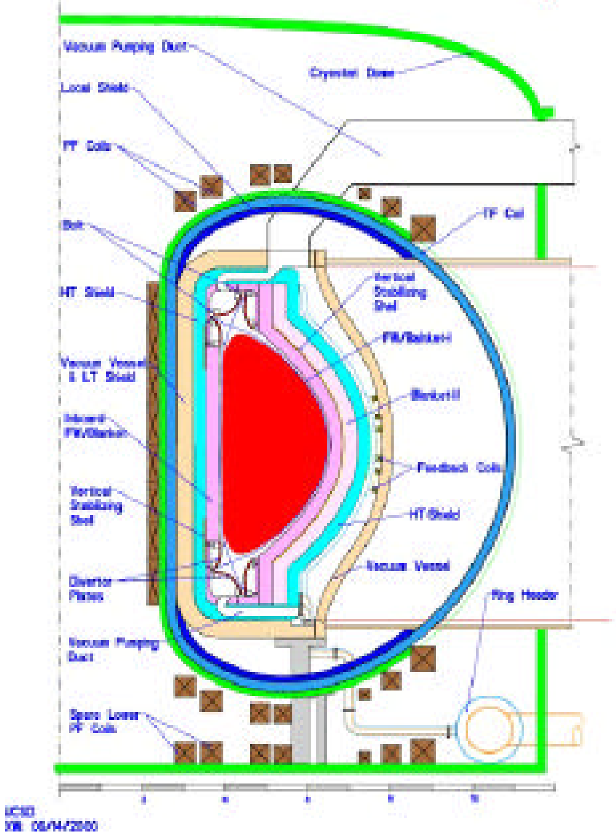
SiC/SiC Properties Used for Design Analysis

(Consistent with SiC/SiC Town Meeting Suggestion)

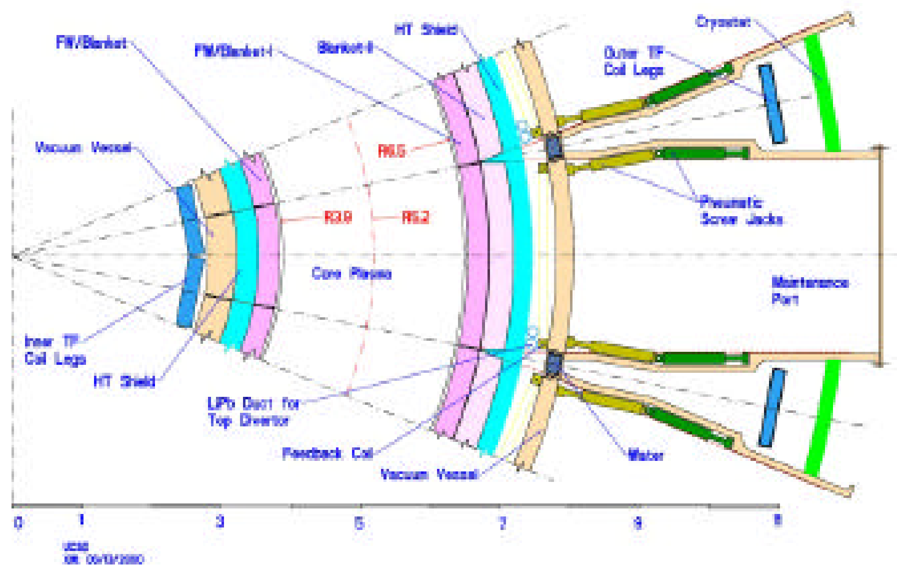
• Density	~3200 kg/m^3
• Density Factor	0.95
• Young's Modulus	~200-300 GPa
• Poisson's ratio	0.16-0.18
• Thermal Expansion Coefficient	4 ppm/°C
• Thermal Conductivity in Plane	~20 W/m-K
• Therm. Conductivity through Thickness	~20 W/m-K
• Maximum Allowable Combined Stress	~190 MPa
• Maximum Allowable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

Cross-Section and Plan View of ARIES-AT Showing Power Core Components

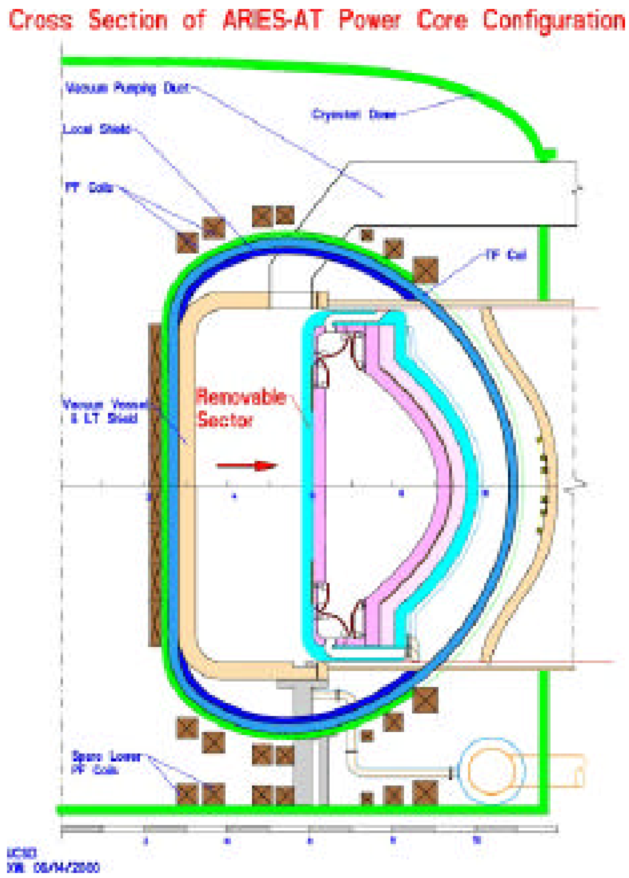
Cross Section of ARIES-AT Power Core Configuration



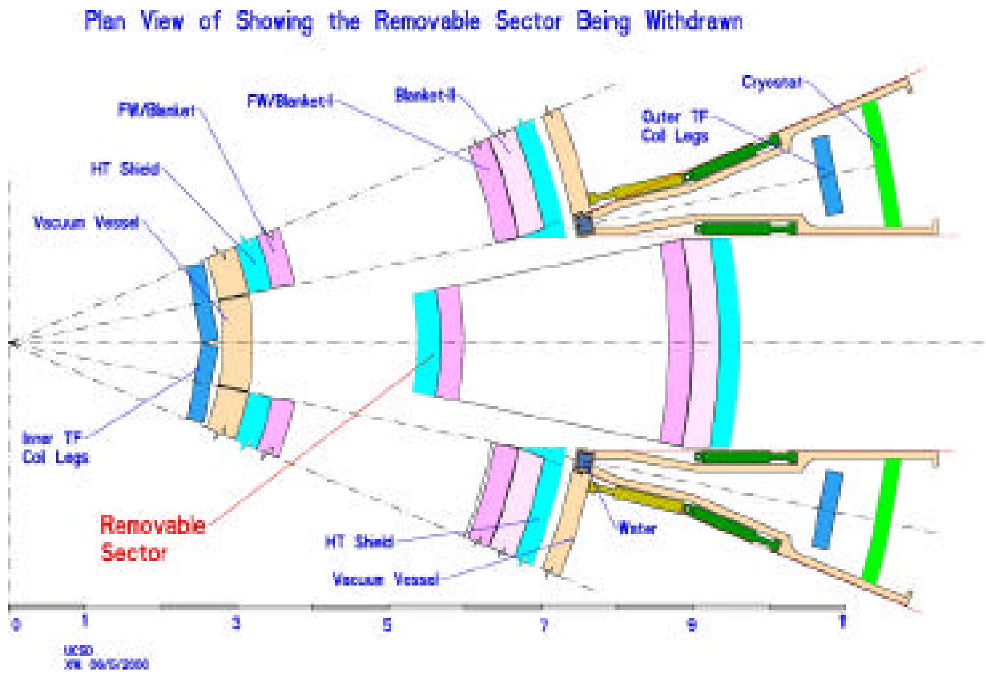
Plan View of ARIES-AT Power Core(1/16 Sector)



Cross-Section and Plan View of ARIES-AT Showing Maintenance Approach



- **All Lifetime Components Except for: Divertor, IB Blanket, and OB Blanket I**



Coolant Routing Through 5 Circuits Serviced by Annular Ring Header (I)

LiPb Coolant

Inlet Temperature	653 °C
Outlet Temperature	1100 °C
Blanket Inlet Pressure	1 MPa
Divertor Inlet Pressure	1.7 MPa
Mass Flow Rate	22,700 kg/s

Circuit 1 - Lower Divertor + IB Blkt Region

Thermal Power and Mass Flow Rate:

501 MW and 6100 kg/s

Circuit 2 - Upper Divertor + 1/2 OB Blanket I

598 MW and 7270 kg/s

Circuit 3 - 1/2 OB Blanket I

450 MW and 5470 kg/s

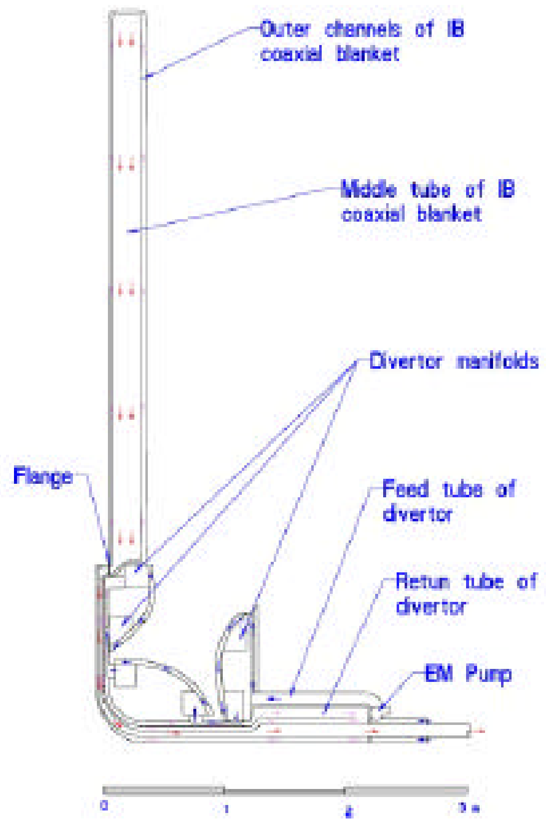
Circuit 4 - IB Hot Shield + 1/2 OB Blanket II

182 MW and 4270 kg/s

Circuit 5 - OB Hot Shield + 1/2 OB Blanket II

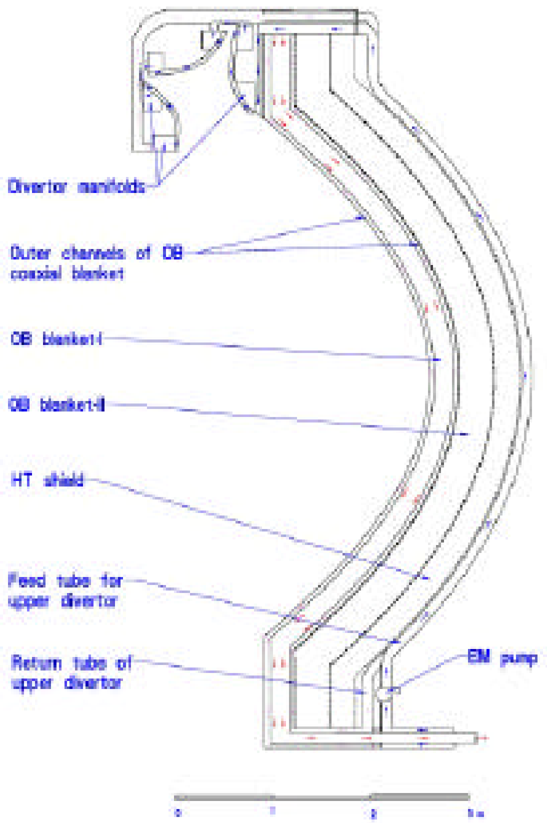
140 MW and 1700 kg/s

Circuit 1: Lower Divertor + IB Blanket

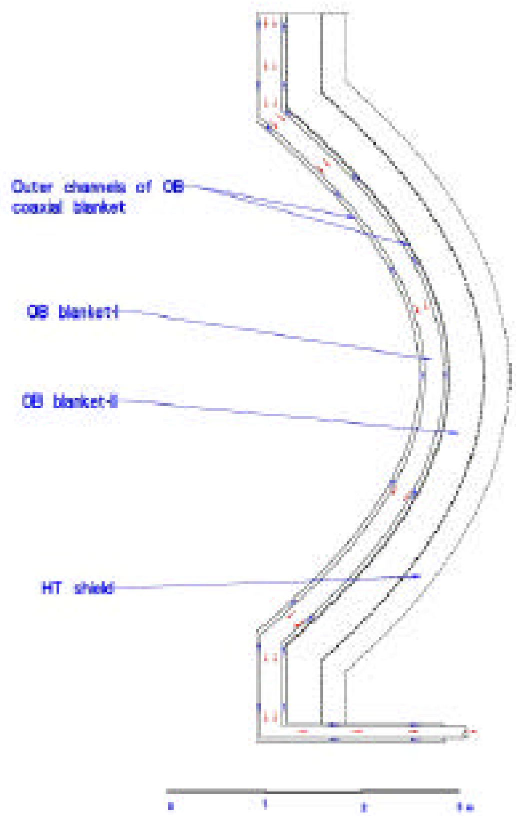


Coolant Routing Through 5 Circuits Serviced by Annular Ring Header (II)

Circuit 2: Upper Divertor + 1/2 OB Blanket I

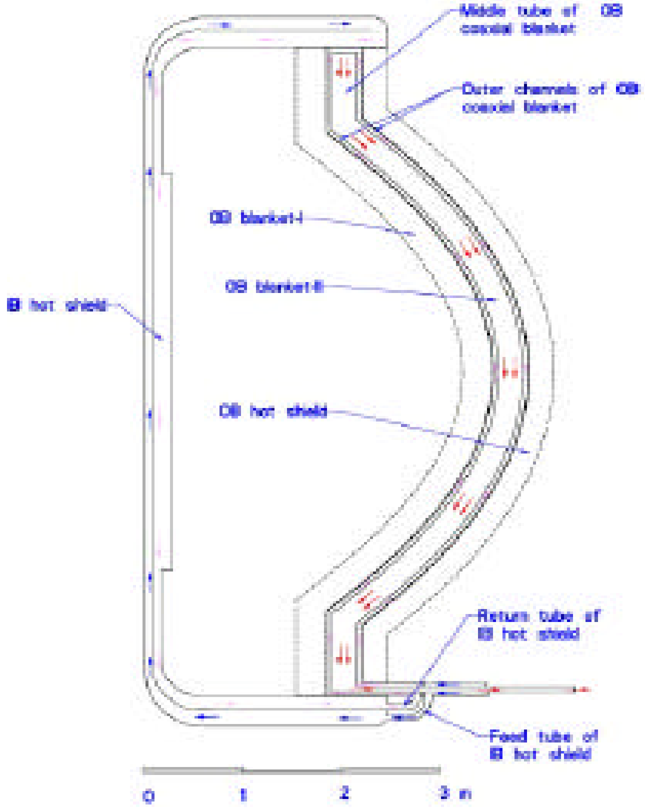


Circuit 3: 1/2 OB Blanket II

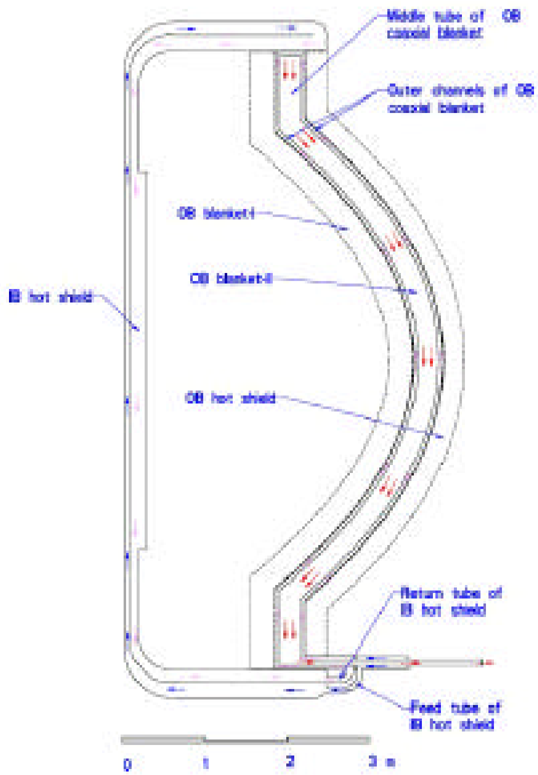


Coolant Routing Through 5 Circuits Serviced by Annular Ring Header (III)

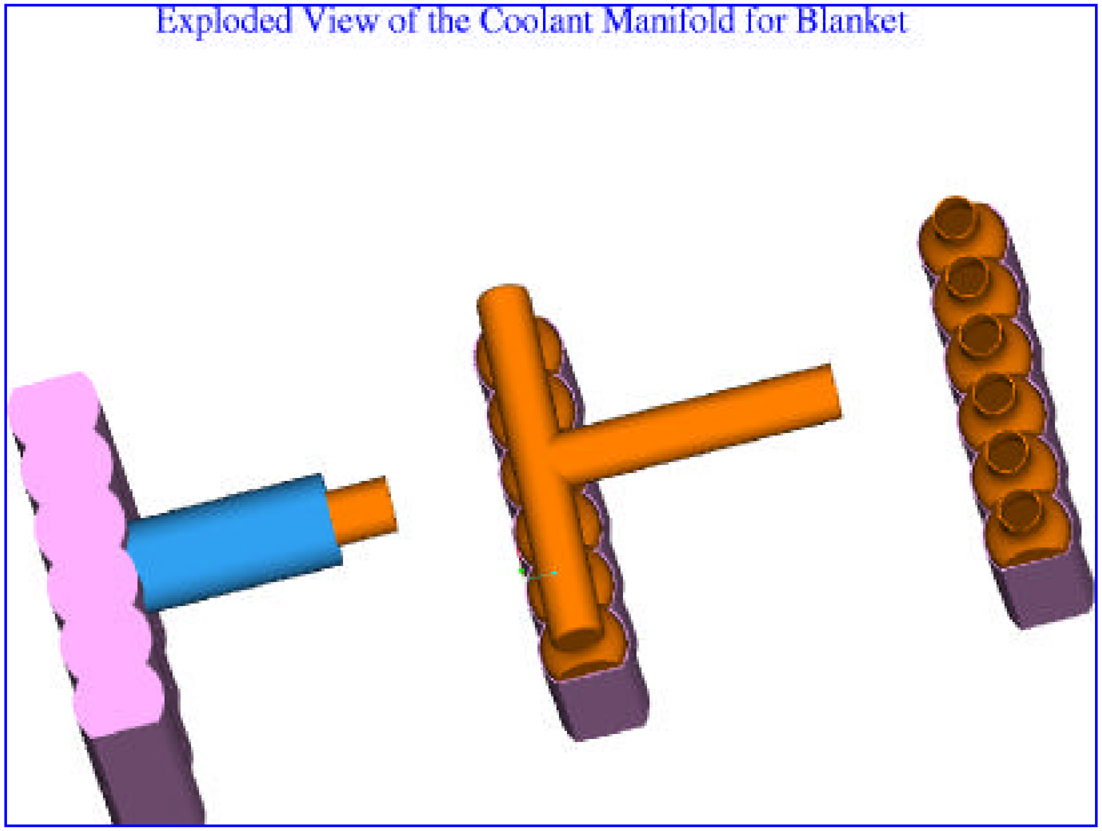
Circuit 4: IB Hot Shield + 1/2 OB Blanket II



