Near-Final Radial Build and Nuclear Parameters

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ARIES-CS Project Meeting
April 27 - 28, 2006
UW
UW Action Items

1. Check blanket coverage and TBR for R = 7.5 and 8 m. Need plasma-midcoil separation contours from PPPL
2. Optimize local shield behind helium access tubes
3. Provide radial build at cross-section through He access tube near delta-min
4. Update shield vs. NWL scaling law
5. Update power fraction to blanket Pb-17Li coolant, blanket and shield He, shield-only zone He and divertor He
6. Update He:LiPb power split using 28 MWe pumping power for div He and 97 MWe for blanket He.
7. Check magnet activation for candidate structures (get composition from Leslie)
8. Provide heat load to 35-cm thick inter coil structure
9. Provide radial build for 2 field period configuration. Received plasma-midcoil separation contours from PPPL
10. Provide radial build for advanced LiPb/SiC system
11. Provide radial build for full blanket coverage
12. Redefine reference radial build and post it on UW website
Contents

• Plasma - mid-coil separation contours for $R = 7 - 8.5$ m machines.

• Rationale for $R = 7.5$ m design.

• Near-final radial build and nuclear parameters.

• Orientation of He access tubes to mitigate streaming problem.

• Streaming concerns for divertor region.

• Updates:
  – Heat load to all components
  – Power split between He/LiPb coolants.

• Future plan and publications.
Insufficient Breeding for R=7 m Machine
Mandates Another Iteration

**Prelim. Physics**
(R, a, P_f, \( \Delta_{\text{min}} \), plasma contour, magnet CL)

**NWL Profile**
(\( \Delta_{\text{min}} \), peak, average, ratio)

- no \( \Delta_{\text{min}} \) match
- or insufficient breeding

**Design Requirements**

**1-D Nuclear Analysis**
(\( \Delta_{\text{min}} \), TBR, \( M_n \), damage, lifetime)

**Radial Build Definition**
@ \( \Delta_{\text{min}} \) and elsewhere
Optimal dimension and composition, blanket coverage, thermal loads

**Blanket Concept**

**Init. Magnet Parameters**

**Init. Divertor Parameters**

**3-D Neutronics**
(Overall TBR, \( M_n \))

**Activation Assessment**
(Activity, decay heat, LOCA/LOFA, Radwaste classification)

**Blanket Design**

**Systems Code**
(R, a, P_f)

**CAD Drawings**

**Safety Analysis**
New Plasma – Mid-coil Separation Contours

- **From:** L-P Ku (PPPL)
- **Basis:** ARE physics
- **Configuration:** 3 FP
- 4 $D_{\text{min}}$ per FP
- $D_{\text{min}}$ $R$, starting at 1.18 m for $R=7$ m
**CAD Confirmed UW Estimate for Blanket Coverage Fractions**

<table>
<thead>
<tr>
<th>R= 7 m machine</th>
<th>UW Estimate</th>
<th>CAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-uniform Blanket</td>
<td>35%</td>
<td>36%</td>
</tr>
<tr>
<td>Uniform Blanket</td>
<td>65%</td>
<td>64%</td>
</tr>
</tbody>
</table>
• Uniform blanket and divertor outside blue contour covers \(~65\%\) of FW area.
• Non-uniform, tapered blanket inside blue contour covers \(~35\%\) of FW area.
• Uniform blanket and divertor outside red contour covers \( \sim 72\% \) of FW area.
• Non-uniform, tapered blanket inside red contour covers \( \sim 28\% \) of FW area.
R = 8 m
[ 4 $a_{\text{min}}$ (= 1.34 m) marked in red ]

- Uniform blanket and divertor outside green contour covers ~$80\%$ of FW area.
- Non-uniform, tapered blanket inside green contour covers ~$20\%$ of FW area.
R = 8.5 m

[ 4 $\Box_{\text{min}}$ (= 1.43 m) marked in red ]

