ARIES-AT Blanket and Divertor Concepts

The ARIES Team

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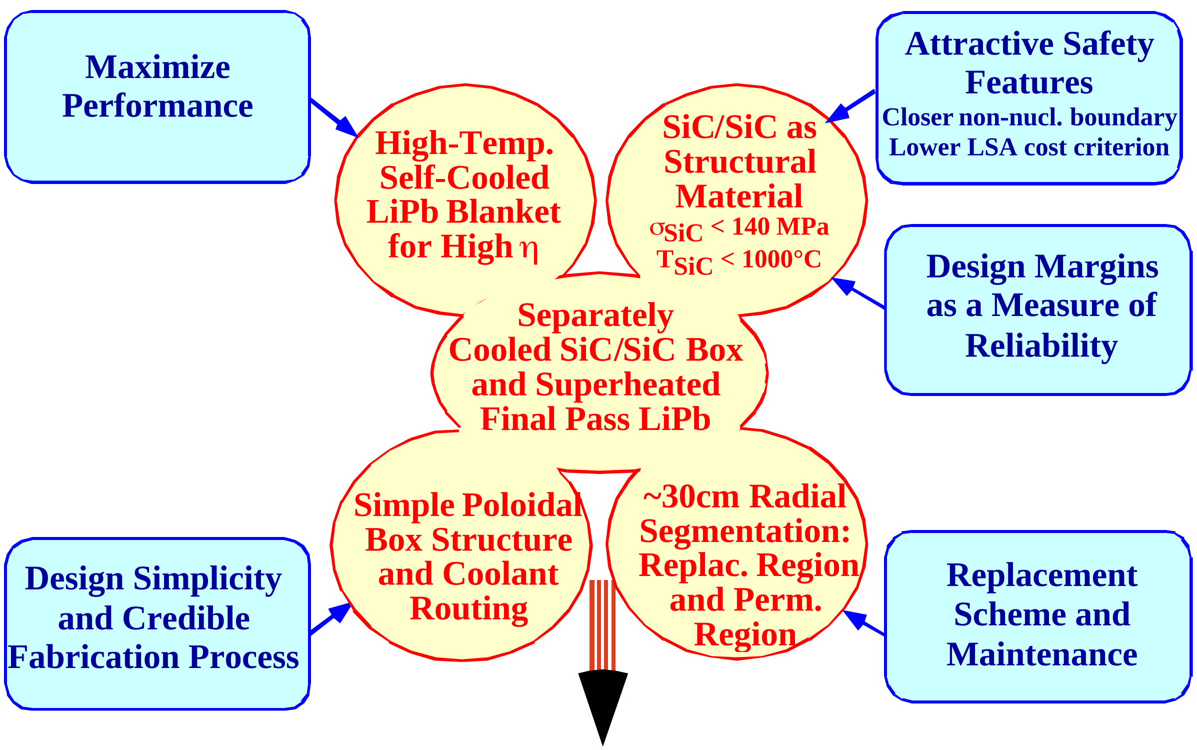
Presentation Outline

- **Design Process**
- **Power Cycle**
  - Benefit of high-temperature operation
- **Blanket**
  - MHD flow considerations
  - Coolant routing
  - Performance and margins for given constraints
- **Divertor**
  - Possibility of LiPb as coolant

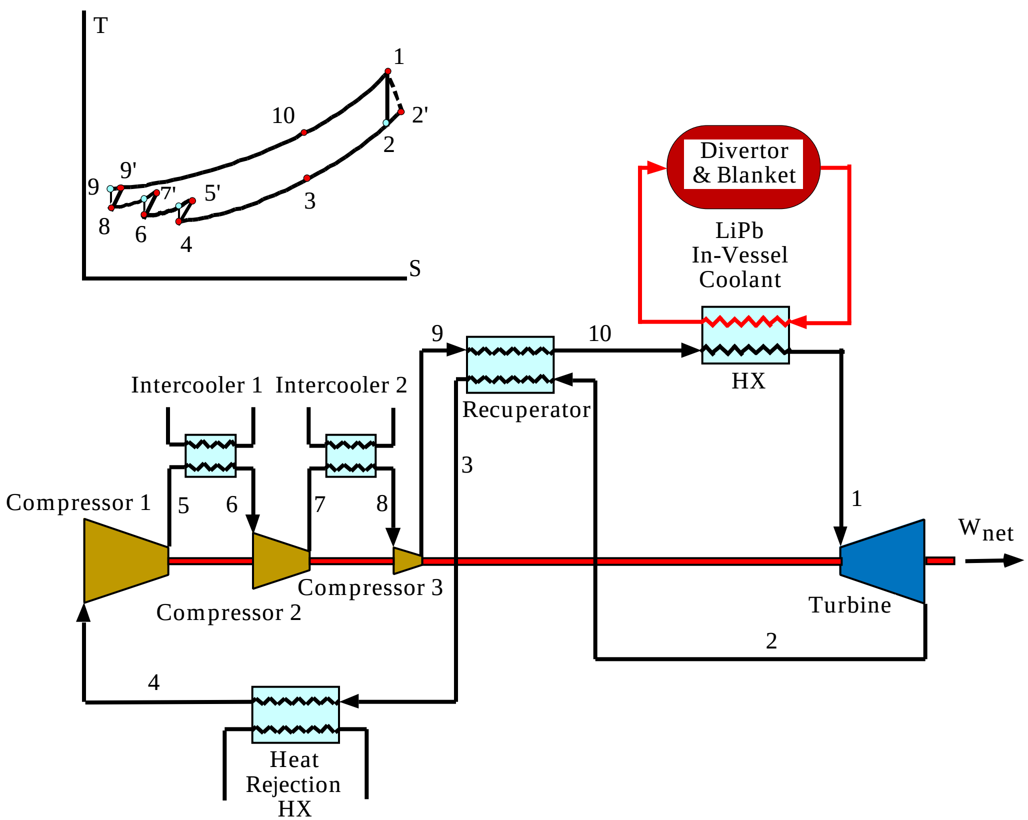
Design Process

Minimize COE while maintaining reasonable margins, credible fabrication and maintenance processes, and attractive safety features