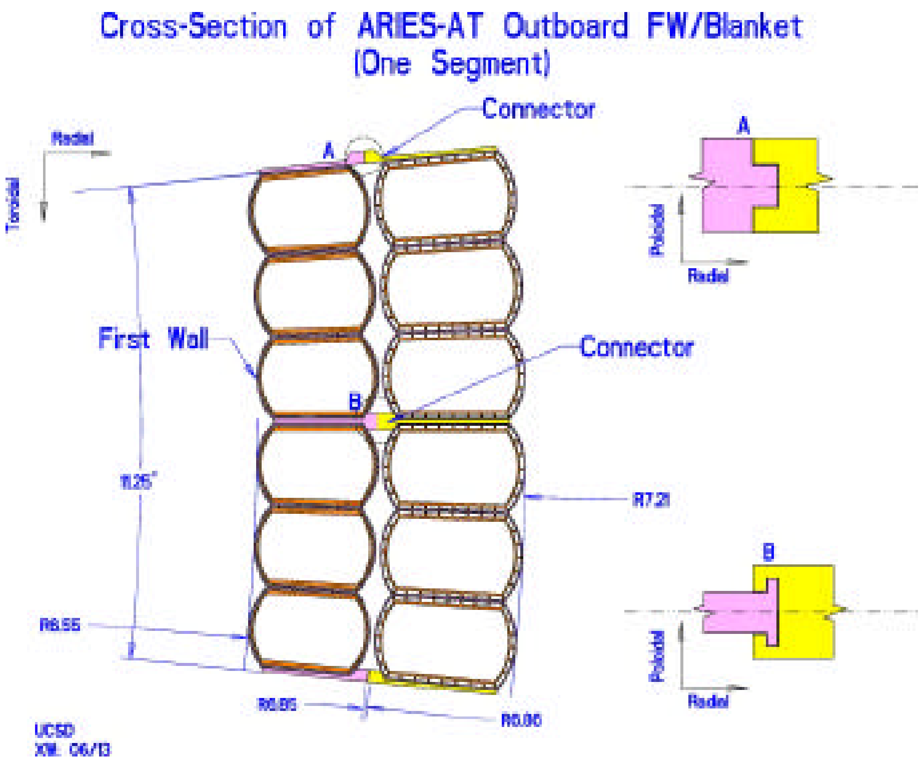
Circuit 5: OB Hot Shield + 1/2 OB Blanket II

