ARIES: Fusion Power Core and Power Cycle Engineering

The ARIES Team

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Presentation Outline

Power Core and Power Cycle Engineering:

- Power Cycle
- Blanket
- Divertor
- Material

Approach Relies on:

- Detailed Analysis
  - Using up-to-date analysis tools
  - Developing tools for specific analytical needs
- Application of creative solutions to extend design window
- Building Block
  - build on previous ARIES design experience in bettering the end product
- Community Interaction
  - utilize national and international community input in evolving material properties and component parameters
  - develop clear goals for R&D program showing benefits

Power Cycle: Quest for High Efficiency

Conventional Steam Cycle: Steel/Water
h = 35%

→

ARIES-RS
Li/V
Supercritical Rankine (water):
h = 45%

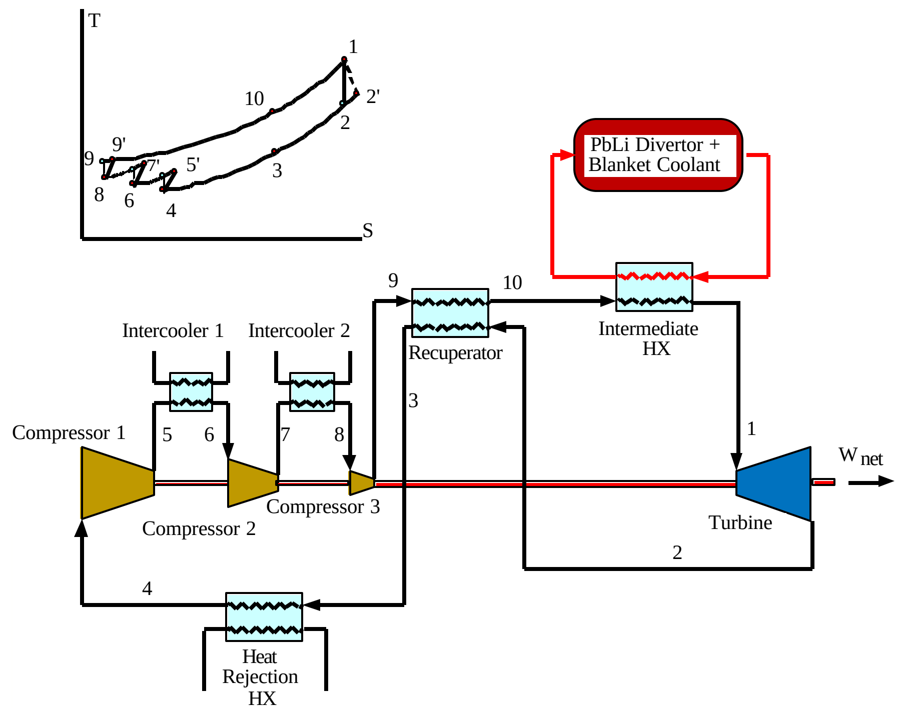
→

ARIES-ST
FS/He/Pb-17Li
Brayton (Low Temp. He):
h > 45%

→

ARIES-AT
(SiC/SiC)/Pb-17Li
Brayton (High Temp. He):
h = 59%

- **High efficiency translates in lower COE and lower heat load**
- **Brayton cycle is 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 IHX**



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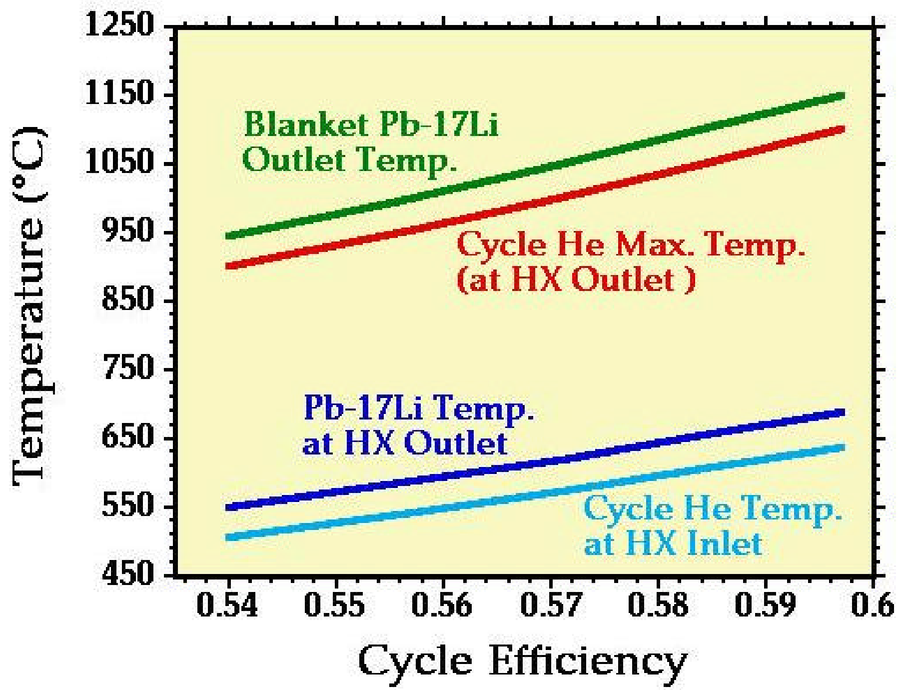
Brayton Cycle Based on Near-Term Technology and Advanced Recuperator Design Yields High Efficiency

Advanced Brayton cycle developed with expert input from GA and FZK, Karlsruhe

- FZK/UCSD ISFNT-4 paper, 1997
- GA/UCSD ANS TOFE-14 paper, 2000

- Min. He Temp. in cycle (heat sink) = 35°C
- 3-stage compression with 2 inter-coolers
- Turbine efficiency = 0.93
- Compressor efficiency = 0.88
- Recuperator effectiveness = 0.96
- Cycle He fractional DP = 0.03
- Total compression ratio set to optimize system (= 2-3)



