Activation Assessments of 316-SS Vacuum Vessel and W-Based Divertor

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ARIES Project Meeting
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UCSD
Nuclear Assessments

- **Activation** assessment identifies parameters **after operation**:
  - Specific activity (Ci/m$^3$)
  - Decay heat (MW/m$^3$)
  - Transmutation products
  - Radwaste management schemes:
    - Clearance - release to commercial market to fabricate as consumer products
    - Recycling - Reuse within nuclear industry
    - Geological disposal classification:
      - Low Level Waste (LLW: Class A or C)
      - High Level Waste (HLW). Materials generating HLW should be excluded.

- **ARIES requirement**: all materials should be recyclable and qualify as LLW.

- **Radiation damage** assessment determines parameters **during operation**:
  - Atomic displacement (dpa) – life-limiting factor for structural components
  - He production (in appm) – reweldability of steel-based VV and manifolds
  - H production (in appm).
ARIES Vacuum Vessel

- What is new?
- Neutron-induced swelling vs dpa
- VV Activation assessment:
  - Specific activity (Ci/m³)
  - Radwaste management schemes:
    - Clearance - release to commercial market to fabricate as consumer products
    - Recycling - Reuse within nuclear industry
    - Geological disposal classification:
      - Low Level Waste (LLW: Class A or C)
      - High Level Waste (HLW). Materials generating HLW should be excluded.
- All ARIES materials should be recyclable and qualify as LLW.
Rationale

• No reweldability data for ferritic steel (FS).
• **ITER** reweldability limit* for **316-SS**:
  – 1 He appm for **thick plate** welding
  – 3 He appm for **thin plate** (or **tube**) welding.
• Double-walled vacuum vessels with internal ribs:
  – **ITER**: **6 cm** plate of **316-SS** and 1 appm limit
  – **ARIES**: **2 cm** plate of **F82H-FS** and 1 appm limit
    (Note discrepancy between ARIES VV plate thickness and ITER reweldability limit)
• Should we adopt 316-SS reweldability limits for F82H-FS?
• Or, could 316-SS be used in **ARIES VV**?

Issues:
  – Neutron-induced swelling
  – Activation of 316-SS with 2.5 wt% Mo
  – Ferromagnetism
  – Structural properties and performance limits#.
  – Others?

* Reference: ITER Nuclear Analysis Report G 73 DDD 2 01-06-06 W 0.1 - Section 2.5.1, page 15.
# R.J.Kurtz and R.E. Stoller, “Performance Limits for Austenitic & RAFM Steels,”
UCLA Meeting, August 12-14, 2008.
Comparison of Properties*

**Austenitic Steels** (such as 316-SS):
- Well-developed technology for nuclear and other advanced technology applications
- High long-term activation due to 2.5 wt% Mo (alloying element)
- Susceptible to swelling at high dose
- High He production
- Poor thermal conductivity and low thermal stress parameter
- Non ferromagnetic
- New alumina forming creep resistant versions offer better high-temperature strength and oxidation resistance.

**Ferritic/Martensitc Steels** (such as F82H FS):
- Well-developed technology for nuclear and other advanced technology applications
- Low long-term activation
- Resistance to swelling at high dose
- Good thermal conductivity and thermal stress parameter
- Ferromagnetic
- Heat treatable
- ODS versions offer route to better high-temperature strength, improved He management, and mitigate displacement damage.

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Higher Swelling in 316-SS than in FS

Fission reactor, low He data

![Graph showing volumetric swelling vs. damage level](image)

<table>
<thead>
<tr>
<th>VV dpa @ 40 FPY</th>
<th>IB</th>
<th>OB</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARIES-AT</td>
<td>~ 30*</td>
<td>~ 5*</td>
</tr>
<tr>
<td>ARIES-DB</td>
<td>~ 10*</td>
<td>~ 5*</td>
</tr>
</tbody>
</table>

*assembly gaps may increase damage level, unless well shielded.