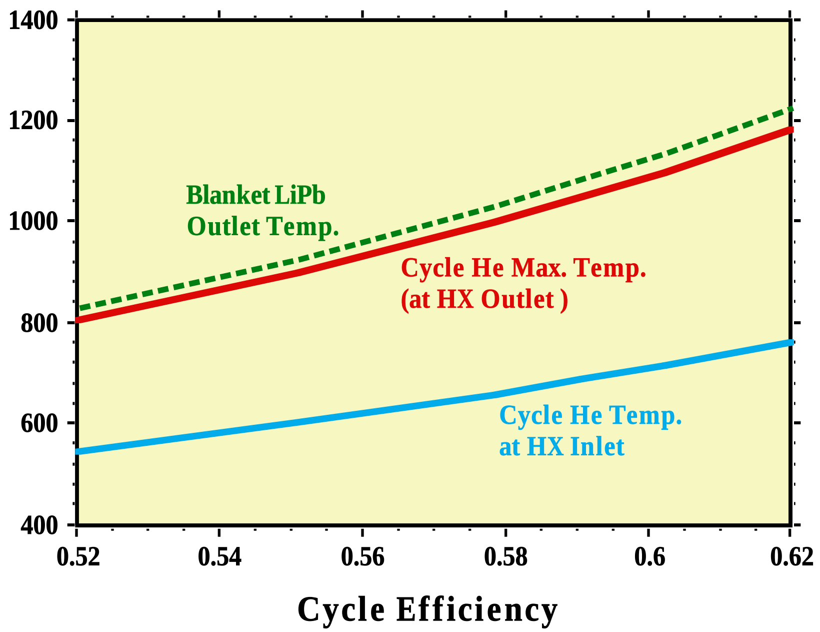
ARIES-AT BLANKET DESIGN

Brayton Power Cycle



- **Best near-term possibility of power conversion with high efficiency**
  - Maximize potential gain from high-temperature operation with SiC/SiC
- **Compatible with liquid metal blanket through use of HX**

Power Cycle Parameters



Brayton Cycle Parameters:

- Min. T_{He} in cycle (heat sink) = 35°C
- 3-stage compression with 2 inter-coolers
- Turbine efficiency = 0.93
- Compressor efficiency = 0.88
- Recuperator effectiven. = 0.96
- Cycle He fractional ΔP = 0.03
- Total compression ratio set to maximize efficiency (=2-2.5)

Intermediate Heat Exchanger

- Effectiveness = 0.9
- $(mCp)_{He}/(mCp)_{LiPb} = 1$

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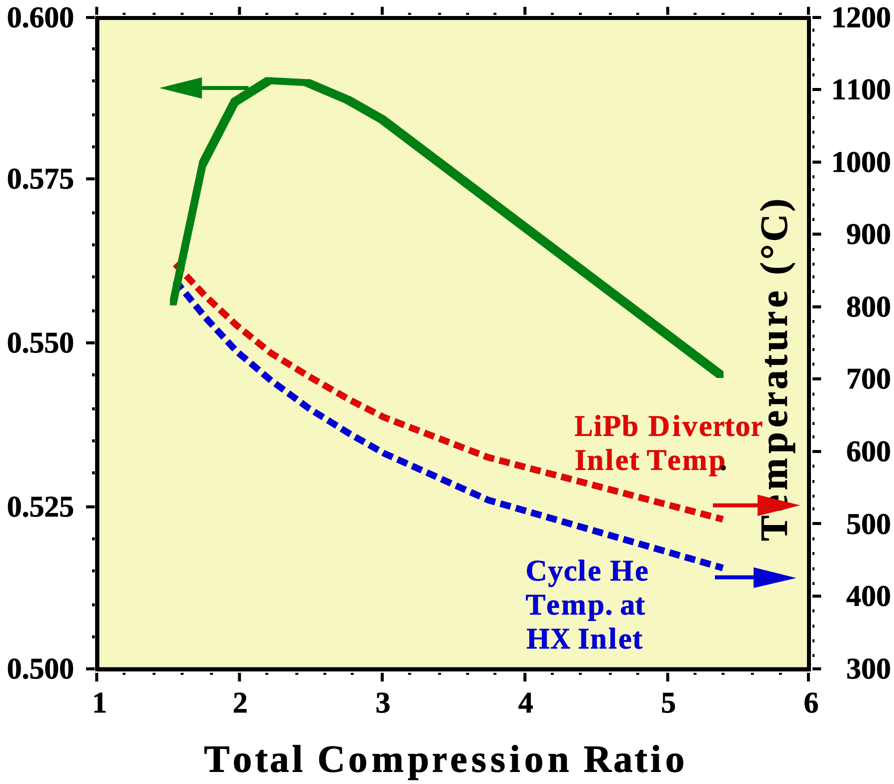
Brayton Cycle Efficiency, He HX Inlet Temp. and LiPb HX Outlet Temp. as a Function of Total Compression Ratio



Max. Cycle He Temp. = 1050°C

Example Design Point:

- Total compression ratio = 3
- Cycle efficiency = 0.585
- Cycle He temp. at HX inlet = 604°C
- LiPb Inlet Temp. to Divertor = 650°C

