ARIES-AT Nuclear Parameters, Radial Build, and Activation Analysis

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C. Kessel (PPPL), M. Billone (ANL)

Web address:

ARIES Project Meeting
1-3 December 1999
UCSD
<table>
<thead>
<tr>
<th>Design Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fusion power</strong></td>
<td>1737 MW</td>
</tr>
</tbody>
</table>
| **FW location** | at midplane – OB, IB 6.05, 3.55 m  
  at top/bottom – OB, IB 4.5, 3.55 m |
| **Γ** | Peak OB, IB 6.1, 4 MW/m²  
  Average OB, IB 5.2, 2.8 MW/m² |
| **FW poloidal length** | ~5.5, 4.5 m |
| **SiC burnup limit** | 3% |
| **FS dpa limit** | 200 dpa |
| **Machine lifetime** | 40 FPY |
| **HT magnet/cryostat composition from L. Bromberg** |  |

**ARIES-RS’ vacuum vessel configuration**  
(to be modified based on Clearance considerations)

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* Between X points
Nuclear Parameters

- **Key features of FW/Blanket:**
  - Self-cooled LiPb/SiC FW/blanket
  - Constant-flow, integral FW design (3.3 cm thick; 40% SiC, 60% LiPb)
  - IB and OB blankets only (no blanket behind divertor)
  - 90% enriched LiPb
  - 30 cm thick IB FW/blanket
  - 65 cm thick OB FW/blanket segmented into:
    - 30 cm FW/Blanket -I
    - 35 cm Blanket-II
  - 6 cm thick vertical stabilizing shell (90% W, 10% LiPb) at top/bottom:
    - Between blanket segments on OB
    - Between blanket and shield on IB
  - Penetrations:
    - 1.5 m² on OB for CD and plasma control, per TK
    - 2 cm radial gaps between 16 blanket modules

- **Reference nuclear parameters:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall TBR</td>
<td>1.1</td>
</tr>
<tr>
<td>Overall Mn</td>
<td>1.1</td>
</tr>
<tr>
<td>SiC Burnup rate</td>
<td>1% per FPY*</td>
</tr>
<tr>
<td>FW EOL Fluence</td>
<td>18.5 MWy/m²</td>
</tr>
<tr>
<td>FW Lifetime</td>
<td>3 FPY</td>
</tr>
</tbody>
</table>

- **Comments:**
  - Breeding is marginal
  - More SiC content in FW will degrade breeding
  - Thicker blanket will increase breeding
  - Higher enrichment (> 90%) is expensive and has insignificant impact on breeding

* 0.7% Si, 0.3% C
SiC content in FW has significant impact on breeding

Thicker OB blanket increases breeding slightly (~3%)
TBR vs. Li Enrichment

Blanket will not breed if enrichment drops below 90%
• Two separate shells placed at top/bottom of IB and OB sides
• OB shells cover 50% of poloidal length
• Shell has no significant impact on breeding of FW/B-I
• 6 cm thick shell reduces breeding behind it by 50%
• Based on 3-D calculations, regions behind shells contribute 10% to TBR
  ⇒ Shell reduces breeding by ~0.05, resulting in overall TBR of 1.1
Components’ Lifetimes

- Service lifetimes are based on:
  - 3% burnup limit for SiC structure of FW, blanket, HT shield
  - 200 dpa limit for FS structure of LT shield and V.V.

- Back wall of B-I is lifetime component. BW could be reused to reduce radwaste stream

- Ratio of replaceable component volume to total radwaste volume is 20-30% and drops to 10-20% if B-I back wall is reused
## Nuclear Heat Load to In-vessel Components

*(P_n = 1390 MW)*

<table>
<thead>
<tr>
<th>Nuclear Heating (MW)</th>
<th>Inboard</th>
<th>Outboard</th>
<th>Divertor</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>FW or DP</td>
<td>90</td>
<td>212</td>
<td>36**</td>
<td>338   (22%)</td>
</tr>
<tr>
<td>Blanket</td>
<td>230</td>
<td>708#</td>
<td>---</td>
<td>938   (61%)</td>
</tr>
<tr>
<td>HT Shield</td>
<td>60##</td>
<td>20</td>
<td>174</td>
<td>254   (17%)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>380</td>
<td>940</td>
<td>210</td>
<td>1530</td>
</tr>
</tbody>
</table>