- **Uniform blanket and divertor** outside **brown** contour covers $\sim$87% of FW area.
- **Non-uniform, tapered blanket** inside **brown** contour covers $\sim$13% of FW area.
Non-uniform Blanket Coverage Decreases with R
Near-Final Radial Build
(R= 7.5 m ; 4.5 MW/m² peak)

- Replaceable FW/Blkt/BW
- Full Blanket & Shield
- Non-uniform Blanket & Shield

Thickness (cm)

Plasma

SOL

- 3.8 cm FW
- 25 cm Breeding Zone-I
- 25 cm Breeding Zone-II
- 1.5 cm FS/He
- 0.5 cm SiC Insert

- 5 cm Back Wall

- 5 cm Back Wall

- HT FS Shield (permanent)
- He & LiPb Manifolds

- Gap
- Vacuum Vessel
- Gap + Th. Insulator
- Coil Case & Insulator
- Winding Pack
- External Structure

- 3.8 cm FW
- Blanket
- WC Shield-I (replaceable)
- Back Wall
- WC Shield-II (permanent)

- Gap
- Vacuum Vessel
- Gap + Th. Insulator
- Coil Case & Insulator
- Winding Pack
- External Structure

- 3.8 cm FW

Thickness (cm)

- Dmin = 126 cm
- Dmin = 177 cm
Radial / Toroidal Xn
(R = 7.5 m; 4.5 MW/m² peak)

Full Blanket/shield and Divertor
(57% + 15% = 72% of FW area)

Non-uniform, Tapered Blanket/Shield
(28% of FW area)
Streaming Through Blanket He Access Tubes (Cont.)
(Non-uniform Blanket Region)

~22 cm available space for local shield

Tube axis should be oriented toward low n source regions (away from plasma center)

~20 cm available space for local shield

Monitor location/orientation of He access tubes as design develops
Streaming Through Blanket He Access Tubes (Non-uniform Blanket Region)

- Thermal analysis calls for 32 cm OD tubes to supply He from manifolds to blanket.

- Each tube replaces 32-40 cm of WC-shield and back wall.

- Neutrons streaming through He tube increase damage at VV and magnets.

- Careful choice of location and orientation of tubes alleviate streaming problem.

- ~20 cm thick local shield needed behind manifolds to protect VV and magnets.
Xn through Divertor System

(R = 7.5 m)
• **Damage** at shield and manifolds depends on NWL at divertor location.

• **Xn through divertor and blanket** (away from pipes) indicates **no problem if** peak NWL remains **below 2 MW/m^2** at divertor surface.

• Neutron **streaming through He access pipes** increases damage to all components surrounding pipes.

• Malang suggested **shield inserts** to protect surrounding components. Shielding effectiveness of inserts will be assessed with 3-D analysis.
### Compositions and Coverage Fractions
(R = 7.5 m; 4.5 MW/m² peak)

<table>
<thead>
<tr>
<th>Component</th>
<th>Thickness</th>
<th>Coverage Fraction</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>FW*</td>
<td>3.8 cm</td>
<td>85%</td>
<td>34% FS Structure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>66% He Coolant</td>
</tr>
<tr>
<td>Divertor System*</td>
<td>20 cm</td>
<td>15%</td>
<td>32.6% FS Structure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.0% W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>63.4% He Coolant</td>
</tr>
<tr>
<td>Blanket behind Divertor*</td>
<td>35 cm</td>
<td>15%</td>
<td>75% LiPb (90% enriched Li)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>9% SiC Inserts</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8% FS Structure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8% He Coolant</td>
</tr>
<tr>
<td>Non-uniform Blanket*</td>
<td>23 - 54.3 cm</td>
<td>28%</td>
<td>76% LiPb (90% enriched Li)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8% SiC Inserts</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8% FS Structure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8% He Coolant</td>
</tr>
<tr>
<td>Full Blanket*</td>
<td>54.3 cm</td>
<td>57%</td>
<td>79% LiPb (90% enriched Li)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7% SiC Inserts</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6% FS Structure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8% He Coolant</td>
</tr>
<tr>
<td>Back Wall*</td>
<td>5 cm</td>
<td>100%</td>
<td>80% FS Structure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20% He Coolant</td>
</tr>
<tr>
<td>FS Shield</td>
<td>30 cm</td>
<td>72%</td>
<td>15% FS Structure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10% He Coolant</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>75% Borated Steel Filler</td>
</tr>
<tr>
<td>Manifolds</td>
<td>35 cm</td>
<td>75%</td>
<td>52.0% FS Structure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>22.7% LiPb (90% enriched Li)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>24.0% He Coolant</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.3% SiC Inserts</td>
</tr>
</tbody>
</table>