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

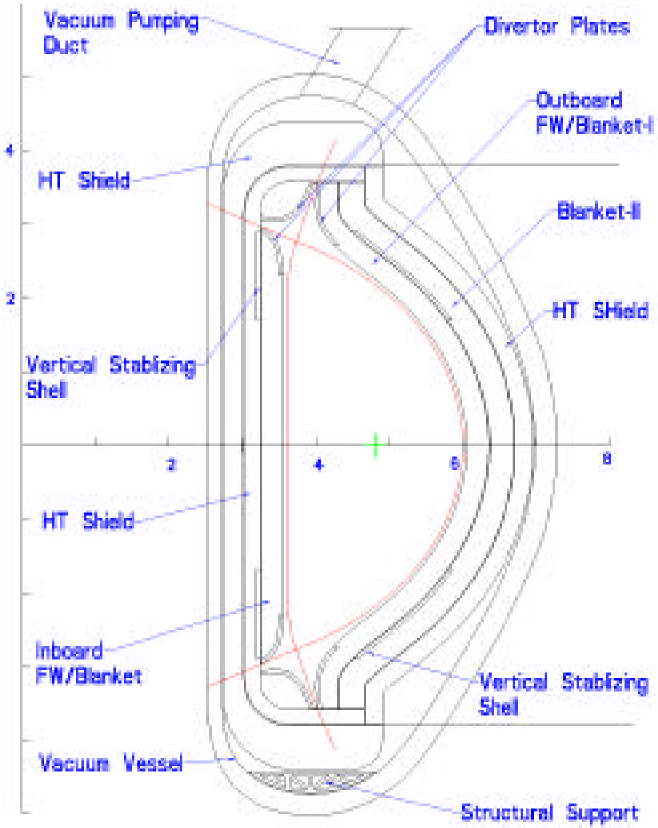
Machine Geometry

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

Cross-Section of ARIES-AT Showing Power Core Components



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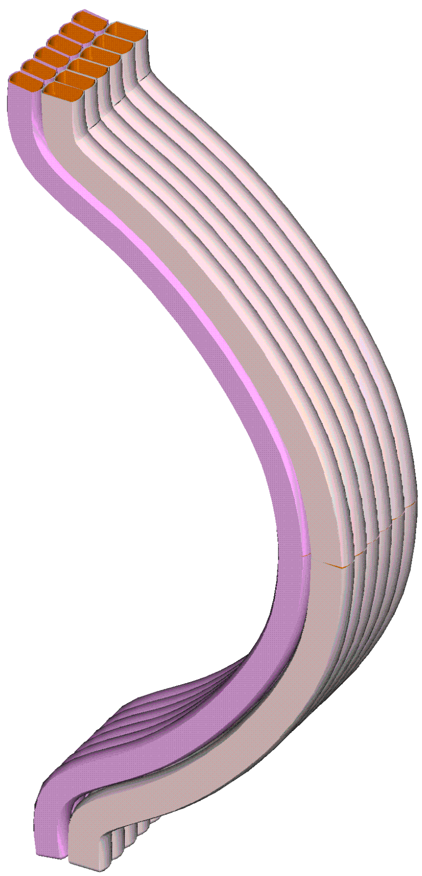
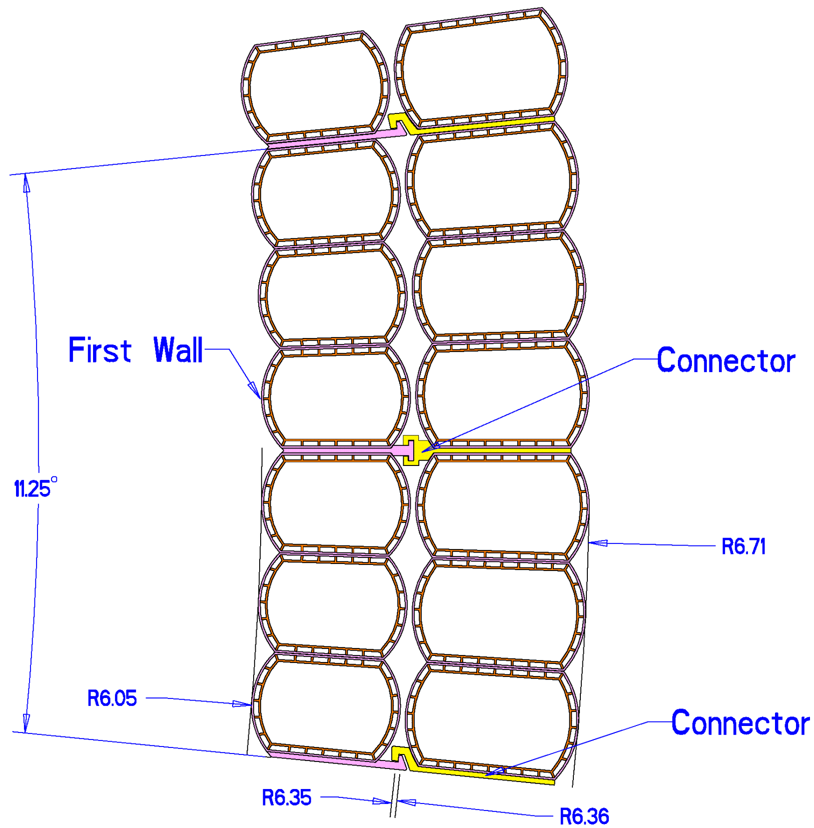
Example LiPb Coolant Circuits

- **Circuit 1 - Lower Divertor + Inboard Region**
  - Thermal Power 535 MW
  - Mass Flow Rate 66500 kg/s
  - Pressure Drop 0.85 MPa
  - Pumping Power 0.79 MW
- **Circuit 2 - Upper Divertor + First Outboard Region**
  - Thermal Power 1040 MW
  - Mass Flow Rate 12,700 kg/s
  - Pressure Drop 0.83 MPa
  - Pumping Power 1.44 MW
- **Circuit 3 - *Hot Shield (Tentative)* + Second Outboard Region**
  - Thermal Power 352 MW
  - Mass Flow Rate 4270 kg/s

