Scoping Assessment of Advanced Tokamak with DCLL Blanket: Design Challenges and Economic Implications

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Objectives

- **Scoping assessment** of ARIES-AT* with Dual-Coolant LiPb (DCLL) blanket (previously developed for ARIES-ST@ in 1997 and ARIES-CS# in 2003)

  ⇒ redefine ARIES-AT radial builds with:
  - DCLL blanket and shield system
  - < 90% Li enrichment
  - LiPb/He Manifolds (*tentative* composition/dimension/location)
  - No stabilizing shells (will be added later)
  - Low-temperature magnets (replacing high-temperature magnets).

- **Impact of SiC inserts on TBR:**
  - **Reference:** 100% dense, 0.5 cm thick SiC inserts
  - **Alternative:** 0.5-0.7 cm thick, less dense SiC inserts (0.3-0.5 cm 10% dense SiC foam sandwiched between 1 mm 100% dense impermeable CVD-SiC face sheets; 0.23-0.25 cm equivalent SiC thickness).

- **Compare reference** ARIES-AT-SiCLL design with **proposed** ARIES-AT-DCLL design, highlight impact of DCLL system on overall design, and **recommend improvements** for final ARIES-AT-DCLL design.

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ARIES-AT Reference Design

Fusion Power 1755 MW
Major Radius 5.2 m
Minor Radius 1.3 m
Peak $\Gamma @$ IB, OB, Div 3.1, 4.8, 2 MW/m$^2$

SiC/SiC Composite Structure
LiPb/SiC Blanket
Discrete LiPb Manifolds
High Temperature S/C Magnet @ 70-80 K
No W on FW

Calculated Overall TBR 1.1
$\eta_{th} \sim 60\%$
Availability 85%

Plasma Control:
5 Tungsten Shells on IB and OB
2 Vertical Position Coils
2 Feedback Coils

Cross Section of ARIES-AT Power Core Configuration
Radial Build Definition Involves Active Interaction with many Disciplines

- Prelim. Physics (R, a, P_f, Plasma Contour, etc.)
- NWL Profile (Γ average and peak)
- Activation Assessment (Activity, decay heat, LOCA/LOFA, Radwaste classification)
- Safety Analysis

1-D Nuclear Analysis (TBR, M_n, damage, lifetime, Shield vs NWL scaling law)

Radial Build Definition (Optimal dimension and composition of all components, heat loads)

- Design Requirements
- Initial Divertor Parameters
- Initial Magnet Parameters

- Blanket Concept
- Systems Code (R, a, P_f, COE)
- Blanket Design
- CAD Drawings
- 3-D Neutronics (Overall TBR, M_n)

Safety Analysis
ARIES-AT Radial Builds: IB, OB, Div
(SiC Structure; HT Magnets)
ARIES-AT Blanket Options

**Reference**
ARIES-AT OB Blanket

**New**
ARIES-AT-DCLL OB Blanket
(a la ARIES-CS)

### SiC Structure

- **Breeder**: LiPb
- **Coolant**: LiPb
- **LiPb T_{out} Temp**: ~1100 °C
- **η_{th}**: ~60%

### FS Structure

- **Breeder**: LiPb
- **Dual Coolant**: LiPb and He
- **LiPb T_{out} Temp**: ~700 °C
- **η_{th}**: 40-45%
ARIES-AT Compositions