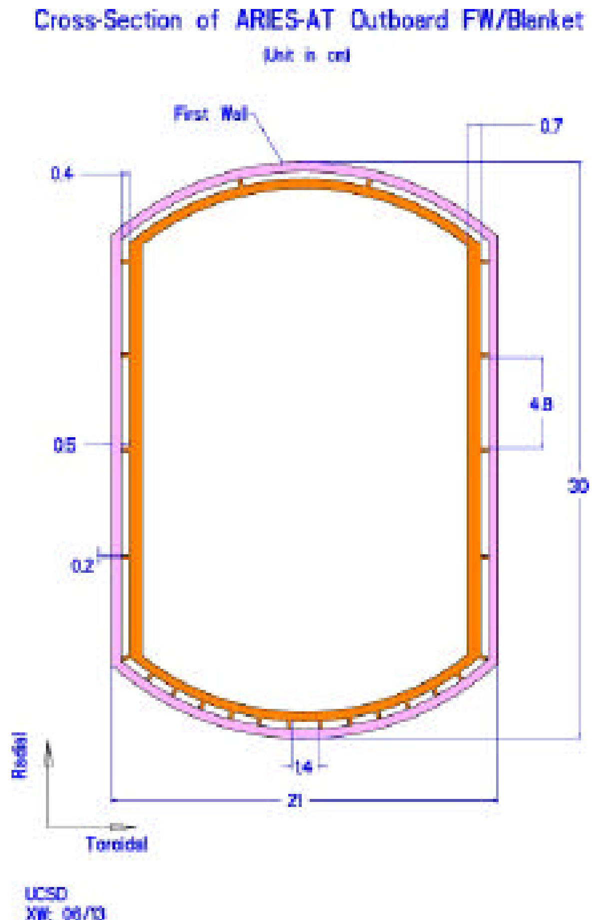


ARIES-AT Outboard Blanket Segment Configuration and Coolant Manifold



Cross-Section of ARIES-AT Outboard Blanket





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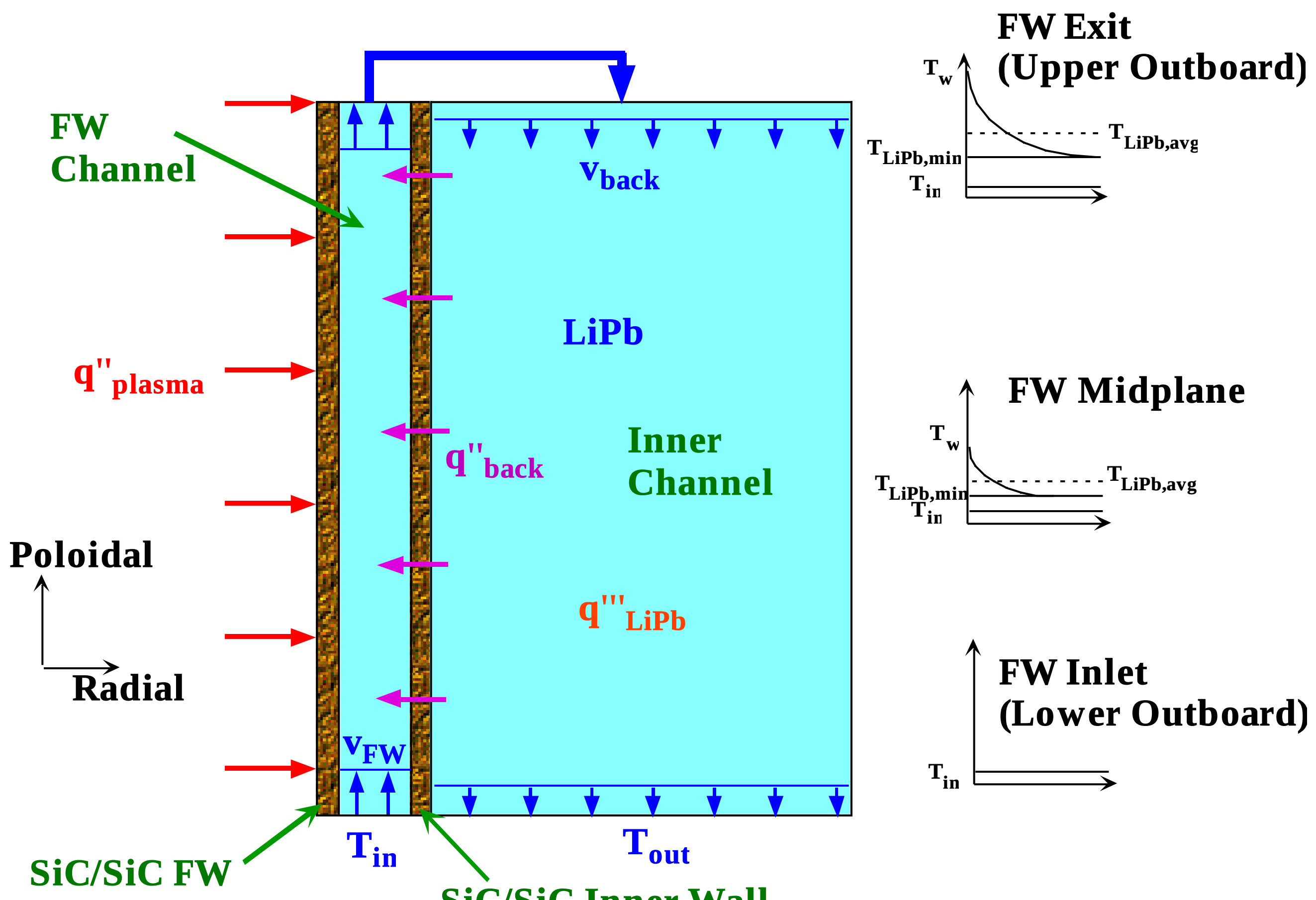
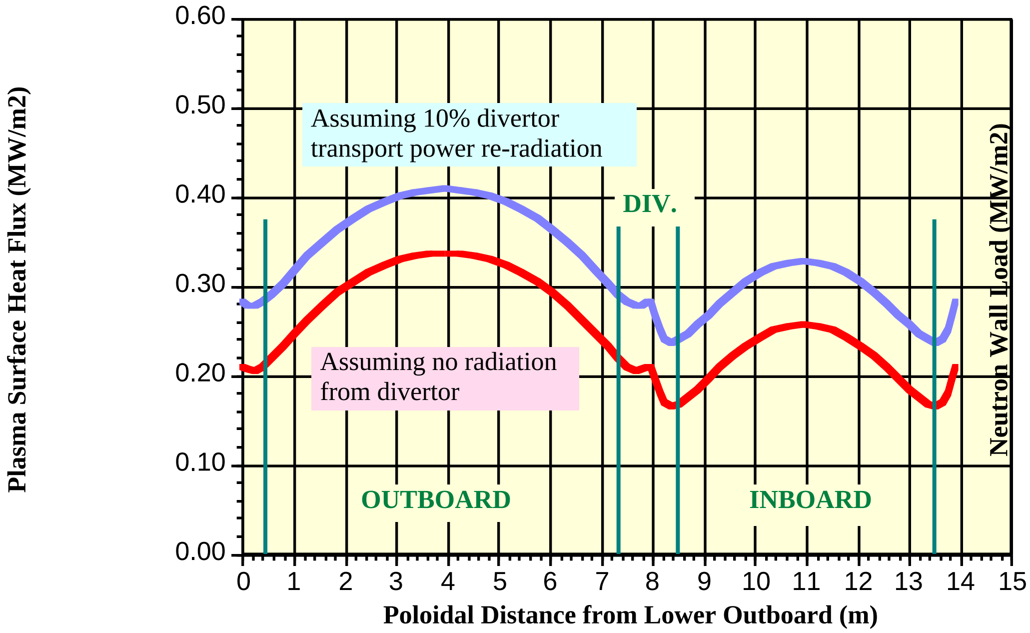
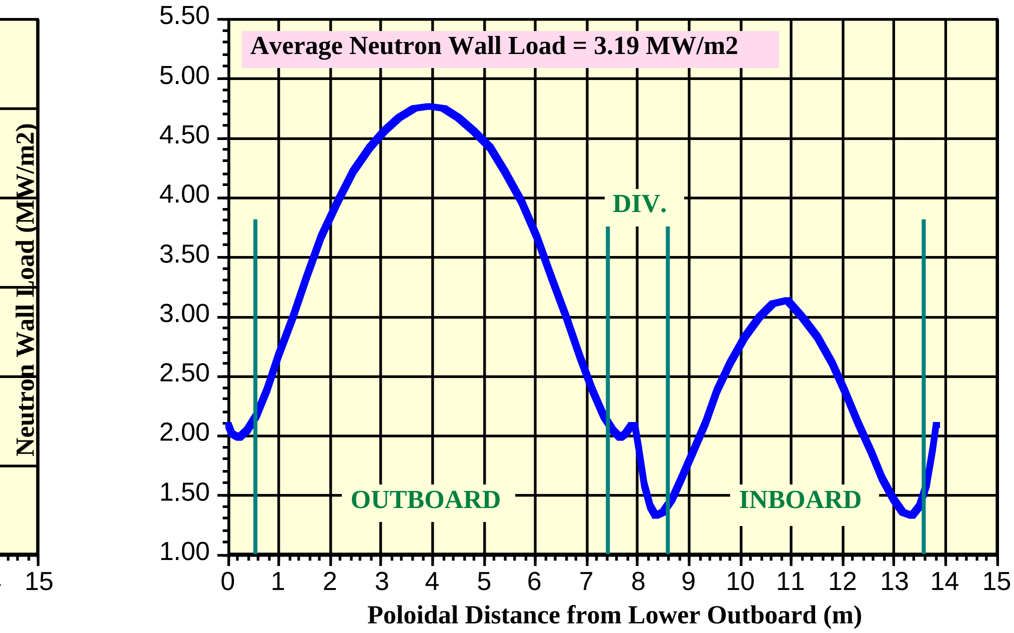
LiPb Temperature Distribution in FW Channel and Inner Channel under MHD-Laminarization

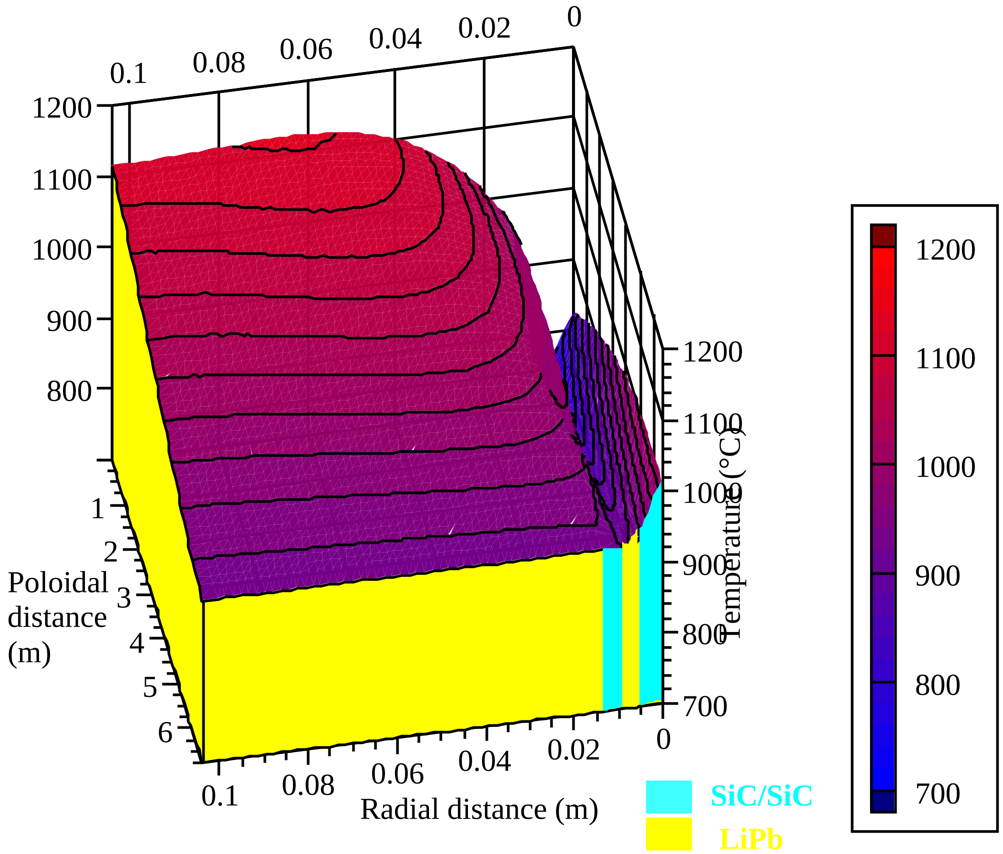


Poloidal Distribution of Surface Heat Flux and Neutron Wall Load from 3/10/00 Strawman





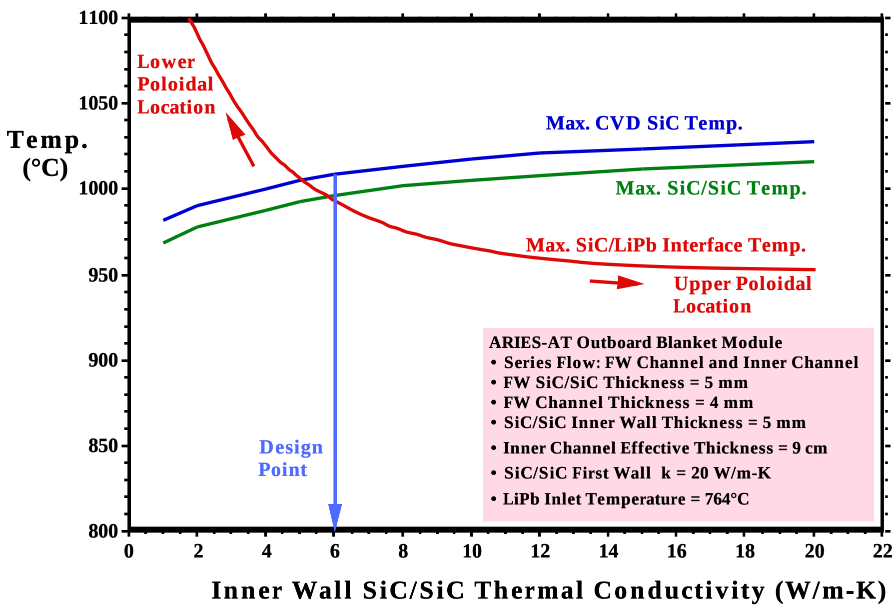
Temperature Distribution in ARIES-AT Blanket Based on 2-D Moving Coordinate Analysis