ARIES-AT Outboard Blanket Configuration





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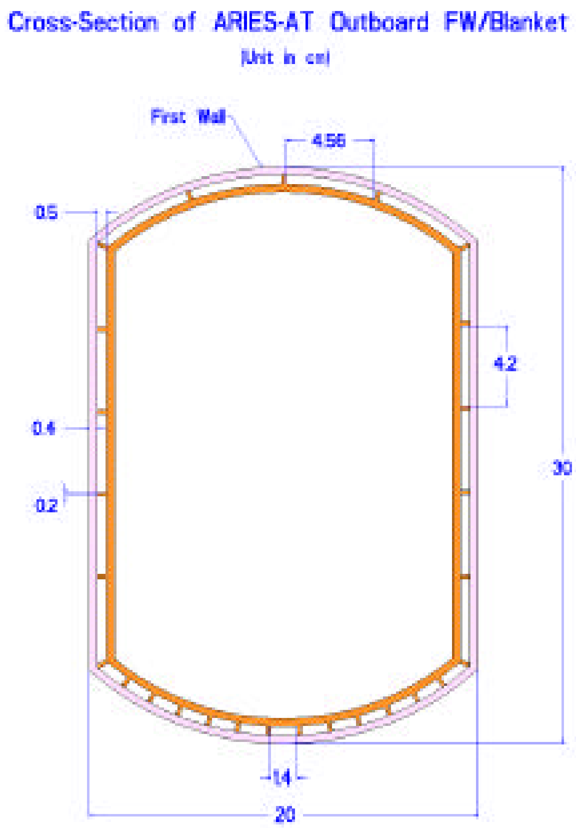
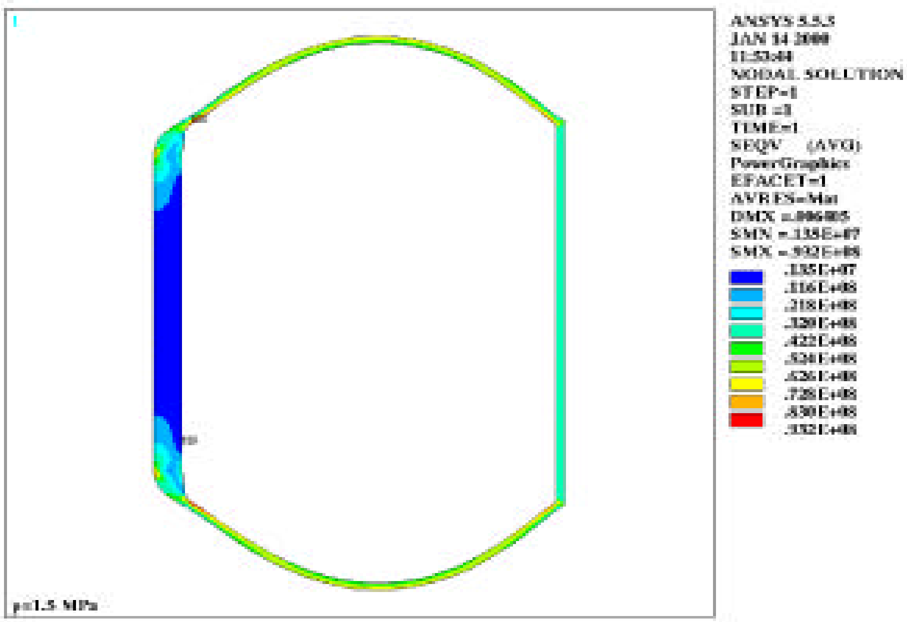
Cross-Section of First Outboard Region of ARIES-AT Blanket



Pressure Stress on Blanket Outer Module Shell



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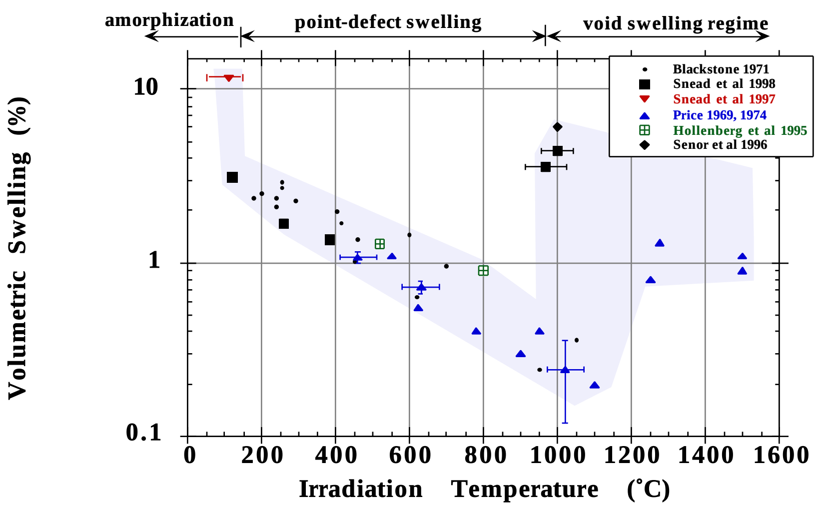
SiC/SiC Properties Assumed for ARIES-AT Analysis

• Density	3200 kg/m^3
• Density Factor	0.95
• Young's Modulus	360 GPa
• Poisson's ratio	0.16
• Thermal Expansion Coefficient	4.4 ppm/°C
• Thermal Conductivity in Plane	25 W/m-K
• Therm. Conductivity through Thickness	20 W/m-K
• Maximum Allowable Primary Stress	~140 MPa
• Maximum Allowable Secondary Stress	~190 MPa
• Maximum Allowable Operating Temperature	1000 °C
• Max. Allowable SiC/LiPb Interface Temperature	~ 1000°C(TBD)
• Maximum Allowable SiC Burnup	3%

Maximum SiC/SiC Temperature Limit

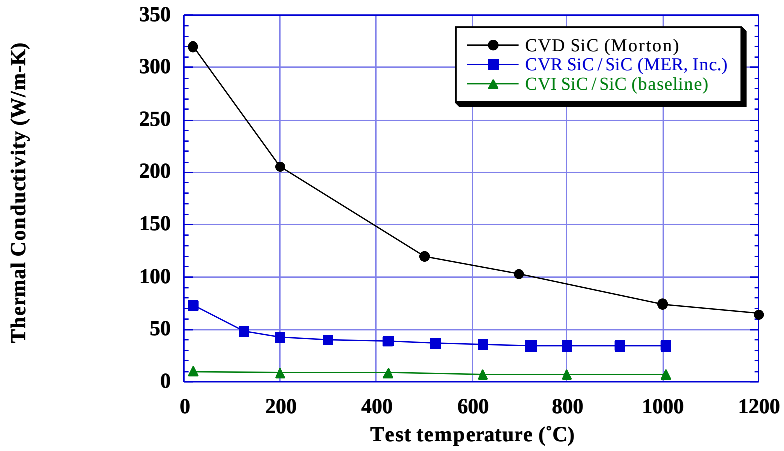


Radiation induced swelling in bulk SiC as a function of irradiation temperature

(from S. Zinkle and L. Snead, ORNL)