<table>
<thead>
<tr>
<th>Arrows</th>
<th>ARIES-AT-LiPb/SiC</th>
<th>ARIES-AT-DCLL*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inboard:</strong></td>
<td>(Reference Design)</td>
<td>0.5 cm Ultramet SiC, No Shells</td>
</tr>
<tr>
<td>FW/Blanket</td>
<td>81% LiPb, 19% SiC</td>
<td>79% LiPb, 12% He/void,</td>
</tr>
<tr>
<td>HT Shield</td>
<td>15% SiC, 10% LiPb,</td>
<td>6% FS, 3% SiC inserts</td>
</tr>
<tr>
<td></td>
<td>70% B-FS Filler, 5% W shells</td>
<td>15% FS, 10% He,</td>
</tr>
<tr>
<td>Manifolds</td>
<td>---</td>
<td>75% B-FS Filler</td>
</tr>
<tr>
<td>VV</td>
<td>13% FS, 22% H₂O, 65% WC</td>
<td>50% FS, 25% He, 24% LiPb, 1% SiC</td>
</tr>
<tr>
<td><strong>Outboard:</strong></td>
<td></td>
<td>17% FS, 34% H₂O, 49% WC</td>
</tr>
<tr>
<td>FW/Blanket-I</td>
<td>80% LiPb, 20% SiC</td>
<td>79% LiPb, 12% He/void,</td>
</tr>
<tr>
<td>FW/Blanket-II</td>
<td>77% LiPb, 20% SiC, 3% W shells</td>
<td>6% FS, 3% SiC inserts</td>
</tr>
<tr>
<td>HT Shield</td>
<td>15% SiC, 10% LiPb,</td>
<td>15% FS, 10% He,</td>
</tr>
<tr>
<td></td>
<td>75% B-FS Filler</td>
<td>75% B-FS Filler</td>
</tr>
<tr>
<td>Manifolds</td>
<td>---</td>
<td>50% FS, 25% He, 24% LiPb, 1% SiC</td>
</tr>
<tr>
<td>VV</td>
<td>30% FS, 70% H₂O</td>
<td>17% FS, 34% H₂O, 49% WC</td>
</tr>
<tr>
<td><strong>Top/Bottom:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Divertor System</td>
<td>40% SiC, 50% LiPb, 10% W</td>
<td>33% FS, 4% W, 63% He</td>
</tr>
<tr>
<td>Replaceable HT Shield</td>
<td>15% SiC, 10% LiPb,</td>
<td>15% FS, 10% He,</td>
</tr>
<tr>
<td></td>
<td>75% FS Filler</td>
<td>75% B-FS Filler</td>
</tr>
<tr>
<td>Permanent HT Shield</td>
<td>15% SiC, 10% LiPb,</td>
<td>15% FS, 10% He,</td>
</tr>
<tr>
<td></td>
<td>75% B-FS Filler</td>
<td>75% B-FS Filler</td>
</tr>
<tr>
<td>Manifolds</td>
<td>---</td>
<td>50% FS, 25% He, 24% LiPb, 1% SiC</td>
</tr>
<tr>
<td>VV</td>
<td>13% FS, 22% H₂O, 65% WC</td>
<td>22% FS, 48% H₂O, 30% B-FS</td>
</tr>
</tbody>
</table>

* Tentative compositions. Will change as design evolves.
## ARIES-AT-DCLL Radiation Limits and Key Parameters

<table>
<thead>
<tr>
<th>Calculated Overall TBR</th>
<th>1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net TBR (for T self-sufficiency)</td>
<td>~1.01</td>
</tr>
</tbody>
</table>

### Damage to Structure
(for structural integrity)

- Damage to Structure: 200 dpa - advanced FS
- ??? W structure

### Helium Production @ Manifolds and VV
(for reweldability of FS)

- Helium Production: 1 He appm

### LT S/C TF & PF Magnets (@ 4 K):

- Peak Fast n **fluence** to Nb$_3$Sn (E$_n$ > 0.1 MeV): $10^{19}$ n/cm$^2$
- Peak Nuclear **heating**: 2 mW/cm$^3$
- Peak dpa to Cu stabilizer: $6 \times 10^{-3}$ dpa
- Peak Dose to GFF Polyimide insulator: $< 10^{11}$ rads

### Plant Lifetime

- Plant Lifetime: 40 FPY

### Availability

- Availability: 85%

### Operational Dose to Workers and Public

- Operational Dose to Workers and Public: $< 2.5$ mrem/h
Radial Build Optimization Criteria

- **Adjust blanket dimension to provide overall TBR of 1.1**
  - Check impact of less dense SiC inserts on breeding

- **Maximize number of permanent components to minimize radwaste stream:**
  - Segment OB blanket into replaceable and permanent components
  - Protect external components (shield, manifolds, VV, and magnets) to serve for entire plant lifetime

- **All in-vessel components should provide shielding function:**
  - Blanket protect shield for plant life (40 FPY)
  - Blanket and shield protect manifolds and VV
  - Blanket, shield, manifolds, and VV protect magnets
Ultramet SiC Inserts
(Ref: S. Sharafat, Development Status of Flow Channel Inserts for the U.S.-ITER DCLL TBM; 18th TOFE, 2008)

Main features and advantages:
- 3-5 mm 10% dense foam ⇒ Low SiC content (to alleviate impact on TBR)
- Fully dense CVD SiC face sheets prevent LiPb ingress into foam
- Construction of long segments (> 75 cm) seems feasible
- Low-cost manufacturability
- Good strength, stiffness, and thermal stress resistance
- Low thermal and electrical conductivity.

