Tungsten Structures for High Heat Flux Components: Opportunities & Challenges

M. S. Tillack
and the ARIES Team

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Tungsten has a long history in fusion research

1. Often chosen for its PMI properties
   • As a limiter in PLT (1970’s)
   • As a coating *e.g.* in ASDEX since 1990’s
   • As armor in the ITER divertor

2. In ARIES-ST we proposed W as a heat sink material, requiring mechanical and pressure-vessel functions

3. Since then, design efforts have expanded in the US and EU
He-cooled W structure offers significant performance advantages for PFC’s

- High conductivity and strength enable high heat flux capability
  - $>10 \text{ MW/m}^2$ is possible (maybe $>15 \text{ MW/m}^2$)

- High temperature capability gives high conversion efficiency.

- Good activation, radiation damage and safety characteristics.

- Currently the subject of much attention in the design and materials R&D communities.
  - R&D in EU on their jet-cooled finger design (HEMJ)
  - Significant increase in materials research in the US
The ARIES-ST power core used W structures in the divertor and actively-cooled stabilizers

- Dual-cooled (He + PbLi) blanket
- He-cooled high-heat-flux components
Three configurations and cooling schemes were scoped in ARIES-ST

1. Slot duct with extended surfaces (fins)
2. Porous metal heat exchanger in tube
3. Normal (impinging) flow
Far more detailed W-He divertor designs have been developed since ARIES-ST.

- **T-tube**
- **Plates with jet and/or pin-fin cooling**
- **Finger/plate combinations**
- **Fingers**
These concepts trade complexity vs. performance

- **T-Tube**: ~1.5 cm diameter x 10 cm long
  - Impinging slot-jet cooling
  - ~110,000 units for a full power plant

- **EU finger**: 2.6 cm diameter
  - Impinging multi-jet cooling
  - ~535,000 units for a full power plant

- **Plate**: 20 cm x 100 cm
  - Impinging slot-jet cooling (with pin fins)
  - ~750 units for a full power plant

- **Combined plate and finger**
  - Increased design margin in exchange for more finger units, ~89,000
Material options and properties used in design

<table>
<thead>
<tr>
<th></th>
<th>Pure W</th>
<th>W-alloy</th>
<th>VM-W</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Composition</strong></td>
<td>100% W</td>
<td>W-1%La$_2$O$_3$ or W-1.1TiC</td>
<td>ppm of Al$_2$(SiO$_3$)$_3$ or K$_2$SiO$_3$</td>
</tr>
<tr>
<td><strong>Fabrication</strong></td>
<td>HIP</td>
<td>HIP</td>
<td>Drawn and rolled from sheet</td>
</tr>
<tr>
<td><strong>Application</strong></td>
<td>Armor (or back plates)</td>
<td>Structures</td>
<td>Thin HHF shell (up to 1 mm)</td>
</tr>
<tr>
<td><strong>Minimum T</strong></td>
<td>800°C</td>
<td>800°C</td>
<td>800°C</td>
</tr>
<tr>
<td><strong>Maximum T</strong></td>
<td>2500°C (2/3 mp)</td>
<td>1200°C</td>
<td>&gt;1300°C</td>
</tr>
<tr>
<td><strong>Uniform elongation</strong></td>
<td>1.6% at 270°C, 2% at 1200°C</td>
<td>Unknown (same as W)</td>
<td>Unknown (same as W)</td>
</tr>
<tr>
<td><strong>Yield strength at 1200°C</strong></td>
<td>346 MPa</td>
<td>246 MPa</td>
<td>(same as W)</td>
</tr>
<tr>
<td><strong>Thermal cond. at 1200°C</strong></td>
<td>108 W/mK</td>
<td>96 W/mK</td>
<td>Same as W</td>
</tr>
<tr>
<td><strong>Fracture toughness</strong></td>
<td>&lt;30 MPa-m$^{1/2}$</td>
<td>&lt;30 MPa-m$^{1/2}$</td>
<td>&lt;30 MPa-m$^{1/2}$</td>
</tr>
</tbody>
</table>

Note: W-Re alloy is considered undesirable due to transmutation and waste disposal concerns
Material applications in the finger divertor

- **Plasma facing armor - Pure W**
  - Tiles operate in a temperature range of ~1000 ºC to 2000 ºC, without strict requirements on mechanical strength. Good conductivity is required.
  - The most economical way to fabricate tiles is by tungsten powder HIP or injection molding.

- **Cup-shaped thimbles - VMW**
  - Vacuum metalized W is doped with ppm levels of K, offering improved mechanical properties and a higher re-crystallization temperature. The thinner the better.
  - Since the thimble wall is ~1 mm thick, we can take advantage of VMW and fabricate them by deep drawing of a thin sheet, rolled in two directions.

- **Front, side and back plates - WL10 (W-1%La₂O₃)**
  - The plates are constructed by brazing together the front, back and side plates.
  - All these plates have thickness < 10 mm and operate in a small temperature range between 750 ºC – 850 ºC. The material requirements are relatively moderate, and it should be possible to fabricate them from standard tungsten plates as an alternative.
Issues related to tungsten as a structural and heat sink material for fusion

1. Inherently low ductility and fracture toughness
2. Limited temperature window (800~1200) due to DBTT and recrystallization, and overlap with steels
3. Difficult fabrication – limited to simpler shapes and joining with brazes
4. Uncertain plasma-material interactions
5. Tritium retention
Rods: Fracture Characteristics

Charpy Energy, J

Test Temperature, °C

Rod Materials
- W, 6.9 mm
- W, 20 mm
- WL10, 6.9 mm
- WL10, 20 mm

Ductile
Delamination
Brittle
Limited ductility can lead to catastrophic failure

Faleschini JNM 2007

(M. Rieth, SOFT 2010)
Consequences of surface evolution are still under investigation

W cracking after a few shots at 0.5 MJ/m²

250 eV

Very complex behavior of surfaces vs. temperature, ion energy, etc.
(R. Doerner)

200 eV

Fuzzy W does not crack after repeated exposure at 0.7 MJ/m²

60 eV (no erosion)
High tritium retention can occur in tungsten as a result of trapping sites

(D. Whyte)
Summary

1. Tungsten as a structural material offers the possibility of high performance in a divertor operating at high temperature and high heat flux.

2. Design efforts have shown the possibility of reliable operation above 15 MW/m² heat flux.

3. As a relatively new structural material in fusion R&D programs, many problems remain to be solved.