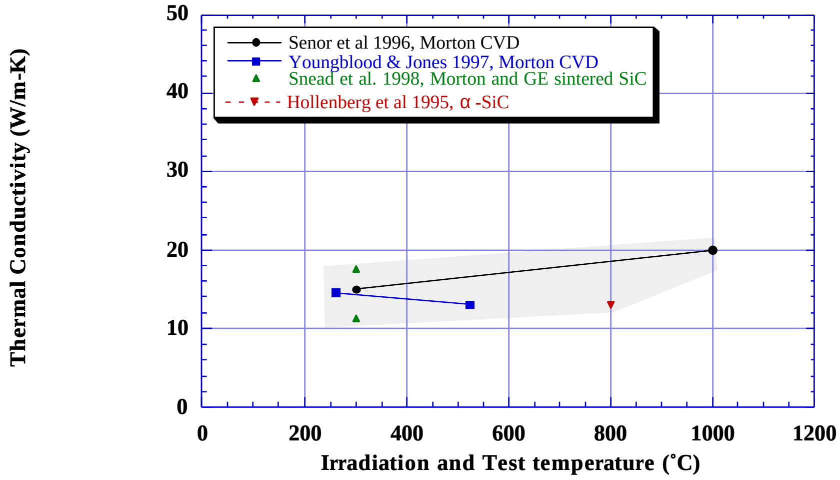
- **Strength degradation arising at interface due to O presence and non-stoichiometry of fibers could be alleviated by improving the fabrication procedure with a potentially large increase in the allowable temperature (1100-1400°C?)**
- **However, consideration of void swelling under irradiation imposes a more severe constraint (~1000°C)**

SiC/SiC Thermal Conductivity



Comparison of the transverse thermal conductivity of monolithic CVD SiC and two grades of SiC/SiC composites

(From S. Zinkle and L. Snead, ORNL)



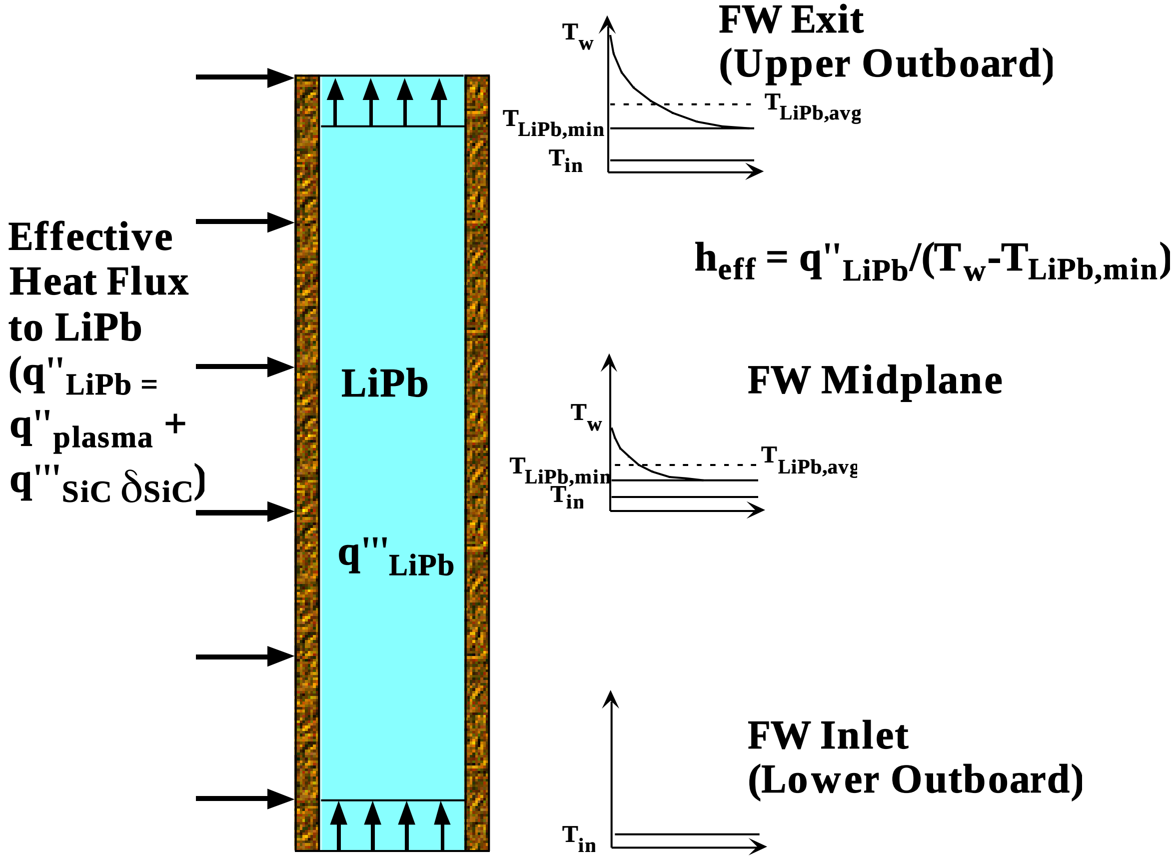
Effect of neutron irradiation on the thermal conductivity of bulk SiC. Data were from samples irradiated to 25-43 dpa, except for the data by Snead et al. Which were obtained on samples irradiated to 0.1 dpa.

