Electrical Resistivity Changes with Neutron Irradiation and Implications for W Stabilizing Shells

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

With input from:
C. Kessel (PPPL)

ARIES Project Meeting
Bethesda, MD
July 29 - 30, 2010
Why Tungsten Shell?

- Per Kessel:
  \[(\text{Shell thickness (in cm)}) / (\text{Resistivity (in Ohm.cm)}) > 15,000\]

- **Tungsten:** preferred material for ARIES stabilizing shells:
  - Reasonable resistivity \(\rho\) and shell thickness (~0.08 cm for \(\rho=5.4\) micro Ohm.cm @ RT)
  - High temperature operation (800 - 1200°C)
  - No active cooling
    ⇒ radiate heat to surrounding blanket and shield
    ⇒ simple shell design.
  - Impact on tritium breeding depends on shell location within blanket.
Concerns

- W resistivity **increases** with:
  - Temperature
  - Neutron irradiation.

- Higher resistivity means thicker stabilizing shell.

- **Concerns:**
  - Impact on TBR
  - Temperature gradient within shell
  - Thermal stresses
  - Feasibility of radiative cooling?
Unirradiated W: Variation of Resistivity with Temperature*

- Electric resistivity of unirradiated W is well established.
- W resistivity (in micro Ohm.cm):
  \[ \rho_W = 4.8 \left( 1 + 4.8297 \times 10^{-3} T + 1.1663 \times 10^{-6} T^2 \right) \]
  for \( 25^\circ C < T < 625^\circ C \)

At 1000\(^\circ\)C, \( \rho_W \) increases 6 times, requiring ~0.5 cm thick W shell (> 0.08 cm thick shell at RT).

Tungsten Composition Changes with Neutron Irradiation

- Some W atoms transmute into Re, Ta, Os, and other radioisotopes (see my 5/2010 presentation).
- Transmutation level depends on irradiation time and neutron spectrum (hard near FW or soft behind blanket).
- Example of W transmutations: W armor of ARIES divertor:

- Main transmutation products (Re, Ta, and Os) will increase W electrical resistivity further, requiring thicker W shell.

![Graph showing atomic density vs. fluence for different transmutation products in divertor armor.](image-url)
Variation of Resistivity of Transmutation Products with Temperature

Variation of Resistivity of Transmutation Products with Temperature

- W, Re, Os, Ta resistivities (in micro Ohm.cm):
  - W \( \rho_W = 4.8 \left(1 + 4.8297 \times 10^{-3} T + 1.1663 \times 10^{-6} T^2\right) \) for \(25^\circ C < T < 625^\circ C\)
  - Re \( \rho_{Re} = 17.7 \left(1 + 4.5585 \times 10^{-3} T + 1.2447 \times 10^{-6} T^2\right) \) for \(25^\circ C < T < 900^\circ C\)
  - Os \( \rho_{Os} = 9.49 \left(1 + 4.425 \times 10^{-3} T\right) \) for \(0^\circ C < T < 100^\circ C\)
  - Ta \( \rho_{Ta} = 12.45 \left(1 + 3.83 \times 10^{-3} T\right) \) - Ref. 2 - for \(25^\circ C < T < 100^\circ C\)

W and Re exhibit parabolic variations with temperature.

Linear variations assumed for Ta and Os at \(T > 100^\circ C\). Parabolic variation yields higher resistivity.

Q: How much Re, Ta, and Os in W shell?

Note errors in Billone’s memo: marked in red

Available at: http://www-ferp.ucsd.edu/LIB/PROPS/w.html
Re, Ta, Os Atomic Fractions Estimated using ALARA Activation Code

- Two locations examined for W shells in ARIES-DB:
  I- 0.5 cm thick W shell behind OB FW
  II- 0.5 cm thick W shell between OB blanket segments.

- Two lifetimes considered: **3.4 FPY** and **40 FPY**.

Ave. OB NWL
\(~ 4 \text{ MW/m}^2\)

Potential Locations for Kink Shell
(discrete toroidally)

Potential Locations for Vertical Stabilizing Shell
(continuous toroidally)
Transmutation Products in ARIES-DB W Shell

- W Shell-I (behind FW) generates highest transmutation products.
- Transmutation products build up with irradiation time.
• Experimental data for irradiated W with 14 MeV neutrons does not exist.

• Per Billone, electrical resistivity of irradiated W can be estimated by law of mixtures:

\[ \rho = f_W \rho_W + f_{Re} \rho_{Re} + f_{Ta} \rho_{Ta} + f_{Os} \rho_{Os} \]

where \( f \) = atomic fraction.
Change of W Shell Resistivity with Irradiation and Temperature

W Shell-I behind OB FW

W Shell-II between OB Blanket Segments

W Shell-I Resistivity (micro Ohm.cm) vs Temperature (°C)

- 3.4 FPY
- 40 FPY
- Unirradiated W @ 500-1000 °C
- Unirradiated W @ RT

W Shell-II Resistivity (micro Ohm.cm) vs Temperature (°C)

- 3.4 FPY
- 40 FPY
- Unirradiated W @ 500-1000 °C
- Unirradiated W @ RT
Impact of Change in W Resistivity on W Shell Thickness

\[ \Delta_{\text{shell}} = 15,000 \rho_{\text{shell}} \]

W Shell-I behind OB FW

W Shell-II between OB Blanket Segments
Could LiPb Serve as Stabilizing Shell?

- At 700 °C, $\rho_{\text{LiPb}} \sim 150$ micro Ohm.cm*  $\Rightarrow$ 2-3 cm LiPb

**Options:**
- Encase 2-3 cm thick LiPb in FS structure to serve as stabilizing shell
- Cool FS structure with He to remove nuclear heating
- Place LiPb Kink shell behind FW to enhance physics
- T removal in batch process
- Flowing LiPb?
- Start with solid LiPb?

**UW experimental Na loop** at Forest’s lab could assess feasibility.

---

*U.Jauch, G.Haase, B.Schulz, Thermophysical properties of Li(17)Pb(83) eutectic alloy, KFK 4144 (1986).
Conclusions

• **W shell thickness** should reflect change in resistivity with temperature and irradiation.

• **Change due temperature** is dominant.

• **Kink shell behind FW** offers physics advantages, but exhibits largest change in resistivity.

• **TBD**: Impact of shell on ARIES-DB TBR. Need location and thickness of both shells.

• **Q**: Could “2-3 cm LiPb encased in FS structure” serve as stabilizing shell?