High Efficiency Requires High Temperature Operation

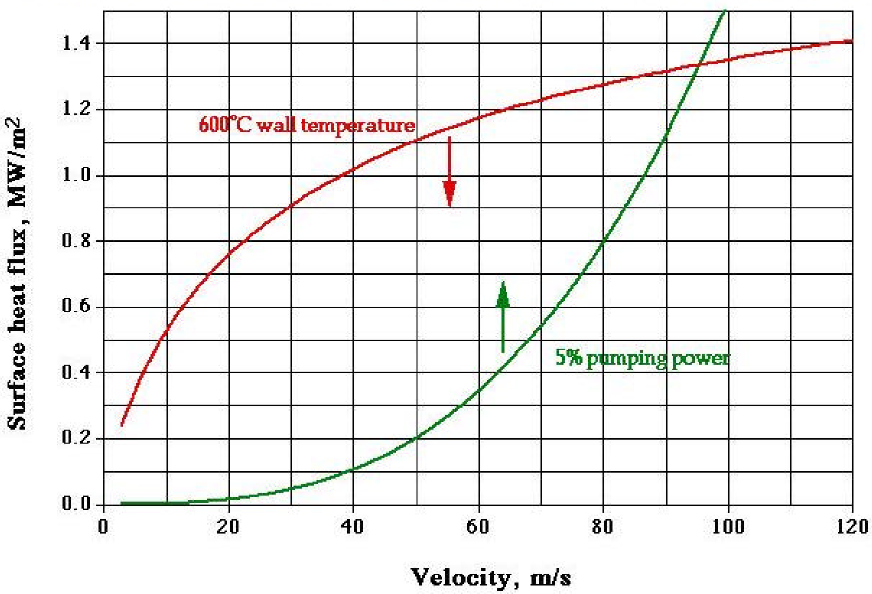
- **Conventionally, maximum coolant temperature is limited by structural material maximum temperature limit**

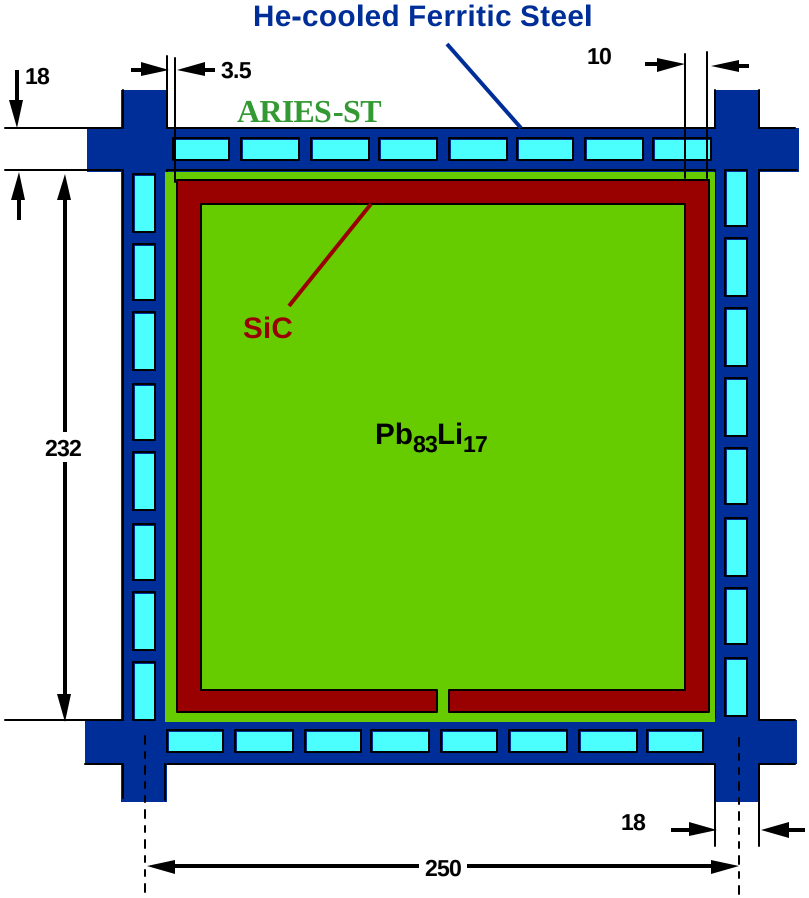
- **Innovative design solutions in ARIES-ST and ARIES-AT allow the blanket coolant exit temperature to be higher than the structure temperature**

ARIES-ST Utilizes a Dual Coolant Approach to Uncouple Structure Temperature from Main Coolant Temperature

- **ARIES-ST: Ferritic steel+Pb-17Li+He**
- **Flow lower temperature He (350-500°C) to cool structure and higher temperature Pb-17Li (480-800°C) for flow through blanket**

ARIES-ST First Wall Thermal-Hydraulic Design Window

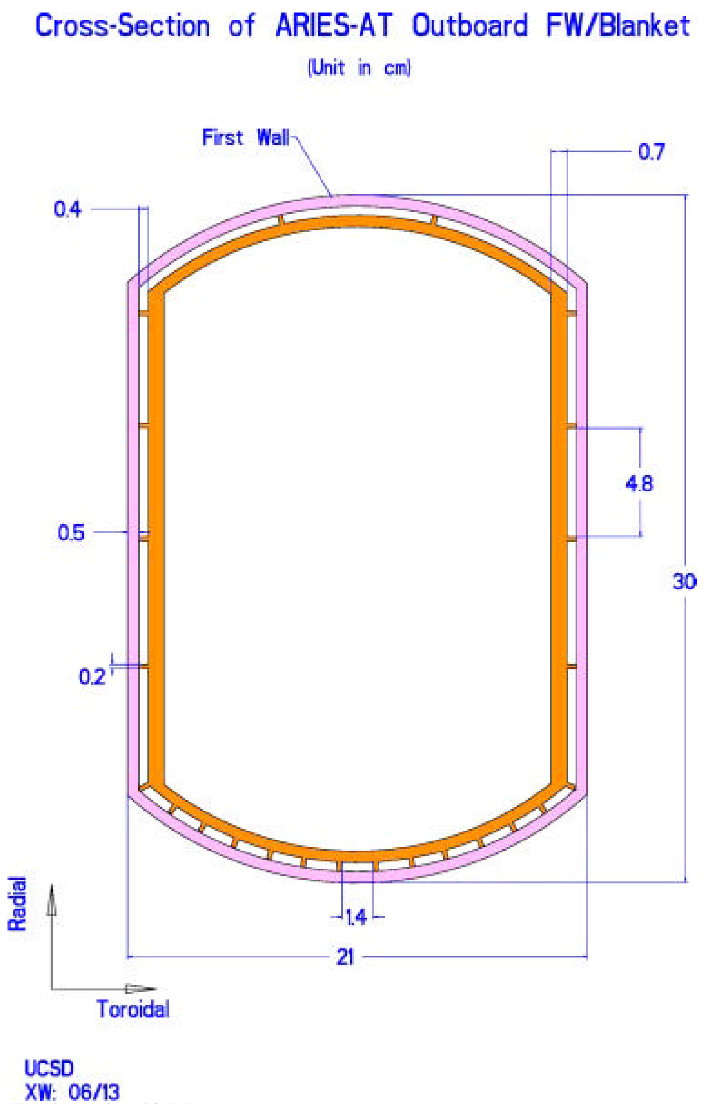




ARIES-AT Utilizes a 2-Pass Coolant Approach to Uncouple Structure Temperature from Outlet Coolant Temperature