(From S. Zinkle and L. Snead, ORNL)

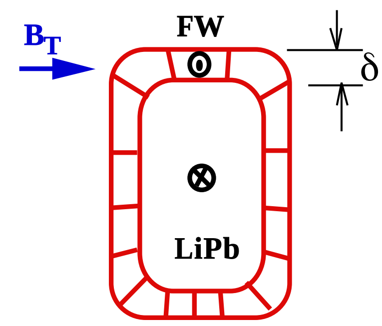
Some Key SiC/SiC Properties

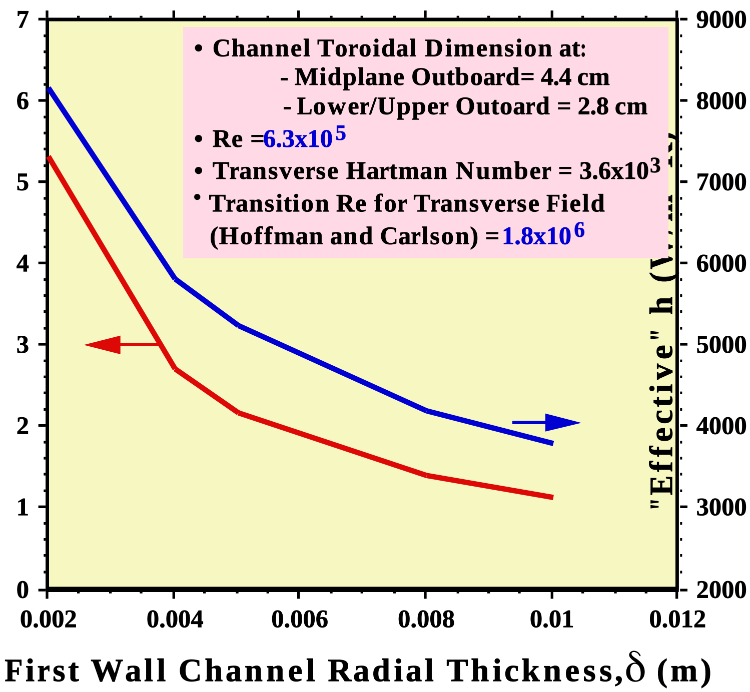
- **SiC/SiC Thermal Conductivity**
  - Decreases with temperature and irradiation
  - ARIES-I assumed 15 and 12 W/m-K for inplane and through thickness k, respectively.
  - Recent measurement of MER CVR SiC/SiC sample yielded 75 W/m-K at RT and 30-35 W/m-K at 1000°C
  - In-situ k measurement of SiC/SiC samples at ORNL being finalized
- **SiC/SiC Allowable Stress**
  - ARIES-I: Primary stress < 140 MPa; Secondary stress < 190 MPa
    (Based on a fraction of the computed tensile strength of 286 MPa for SiC/SiC with 60% fiber volume fraction)
  - Design Code and stress calculations for orthotropic material (Von Mises?, stress in each direction (TAURO))
- **SiC/SiC Compatibility with LiPb**
  - One data point indicates no problem for stagnant LiPb/SiC compatibility after 1500 hours exposure at 800°C (ISPRA)

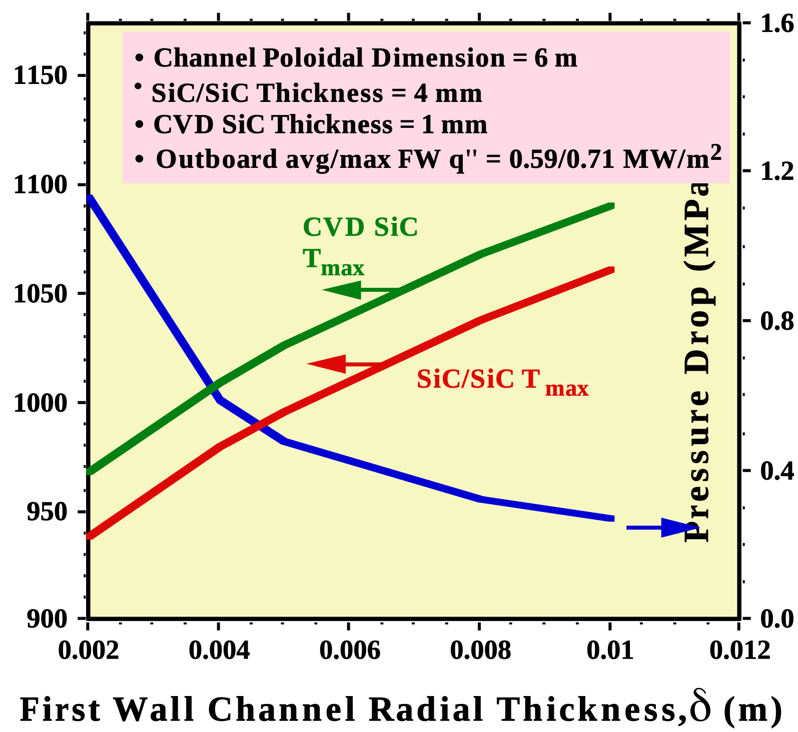
LiPb Temperature Distribution in FW Poloidal Channel under MHD-Laminarization Effect



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







Divertor Design Considerations

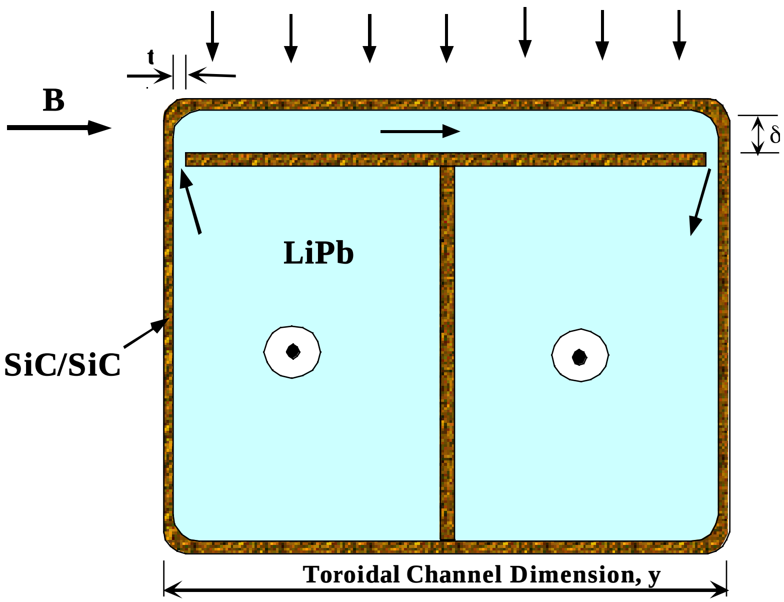
- **Compatibility with Blanket Configuration**

- **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)