* Replaceable component.
### Compositions and Coverage Fractions (Cont.)

<table>
<thead>
<tr>
<th>Component</th>
<th>Thickness</th>
<th>Coverage Fraction</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>WC Shield-I*</td>
<td>0 – 12 cm</td>
<td>28%</td>
<td>15% FS Structure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10% He Coolant</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>75% WC Filler</td>
</tr>
<tr>
<td>WC Shield-II</td>
<td>26 – 34 cm</td>
<td>28%</td>
<td>15% FS Structure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10% He Coolant</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>75% WC Filler</td>
</tr>
<tr>
<td>VV</td>
<td>28 cm</td>
<td>100%</td>
<td>28% FS Structure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>49% Water</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>23% Borated Steel Filler</td>
</tr>
<tr>
<td>Inner Coil Case</td>
<td>2 cm</td>
<td>33%</td>
<td>95% Incoloy-908 Structure</td>
</tr>
<tr>
<td>(in front of WPs only)</td>
<td></td>
<td></td>
<td>5% LHe Coolant</td>
</tr>
<tr>
<td>Winding Pack @ 4K</td>
<td>18 cm</td>
<td>33%</td>
<td>18.5% Incoloy-908 Structure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>48.2% Cu</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12.8% Nb,Sn</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10.0% GFF Polyimide</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10.5% LHe Coolant</td>
</tr>
<tr>
<td>External Structure</td>
<td>56 +10 cm</td>
<td>33%</td>
<td>95% Incoloy-908 Structure</td>
</tr>
<tr>
<td>(behind WPs only)</td>
<td></td>
<td></td>
<td>5% LHe Coolant</td>
</tr>
<tr>
<td>Inter Coil Structure</td>
<td>35 cm</td>
<td>67%</td>
<td>95% Incoloy-908 Structure</td>
</tr>
<tr>
<td>(between WPs)</td>
<td></td>
<td></td>
<td>5% LHe Coolant</td>
</tr>
</tbody>
</table>

* Replaceable component.
Overall TBR

• 1-D and 3-D TBR comparison indicated good agreement for **full** blanket coverage (no blanket variation, no divertor system, no penetrations) - refer to June 05 presentation.

• Overall TBR reported herein is based on 1-D results combined with blanket/divertor coverage.

• **Assumptions:**
  – All regions (divertor, full and tapered blankets) have same importance for breeding. Local breeding usually follows NWL distribution.
  – **Divertor system** covers 15% of FW area:
    – No variation of divertor coverage fraction with R
    – 12.5 cm thick **divertor targets/baffles and** alpha modules followed by 7.5 cm thick He manifolds
    – 55 cm OD He access pipe for each divertor plate (∼ 2x 2 m each)
    – 3 cm wide gap between divertor and blanket.
  – **Thin blanket** (35 cm thick) behind divertor system.
  – **Penetrations** occupy 1% of FW area.
Overall TBR (Cont.)

R = 7.5 m
15% Divertor Coverage
Overall TBR ~ 1.1 based on 1-D estimate
Overall TBR (Cont.)