- **ARIES-AT: 2-pass Pb-17Li flow, first pass to cool SiC/SiC box and second pass to “superheat” Pb-17Li**

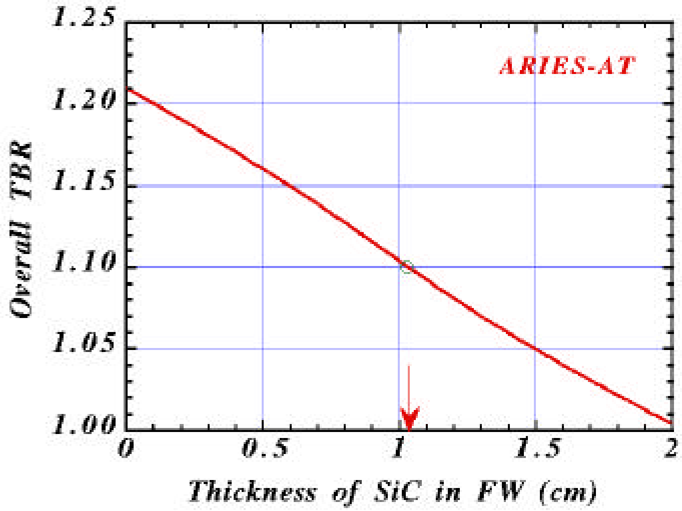
- **Maintain blanket SiC/SiC temperature (~1000°C) < Pb-17Li outlet temperature (~1100°C)**

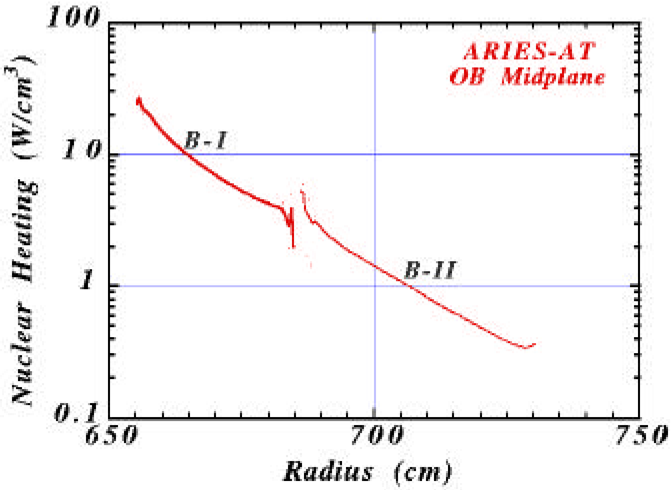


Detailed Modeling and Analysis Required to Demonstrate Blanket Performance

Multi-dimensional neutronics analysis

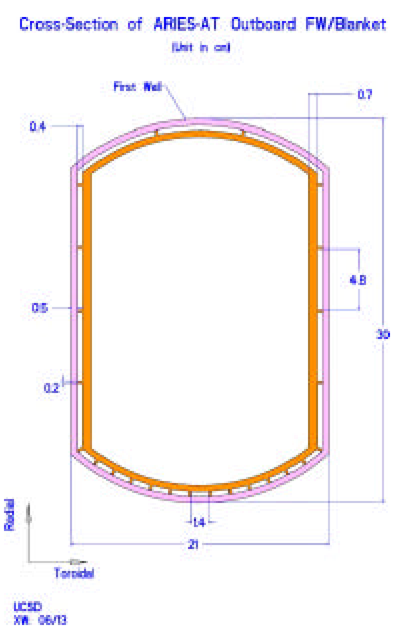
- **Latest data and code**
- **Tritium breeding requirement influences blanket material and configuration choices**
- **Blanket volumetric heat generation profiles used for thermal-hydraulic analyses**



