Neutron Streaming Through Divertor He-Access Pipes: 
3-D Assessment and Recommendations

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ARIES-Pathways Project Meeting
December 12 - 13, 2007
Georgia Tech
Background

- **Radial builds** and radiation levels are normally defined for perfect geometry without penetrations.

- **Penetrations** are necessary for vacuum pumping, coolant supply lines, plasma control, and maintenance ports.

- Such penetrations *compromise shielding performance* as streaming neutrons:
  - Enhance damage at surrounding components (shield, manifolds, VV, and magnet)
  - Increase flux and dose levels behind magnet.

- Unlike liquid-cooled system, **He coolant tubes/pipes** raise streaming concerns.

- Designing **penetration shields** for He system represents challenging task.

- **Example**: ARIES-CS dual-cooled LiPb/He/FS design.

- Results applicable to ARIES-AT with DCLL system.
ARIES-CS Penetrations

- **Eight types of penetrations:**
  - 198 He tubes for blanket (32 cm inner diameter (ID))
  - **24 Divertor He access pipes (30-60 cm ID)**
  - 30 Divertor pumping ducts (42 x 120 cm each)
  - 12 Large pumping ducts (1 x 1.25 m each)
  - 3 ECH ducts (24 x 54 cm each)
  - 6 main He pipes connecting HX to blanket and shield (72 cm ID each)
  - 6 main He pipes connecting HX to divertor (70 cm ID each)
  - 4 access holes (3 cm diameter) for each blanket module.

- **Potential solutions:**
  - Local shield behind penetrations
  - He tube axis oriented toward lower neutron source
  - Penetration shield surrounding ducts
  - Replaceable shield close to penetrations
  - Avoid rewelding of manifolds and VV close to penetrations
  - Several bends along penetration lines.
ARIES-CS Divertor System

- 2 divertor systems per field period
- 4 He-access pipes for each divertor system
- 24 He-access pipes in 3 FP of ARIES-CS
Streaming problems:

- Shield surrounding pipe is not life-of-plant component
- Manifolds and VV close to pipe are not reweldable
- Winding pack should be 30-40 cm from pipe
- Inner part of pipe wall should be replaceable
- Pipe wall not reweldable
- Flux at end of pipe is excessive ⇒ protect externals with local shields.
S. Malang Proposed 4 Options for He Access Pipes with Shield Plug and Inserts (30-60 cm ID)

Preferred Option

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(A) Sliding Seal
Shielding Block
Shielding Ring
Ribs Connecting Inner Tube, Shielding Ring and Block into a Single Unit

(B) Shield Attache' to Blanket
Blanket
Shield
Manifold
Vacuum Vessel
Magnet

(C) Sliding Seal
Shield Plug
Shielding Insert
Ribs Connecting Inner Tube, Shielding Plug and inserts into Single Assembly

(D) Blanket/Shield Extension
Blanket
Bulk Shield
Manifolds
Vacuum Vessel
Magnet
Selected Design for Streaming Analysis

WC Shielding Plug and Inserts

<table>
<thead>
<tr>
<th></th>
<th>1 Pipe</th>
<th>24 Pipes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Volume (m^3)</strong></td>
<td>0.05+0.4</td>
<td>11</td>
</tr>
<tr>
<td><strong>Mass (tons)</strong></td>
<td>7</td>
<td>170*</td>
</tr>
</tbody>
</table>

* 3 times total divertor mass (54 Tons).

Could this structure support 9-10 tons? How to attach to VV?
3-D Neutronics Model

**Purpose:**
- Examine effectiveness of shield plug and inserts
- Estimate peaking in damage due to streaming:
  - dpa at shield
  - He production at manifolds
  - He production at VV
  - Fast neutron fluence at winding pack
  - dpa & He production along pipe wall
- Assess radiation environment behind magnet due to streaming.

Peak NWL @ divertor ~2.7 MW/m².

**3-D codes:**  
- **Attila**: discrete ordinates; 46 n + 21 γ group structure, FENDL-2.1 data  
- **MCNPX**: Monte Carlo; FENDL-2.1 data.

Direct CAD/Attila and MCNPX coupling approach.

**Dimensions and compositions** based on reference radial build: http://fti.neep.wisc.edu/aries-cs/builds/build.html
### Peaking Factor

Peaking Factor due to streaming calculated by Attila/MCNPX codes relative to nominal values (away from pipe).