Neutron-induced swelling is not significant at low dpa of ARIES VV
VV Activation

- ARIES-CS geometry and parameters:
  - 2.6 MW/m² average NWL
  - 40 FPY VV lifetime
  - 85% availability.
Long-term Activity of 316-SS is higher Relative to F82H-FS
Both Materials are Not Clearable, but Recyclable with Advanced RH Equipment

![Graphs showing Proposed U.S. Clearance Index and Recycling Dose Rate over time after shutdown.](image-url)
Waste Disposal Rating
(@ 100 y after shutdown)

316-SS generates HLW ⇒ do not employ for ARIES VV
ARIES W-Based Divertor

- **Candidate W alloys:**
  - Status of development
  - Concerns: activation and radiation damage.

- **Activation** of W and W-alloys:
  - Specific activity (Ci/m³)
  - Radwaste management schemes:
    - Clearance - release to commercial market to fabricate as consumer products
    - Recycling - Reuse within nuclear industry
    - Geological disposal classification:
      - Low Level Waste (LLW: Class A or C)
      - High Level Waste (HLW). Materials generating HLW should be excluded.
    - All ARIES materials should be recyclable and qualify as LLW
      - Transmutation products.

- **Radiation damage** to W:
  - Atomic displacement (dpa)
  - He production (in appm)
  - H production (in appm).
Latest Divertor Design
(X. Wang and S. Malang)

Combined Plate and Finger Divertor Concept

0.5 cm W Armor: 88.4% W
(sacrificial layer) 11.6% void

7.2 cm Cooling Channel:
29.6% W alloy structure
2.6% W
11.6% ODS-FS
56.2% He
Brazing materials ?!
Status of W Alloy Development

• Materials program just started working on W alloys for fusion.

• Emphasis will be to:
  – Look for novel ways to enhance ductility and fracture toughness of W alloys using modern computational materials science approaches.
  – Perform key experiments on existing advanced alloys to benchmark the state-of-the-art materials using test procedures designed to yield true measures of mechanical and physical properties.

• Even in un-irradiated state, W ductility and fracture toughness are low.

• Radiation-induced changes:
  – Bombarding W with neutrons will only degrade these properties (as well as thermal conductivity).
  – He and H transmutation products are expected to degrade bulk properties in addition to displacement damage from neutrons.
  – Other transmutation-induced composition changes are likely to be significant because transmutation rate in W alloys is high.
  – Effects of He and H (as well as other implanted particles from plasma) are known to significantly alter surface morphology and properties.
Additional Concerns

• **Activation-related issues:**
  – Recyclability of W alloys
  – Waste disposal rating (WDR). Any high-level waste?
  – Transmutation rate
  – W decay heat and divertor temperature during LOCA/LOFA. [In ARIES-CS divertor with W armor, temperature during LOCA exceeded FS reusability limit (740°C) ⇒ divertor must be replaced after each LOCA event].

• **Radiation damage level:**
  • Atomic displacement
  • He production
  • H production

• **Survivability of W armor** during steady state and off-normal events:
  Per G. Kulcinski (UW):
  • Lifetime could be few days, if bombarded with $10^{20}$ He atoms/cm$^2$
  • UW could simulate ARIES divertor conditions using UW-IEC experiment:
    • Two options: HOMER and MITE-E, depending on whether particle flux is perpendicular or isotropically incident on surface
    • Can simulate energies from ~0.1 keV to > 150 keV
    • Can heat samples separately to ~1000°C
    • Need He spectrum and angular distribution.
W-Based Materials and Alloys

- Pure W (impractical)
- W with impurities (99.99 / 0.01 wt%) for armor (sacrificial layer) (brittle; cracks during fabrication and/or operation)
- W/W composites
- W alloys for structural components:
  - W-Re (74 / 26 wt%)
  - W-Ni-Cu (90 / 6 / 4 wt%)
  - W-Ni-Fe (90 / 7 / 3 wt%)
  - W-La$_2$O$_3$ (99 / 1 wt%) - for EU divertor, per Rieth (Germany)
  - W-TiC (98.9 / 1.1 wt%) - nano-composited alloy developed by Japan.

Optimized for fusion divertors to improve ductility and fracture toughness
W-TiC Alloy for Fusion Applications


**Composition:** TiC (1.1 wt%), Mo (~ 3 wt%), O (200 wppm), N (40 wppm).

Mo is from TZM vessel used for mechanical alloying ⇒ ignore Mo

Consider nominal W impurities with W_TiC alloy, per H. Kurishita.