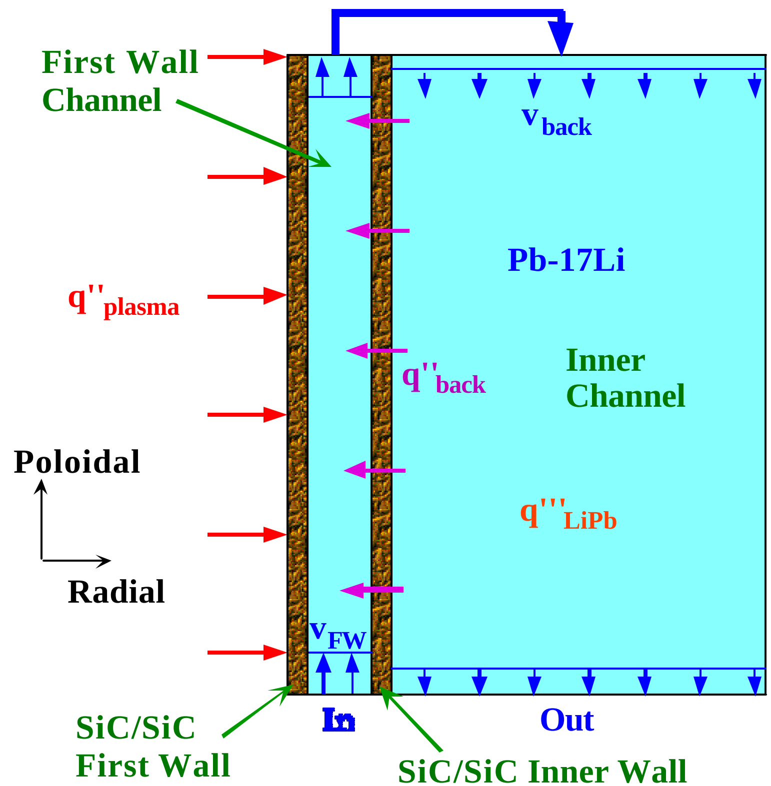


Accommodation of Material Temperature Limits Verified by Detailed Modeling

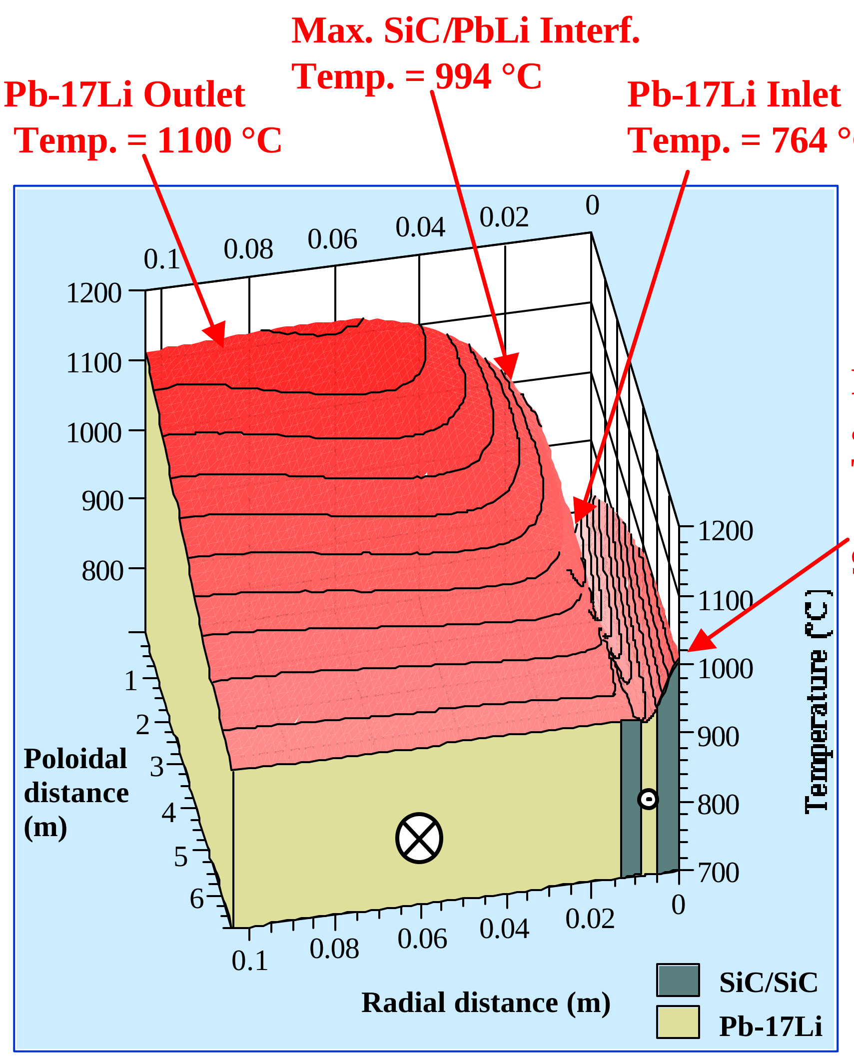
Moving Coordinate Analysis to Obtain Pb-17Li Temperature Distribution in ARIES-AT First Wall Channel and Inner Channel under MHD-Laminarization Effect



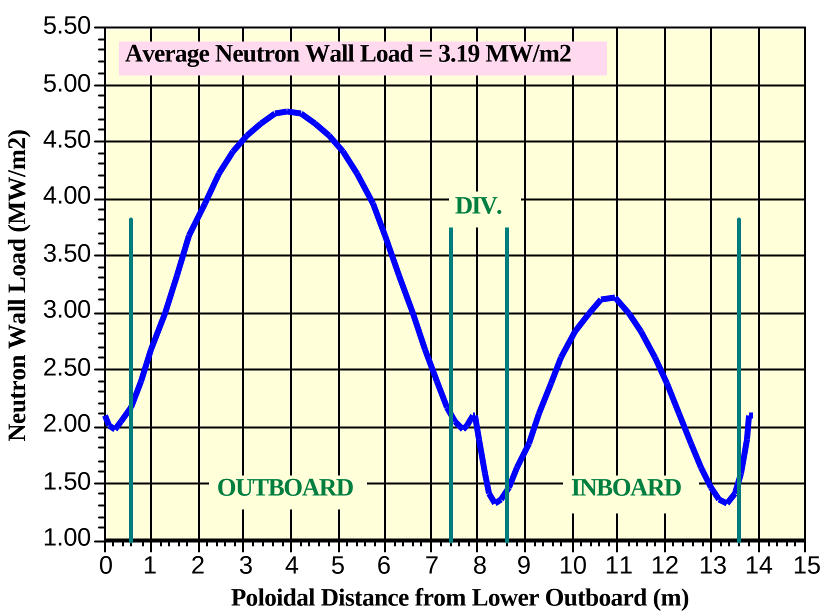
ARIES-AT Outboard Blanket Segment



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



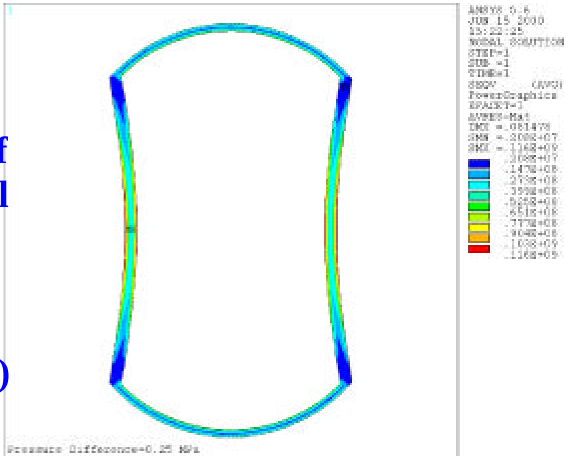
- Use plasma heat flux poloidal profile
- Use volumetric heat generation poloidal and radial profiles
- Iterate for consistent boundary conditions for heat flux between Pb-17Li inner channel zone and first wall zone
- Calibration with ANSYS 2-D results



Detailed Stress Analysis Using Latest Tool for Maintaining Conservative Design Margins

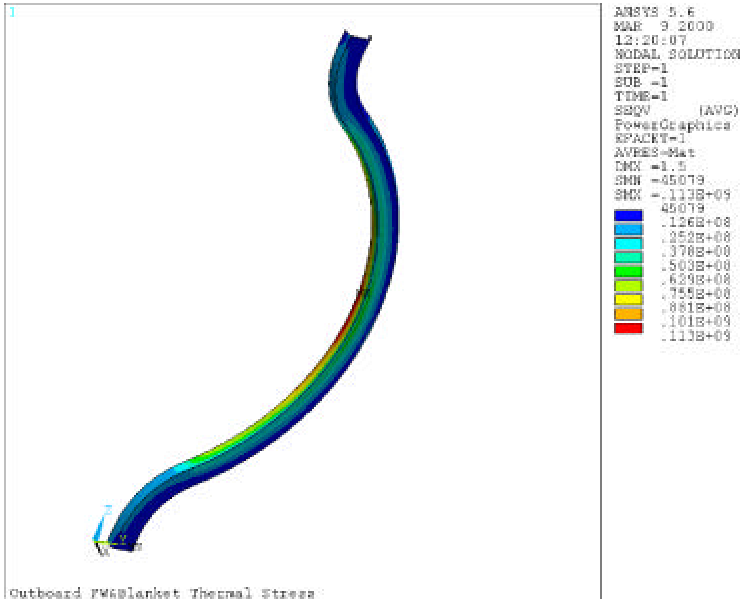
Example of 2-D and 3-D Thermal and Stress Analysis of ARIES-AT Blanket Using ANSYS