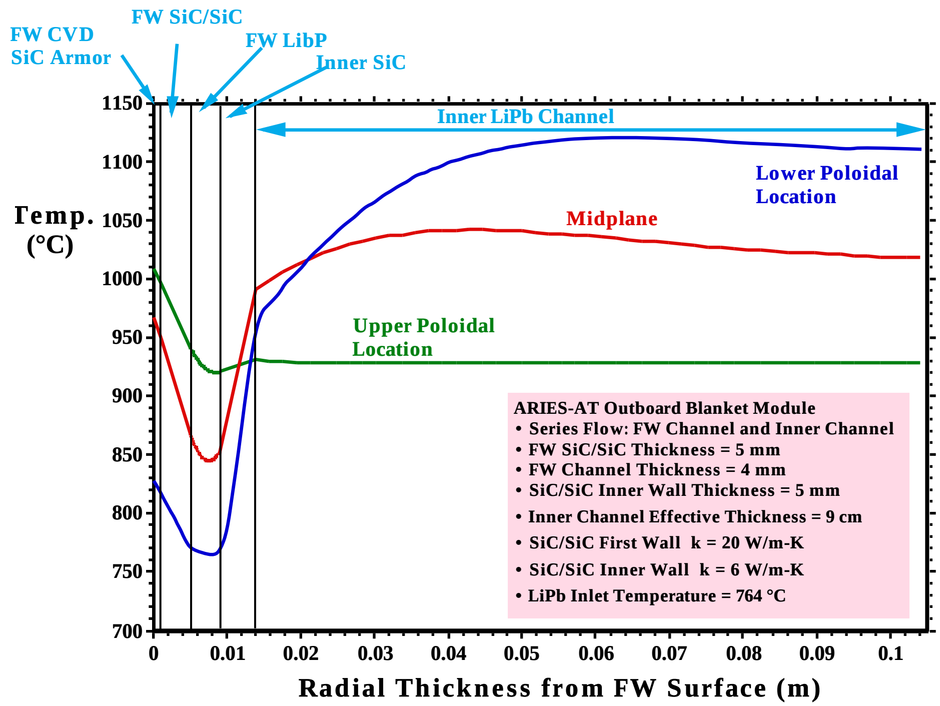


- LiPb Inlet Temperature = 764 °C
- From Plasma Side:
  - CVD SiC Thickness = 1 mm
  - SiC/SiC Thickness = 4 mm
    (SiC k = 20 W/m-K)
  - LiPb Channel Thickness = 4 mm
  - SiC/SiC Separ. Wall Thickness = 5 mm
    (SiC k = 6 W/m-K)
- LiPb Velocity in FW Channel= 4.2 m/s
- LiPb Velocity in Inner Channel = 0.1 m/s
- Poloidal neutron wall load and plasma heat flux profiles used as input (assuming no radiation from divertor)

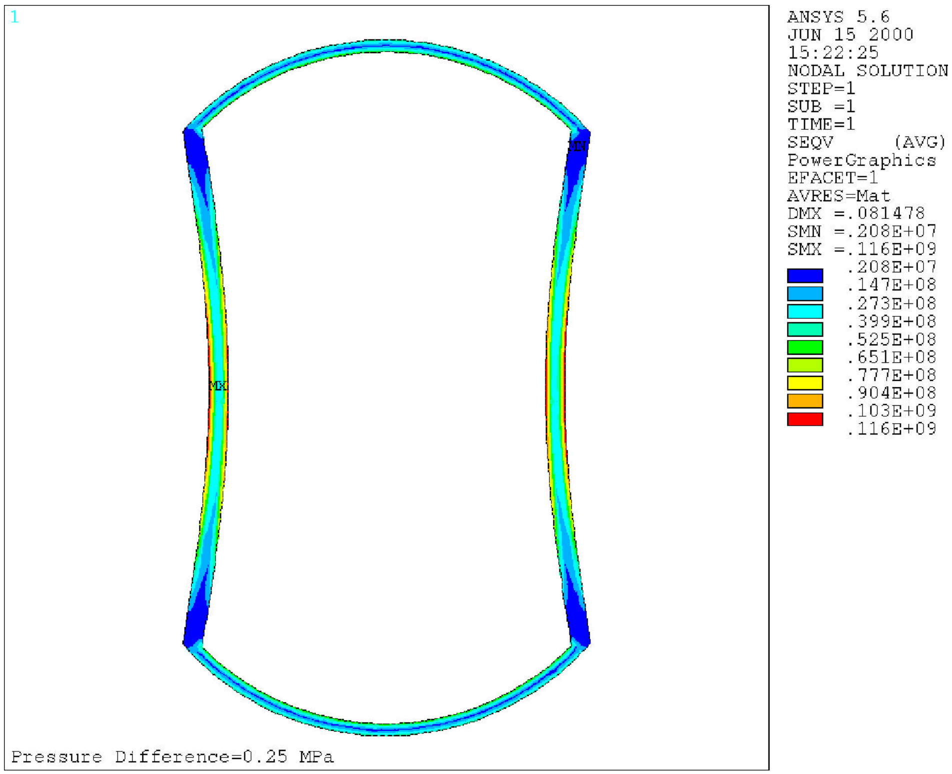
2-D Moving Coordinate Analysis of FW and Inner Channel

- Poloidal neutron wall load and plasma heat flux profiles used as input (assuming no radiation from divertor)
- FW Maximum CVD and SiC/SiC Temperature = 1009°C° and 996°C°
- Maximum SiC/LiPb Interface Temperature at Inner Wall = 994 °C (occurs at higher $y_{poloidal}$ as k_{SiC} increases)



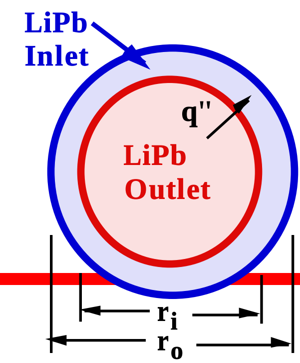


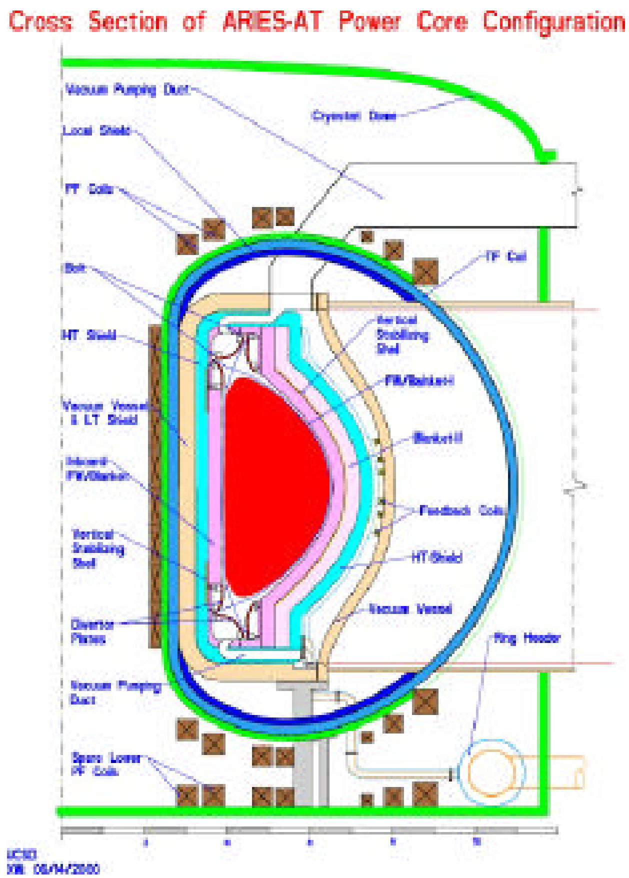
Pressure Stress Analysis of Inner Shell of Blanket Module



- **Differential Pressure Stress on Blanket Module Inner Shell Varies Poloidally from ~ 0.25 MPa at the Bottom to ~ 0 MPa at the Top**
- **Maximum Pressure Stress for 0.25 MPa Case**
  - **218 MPa for 5-mm thickness**
  - **116 MPa for 8-mm thickness**
- **Use 7 mm as reference case to comfortably maintain combined stress limit < 190 MPa**
- **Thickness Varies from7 mm at Bottom to ~ 3 mm at Top**

Manifolding Analysis





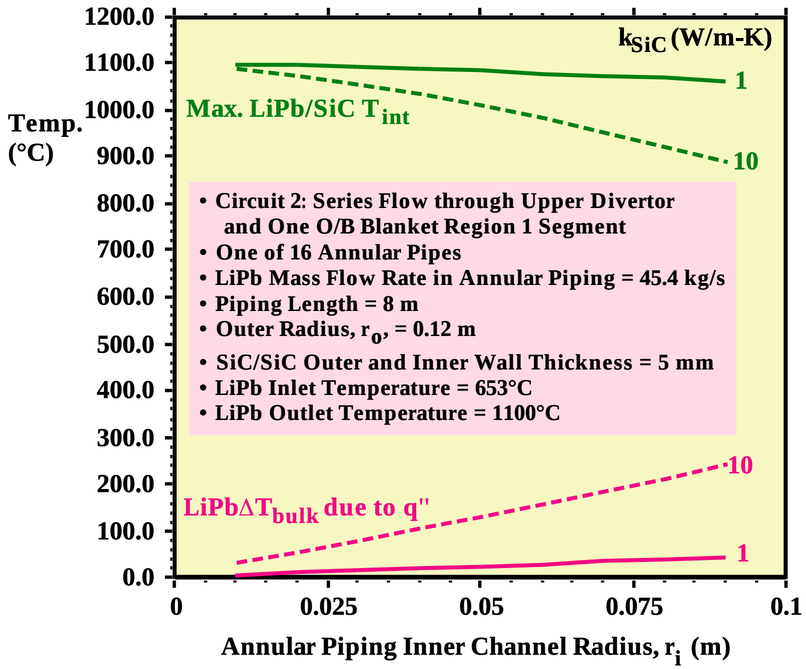
- Annular manifold configuration with low temperature inlet LiPb in outer channel and high temperature outlet LiPb in inner channel