**Improved radiation performance.** Section 3.4 of Kurishita’s paper:

Very recently, blister formation and D retention in W have been investigated for low energy (55 ± 15 eV), high flux \((10^{22} \text{ m}^{-2} \text{s}^{-1})\), high fluence \((4.5 \times 10^{26} \text{ m}^{-2})\) ion bombardment at moderate temperature \((573 \text{ K})\) in pure D and mixed species D + 20%He plasmas in the linear divertor plasma simulator PISCES-A at the University of California, San Diego [13]. The W materials used are stress-relieved pure W (SR-W), re-crystallized pure W (RC-W) and the compression formed samples of W–1.1TiC/Ar-UH and W–1.1TiC/H2-UH. It has been found that W–1.1TiC/Ar-UH and W–1.1TiC/H2-UH exhibit superior performance to SR-W and RC-W; no holes and no blisters are formed, and consequently D retention is much less than those in SR-W and RC-W of \(10^{21} \text{ m}^{-2}\) by around two orders of magnitude [13]. The observed superior properties of W–1.1TiC/Ar-UH and W–1.1TiC/H2-UH can be attributed not only to their much finer grain size than that of SR-W and RC-W [13], but also to the modified microstructure where the grain boundaries are significantly strengthened in the re-crystallized state. In addition, it is important to state the finding that addition of He to pure D (mixture of D and He) significantly suppresses blistering and D retention in the W materials [13]. This is most likely because the formation of nano-sized high density He bubbles in the near surface act as a diffusion barrier to implanted D atoms and consequently reduces the amount of uptake in the W material [13].


- Modified W-TiC compacts exhibited superior surface resistance to low-energy D irradiation.

- Because of microstructural modifications, W–1.1%TiC compacts exhibited very high fracture strength and appreciable ductility at room temperature.

- Per R. Kurtz, US materials program hopes to obtain some of Kurishita’s material for testing.
List of W Impurities (0.01 wt%) 
(M. Rieth - Germany)

<table>
<thead>
<tr>
<th>Element</th>
<th>Garantierte Analyse max. [μg/g]</th>
<th>Typische Analyse [μg/g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>10</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Al</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>As</td>
<td>5</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Ba</td>
<td>5</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Ca</td>
<td>5</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Cd</td>
<td>5</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Co</td>
<td>10</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Cr</td>
<td>20</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Cu</td>
<td>10</td>
<td>&lt; 5</td>
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<tr>
<td>Fe</td>
<td>30</td>
<td>10</td>
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<td>K</td>
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<tr>
<td>Mg</td>
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<td>&lt; 2</td>
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<td>Mn</td>
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<td>Na</td>
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<tr>
<td>Nb</td>
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<tr>
<td>Ni</td>
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<td>&lt; 2</td>
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<td>Pb</td>
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<td>Ta</td>
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<td>&lt; 10</td>
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<td>Ti</td>
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<td>Zn</td>
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<tr>
<td>Zr</td>
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<td>&lt; 2</td>
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<tr>
<td>Mo</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>W</td>
<td>min. 99.97 % *)</td>
<td>99.99 % *)</td>
</tr>
</tbody>
</table>

*) metallische Reinheit ohne Mo / metallic purity excluding Mo.

Undesirable impurity for geological disposal
Key Parameters for Nuclear Analysis

- 1 MW/m$^2$ average NWL over divertor plates

- Divertor replaced with blanket on same time scale
  \[\implies \sim 4 \text{ y of operation (3.4 FPY with 85\% availability)}\]

- 1 MW/m$^2$ NWL and 3.4 FPY \[\implies 3.4 \text{ MWy/m}^2 \text{ fluence}\]

- Other fluences examined (up to 20 MWy/m$^2$).
Source Terms for Nuclear Analysis: Neutron Flux and Specific Activity

Neutron Spectrum at Divertor Surface

Specific Activity of W Alloys in Cooling Channel
Divertor is Not Clearable

- Even highly pure W cannot be cleared after 100 y following shutdown.
- Divertor should preferably be recycled or disposed of.
Candidate W Alloys are Recyclable with Advanced Remote Handling Equipment

- All W alloys can be recycled after few days with advanced RH equipment.
- W-TiC and W-La$_2$O$_3$ alloys exhibit lowest recycling dose.
- All W-based components require active cooling during recycling to remove decay heat.
- Conventional RH equipment cannot be used during plant life (~50 y).
Candidate W Alloys are Recyclable with Advanced RH Equipment (Cont.)