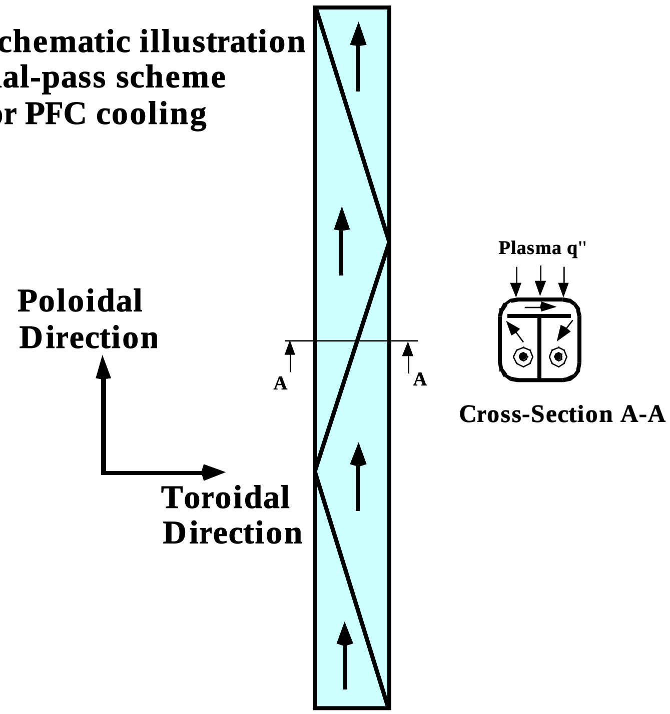
LiPb Cooling Scheme for ARIES-AT Divertor

LiPb Poloidal/Toroidal Flow for ARIES-AT Divertor

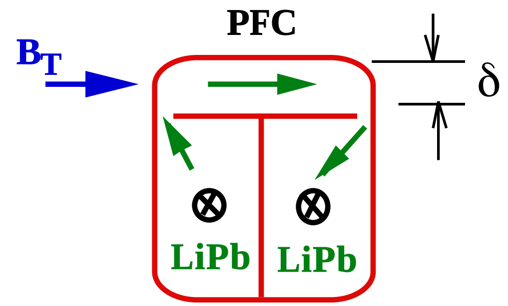


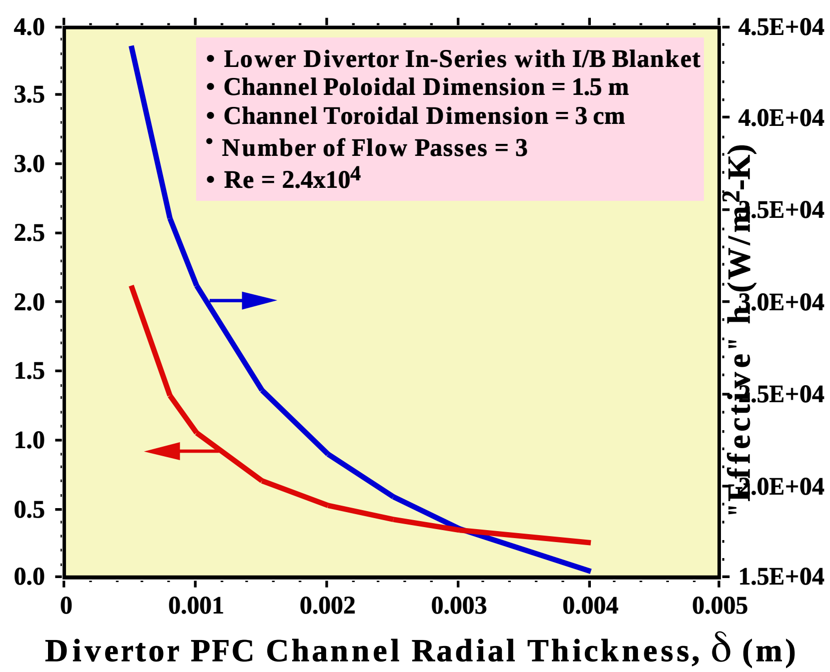
LiPb Poloidal Flow in ARIES-AT Divertor Header

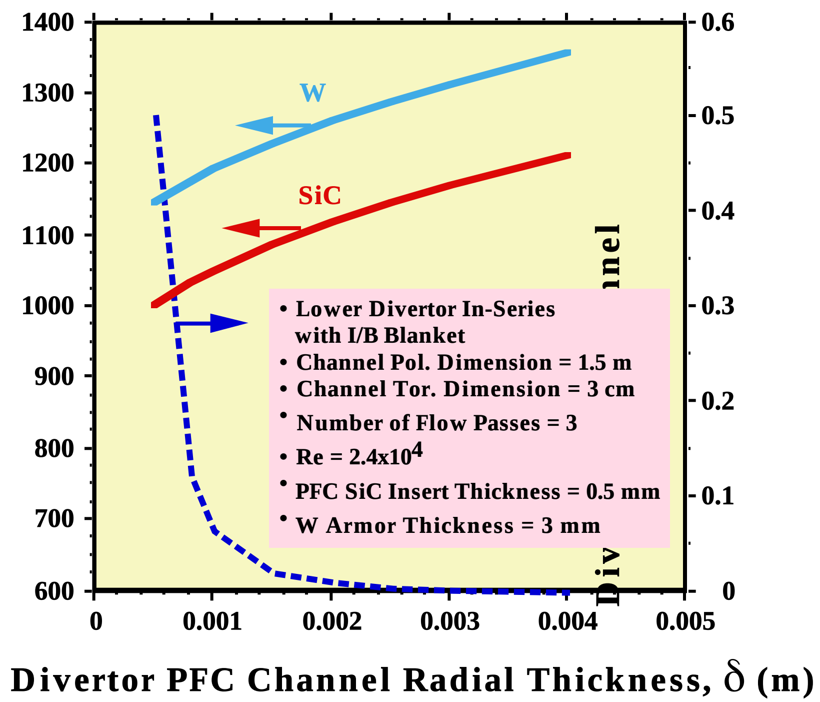
Example schematic illustration of 3-toroidal-pass scheme for divertor PFC cooling