Pressure Stress Analysis of Inner Shell of Blanket Module (Max. s =116 MPa)

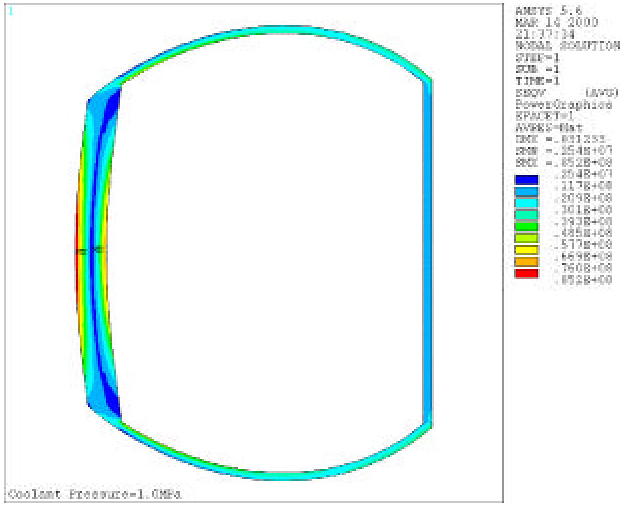


Conservative SiC/SiC stress limit from Town Meeting: Max. allowable thermal + pressure s = 190 MPa

Thermal Stress Distribution in Toroidal Half of Outboard Blanket Module (Max. s =113 MPa)



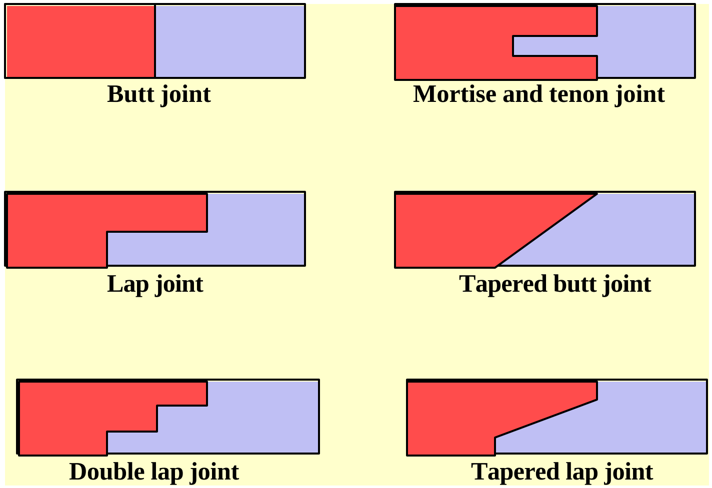
Pressure Stress Analysis of Outer Shell of Blanket Module (Max. s =85 MPa)

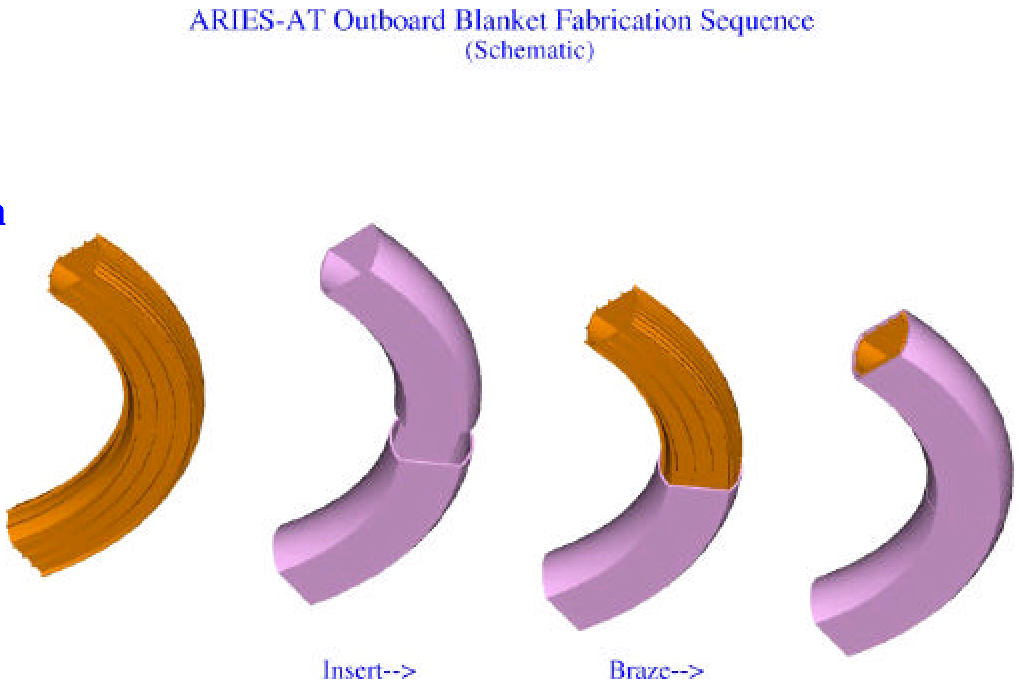


Develop Plausible Fabrication Procedure and Minimize Joints in High Irradiation Region

Example Procedure for ARIES-AT Blanket

1. Manufacture separate halves of the SiC_f/SiC poloidal module by SiC_f weaving and SiC Chemical Vapor Infiltration (CVI) or polymer process;
2. Insert the free-floating inner separation wall in each half module;
3. Braze the two half modules together at the midplane;





ARIES-AT Blanket Fabrication Procedure Comprises:

1. Manufacturing separate halves of the SiC$_f$/SiC poloidal module by SiC$_f$ weaving and SiC Chemical Vapor Infiltration (CVI) or polymer process;

