Near-Final Radial Build and Nuclear Parameters

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ARIES-CS Project Meeting
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UW
UW Action Items

1. Check blanket coverage and TBR for $R = 7.5$ and $8\,\text{m}$. 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
• 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, Δ_min, plasma contour, magnet CL)

NWL Profile
(peak, average, ratio)

Design Requirements

Blanket Concept
Init. Magnet Parameters
Init. Divertor Parameters

Radial Build Definition
(Δ_min and elsewhere
Optimal dimension and composition, blanket coverage, thermal loads)

1-D Nuclear Analysis
(Δ_min, TBR, M_n, damage, lifetime)

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

no Δ_min match
or insufficient breeding
New Plasma – Mid-coil Separation Contours

• **From:** L-P Ku (PPPL)
• **Basis:** ARE physics
• **Configuration:** 3 FP
• 4 $D_{\text{min}}$ per FP
• $D_{\text{min}}$ vs. $R$, starting at 1.18 m for $R = 7$ m

![Graph showing minimum separation distance vs. radius](image)

![Diagram showing plasma boundary and mid-coil](image)
CAD Confirmed UW Estimate for Blanket Coverage Fractions

<table>
<thead>
<tr>
<th></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 ~72% of FW area.
• **Non-uniform, tapered blanket** inside **red** contour covers ~28% of FW area.

\[ R = 7.5 \text{ m} \]  
[ 4 \( \Box_{\text{min}} \) (= 1.26 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 \( D_{\text{min}} (= 1.43 \text{ m}) \) 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

![Graph showing coverage fraction vs. R for uniform and non-uniform blankets.](image)

- **Coverage Fraction (%)**
- **R (m)**
  - Uniform Blanket: 8.5 m
  - Non-uniform Blanket: 7 m
Near-Final Radial Build
(R= 7.5 m ; 4.5 MW/m² peak)

<table>
<thead>
<tr>
<th>Thickness (cm)</th>
<th>SOL</th>
<th>Blanket</th>
<th>WC Shield-I (replaceable)</th>
<th>Back Wall</th>
<th>WC Shield-II (permanent)</th>
<th>Gap</th>
<th>Vacuum Vessel</th>
<th>Gap + Th. Insulator</th>
<th>Coil Case &amp; Insulator</th>
<th>Winding Pack</th>
<th>External Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8 cm FW</td>
<td>5</td>
<td>23</td>
<td>12</td>
<td>5</td>
<td>34</td>
<td>2</td>
<td>28</td>
<td>2</td>
<td>2.2</td>
<td>18</td>
<td>?</td>
</tr>
<tr>
<td>1.5 cm FS/He</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 cm SiC Insert</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 cm Breeding Zone-I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 cm Breeding Zone-II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 cm Back Wall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replaceable FW/Blkt/BW</td>
<td>63</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Thickness**
- D_{min} = 126 cm
- D ≥ 177 cm

**Non-uniform Blanket & Shield**
@ D_{min}

**Full Blanket & Shield**
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)

Diagram showing:
- Vacuum Vessel
- LiPb & He Manifolds
- FS-Shield
- Back Wall
- Full Blanket
- WC-Shield-II
- WC-Shield-I
- SOL
- Plasma
- Min gap = 126 cm
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)
Xn through Divertor System (Cont.)

- **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/m²** 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 10% He Coolant 75% WC Filler</td>
</tr>
<tr>
<td>WC Shield-II</td>
<td>26 – 34 cm</td>
<td>28%</td>
<td>15% FS Structure 10% He Coolant 75% WC Filler</td>
</tr>
<tr>
<td>VV</td>
<td>28 cm</td>
<td>100%</td>
<td>28% FS Structure 49% Water 23% Borated Steel Filler</td>
</tr>
<tr>
<td>Inner Coil Case</td>
<td>2 cm</td>
<td>33%</td>
<td>95% Incoloy-908 Structure 5% LHe Coolant</td>
</tr>
<tr>
<td>(in front of WPs only)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winding Pack @ 4K</td>
<td>18 cm</td>
<td>33%</td>
<td>18.5% Incoloy-908 Structure 48.2% Cu 12.8% Nb,Sn 10.0% GFF Polyimide 10.5% LHe Coolant</td>
</tr>
<tr>
<td>External Structure</td>
<td>56 +10 cm</td>
<td>33%</td>
<td>95% Incoloy-908 Structure 5% LHe Coolant</td>
</tr>
<tr>
<td>(behind WPs only)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inter Coil Structure</td>
<td>35 cm</td>
<td>67%</td>
<td>95% Incoloy-908 Structure 5% LHe Coolant</td>
</tr>
<tr>
<td>(between WPs)</td>
<td></td>
<td></td>
<td></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 (~2x2 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.)

\[
R = 7.5 \text{ m} \\
15\% \text{ Divertor Coverage} \\
\text{Overall TBR} \sim 1.1 \text{ based on 1-D estimate}
\]
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

\((R= 7.5 \text{ m}, P_f= 2561 \text{ MW})\)

<table>
<thead>
<tr>
<th>Thermal Power (MW\textsubscript{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>Total</td>
<td><strong>1330</strong></td>
<td><strong>356</strong></td>
<td><strong>680</strong></td>
<td><strong>2366</strong></td>
</tr>
<tr>
<td></td>
<td>(56%)</td>
<td>(15%)</td>
<td>(29%)</td>
<td></td>
</tr>
</tbody>
</table>

\[ \text{Overall } M_n = 1.155 \]

**Low Grade Heat:**

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

* Contribution included in full blanket/shield manifolds.
## Power Split between He & LiPb Coolants

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

<table>
<thead>
<tr>
<th>Thermal Power</th>
<th>He</th>
<th>LiPb</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>(MW(_{th})) 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>Total</td>
<td>1439</td>
<td>1564</td>
<td>3003</td>
</tr>
</tbody>
</table>

\[ \text{He : LiPb power ratio} = 48 : 52 \]
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 Nb₃Sn (Eₙ > 0.1 MeV)  
10^{19} n/cm²

Peak nuclear **heating**  
2 mW/cm³

Peak **dpa** to Cu stabilizer  
6x10^{-3} dpa

Peak **dose** to electric insulator  
> 10^{11} rads

**Machine Lifetime**  
40 FPY

**Availability**  
~ 85%
### Key Parameters for Economic Analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta_{\text{min}}$</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/m²</td>
</tr>
<tr>
<td>FW Lifetime</td>
<td>3.3 FPY (for 4.5 MW/m² 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>

\(^{94}\)Nb is main contributor to CI and dose after 1 y
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.
• **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**