(25%) (61%) (14%)

**Overall neutron energy multiplication is 1.1**

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*To be confirmed by 3-D analysis

** Assumed 5 cm thick SiC/LiPb (40/60) divertor plates

# 560 MW in B-I, 36 MW in W shells, 112 MW in B-11

## Assumed 15 MW in W shells, 45 MW in shield
Inboard Radial Build

Component Composition#

FW (3.3 cm) 40% SiC, 60% LiPb (90% Li-6)
Blanket (26.7 cm) 7% SiC, 93% LiPb (90% Li-6)
HT Shield 15% SiC, 10% LiPb, 75% B-FS
LT Shield 15% FS, 5% H$_2$O, 80% WC
Vacuum Vessel 35% FS, 40% H$_2$O, 25% WC
HT Magnet 87% SS, 10% LN, 2.5% Y$_1$Ba$_2$Cu$_3$O$_{7-δ}$, 0.5% Ag

• V.V. and TF magnet radiation limits are all met* for peak $\Gamma = 4\ \text{MW/m}^2$
  (1 He appm at V.V and $10^{19}\ \text{n/cm}^2$ at magnet @ EOL)

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* SiC and WC are 95% dense
* Safety factor of 3 considered in all shielding calculations
Outboard Radial Build

**Component** | **Composition**
--- | ---
FW/Blanket-I: | FW (3.3 cm) 40% SiC, 60% LiPb (90% Li-6)  
B-I (26.7 cm) 7% SiC, 93% LiPb (90% Li-6)  
Blanket-II | 8% SiC, 92% LiPb  
HT Shield | 15% SiC, 10% LiPb, 75% B-FS  
Vacuum Vessel | 25% FS, 60% H₂O, 15% B-FS  
HT Magnet | 87% SS, 10% LN, 2.5% Y₁Ba₂Cu₃O₇, 0.5% Ag

- Blanket-II and HT shield could be combined in a single lifetime component
- V.V. and TF magnet radiation limits are all met* for peak $\Gamma = 6 \text{ MW/m}^2$
  (1 He appm at V.V and $10^{19}$ n/cm² at magnet @ EOL)
- No need for separate LT shielding component

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* SiC and WC are 95% dense  
* Safety factor of 3 considered in all shielding calculations
Optimum Water Content in IB LT Shield and V.V.

- Trading WC filler for water, optimum compositions are:
  - IB LT shield: 15% FS structure, 5% H$_2$O, 80% WC filler
  - IB V.V.: 35% FS structure, 40% H$_2$O, 25% WC filler

- Thinner V.V. could be cleared (to be confirmed by activation analysis)
Optimum Water Content in OB V.V.

- Trading B-FS filler for water, optimum V.V. composition is:

  25% FS structure, 60% H₂O, 15% B-FS filler

- Thinner V.V. could be cleared (to be confirmed by activation analysis)
Impact of WC filler on IB Shield Size

- Low-cost manufacturing technique could only be applicable to metallic structural components (without filler)

- WC filler of both IB LT shield and V.V. was replaced by FS structure

- FS shield/V.V. will increase radial build by 15 cm

- Thicker IB components result in larger machine

- Impact on COE of thicker but cheaper IB shield/V.V. needs to be assessed by ASC
Comparison Between ARIES-AT and ARIES-RS Radial Builds

<table>
<thead>
<tr>
<th>ARIES design</th>
<th>Inboard</th>
<th>Outboard</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AT</td>
<td>RS</td>
</tr>
<tr>
<td>Thickness (cm):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FW/Blanket-I</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Blanket-II</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Replaceable Shield</td>
<td>---</td>
<td>20</td>
</tr>
<tr>
<td>HT shield</td>
<td>20</td>
<td>26</td>
</tr>
<tr>
<td>LT shield</td>
<td>27</td>
<td>28</td>
</tr>
<tr>
<td>Vacuum vessel</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td><strong>97</strong></td>
<td><strong>114</strong></td>
</tr>
<tr>
<td>Magnet &amp; cryostat</td>
<td>25</td>
<td>55</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>122</strong></td>
<td><strong>169</strong></td>
</tr>
<tr>
<td><strong>Net reduction in thickness</strong></td>
<td><strong>47</strong></td>
<td><strong>0</strong></td>
</tr>
</tbody>
</table>