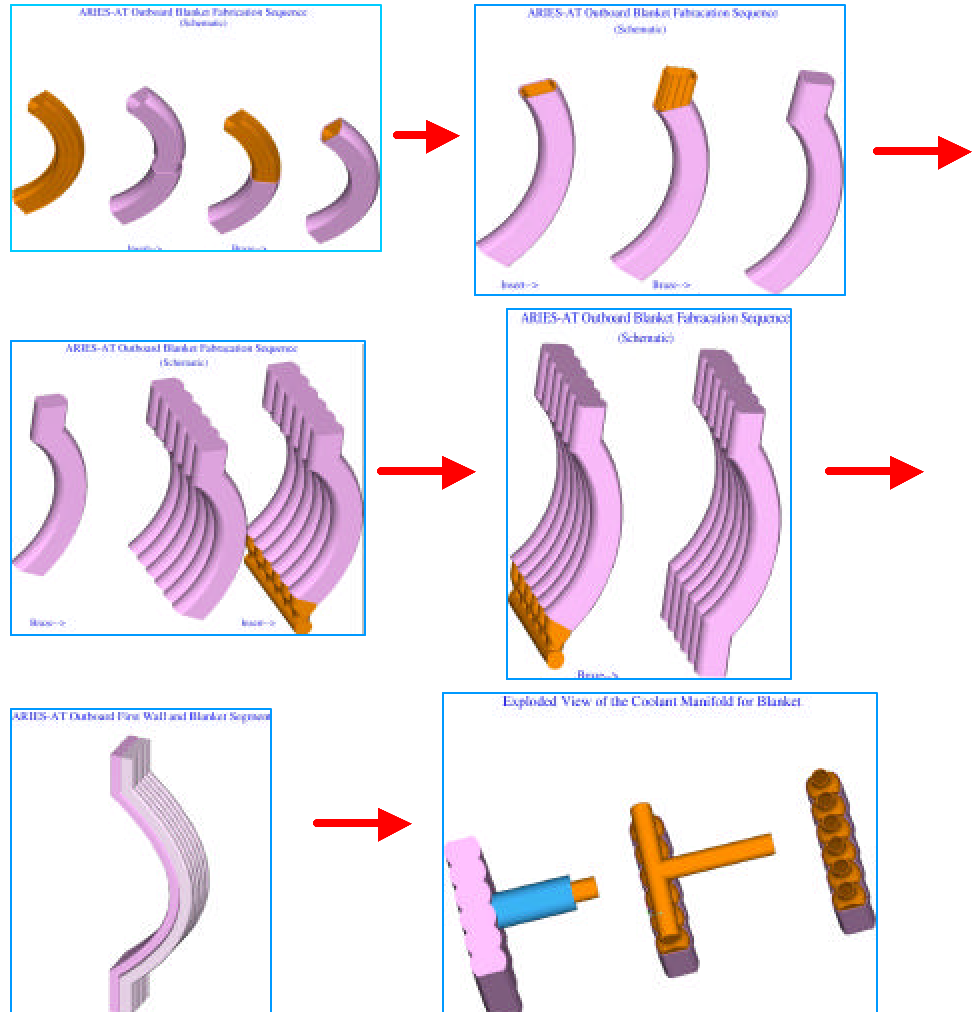
2. Inserting the free-floating inner separation wall in each half module;

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 bond which is not in contact with the coolant); and

6. Brazing the annular manifold connections to one end of the segment.



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Divertor Design Approach Relies on Community Interaction and Innovative Solution to Maximize Performance

PFC and Physics Community Interaction

- Tungsten as plasma-interactive material
- ALPS liquid divertor option collaboration
- Fully radiative divertor to maintain reasonable peak heat fluxes, ~ 5 MW/m^2

Divertor Coolant Compatible with Blanket Coolant and/or Power Cycle Fluid

- ARIES-RS: Li in insulated channel (same coolant as blanket)
- ARIES-ST: He coolant (from power cycle)+high heat flux porous media (Pb-17Li as blanket coolant)
- ARIES-AT: Pb-17Li in SiC/SiC channel (same coolant as blanket)

- Assess Key Limiting Issue
- Detailed Analysis and Innovative Solution to Maximize Performance of Coolant/Material/Concept Combination

e.g. MHD Effects for Liquid Metal Cooled Divertor

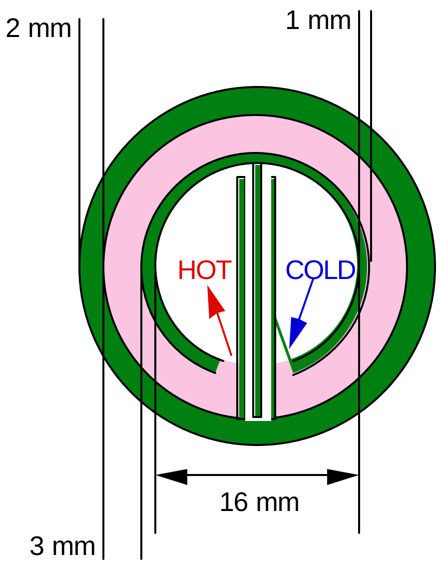
- Minimize MHD effect by design choice; use of coatings, insulating inserts or SiC pipes
- However, solution must be confirmed by R&D

Provide Guidance for R&D

ARIES-ST Divertor Designed for Thermal Expansion Accommodation

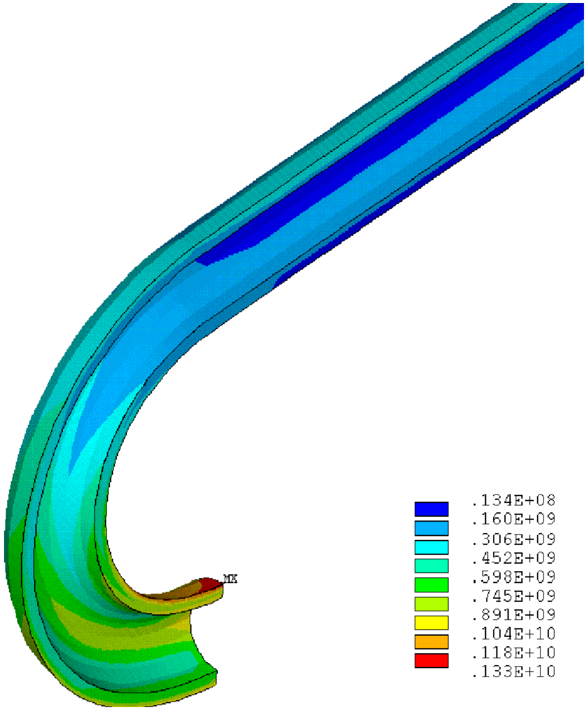
- **Tungsten Armor**
- **High-temperature He coolant**
- **Advanced high heat flux porous media**
- **Several SBIR proposals based on similar configuration**
- **Initial high heat flux testing at Sandia indicate high heat flux capability for this material combination (~30 MW/m^2)**