• 1-D TBR estimate should be confirmed with 3-D analysis.
• **Need** CAD input file from UCSD to couple it with MCNP 3-D neutronics code.
• CAD data should include:
  – Non-uniform SOL (5 - 20 cm)
  – Blanket variation
  – Divertor system
  – Penetrations.

• If 3-D results indicate:
  – **Over-breeding** (overall TBR > 1.1), lower Li enrichment below 90% (see next slide).
  – **Under-breeding** (overall TBR < 1.1):
    - Increase “full blanket” thickness by ~10 cm (see next slide), and/or
    - Increase major radius (R > 7.5 m).
Overall TBR (Cont.)

Full Blanket/Shield Region

Solution for **over-breeding** blanket:
Reduce Li enrichment below 90%.

Solutions for **under-breeding** blanket:
Increase blanket thickness
(or increase major radius).
# Heat Load to In-vessel Components

(R = 7.5 m, $P_f = 2561$ MW)

<table>
<thead>
<tr>
<th>Thermal Power (MW$_{th}$)</th>
<th>Full Blkt/Shld</th>
<th>Divertor Region</th>
<th>Non-uniform Blkt/Shld</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>FW</td>
<td>117</td>
<td>---</td>
<td>57</td>
<td>174</td>
</tr>
<tr>
<td>Divertor</td>
<td>---</td>
<td>159</td>
<td>---</td>
<td>159</td>
</tr>
<tr>
<td>Blanket</td>
<td>1141</td>
<td>171</td>
<td>516</td>
<td>1827</td>
</tr>
<tr>
<td>WC-Shield-I</td>
<td>---</td>
<td>---</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>Back Wall</td>
<td>9</td>
<td>3</td>
<td>10</td>
<td>22</td>
</tr>
<tr>
<td>Shield</td>
<td>58</td>
<td>21</td>
<td>49</td>
<td>128</td>
</tr>
<tr>
<td>Manifolds</td>
<td>6</td>
<td>2</td>
<td>---*</td>
<td>8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1330</strong></td>
<td><strong>356</strong></td>
<td><strong>680</strong></td>
<td><strong>2366</strong></td>
</tr>
</tbody>
</table>

(56%) (15%) (29%)

* Contribution included in full blanket/shield manifolds.

Low Grade Heat:

| VV | 13 | 0.5  | 0.6  | 14  |
|    |    |      |      | (< 1%) |

Overall $M_n = 1.155$
## Power Split between He & LiPb Coolants
(R = 7.5 m, Pf = 2561 MW)

<table>
<thead>
<tr>
<th>Component</th>
<th>He</th>
<th>LiPb</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermal Power</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(MW&lt;sub&gt;th&lt;/sub&gt;)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Heat</td>
<td>512</td>
<td>---</td>
<td>512</td>
</tr>
<tr>
<td>90% of He Pumping Power</td>
<td>125</td>
<td>---</td>
<td>125</td>
</tr>
<tr>
<td>FW</td>
<td>174</td>
<td>---</td>
<td>174</td>
</tr>
<tr>
<td>Divertor</td>
<td>159</td>
<td>---</td>
<td>159</td>
</tr>
<tr>
<td>Blanket</td>
<td>168</td>
<td>1659</td>
<td>1827</td>
</tr>
<tr>
<td>WC-Shield-I</td>
<td>48</td>
<td>---</td>
<td>48</td>
</tr>
<tr>
<td>Back Wall</td>
<td>22</td>
<td>---</td>
<td>22</td>
</tr>
<tr>
<td>Shield</td>
<td>128</td>
<td>---</td>
<td>128</td>
</tr>
<tr>
<td>Manifolds</td>
<td>3</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Leakage from LiPb to He</td>
<td>+100</td>
<td>-100</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1439</td>
<td>1564</td>
<td>3003</td>
</tr>
</tbody>
</table>

He : LiPb power ratio = 48 : 52
Design Requirements Satisfied Except at Divertor (Unknown Location and NWL)