Testing is underway.

Results so far are promising.

For any type of SiC inserts:
Change of electrical conductivity with neutron irradiation could be significant (0.4 atom% Mg @ 3 FPY for 6 MW/m² NWL, per Sawan (UW)).
SiC Inserts Degrade Tritium Breeding

Less dense Ultramet alleviates impact of SiC on TBR, allowing lower enrichment (< 90%) and/or thinner blanket.
ARIES-AT-DCLL TBR

45 cm IB FW/Blanket/Back Wall
80 cm OB FW/Blanket/Back Wall
No Shells

90% Li-6 Enrichment

Overall TBR vs. Equivalent SiC Thickness (mm)

Required Calculated TBR

0.5 cm SiC Insert
0.5 cm Ultramet
0.7 cm Ultramet

0.5 cm Ultramet

Overall TBR vs. Li Enrichment (% $^6$Li)

Required Calculated TBR
ARIES-AT IB Radial Build

Reference

Proposed
ARIES-AT-DCLL

0.5 cm Ultramet
70% $^6$Li Enrichment
No Shells

$\Delta = 48$ cm
ARIES-AT OB Radial Build

Reference

Proposed
ARIES-AT-DCLL

0.5 cm Ultramet
70% ⁶Li Enrichment
No Shells

Δ = 57 cm
ARIES-AT Divertor Radial Build

133.35 cm w/o gaps

Δ = 45 cm

Reference

Proposed
ARIES-AT-DCLL

Coil Case
Winding Pack
Vacuum Vessel
Large Gap + Th. Insulation
HT SiC Shield
He Manifolds
HT FS Shield
Divertor System (plates & He manifolds, a la ARIES-CS)

SS Jacket, Insulator, Coil Case
Large Gap
HT FS Shield (replaceable every 6 FPY)
Gap
Gap
Gap
Gap
Gap
Gap
Gap
Gap

178 cm w/o gaps

14
17
14
40
2
30
1
15
3.35 cm
3.2
cm

3.35 cm
5
50
3.2
> 2
> 2
20
20
20
20
15

Δ
# Radiation Level

<table>
<thead>
<tr>
<th></th>
<th>IB</th>
<th>OB</th>
<th>Div.</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peak NWL (MW/m²)</strong></td>
<td>3.4</td>
<td>4.8</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td><strong>Peak atomic displacement @ FW and W of div:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dpa / FPY</td>
<td>68</td>
<td>73</td>
<td>7.4</td>
<td>200</td>
</tr>
<tr>
<td>FW dpa @ 2.8 FPY</td>
<td>190</td>
<td>200</td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>dpa at W of Div @ 2.8 FPY</td>
<td></td>
<td></td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>dpa at shield (dpa @ 40 FPY):</td>
<td></td>
<td></td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>Replaceable</td>
<td>640</td>
<td>---</td>
<td>1080</td>
<td></td>
</tr>
<tr>
<td>Permanent</td>
<td>160</td>
<td>109</td>
<td>160</td>
<td></td>
</tr>
<tr>
<td><strong>He production at manifolds</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(He appm @ 40 FPY)</td>
<td>5*</td>
<td>1</td>
<td>0.8</td>
<td>1</td>
</tr>
<tr>
<td><strong>He production at VV</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(He appm @ 40 FPY)</td>
<td>1</td>
<td>0.2</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td><strong>LT Magnet @ 4 K:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast neutron fluence</td>
<td>1</td>
<td>0.5</td>
<td>0.7</td>
<td>1</td>
</tr>
<tr>
<td>(10^{19} n/cm² @ 40 FPY)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nuclear heating (mW/cm³)</td>
<td>0.6</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

* Rewelding allowed at top/bottom, not around midplane.
Isometric View of Proposed DCLL Blanket
Kink Shell Behind OB FW?

- Could Cu or W kink shell be placed behind OB FW?
- Could Cu operate at 700 °C? Is W the only option?
- Integration of kink shell with blanket?
- Impact on breeding?