ARIES-ST Divertor Tube Cross Section



3-D stress analysis

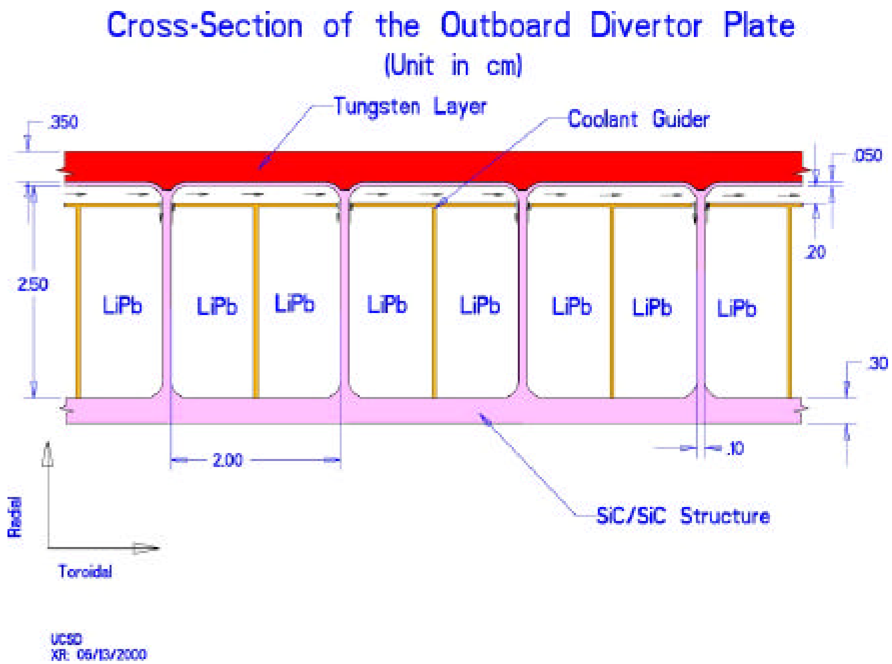
- **Moderate stresses in high heat flux region**
- **High local stress at attachment, can be relieved by flexible joint**



MHD Effects Influence Both Pressure Drop and Heat Transfer Even in Insulated Channels

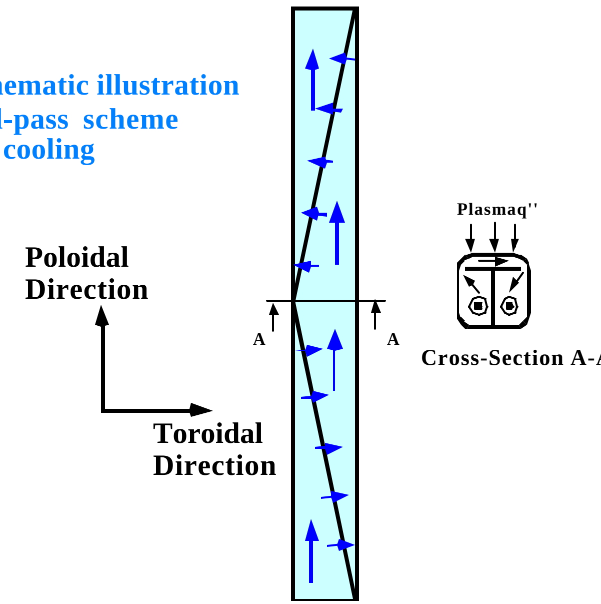
MHD Accommodation Measure for ARIES-AT Divertor Design

- 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

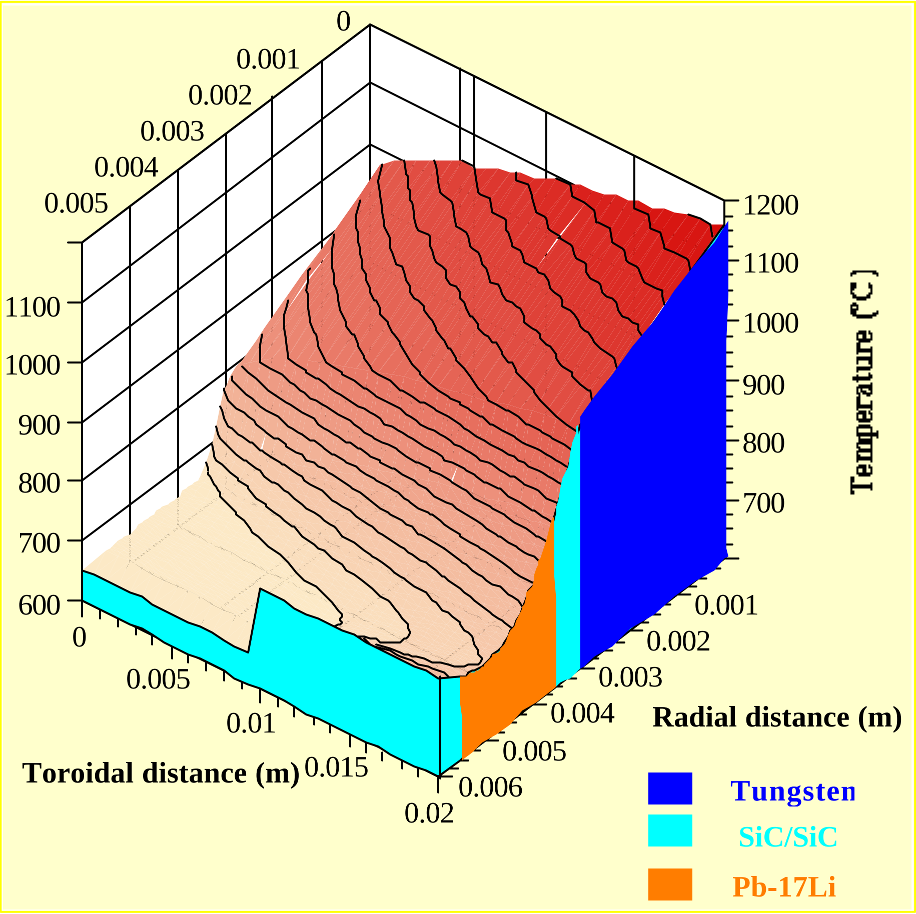


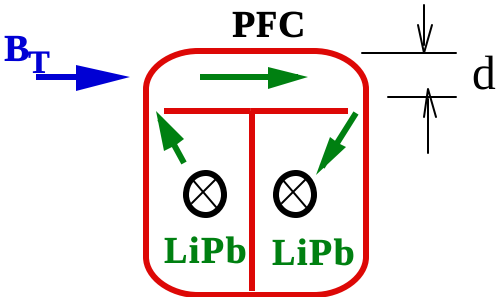
Pb-17Li Poloidal Flow in ARIES-AT Divertor Header

Example schematic illustration of 2-toroidal-pass scheme for divertor cooling



Temperature Distribution in Outer Divertor PFC Channel Assuming MHD-Laminarized Pb-17Li Flow



