SiC/SiC Composite for an Advanced Fusion Power Plant Blanket

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Background

- The use of SiC/SiC composite as structural material in a fusion reactor is attractive based on its low induced radioactivity and afterheat and potential for high temperature operation
  - High risk, high payoff
  - Possibility of high cycle efficiency
  - Safety premium
    - Possibility of extending non-nuclear boundary closer
    - Possibility of lower LSA criterion in costing

- Considered in previous power plant studies
  - ARIES-I and ARIES-IV
  - TAUNO
  - DREAM

- Several issues exist, including:
  - Factors limiting the range of operation
    - Limited thermal conductivity at high temperature and under irradiation
    - Maximum allowable operating temperature
  - Cost of fabrication
  - Joining methods
Exploratory Study

• Assess attractiveness of a SiC/SiC based blanket for high performance blanket design
  - High temperature operation
  - Use latest SiC/SiC R&D results and reasonable future extrapolation

• Liquid metal breeder
  - Potential for high performance, high temperature blanket system
  - Self cooled or dual coolant (He for FW)
  - LiPb and LiSn

• Divertor region
  - Free LiSn flow
  - He-cooled refractory metal

• Recommendation of reference design for detailed integrated analysis as part of ARIES-AT
Input Parameters

• Power
  - Max. Heat Load = 1.5 x ARIES-RS
  - Total Fusion Power Same as ARIES-RS

• Latest SiC/SiC Property Data
  - Max. SiC/SiC Temperature Limit
    - ~ 1000°C to avoid irradiation-induced void swelling regime
  - SiC/SiC Thermal Conductivity
    - Decreases with temperature and irradiation
    - Recent measurement of unirradiated 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 underway
    - Assume transverse k = 20 W/m-K

- Lifetime Based on ~3% Burn-Up

- Max. LiPb/SiC Interface Temp. Limit
  - One data point from ISPRA indicated no compatibility problem for SiC exposed over 1500 hours to static LiPb at 800°C
  - Future R&D required for flowing LiPb at high temperature
## SiC/SiC Properties Used in this Study

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Density (kg/m$^3$)</td>
<td>3200</td>
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<tr>
<td>Density Factor</td>
<td>0.95</td>
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<tr>
<td>Young's Modulus (GPa)</td>
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<tr>
<td>Poisson's ratio</td>
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<tr>
<td>Thermal Expansion Coef. (ppm/°C)</td>
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<tr>
<td>Thermal Conduct. in Plane (W/m-K)</td>
<td>25</td>
</tr>
<tr>
<td>Therm. Conduct. through Thickness (W/m-K)</td>
<td>20</td>
</tr>
<tr>
<td>Maximum Allowable Primary Stress (MPa)</td>
<td>~140</td>
</tr>
<tr>
<td>Maximum Allowable Secondary Stress (MPa)</td>
<td>~190</td>
</tr>
<tr>
<td>Maximum Allowable Operating Temp. (°C)</td>
<td>1000</td>
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<tr>
<td>Max. Allow. SiC/LiPb Interface Temp. (°C)</td>
<td>TBD</td>
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<tr>
<td>Maximum Allowable SiC Burnup (%)</td>
<td>3</td>
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Machine and Power Parameters Assumed for the Study
(OB=Outboard, IB=Inboard, FW= First Wall)

<table>
<thead>
<tr>
<th>Power Parameters</th>
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<tbody>
<tr>
<td>Fusion Power (MW)</td>
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<td>Neutron Power (MW)</td>
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<td>Alpha Power (MW)</td>
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<td>Current Drive Power (MW)</td>
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<tr>
<td>Maximum Surface Heat Flux (MW/m²)</td>
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<td>Average Surface Heat Flux (MW/m²)</td>
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<td>Power to the Divertor (MW)</td>
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<table>
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<tr>
<th>From Neutronics Analysis</th>
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<tr>
<td>Overall Energy Multiplication</td>
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<tr>
<td>Maximum Thermal Power (MW)</td>
<td>2394</td>
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<tr>
<td>OB Max. Neutron Wall Load (MW/m²)</td>
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<tr>
<td>OB Avg. Neutron Wall Load (MW/m²)</td>
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<tr>
<td>IB Max. Neutron Wall Load (MW/m²)</td>
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<tr>
<td>IB Avg. Neutron Wall Load (MW/m²)</td>
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<tr>
<td>OB Max. Heat Generation in FW SiC (MW/m³)</td>
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<tr>
<td>OB Avg. Heat Generation in FW SiC (MW/m³)</td>
<td>28</td>
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<tr>
<td>OB Max. Heat Generation in FW LiPb (MW/m³)</td>
<td>25</td>
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<tr>
<td>OB Avg. Heat Generation in FW LiPb (MW/m³)</td>
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<table>
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<tr>
<th>Machine Geometry</th>
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<tbody>
<tr>
<td>Major Radius (m)</td>
<td>4.5</td>
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<tr>
<td>Minor Radius (m)</td>
<td>1.13</td>
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<tr>
<td>Outboard FW Location at Midplane (m)</td>
<td>6</td>
</tr>
<tr>
<td>Outboard FW Location at Lower/Upper End (m)</td>
<td>4.5</td>
</tr>
<tr>
<td>Inboard FW Location (m)</td>
<td>3.5</td>
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Study Based on He 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 a liquid metal blanket through use of intermediate HX
Power Cycle Parameters