ARIES-AT-DCLL OB Blanket with kink shell behind FW

IB and/or OB Blanket should be thickened to compensate for losses in breeding
Shells Between OB Blanket Segments?

- **Could OB blanket be segmented into two segments to accommodate shells** (al la ARIES-AT)?

  - **Advantages:**
    - Less integration problems
    - Less impact of shells on breeding
    - Lifetime of back blanket segment > 3 FPY (~15 FPY)
    - Notable reduction in lifecycle radwaste volume.

- **Need:**
  Innovative method to support and cool both blanket segments.

ARIES-AT-DCLL OB Blanket with Cu kink and VS shells between OB blanket segments (blanket temp < 700 °C)
## Economic Trend

<table>
<thead>
<tr>
<th></th>
<th>ARIES-AT-LiPb/SiC (Reference)</th>
<th>ARIES-AT-DCLL</th>
<th>Cost of ARIES-AT-DCLL</th>
</tr>
</thead>
<tbody>
<tr>
<td>IB, OB, Div radial standoff*</td>
<td>135, 160, 133 cm</td>
<td>185, 219, 178 cm</td>
<td>↑</td>
</tr>
<tr>
<td>Limit on max. NWL (MW/m²)</td>
<td>~6</td>
<td>&lt; 5.5</td>
<td></td>
</tr>
<tr>
<td>Major radius</td>
<td>5.2 m</td>
<td>&gt; 5.2 m</td>
<td>↑</td>
</tr>
<tr>
<td>Calculated overall TBR</td>
<td>1.1 w/ 90% ⁶Li enrichment</td>
<td>1.1 w/o shells w/ 70% ⁶Li enrichment</td>
<td></td>
</tr>
<tr>
<td>FW/blanket lifetime</td>
<td>~4 FPY</td>
<td>~2.8 FPY</td>
<td>↑</td>
</tr>
<tr>
<td></td>
<td>⇒ 18 MWy/m²</td>
<td>⇒ 13 MWy/m²</td>
<td></td>
</tr>
<tr>
<td>Overall energy multiplication</td>
<td>1.1</td>
<td>~1.15</td>
<td>↓</td>
</tr>
<tr>
<td>Structure unit cost#</td>
<td>~620 $/kg</td>
<td>~95 $/kg</td>
<td>↓</td>
</tr>
<tr>
<td>ηₘₜ</td>
<td>~ 60%</td>
<td>40-45%</td>
<td>↑</td>
</tr>
<tr>
<td>Cost of heat transfer/transport system#</td>
<td>~$160M</td>
<td>&gt; $300M</td>
<td>↑</td>
</tr>
<tr>
<td>He pumping power</td>
<td>---</td>
<td>&gt; 100 MWₑ</td>
<td>↑</td>
</tr>
<tr>
<td>Level of Safety Assurance (LSA) factor</td>
<td>1</td>
<td>2</td>
<td>↑</td>
</tr>
<tr>
<td>COE:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>in 1992 $</td>
<td>48 mills/kWh</td>
<td>&gt; 60 mills/kWh</td>
</tr>
<tr>
<td></td>
<td>in 2008 $</td>
<td>70 mills/kWh</td>
<td>&gt; 90 mills/kWh</td>
</tr>
</tbody>
</table>

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* Excluding gaps.
# In 2008 $.
Observations and Recommendations

Observations:

- **DCLL system** increases ARIES-AT radial standoff by 50-60 cm
  - ⇒ Larger and more costly ARIES-AT-DCLL machine
- Less dense SiC inserts lessen -ve impact on breeding
- Adding **stabilizing shells** will degrade breeding, requiring thicker IB/OB blankets, if effective.

To enhance ARIES-AT-DCLL design:

- **Investigate means** to reduce radial build standoffs, machine size, and cost
  (e.g., relocate manifolds at top/bottom*, lower He pumping power, etc.)
- **Thicken IB blanket** to protect IB shield for plant life (40 FPY)
- **Segment OB blanket** to accommodate stabilizing shells, alleviate impact of shells on breeding, and reduce radwaste stream.

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* As suggested by El-Guebaly @ Dec-07 ARIES meeting: DCLL Blanket for ARIES-AT: Major Changes to Radial Build and Design Implications.