<table>
<thead>
<tr>
<th></th>
<th>Nominal Values</th>
<th>Design Limits</th>
<th>Allowable Peaking Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>dpa</strong> at shield (dpa @ 40 FPY)</td>
<td>135</td>
<td>200</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>He</strong> production at manifolds (He appm @ 40 FPY)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>He</strong> production at VV (He appm @ 40 FPY)</td>
<td>0.2</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Fast neutron <strong>fluence</strong> @ magnet (n/cm² @ 40 FPY)</td>
<td>0.2x10^{19}</td>
<td>1x10^{19}</td>
<td>5</td>
</tr>
</tbody>
</table>
3-D Attila Model

1/4 Model of Divertor System w/o Pipe in 45° Torus

1/4 model of Divertor System w/ Pipe in 45° Torus

Tetrahedral mesh representation
Attila Results: Neutron Flux Map  
(Relative values; Log scale)

- Streaming causes 3-4 orders of magnitude increase in flux behind magnet.
- Shielding plug attenuates flux by 20 fold.
Shield Plug Helps Protect Bulk Shield

Peaking Factor $= 1.3 \Rightarrow \sim 175$ dpa @ 40 FPY ($< 200$ dpa limit)

$\Rightarrow$ Bulk shield is permanent component

$\Rightarrow$ No need for blanket/shield extension.
Part of Manifolds Surrounding Pipe Cannot be Rewelded after 0.5 FPY

Peaking Factor = 8.3 \Rightarrow \sim 8 \text{ He appm} @ 40 \text{ FPY} (> 1 \text{ appm limit})
\Rightarrow \text{Avoid rewelding 40 cm thick manifolds surrounding pipe}
Part of VV Surrounding Pipe Cannot be Rewelded after 30 FPY

Peaking Factor = 6.7  ⇒  ~ 1.3 He appm @ 40 FPY (> 1 appm limit)  ⇒  Avoid rewelding 20 cm thick VV surrounding pipe
**40 cm Inter-coil Structure around Pipe Helps Protect Winding Pack**

Peaking Factor = 37  \Rightarrow  \sim 9 \times 10^{19} \text{ n/cm}^2 @ 40 \text{ FPY} (> 10^{19} \text{ n/cm}^2 \text{ limit})

\Rightarrow  \text{ Winding pack should be placed 40 cm away from pipe}
Behind magnet:

- High flux covers large area
- Around pipe, fast flux ($E_n > 0.1$ MeV) comprises 20% of total flux.

Excessive Neutron Flux Behind Pipe Calls for Local Shield to Protect Externals
Pipe wall lifetime ~ 4.5 FPY, exceeding divertor lifetime (3 FPY)

Damage to screws (at ~2 m) will not exceed 10 dpa @ 40 FPY
⇒ < 0.05% n-induced swelling at screws, causing no problem, per Malang.

- Front 60 cm of pipe wall is not reweldable after 3 FPY and should be replaced with divertor
- End of pipe (> 120 cm) can be reused repeatedly during 40 FPY
- Middle of pipe (60-120 cm) reaches 1 appm limit gradually at various times, ranging between 3 and 40 FPY.
Concluding Remarks and Recommendations

• **3-D results indicate:**
  - Bulk shield is well protected ⇒ no need for blanket/shield extension
  - Peaking in damage is more pronounced at magnet than at shield
  - Helium production at manifolds and VV exceeds reweldability limit by 2-8 fold
    ⇒ avoid rewelding within 20-40 cm from pipe
  - Winding pack should be placed at least 40 cm from pipe
  - Neutron-induced swelling in screws (that adjust divertor plates during operation) is negligible (< 0.05%)
  - Front 60-120 cm of pipe wall is not reweldable and should be replaced along with divertor system every 3 FPY.

• Final ARIES-CS design accords with these recommendations.

• Neutron flux behind pipe is excessive, calling for **60-80 cm thick local shield** to protect externals.

• Neutron attenuation through **shielding plug and inserts** is not sufficient to eliminate streaming problems entirely.

• Future studies could develop **more effective scheme(s)** to attenuate streaming neutrons and reduce flux outside pipes. For example, **simple pipe with smaller diameter** (< 60 cm) and **several right-angle bends** represents a better approach, eliminating the need for massive shielding plug and inserts (170 tons for 24 pipes of ARIES-CS).
Publications

- D. Henderson presented preliminary results at SOFE meeting - June 07, Albuquerque, NM.

- **UWFDM-1331** report published:
  A. Ibrahim, D.L. Henderson, L. El-Guebaly, and P.P.H. Wilson,
  “Analysis of Radiation Streaming Through ARIES-CS He-Access Pipes using Attila and DAG-MCNPX 3-D Neutronics Codes,”
  University of Wisconsin Fusion Technology Institute Report, UWFDM-1331 (Dec. 2007).

- Presentation will be given by A. Ibrahim at **2008 ANS Student Conference**, Feb 28 - March 1, 2008, College Station, TX.

- Abstract and full paper will be submitted to **18th TOFE**, October 08, San Francisco.