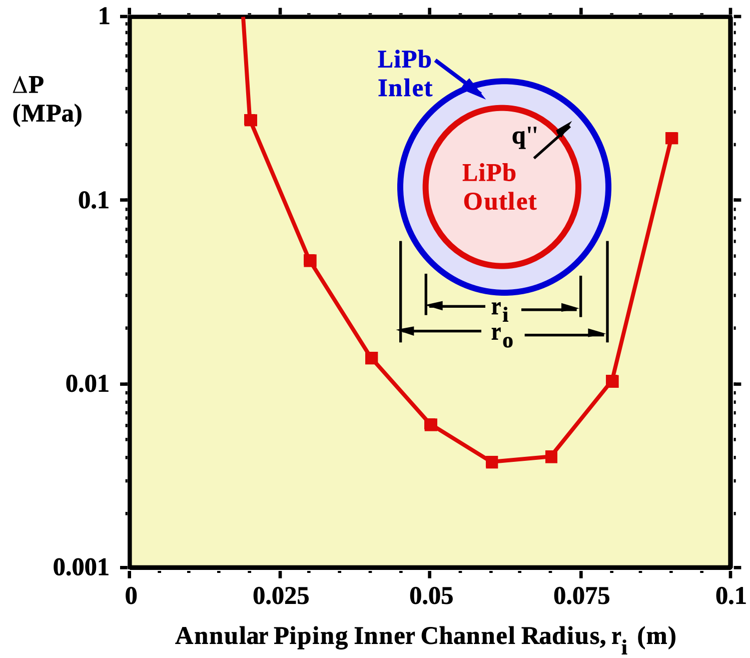
- Can the manifold be designed to maintain LiPb/SiC $T_{interface}$< LiPb T_{outlet} while maintaining reasonable ΔP?

- Use manifold between ring header and outboard blanket I as example

LiPb/SiC $T_{interface}$, LiPb ΔT_{Bulk} due to Heat Transfer in SiC/SiC Annular Piping, and ΔP as a Function of Inner Channel Radius

- Reduction in $T_{interface}$ at the expense of additional heat transfer from outlet LiPb to inlet LiPb and increase in LiPb T_{inlet}
- Very difficult to achieve maximum LiPb/SiC $T_{interface}$ < LiPb T_{outlet}
- However, manifold flow in region with very low or no radiation
- Set manifold annular dimensions to miminimize ΔT_{bulk} while maintaining a reasonable ΔP





Divertor Design

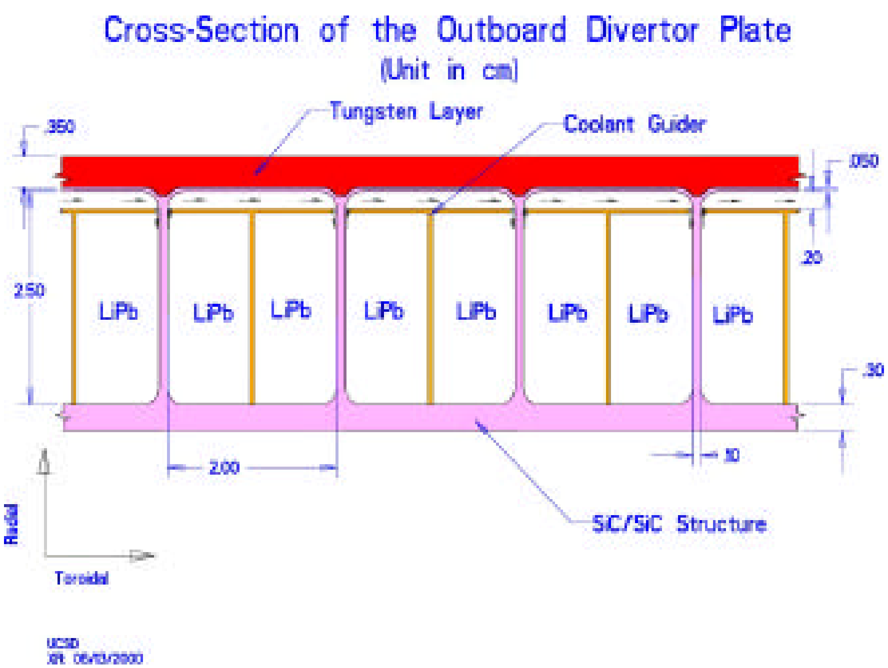
- **Preferred Option: LiPb Cooled Configuration**
  - **Single power core cooling system**
  - **Low pressure and pumping power**
  - **Analysis indicates that proposed configuration can accommodate a maximum heat flux of ~5-6 MW/m^2**

- **Alternate Options:**
  - **He-Cooled Porous Exchanger**
    - Higher pressure, pressure drop and pumping power
    - Challenging heat transfer performance if He from power cycle at ~600°C inlet temperature
  - **Liquid Wall (Sn-Li)**

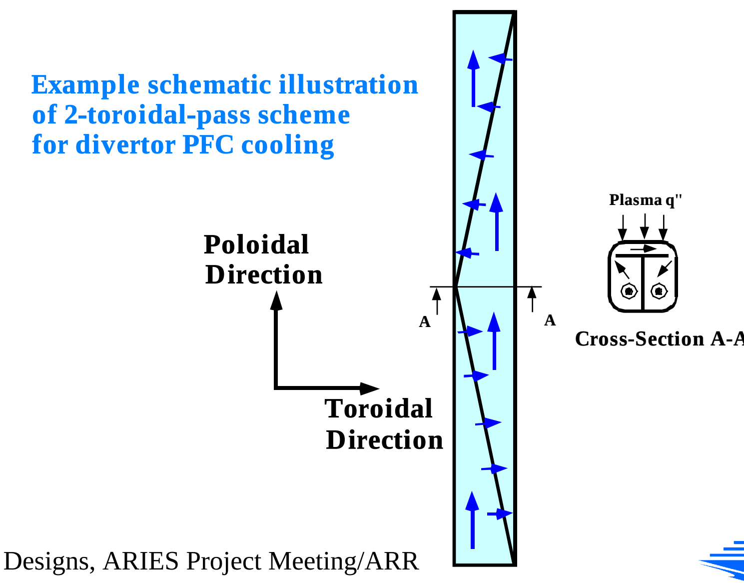
ARIES-AT Divertor Configuration and LiPb Cooling Scheme

Accommodating MHD Effects:

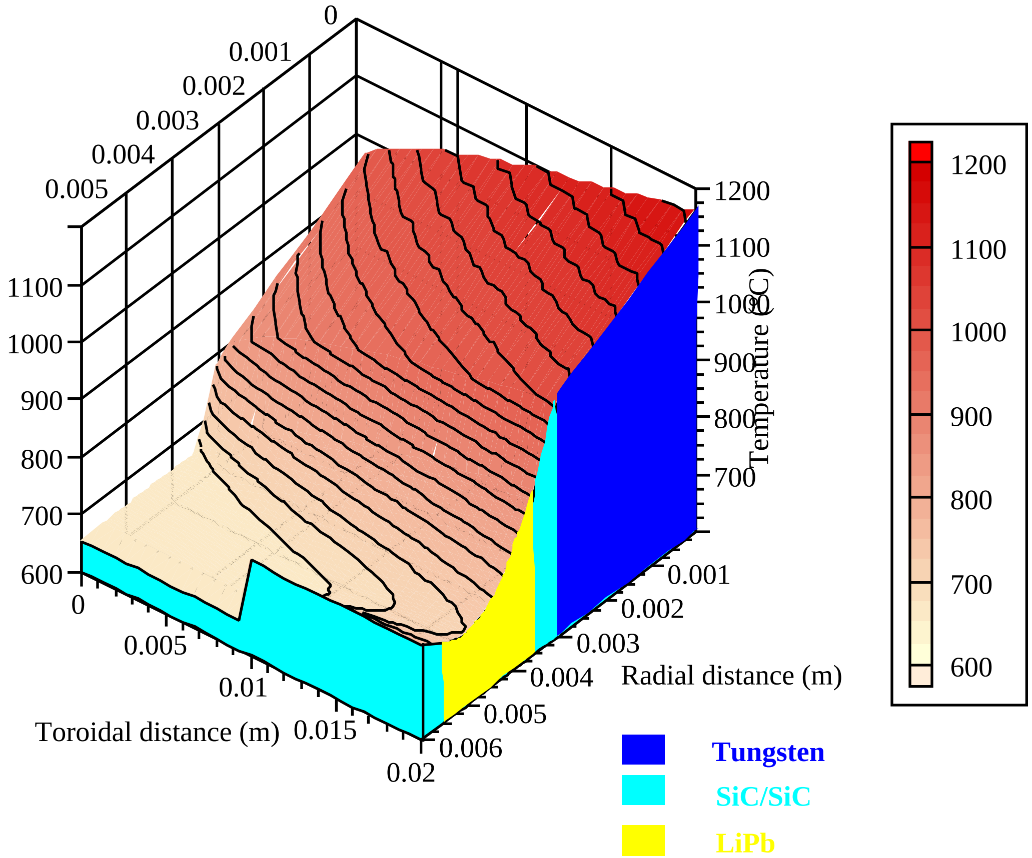
- Minimize Interaction Parameter (<1) (Strong Inertial Effects)
- Flow in High Heat Flux Region Parallel to Magnetic Field (Toroidal)
- Minimize Flow Length and Residence Time
- Heat Transfer Analysis Based on MHD-Laminarized Flow