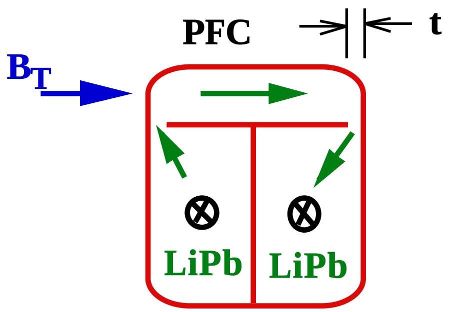
Flow and Thermal Parameters for LiPb-Cooled Divertor PFC as a Function of PFC Channel Thickness



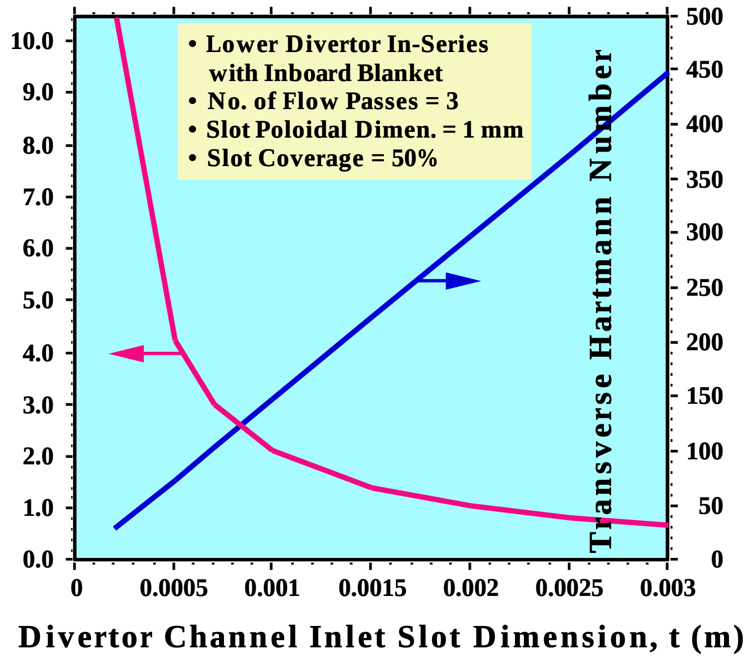


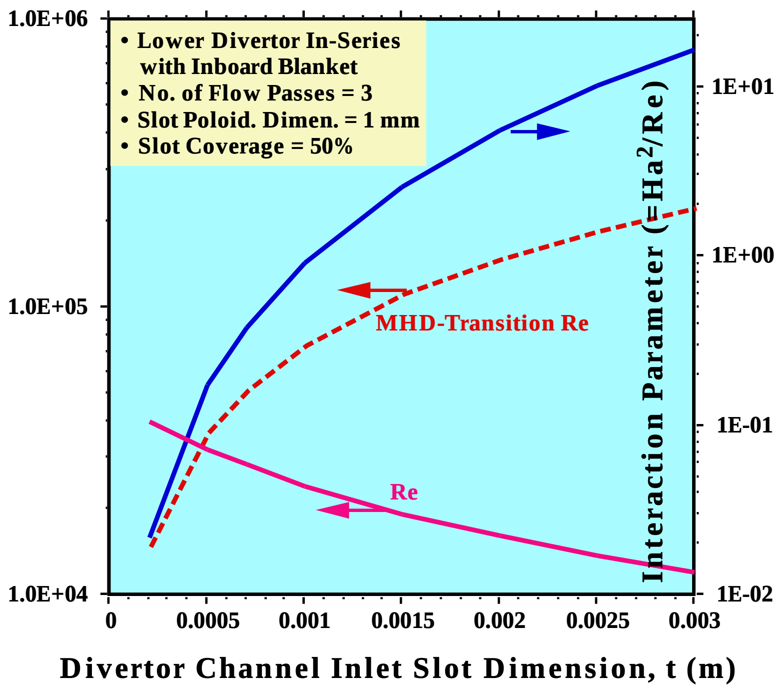


Velocity, Ha, Re, and Interaction Parameter as a Function of Divertor Channel Inlet/Outlet Slot Dimension



- 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
LiPb Average Velocity in FW	2.2 m/s
FW Channel Re	6.2×10^5
FW Channel Transverse Ha	3540
MHD Turbulent Transition Re	1.8×10^6
Eff. MHD-Laminarized h	5240 W/m^2-K
FW MHD Pressure Drop	0.49 MPa
Maximum SiC/SiC Temp.	997°C
Maximum CVD SiC Temp. (°C)	1030 °C
SiC/SiC FW Hoop Stress	36 MPa

Lower Divertor	
Poloidal Dimension	1.5 m
Divertor Channel Toroidal/Radial Dimen.	3.8/3.75 cm
Number of Divertor Channels in OB/IB	794/595
SiC Insert Thickness	0.5 mm
W Thickness	3 mm
PFC Channel Thickness	1.5 mm
Number of Toroidal Passes	3
Velocity in PFC Channel	0.7 m/s
Eff. MHD-Laminarized h (W/m^2-K)	25,200
Maximum SiC Temperature	1090°C
Maximum W Temperature	1230°C
W (1-D) Thermal Stress	162 MPa
Toroidal Dimension of Inlet/Outlet Slot	0.5 mm
Velocity in Inlet/Outlet Slot to PFC Channel	4.25 m/s
Interaction Parameter in Inlet/Outlet Slot	0.17
Total Divertor Pressure Drop	0.18 MPa

Conclusions

- **High Performance SiC/SiC + LiPb Blanket**
  - Major impact in lowering COE
  - Attractive safety features

- **Balanced Design Approach**
  - High performance but credible fabrication, reliability, maintenance
    - Maintain reasonable margins as a measure of reliability

- **Specific SiC/SiC Issues Need to be Addressed**
  - Fabrication/joining procedures and cost
  - Better definition of key properties at temperature and under irradiation, including:
    - Thermal conductivity
    - Compatibility with flowing LiPb
    - Operating temperature limit (swelling)
    - Strength degradation
    - Lifetime
  - HX tube material