- Thinner ARIES-AT radial builds are due to:
  - better LiPb shielding performance compared to Li
  - use of water in LT shield and V.V. instead of He
  - compact HT magnet
Activation Analysis

- **Codes and model:**
  - Activation: ALARA code; FENDL-2 activation library
  - Flux: 1-D DANTSYS code; FENDL-1 Xn data
  - 175 n and 42 g group structure
  - 3-D neutron flux used to re-normalize 1-D flux for all components
  - Average OB and IB $\Gamma$ are 5.2 and 2.8 MW/m$^2$, respectively
  - Operation time: 3 FPY for FW/B-I, 40 FPY for all other components

- Activity, decay heat, WDR, and clearance index depend strongly on material, flux level, neutron spectrum, operation time, and cooling period

- **Results reported here are for:**
  - OB side only, as defined by OB radial build.
    (IB side exhibits similar behavior at reduced level)
  - SiC and FS materials with impurities
  - 100% dense compact waste (coolants and void excluded)

- **Results include:**
  - Activity and decay heat as function of time after shutdown
  - Fetter’s and NRC (10CFR61) waste disposal ratings for individual components at end of service lifetime
  - Dominant radionuclides at various times after shutdown

- Clearance calculations are underway

- **Benchmarking of ALARA** (activity, decay heat, and WDR) with DKR-Pulsar code showed excellent agreement
- OB FW contains highest activity among all SiC structures

- Compared to FW, activity generated in back wall (BW) is lower by factor of 10 or more

- Radial SiC structural ribs of B-I contain intermediate activity
OB FW contains highest decay heat among all SiC structures

LiPb may contain higher decay heat than SiC. Coolant activation will be assessed for LOFA analysis.
Class C Waste Disposal Rating
OB FW/Blanket-I
(3 FPY)

<table>
<thead>
<tr>
<th></th>
<th>Fetter’s WDR</th>
<th>NRC WDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>FW</td>
<td>0.3</td>
<td>0.04</td>
</tr>
<tr>
<td>Cell</td>
<td>0.006</td>
<td>0.01</td>
</tr>
<tr>
<td>BW</td>
<td>0.0002</td>
<td>0.007</td>
</tr>
<tr>
<td>Average</td>
<td>0.1</td>
<td>0.02</td>
</tr>
</tbody>
</table>

- WDR is for compact waste (void excluded)
- WDR < 1 means component qualifies as Class C low level waste
- $^{26}\text{Al}$ is dominant nuclide for Fetter’s WDR
  $\text{Si}^{28}(n, np)\text{Al}^{27}(n, 2n)\text{Al}^{26}$
- $^{14}\text{C}$ is dominant nuclide for NRC WDR
  $\text{C}^{12}(n, \gamma)\text{C}^{13}(n, \gamma)\text{C}^{14}$
- BW could last for 40 FPY and qualifies as Class C LLW
  (Fetter’s and NRC WDR$_{BW}$ are 0.01 and 0.1 @ 40 FPY, respectively)

OB FW/Blanket-I qualify easily as Class C LLW after 3 FPY
Activity and Decay Heat
OB Blanket-II, HT Shield, V.V., and Magnet
(40 FPY, 5.2 MW/m², 100% Dense Composition)
## Class C Waste Disposal Rating

**OB Blanket-II, HT Shield, V.V., and Magnet**  
(40 FPY, 5.2 MW/m², Compact Waste)

<table>
<thead>
<tr>
<th>Component</th>
<th>Fetter’s WDR</th>
<th>NRC WDR</th>
</tr>
</thead>
</table>
| Blanket-II   | 0.002  
(Al²⁶)   | 0.05  
(C¹⁴) |
| HT Shield    | 0.17  
(Nb⁹⁴,Tc⁹⁹,Ho¹⁶⁶m) | 0.1  
(Nb⁹⁴,Ni⁶³,⁵⁹) |
| V.V.         | 0.05  
(Nb⁹⁴,Ho¹⁶⁶m) | 0.03  
(Nb⁹⁴) |
| Magnet       | 0.01  
(Ag¹⁰⁸m,Nb⁹⁴) | 0.004  
(Nb⁹⁴) |

All OB permanent components qualify as Class C LLW after 40 FPY
## Dominant Radionuclides for OB Components @ Various Time After Shutdown (in descending order)