- Brayton Cycle Parameters:
  - Min. He temp. in cycle (heat sink) = 35 °C
  - 3-stage compression with 2 inter-coolers
  - Turbine efficiency = 0.93
  - Compressor efficiency = 0.9
  - Recuperator effectiveness = 0.96
  - He fraction. ΔP in out-of-vessel cycle = 0.025

- Intermediate Heat Exchanger:
  - Effectiveness = 0.9
  - $\frac{(m'C_p)_{He}}{(m'C_p)_{LiPb}} = 1$
Preliminary Analysis

Neutronics

• SiC/SiC+liquid breeder
  - 25-cm inboard and 55-cm outboard blanket regions with 8% SiC and 92% liquid breeder
  - 5-cm FW region on the inboard and outboard with 40% SiC and 60% liquid breeder
  - 90% enriched lithium

• TBR = 1.1 for Li\textsubscript{17}Pb\textsubscript{23} and only 0.95 for Li\textsubscript{25}Sn\textsubscript{75}
  - LiSn was not considered further in this study

Concepts Considered

• Self-cooled LiPb configuration

• Dual-coolant configuration (He for the FW and LiPb for the blanket)
Initial Findings Helped Focus the Study

• Poloidal box configuration with large LiPb channels
  - Dimensions set to accommodate the maximum allowable pressure and thermal stresses

• Separate cooling of the blanket box to maintain the SiC/LiPb <1000°C
  - Final LiPb flow pass between the cooled structure to maximize temperature and cycle efficiency

• Radial segmentation of blanket in order to save on replacement cost
  - ~25-cm first layer including the FW to be replaced at the end of its lifetime (~2.8 FPY based on a 3% SiC burnup limit)
  - ~35-cm lifetime second layer

• A poloidally-cooled FW configuration is preferred to a toroidally-cooled one
  - Simpler layout and manifolding configuration
  - Thinner radial build (for He coolant)
Poloidally-Cooled First Wall Configuration with Tapering Channels

- Consistent Parametric Comparison between He and LiPb as Poloidally-Flowing FW Coolant

- For Simplicity, the Minimum Channel Wall Thickness for Both Cases Was Set as One Tenth of the Diameter
  - For the He case this would correspond to a 100 MPa pressure stress for an assumed helium pressure of 20 MPa
  - For the LiPb, the pressure is much lower and the assumption is more conservative.
Cycle Efficiency and Maximum SiC Temperature as a Function of Total Compression Ratio for Different Poloidal He FW Channel Diameters

- Max. Brayton cycle He temp. = 1100°C

- Example design point:
  - Total compression ratio = 3
  - FW channel diameter = 3 cm
  - SiC max. temp. < 1000°C
  - Cycle efficiency ~ 59%
Cycle Efficiency and Maximum SiC Temperature as a Function of Total Compression Ratio for Different Poloidal LiPb FW Channel Diameters

- MHD flow laminarization effect included in heat transfer and pressure drop analysis
- Max. Brayton cycle He temp. = 1050°C
- Example design point:
  - Total compression ratio = 3
  - FW channel diameter = 2 cm
  - SiC max. temp. < 1000°C
  - Cycle efficiency ~ 59%
  - LiPb pressure drop ~ 1.3 MPa
Conclusions

Results are Encouraging for High Performance SiC/SiC-Based Blanket

• Brayton cycle $\eta$ of ~60% can be achieved
  - Cooling box structure with lower temp. LiPb and superheating the LiPb in a final low velocity high temp. pass
  - SiC/LiPb interface temp. in the irradiated blanket region < 1000°C
  - Max. FW SiC temp. < 1000°C

• Safety benefits

However, Issues Need To Be Addressed, Including:

• Better Definition of SiC Material Properties
  - Max. temp. limits for SiC/SiC and LiPb/SiC compatibility under irradiation
  - SiC/SiC $k$ at high temp. and under irrad.
  - Lifetime under irradiation
  - Fabrication quality and cost
  - Joining

• Compatible Divertor Design