Ferritic Steel Lifetime Assessment and Self-Consistent Nuclear Parameters for ARIES-IFE-HIB

L. El-Guebaly
Fusion Technology Institute
University of Wisconsin - Madison

With input from
M. Sawan, R. Peterson, P. Wilson, E. Mogahed (UW),
M. Billone (ANL),
R. Moir, S. Reyes (LLNL),
and P. Peterson (UCB)

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PPPL
Objectives

• Assess nuclear performance of structure-free blanket concept using ARIES design rules
  – Breeding potential of candidate breeders:
    • Flibe
    • Flinabe.
  – Lifetime of ODS ferritic steel (FS) protected with liquid blanket
  – Waste disposal rating and Helium production for structural components: shield, nozzles, feeding tubes.

• Estimate reduction in waste for thick liquid wall concept.
## Key Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target yield</td>
<td>458.7 MJ</td>
</tr>
<tr>
<td>Rep rate</td>
<td>4 Hz</td>
</tr>
<tr>
<td># of pulses</td>
<td>126 million/FPY</td>
</tr>
<tr>
<td>Average source neutron energy</td>
<td>11.75 MeV</td>
</tr>
<tr>
<td>Neutron power</td>
<td>1286 MW</td>
</tr>
<tr>
<td>Neutron wall loading @ 0.5 m</td>
<td>410 MW/m²</td>
</tr>
<tr>
<td>Penetrations coverage</td>
<td>3%</td>
</tr>
<tr>
<td>Plant lifetime</td>
<td>40 FPY</td>
</tr>
<tr>
<td>Availability</td>
<td>85%</td>
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</tbody>
</table>
ARIES Requirements and Design Limits

Overall TBR \( \geq 1.08 \)

dpa* to FS structure \( \leq 200 \) dpa

Helium production for reweldability of FS \( \leq 1 \) He appm

WDR for Class C low level waste \( \leq 1 \)

* Thermal creep strength @ EOL is more restrictive than radiation damage, per M. Billone (ANL).
Flibe vs Flinabe

- Flinabe has substantially lower melting point (~320 °C) compared to Flibe (459 °C), offering low operating temperature and low vapor pressure.
- To provide very low vapor pressure in HIF beam tubes and protect structure against x-rays and target debris, Per Peterson (UCB) recommended Flinabe to create low temperature vortices.
- It is preferable to have single liquid composition everywhere (in chamber and beam tubes), if acceptable from perspectives of breeding and safety.
Schematic of Radial Build

- **Flibe** (BeF$_2$, (LiF)$_2$) and **Flinabe** (NaF, LiF, BeF$_2$) with natural Li.
- **ODS nanocomposited**# FS or 304-SS.
- Innermost layer of shield represents nozzles and feeding tubes.
- Point source and 1-D spherical geometry

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Flibe Breeds more Tritium than Flinabe

- 83 cm thick Flibe and 150 cm thick Flinabe meet ARIES breeding requirement (TBR ≥ 1.08).
- Enrichment does not enhance breeding of thick Flinabe.
- Nuclear energy multiplication amounts to ~1.25.
- ~10% of heating deposited in shield behind Flibe and 1% of heating in shield behind Flinabe.
For Same Blanket Thickness, Flibe Provides Better Attenuation than Flinabe

- 85 cm Flibe blanket meets FS 200 dpa limit.
- 1.5 m Flinabe blanket provides better shielding and meets 25 dpa limit for 304-SS.
Helium Production is Excessive

Innermost shield layer/nozzles/feeding tubes cannot be re-welded at any time during operation.
Nuclear Source Term for Aerosol Calculations

- Heating evaluated at midplane per unit volume of actual blanket composition.
- For isochooric heating analysis, detailed heating in fine meshes and time-dependent nuclear heating will be computed upon request.
### Steel Composition (in wt%)