- W alloys could be recycled* several times during plant life, using advanced RH equipment.
- Multiple cycles require longer storage period (up to 4 months) before recycling.

* 3 y between cycles considered for storage, refabrication, and inspection.
Classification of W-Based Divertor for Geological Disposal

<table>
<thead>
<tr>
<th>Armor</th>
<th>Structural Components</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>WDR*</th>
<th>Classification</th>
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<tbody>
<tr>
<td>Pure W</td>
<td>0.08</td>
<td>Class C LLW</td>
</tr>
<tr>
<td>(99% from $^{186m}$Re)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W + impurities</td>
<td>0.95</td>
<td>Class C LLW</td>
</tr>
<tr>
<td>(50% from $^{94}$Nb)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W-La$_2$O$_3$</td>
<td>0.95</td>
<td>Class C LLW</td>
</tr>
<tr>
<td>(50% from $^{94}$Nb)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W-Ni-Cu</td>
<td>0.93</td>
<td>Class C LLW</td>
</tr>
<tr>
<td>(46% from $^{94}$Nb)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W-Ni-Fe</td>
<td>0.93</td>
<td>Class C LLW</td>
</tr>
<tr>
<td>(46% from $^{94}$Nb)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W-TiC</td>
<td>0.9</td>
<td>Class C LLW</td>
</tr>
<tr>
<td>(54% from $^{94}$Nb)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W-Re</td>
<td>3.2</td>
<td>HLW</td>
</tr>
<tr>
<td>(74% from $^{186m}$Re)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Divertor averaged WDR evaluated at 100 y using Fetter’s limits.
Classification of W-Based Divertor for Geological Disposal (Cont.)

- For 3.4 MWy/m² fluence, all W alloys, except W-Re, qualify as LLW.
- Avoid using W-Re alloy in ARIES divertor as it generates HLW.
- Controlling Nb impurity and Mo helps increase WDR margin.

- W-Re generates HLW at fluences > 1 MWy/m².
- “W alloys with 5 wppm Nb” generate HLW if fluence exceeds 3.6 MWy/m².
- Operating at higher fluences (> 4 MWy/m²) mandates:
  - Controlling Nb to 1 wppm or less
  - Removing Mo from W-TiC alloy.
Transmutation of W

- Unlike Fe, W transmutes at higher rate.

- W transmutes into Re, Ta, Os, and other radioisotopes, producing He and H gases.

- In W-Re alloy, Re transmutes into Ta, Os, W, and other radioisotopes, producing He and H gases.

- Per R. Kurtz:
  - Transmutation of Re into Os is expected to adversely affect properties of W-Re alloy.
  - W-26Re alloy may not be suitable in fusion neutron environment due to formation of intermetallic phases*.
  - Lower concentrations of Re (0.1 - 5 wt%) may be acceptable.

- Both Re and Os increase electric resistivity of W stabilizing shells.

- Transmutation level depends on neutron spectrum and fluence
  ⇒ W armors on divertor and FW and W of stabilizing shells transmute differently.

Transmutation of W in Divertor Armor and Cooling Channel

- 1-2% transmutation of W at ARIES irradiation conditions (3.4 MWy/m² for single-use divertor).
- Re transmutes at faster rate than W.
- Excessive Re transmutation (21%) at 20 MWy/m² fluence.
Example of Transmutation Products

W Armor of ARIES Divertor
(Pure W)

> 90% of W Transmutation Products

< 10% of W Transmutation Products
Will FW Spectrum Make a Difference to Armor Transmutation?

<table>
<thead>
<tr>
<th>Neutron Flux @ Surface</th>
<th>Total</th>
<th>$E_n &lt; 0.1$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Divertor</td>
<td>6e14</td>
<td>25%</td>
</tr>
<tr>
<td>LiPb/FS Blanket</td>
<td>7.5e14</td>
<td>29%</td>
</tr>
<tr>
<td>Li$_4$SiO$_4$/Be/FS Blanket</td>
<td>5e14</td>
<td>43%</td>
</tr>
</tbody>
</table>
Softer Spectrum Results in Higher Transmutation of W

1 MW/m² NWL.

0.5 cm pure W armor attached to:
- W-based divertor
- FW of LiPb/FS blanket
- FW of Li₄SiO₄/Be/FS blanket.