**Overall TBR**  
(for T self-sufficiency)  
1.1

**Damage to Structure**  
200 dpa

**Helium Production @ Manifolds and VV**  
(for reweldability of FS)  
1 appm

**S/C Magnet (@ 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 electric insulator  
$> 10^{11}$ rads

**Machine Lifetime**  
40 FPY

**Availability**  
$\sim 85\%$ ?
### Key Parameters for Economic Analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{\text{min}}$</td>
<td>1.26</td>
</tr>
<tr>
<td>Overall TBR</td>
<td>1.1</td>
</tr>
<tr>
<td>Overall Energy Multiplication</td>
<td>1.155</td>
</tr>
<tr>
<td>He : LiPb Power Ratio</td>
<td>48 : 52</td>
</tr>
<tr>
<td>FW EOL Fluence</td>
<td>15 MWy/m$^2$</td>
</tr>
<tr>
<td>FW Lifetime</td>
<td>3.3 FPY (for 4.5 MW/m$^2$ peak)</td>
</tr>
<tr>
<td>System Availability</td>
<td>~ 85%</td>
</tr>
</tbody>
</table>
Magnet Structure: Incoloy-908 or JK2LB?

<table>
<thead>
<tr>
<th></th>
<th>Incoloy</th>
<th>JK2LB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb content</td>
<td>3 wt%</td>
<td>---</td>
</tr>
<tr>
<td>Class A WDR</td>
<td>0.1</td>
<td>0.0003</td>
</tr>
<tr>
<td>Clearable?</td>
<td>no</td>
<td>after 1 y</td>
</tr>
<tr>
<td>Recycle</td>
<td>remotely</td>
<td>hands-on</td>
</tr>
</tbody>
</table>

Incoloy and JK2LB have different properties, with Incoloy-908 having a higher Nb content compared to JK2LB and a lower Class A WDR. Incoloy-908 is not clearable after 1 year, whereas JK2LB is clearable remotely. Recycle is defined as either remotely or hands-on. 

94 Nb is main contributor to CI and dose after 1 y

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**Graphs:**

1. **US Clearance Index**
   - Incoloy-908 and JK2LB are compared over time after shutdown (s).
   - The US Clearance limit is marked.
   - Incoloy-908 stays above the limit, while JK2LB goes below the limit after 1 year.

2. **IAEA Clearance Index**
   - Similar to the US Clearance Index, but with different time scales and limits.
   - Incoloy-908 and JK2LB are compared over time after shutdown (s).
   - The IAEA clearance index limit is marked.
   - Incoloy-908 stays above the limit, while JK2LB goes below the limit after 1 year.

3. **Recycling Dose Rate (Sv/h)**
   - The recycling dose rate is shown over time after shutdown (s).
   - The recycling dose rate for Incoloy-908 and JK2LB is compared.
   - The Hands-on and RH limits are marked.
   - After 1 year, the dose rate for both materials drops below the limits.
Concluding Remarks and Future Plan

• R= 7.5 m design offers adequate TBR. To be confirmed with 3-D analysis. Need CAD data from UCSD for all components, including divertor and penetrations.

• Monitor location and orientation of He access tubes.

• Protection of components behind divertor system needs further assessment.

• Future plan:
  – Perform 3-D analysis to confirm overall TBR and $M_n$ for R= 7.5 m design.
  – Update NWL distribution for R= 7.5 m design with non-uniform SOL using latest parameters (neutron source profile, plasma surface, magnetic axis trajectory, and SOL variation).
  – Check NWL at divertor and assess streaming through divertor He access pipes
  – Document work.
**ARIES-CS Publications**

- **Two abstracts** submitted to **8th IAEA TM on Fusion Power Plant Safety**
  (July 10-13, 2006, Vienna, Austria). Papers due at the meeting:
  - **L. El-Guebaly**, R. Pampin (UK), and M. Zucchetti (Italy), “Clearance Considerations for Slightly-Irradiated Components of Fusion Power Plants”.

- **Few abstracts will be submitted to 17th TOFE by June 9, 2006**