### Activity:

<table>
<thead>
<tr>
<th>Time Frame</th>
<th>Material 1</th>
<th>Material 2</th>
<th>Material 3</th>
<th>Material 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shutdown</td>
<td>Al$^{28,29,30}$</td>
<td>Fe$^{55}$, W$^{185,187}$, Mn$^{56}$, Cr$^{51}$, Re$^{186}$</td>
<td>W$^{187}$, Re$^{188}$, Mn$^{56}$, Cr$^{51}$, Fe$^{55}$</td>
<td>Ag$^{110}$, Mn$^{56}$, Ag$^{108}$, Fe$^{55}$</td>
</tr>
<tr>
<td>t &lt; 1 d</td>
<td>Na$^{24}$, Si$^{31}$</td>
<td>Fe$^{55}$, W$^{185,187}$, Mn$^{56}$, Cr$^{51}$, Re$^{186}$</td>
<td>W$^{187}$, Fe$^{55}$, W$^{185}$, Cr$^{51}$, Re$^{188}$</td>
<td>Mn$^{55}$, Fe$^{55}$, Co$^{58}$, Ag$^{110}$, Cr$^{51}$</td>
</tr>
<tr>
<td>1d &lt; t &gt; 1w</td>
<td>Na$^{24}$, T, P$^{32}$</td>
<td>Fe$^{55}$, W$^{185}$, Cr$^{51}$, Fe$^{59}$, Mn$^{54}$, Re$^{186}$</td>
<td>Fe$^{55}$, W$^{185}$, Cr$^{51}$, Re$^{186}$, W$^{187}$, Fe$^{59}$</td>
<td>Fe$^{55}$, Co$^{58}$, Ag$^{110}$, Cr$^{51}$, Mn$^{54}$</td>
</tr>
<tr>
<td>1w &lt; t &gt; 1y</td>
<td>T</td>
<td>Fe$^{55}$, W$^{185}$, Mn$^{54}$</td>
<td>Fe$^{55}$, W$^{185}$, Co$^{60}$</td>
<td>Fe$^{55}$, Co$^{58}$, Ag$^{110m}$, Mn$^{54}$</td>
</tr>
<tr>
<td>1y &lt; t &gt; 10y</td>
<td>T, C$^{14}$</td>
<td>Fe$^{55}$, T, Co$^{60}$</td>
<td>Fe$^{55}$, Co$^{60}$, T</td>
<td>Fe$^{55}$, Ni$^{63}$, Co$^{60}$</td>
</tr>
<tr>
<td>&gt; 10 y</td>
<td>C$^{14}$, Be$^{10}$</td>
<td>Ni$^{63}$, T, Mo$^{93}$, Nb$^{93m}$, Ni$^{59}$</td>
<td>Ni$^{63}$, T, Ni$^{59}$, Mo$^{93}$, Nb$^{93m}$</td>
<td>Ni$^{63}$, Ag$^{108m}$, Ni$^{59}$, C$^{14}$, Mo$^{93}$, Nb$^{93m}$</td>
</tr>
</tbody>
</table>

### Decay Heat:

<table>
<thead>
<tr>
<th>Time Frame</th>
<th>Material 1</th>
<th>Material 2</th>
<th>Material 3</th>
<th>Material 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shutdown</td>
<td>Al$^{28,29,30}$</td>
<td>Mn$^{56}$, W$^{187,185}$</td>
<td>W$^{187}$, Mn$^{56}$, Re$^{188}$</td>
<td>Ag$^{110}$, Mn$^{56}$</td>
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<td>t &lt; 1 d</td>
<td>Na$^{24}$, Si$^{31}$</td>
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<td>W$^{187}$, Mn$^{56}$, Re$^{188}$</td>
<td>Mn$^{55}$, Ag$^{110}$, Co$^{58}$</td>
</tr>
<tr>
<td>1d &lt; t &gt; 1w</td>
<td>Na$^{24}$, Si$^{31}$, P$^{32}$</td>
<td>W$^{185}$, Fe$^{59}$, Mn$^{54}$</td>
<td>Co$^{60}$, Fe$^{59}$, W$^{185,187}$</td>
<td>Ag$^{110m}$, Co$^{58}$, Mn$^{54}$</td>
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