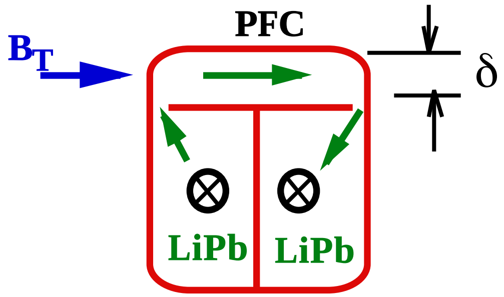


LiPb Poloidal Flow in ARIES-AT Divertor Header



Temperature Distribution in Outer Divertor PFC Channel Assuming MHD-Laminarized LiPb Flow

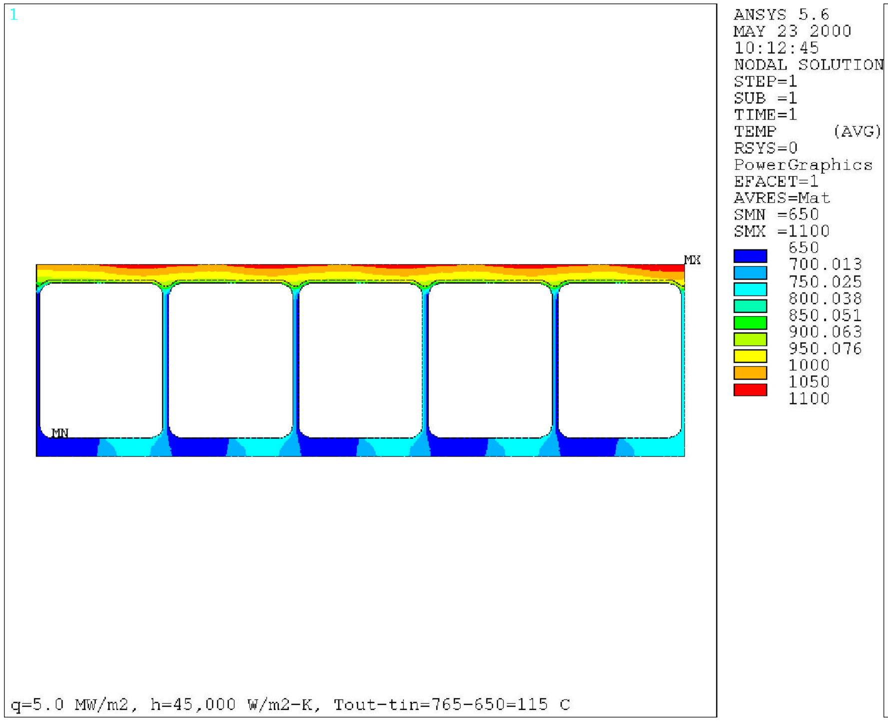


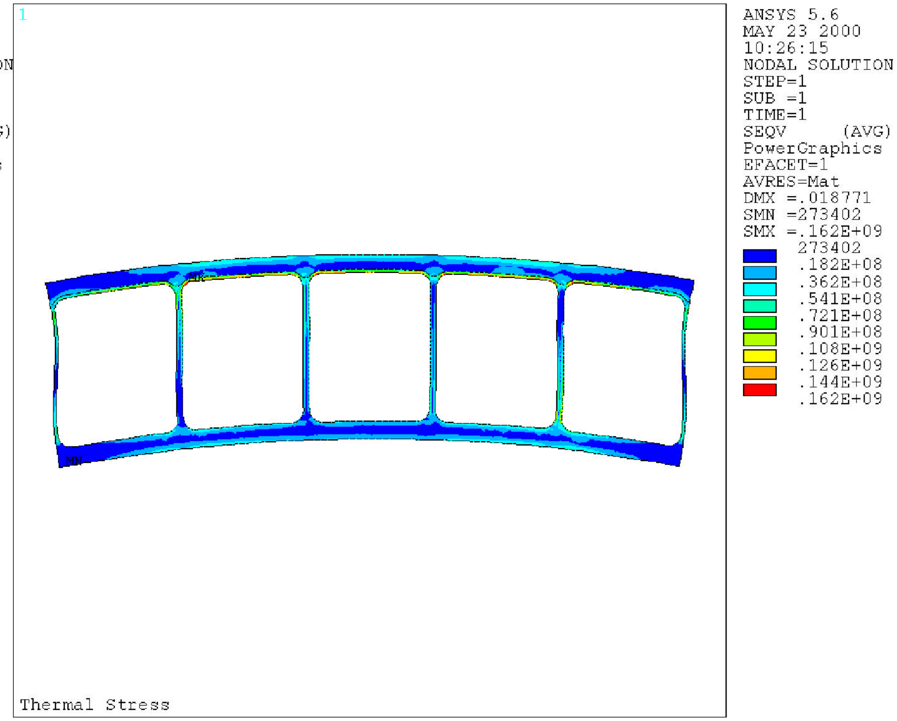


- 2-D Moving Coordinate Analysis
- Inlet temperature = 653°C
- W thickness = 3 mm
- SiC/SiC Thickness = 0.5 mm
- LiPb Channel Thickness = 2 mm
- SiC/SiC Inner Wall Thick. = 0.5 mm
- LiPb Velocity = 0.35 m/s
- Surface Heat Flux = 5 MW/m^2

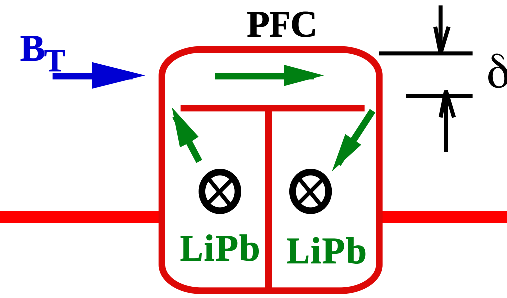
Thermal Analysis of Divertor Channel

- **Maximum SiC/SiC Temperature ~ 950°C**
- **Maximum SiC/SiC Thermal Stress ~ 160 MPa**