- 14 MeV neutrons produce 50-75% of W transmutations, depending on spectrum.
- Solid breeder blanket with beryllium results in highest transmutation.

Transmutation data for non-LiPb designs do not apply to ARIES
Radiation Damage to W Armor

<table>
<thead>
<tr>
<th>Damage/FPY @ 1 MW/m²</th>
<th>dpa (dpa/FPY)</th>
<th>He* (appm/FPY)</th>
<th>H* (appm/FPY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Divertor</td>
<td>3</td>
<td>1.9</td>
<td>7.1</td>
</tr>
<tr>
<td>LiPb/FS Blanket</td>
<td>3.9</td>
<td>2.2</td>
<td>8.1</td>
</tr>
<tr>
<td>Li₄SiO₄/Be/FS Blanket</td>
<td>3.1</td>
<td>2.16</td>
<td>8</td>
</tr>
</tbody>
</table>

For same fluence, materials behind W armor change damage to W by only 10-30%.

Realistic Designs
Peak Damage @ 3.4 FPY

| Divertor @ 2 MW/m² | 20 | 13  | 49  |
| OB LiPb/FS Blanket @ 4 MW/m² | 53 | 30  | 110 |
| OB Li₄SiO₄/Be/FS Blanket @ 4 MW/m² | 42 | 29  | 109 |

* 1-D He/H results increased by 20% to account for additional He/H production from multiple reactions and radioactive decays.
Radiation Damage to W is Low Compared to Ferritic Steel

Peak Radiation Damage (dpa, He appm, or H appm)

- 0.5 cm W Armor
- LiPb/FS Blanket
- 4 MW/m²
- 3.4 FPY

< 200 dpa limit

FS Damage

Plasma

LiPb Blanket

0.5 cm W Armor

What is the life-limiting factor for W alloys?
Brazing Materials May Impact Activation Results

- Brazing materials (or joining methods) are necessary to join:
  - W to W
  - W to FS.

- So far, no brazing materials considered in our activation analysis
  - Need info from US materials program.

- Per M. Rieth (Germany):
  - Thickness of brazing materials ~ 50 microns
    - **For W/W joints:**
      - 3 brazing alloys under investigation in Europe just for preliminary studies:
        - Pd-Ni (60/40 wt%)
        - Cu-Ni (56/44 wt%)
        - Ti or Ti-Fe
      - Ni is undesirable for fusion power plants due to high He generation
      - Cu is undesirable for fusion power plants due to swelling and embrittlement
    - **For W/FS joints:**
      - Cu/Pd (82/18 wt%)
      - Cu is undesirable for fusion power plants due to swelling and embrittlement.
Conclusions and Future Work

- **Vacuum vessel:**
  - Avoid using 316-SS as it generates HLW.
  - Continue using F82H FS for ARIES VV.
  - Should we:
    - Apply ITER reweldability limit (3 He appm for thin 316-SS plate) to ARIES 2-cm F82H-FS plates?
    - Ask materials community for guidance?

- **ARIES divertor:**
  - Avoid using W-26Re alloy as it generates HLW. And transmutation of Re into Os is expected to adversely affect properties of W-26Re alloy
  - W-TiC and W-La$_2$O$_3$ are both recyclable with advanced RH equipment
  - Removing Mo and controlling Nb impurity allow higher fluences while qualifying as LLW
  - For ARIES operating conditions, transmutation products in W is less than 10% even @ high fluence of 20 MWy/m$^2$
  - Need guidance from materials community on:
    - Preferred W alloy: W-1.1TiC or W-La$_2$O$_3$
    - Brazing material
    - Radiation limit for W structure. 20 dpa/FPY ?

- **Future work:**
  - Impact of brazing materials on divertor activation.
  - Decay heat of W and temperature response of divertor during LOCA/LOFA
  - W stabilizing shells:
    - Activation and radwaste classification @ end of life (3-40 FPY)
    - Transmutation products:
      - Impact of Re and Os on W electrical resistivity.