<table>
<thead>
<tr>
<th></th>
<th>ODS-12YWT-FS*</th>
<th>ODS M-F82H-FS**</th>
<th>304-SS#</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Experimental Alloy)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>83.818</td>
<td>87.891</td>
<td>70.578</td>
</tr>
<tr>
<td>C</td>
<td>0.052</td>
<td>0.04</td>
<td>0.046</td>
</tr>
<tr>
<td>N</td>
<td>0.014</td>
<td>0.005</td>
<td>0.038</td>
</tr>
<tr>
<td>O</td>
<td>0.16</td>
<td>0.13</td>
<td>–</td>
</tr>
<tr>
<td>Si</td>
<td>0.1</td>
<td>0.24</td>
<td>0.47</td>
</tr>
<tr>
<td>P</td>
<td>–</td>
<td>0.005</td>
<td>0.026</td>
</tr>
<tr>
<td>S</td>
<td>0.001</td>
<td>0.002</td>
<td>0.012</td>
</tr>
<tr>
<td>Ti</td>
<td>0.35</td>
<td>0.09</td>
<td>0.03</td>
</tr>
<tr>
<td>V</td>
<td>0.01</td>
<td>0.29</td>
<td>–</td>
</tr>
<tr>
<td>Cr</td>
<td>12.58</td>
<td>8.7</td>
<td>17.7</td>
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<tr>
<td>Mn</td>
<td>0.05</td>
<td>0.45</td>
<td>1.17</td>
</tr>
<tr>
<td>Co</td>
<td>–</td>
<td>0.0028</td>
<td>0.1</td>
</tr>
<tr>
<td>Ni</td>
<td>0.27</td>
<td>0.0474</td>
<td>9.3</td>
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<tr>
<td>Cu</td>
<td>0.02</td>
<td>0.01</td>
<td>0.2</td>
</tr>
<tr>
<td>Nb</td>
<td>0.01</td>
<td>0.00033</td>
<td>–</td>
</tr>
<tr>
<td>Mo</td>
<td>0.02</td>
<td>0.0021</td>
<td>0.33</td>
</tr>
<tr>
<td>Ta</td>
<td>–</td>
<td>0.08</td>
<td>–</td>
</tr>
<tr>
<td>W</td>
<td>2.44</td>
<td>2</td>
<td>–</td>
</tr>
<tr>
<td>Y</td>
<td>0.16</td>
<td>0.7</td>
<td>–</td>
</tr>
</tbody>
</table>

* R. Klueh et al., “Microstructure and Mechanical Properties of Oxide Dispersion-Strengthened Steels” fusion materials semiannual progress report for the period ending June 30, 2000 (DOE/ER-0313/28), pp. 123-130. Fe-12Cr-3W-0.4Ti-0.25Y$_2$O$_3$ (12YWT) experimental alloy.

** IEA Modified F82H FS + 0.25wt% Y$_2$O$_3$, per M. Billone (ANL). Other elements include: B, Al, As, Pd, Ag, Cd, Sn, Sb, Os, Ir, Bi, Eu, Tb, Dy, Ho, Er, U.

All Alloys Generate High Level Waste

- **ODS-MF82H-FS** offers lowest WDR.
- **Thicker Flinabe blanket results in lower WDR.**
- **Main contributors** to WDR: $^{94}$Nb (from Nb), $^{99}$Tc (from Mo), and $^{192n}$Ir (from W).
- **Potential solutions** to meet waste requirement (WDR < 1):
  - Control Mo and Nb,
  - Thicken blanket.
• In practice, Mo and Nb impurities cannot be zeroed out. Actual level depends on $/kg to keep Mo and Nb < 1 wppm.
• Flibe shield with Mo/Nb control should be > 50 cm thick to qualify as LLW.
• Flinabe shield without Mo/Nb control meets waste requirement if ≥ 45 cm thick.
• Nozzles/feeding tubes generate high level waste unless protected by thicker blanket or mixed with shield and disposed as single unit at EOL.
Thick liquid wall concept developed to eliminate blanket replacement, reduce waste, and increase availability by 10% ⇒ 20% lower COE, per R. Moir (UCRL-JC-115748, April 1994).

In IFE solid wall designs, blanket generates only 2-4% of total waste ⇒ Thick liquid wall concept offers small waste reduction.

(same conclusion made for MFE - APEX project)
Conclusions

- Class C LLW requirement is more restrictive than breeding and dpa requirements.
- No breeding problem identified for Flibe and Flinabe.
- 85/150 cm thick Flibe/Flinabe blankets provide TBR of 1.08 and meet FS dpa limit.
- Helium production in FS is excessive and precludes FS reweldability during operation.
- All steels produce high level waste (WDR >> 1).
- ODS-MF82H-FS and Flinabe system offer lower WDR for FS structure.
- Low level waste can be achieved with combination of Mo/Nb control and blanket/shield adjustment.
- Nozzles/Feeding tubes need additional protection to qualify as LLW unless combined with shield.
Importance of Results and What needs to be done

• Nuclear assessment is important to feasibility of thick liquid wall concept. Results show impact of thick liquid wall on:
  - FS lifetime
  - Waste level
  - Reduction in waste volume.

• Design-specific analysis needed to meet LLW requirement for nozzles and shield using:
  - Nb and Mo impurity control
  - Thicker blanket (adjust TBR)
  - Thicker shield.

• Need feedback from materials community on acceptable Nb and Mo impurity level and impact on FS unit cost.
Fusion Technology Institute IFE/ICF Reactor Studies

Calendar Year

*In conjunction with other universities, national and international labs
• Many INPORT* units ⇒ high surface area for condensation.
• LiPb seeps through woven, porous SiC flexible tubes.
• Axial tension applied on tubes to limit motion.
• Concerns: vaporized LiPb exerts high impulse load on tubes, uncertainties in applied tension, possible change in SiC porosity, possible deviation from circular tube shape.

* Inhibited flow Porous Tubes
PERIT Unit

- Two rows of PERIT* unit:
  - Perforated to maintain wetted surface through jet fan spray
  - Rigid to withstand shock waves.
- LiPb coolant/breeder and FS tubes.

* Perforated Rigid Tube

Cross-Section of the LIBRA-SP Target Chamber