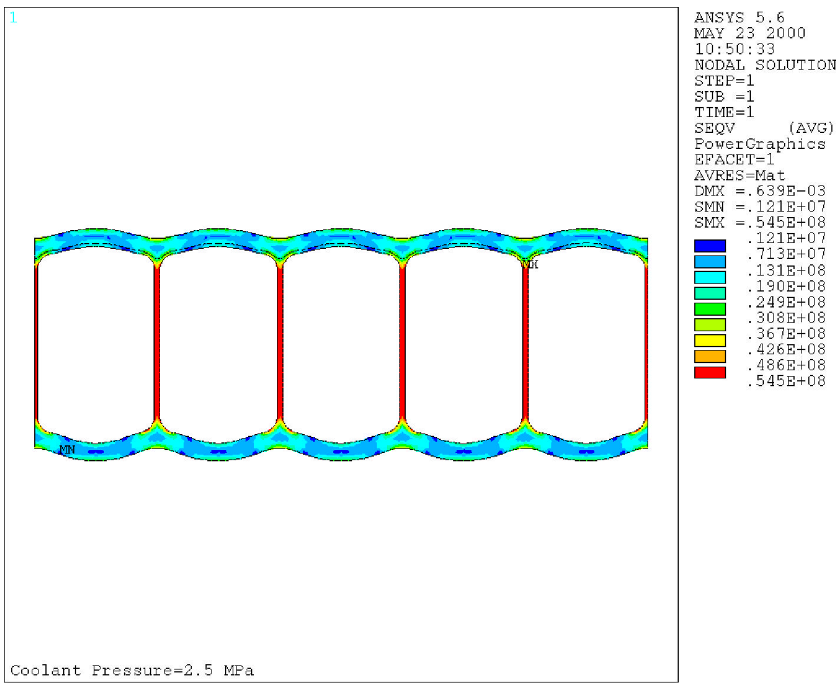


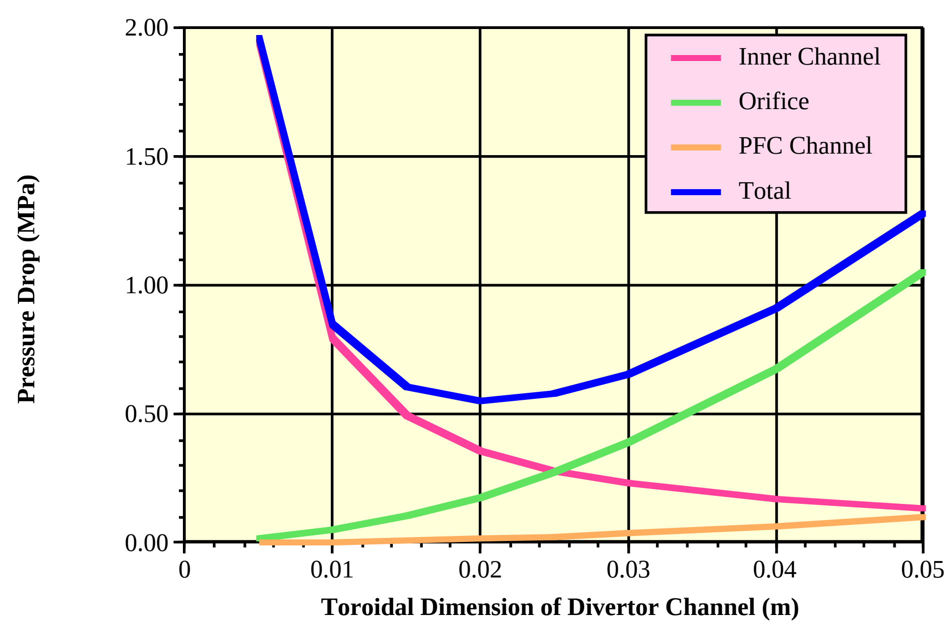


Pressure Stress and Pressure Drop in Divertor Channel

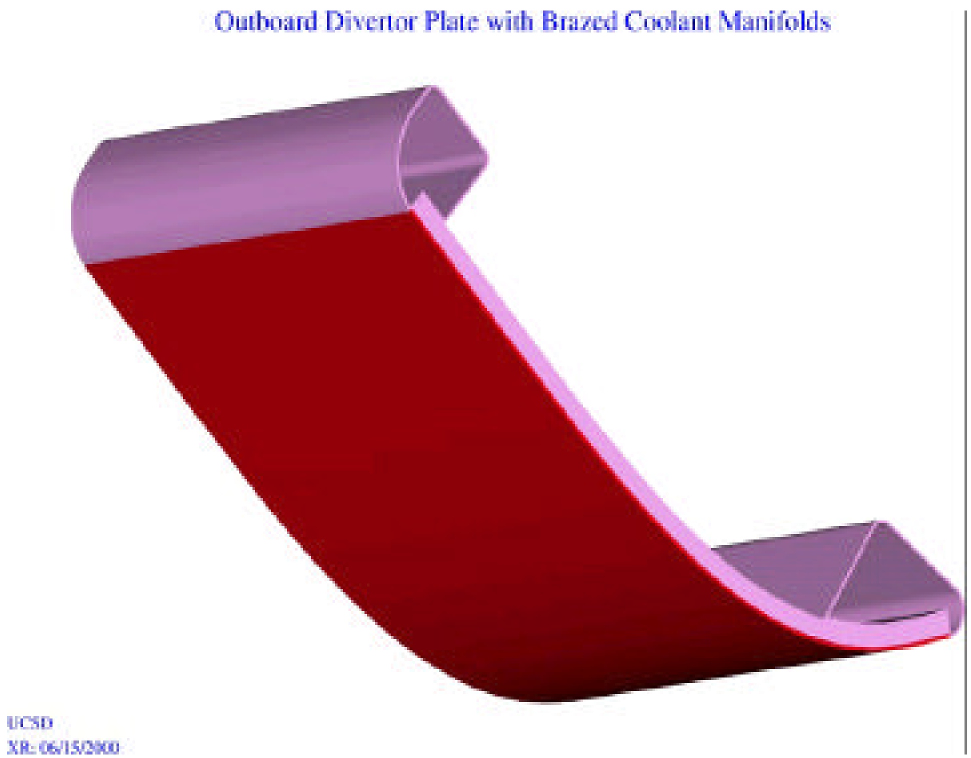


- **2-cm toroidal dimension and 2.5 mm min. W thickness selected** (+ 1mm sacrificial layer)
  - SiC/SiC pressure stress ~ 35 MPa for a combined stress of ~195 MPa
  - ΔP is minimized to ~0.55 MPa for lower divertor and ~0.7 MPa for upper divertor
- **Maximum SiC/SiC Temperature ~ 950°C**





Outer Divertor Plate with Brazed Coolant Manifold



- **Minimize brazing**
  - **SiC/SiC plate manufactured in two toroidal halves with constant dimension channels**
  - **Flow insert slided in**
  - **Two halves brazed together**
  - **End cap + manifold brazed on each end**
  - **W layer bonded to SiC/SiC (possibly by plasma spray, to be checked by M. Billone)**

Typical Blanket and Divertor Parameters for Design Point

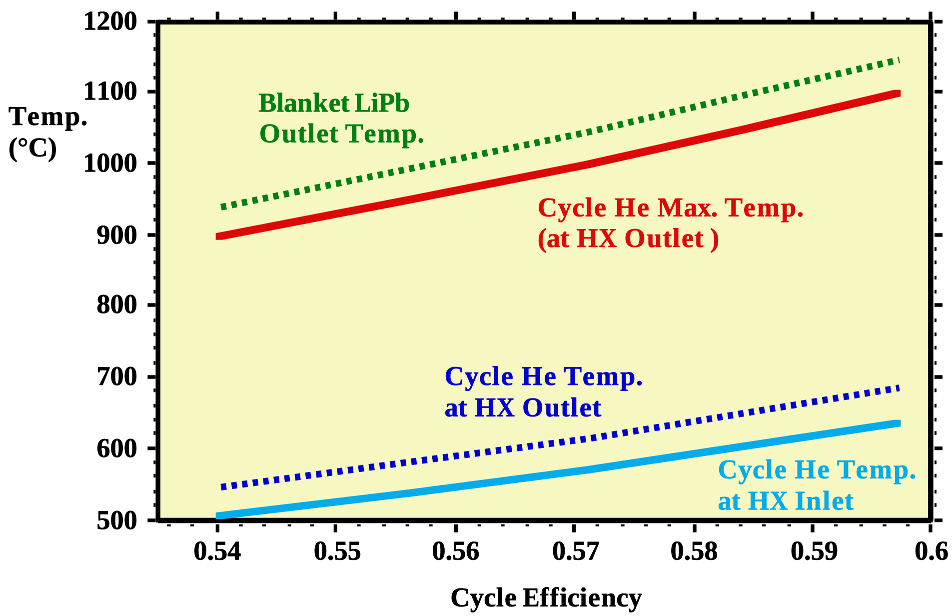
Blanket Outboard Region 1

No. of Segments	32
No. of Modules per Segment	6
Module Poloidal Dimension	6.8 m
Avg. Module Toroidal Dimen.	0.19 m
FW SiC/SiC Thickness	4 mm
FW CVD SiC Thickness	1 mm
FW Annular Channel Thickness	4 mm
Avg. LiPb Velocity in FW	4.2 m/s
FW Channel Re	3.9×10^5
FW Channel Transverse Ha	4340
MHD Turbulent Transition Re	2.2×10^6
FW MHD Pressure Drop	0.19 MPa
Maximum SiC/SiC Temp.	996°C
Maximum CVD SiC Temp. (°C)	1009 °C
Max. LiPb/SiC Interface Temp.	994°C
Avg. LiPb Vel. in Inner Channel	0.11 m/s

Divertor

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 Divertor Channels (Outer/Inner)	1316/1167
SiC/Si Plasma-Side Thickness	0.5 mm
W Thickness	3.5 mm
PFC Channel Thickness	2 mm
Number of Toroidal Passes	2
Outer Div. PFC Channel V (Lower/Upper)	0.35/0.42 m/s
LiPb Inlet Temperature (Outer/Inner)	653/719 °C
Pressure Drop (Lower/Upper)	0.55/0.7 MPa
Max. SiC/SiC Temp. (Lower/Upper)	970/950°C
Maximum W Temp. (Lower/Upper)	1145/1125°C
W Pressure + Thermal Stress	~35+50 MPa
SiC/SiC Pressure + Thermal Stress	~35+160 MPa
Toroidal Dimension of Inlet and Outlet Slot	1 mm
Vel. in Inlet & Outlet Slot to PFC Channel	0.9-1.8 m/s
Interaction Parameter in Inlet/Outlet Slot	0.46-0.73

Extra Margin on Accommodating Temperature Limit by Reducing Coolant Temperature with Relatively Small Impact on Brayton Cycle η



- **Brayton Cycle Parameters:**
  - Min. He Temp. in cycle (heat sink) = 35 °C
  - 3-stage compression with 2 inter-coolers
  - Turbine efficiency = 0.93
  - Compressor eficiency = 0.88
  - Recuperator effectiveness = 0.96
  - Cycle He fractional ΔP = 0.03
  - Total Compression ratio = 3
- **Heat Exchanger:**
  - Effectiveness = 0.9
  - $(mCp)_{He}/(mCp)_{LiPb} = 1$

Future Work Includes:

- **Complete 3-D structural analysis of divertor**
  - **Surface heat flux profile required (GA)**
- **Evolve in more detail blanket and divertor fabrication flow diagrams**
- **Documentation**