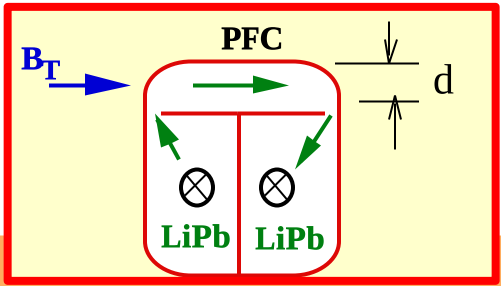


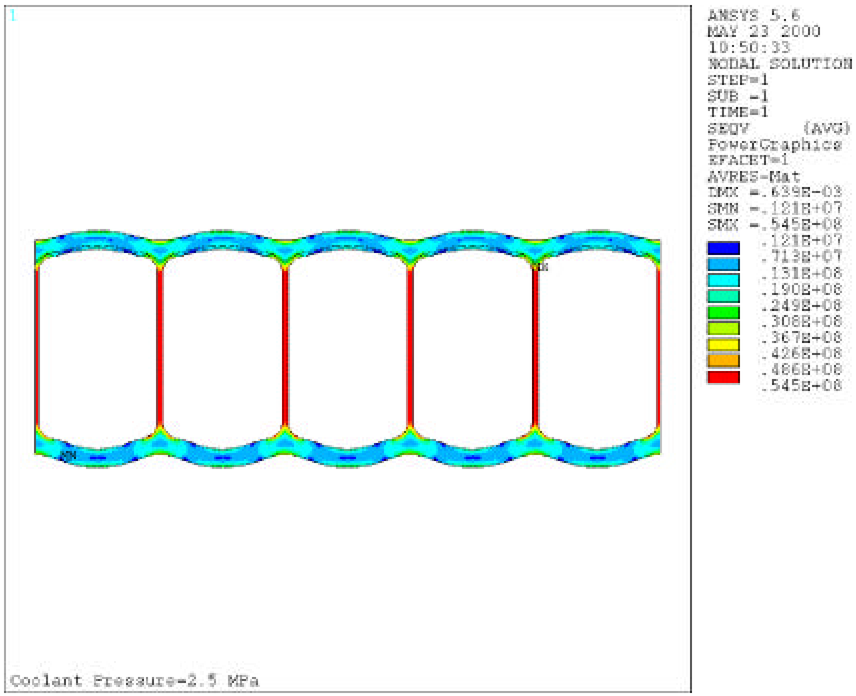
- Moving Coordinate Analysis
- Inlet Temperature = 653°C
- W Thickness = 3 mm
- SiC/SiC Thickness = 0.5 mm
- Pb-17Li Channel Thickness = 2 mm
- SiC/SiC Inner Wall Thick. = 0.5 mm
- Pb-17Li Velocity = 0.35 m/s
- Surface Heat Flux = 5 MW/m^2
- Max. SiC/SiC Temp. = 1000°C

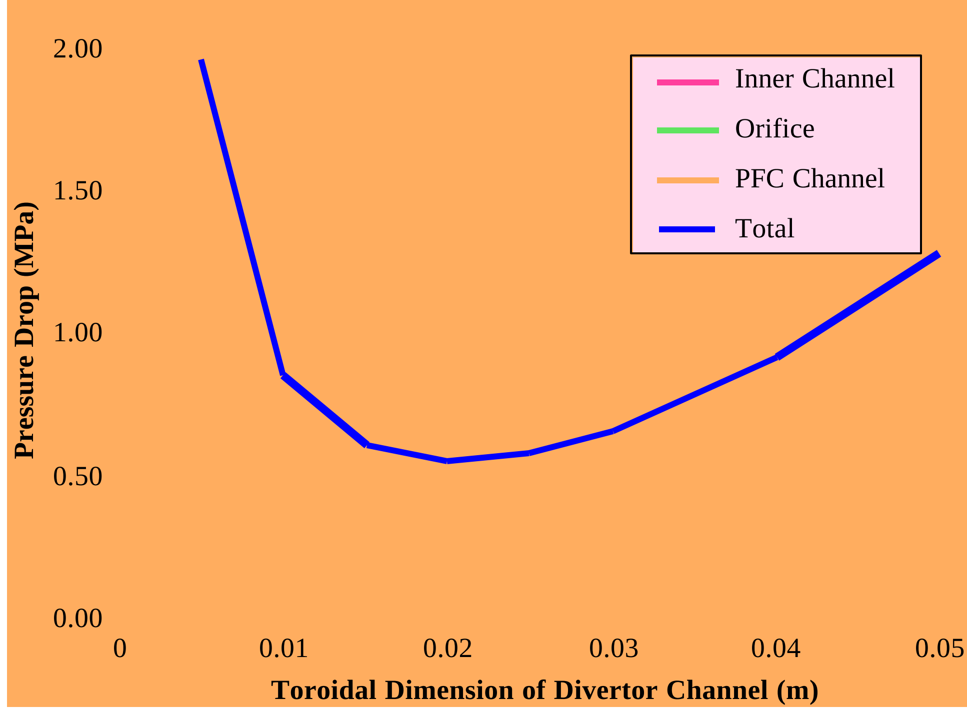
Divertor Design Optimized for Stress Limit Accommodation and Acceptable Coolant Pressure Drop

Example ARIES-AT Divertor Analysis

- For 2.5 mm tungsten, SiC/SiC pressure stress ~ 35 MPa (combined SiC/SiC pressure +thermal stress ~ 190 MPa)
- DP is minimized to ~0.55 MPa







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Close Interaction with International Material and Blanket Design and R&D Communities

Combination of Low Activation Structural Material + Liquid Breeder Result in Attractive, High Performance Blankets

- ARIES-RS: Li + Vanadium; ARIES-ST: Pb-17Li+FS+He; ARIES-AT: Pb-17Li+SiC/SiC

Recent Example of Interaction with International Material and Design Communities

- **Organize International Town Meeting to bring together international (US, EU and Japan) material and design SiC/SiC communities (ORNL, Jan 2000)**
  - Current material development and characterization status
  - Latest SiC/SiC-based blanket design: TAURO(EU), DREAM(Japan(), ARIES-AT(US)
  - Key SiC/SiC issues affecting blanket performance
  - Detailed info on website (http://aries.ucsd.edu/PUBLIC/SiCSiC/)
- **Town Meeting was very successful; achievements include:**
  - Develop list of properties and parameters for design study
  - Clear R&D need for high temperature high performance blanket
    - Need better-quality material with reasonable thermal conductivity-stoichiometry goal
    - Temperature limit: Compability between Pb-17Li and SiC at high temperature
      - Included in US R&D plan and being carried out in Europe
  - Paper deriving from meeting submitted to FE&D