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?

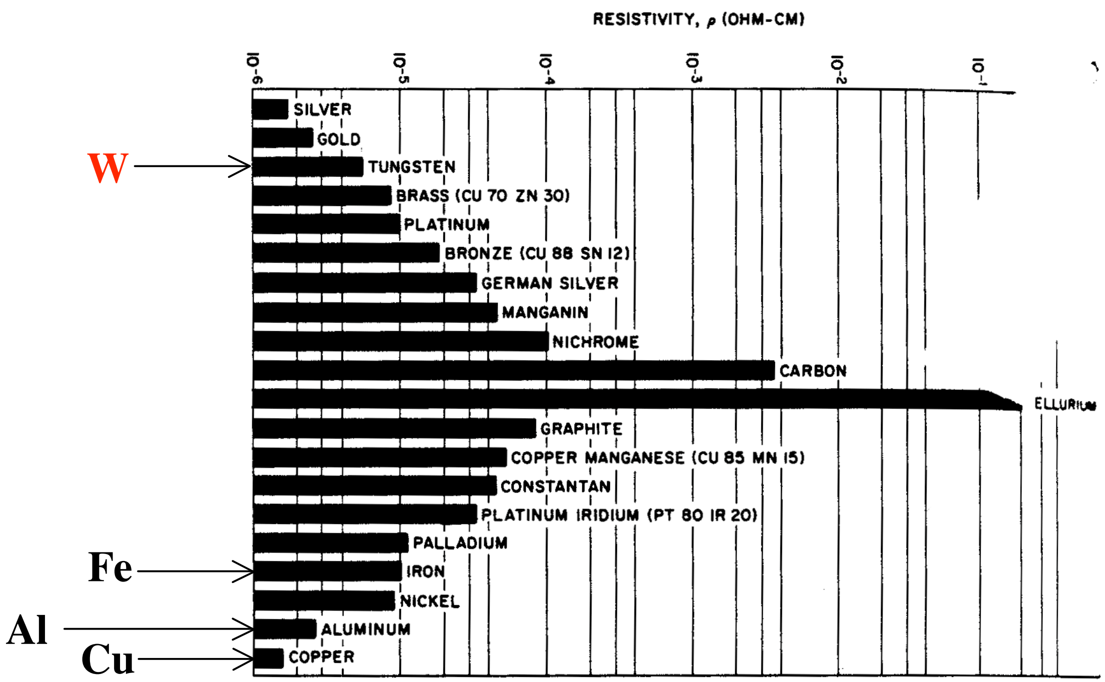
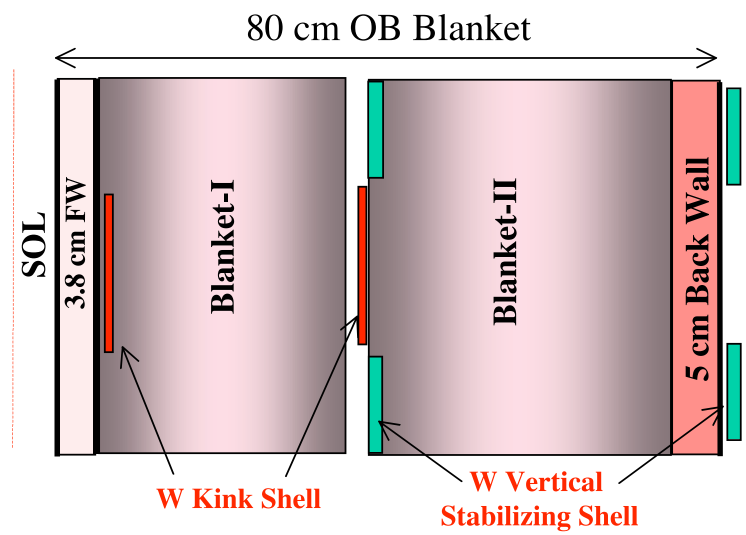


Fig. 16.1 Resistivities of common metals and alloys

Potential Locations for W Stabilizing Shells



- Per Kessel:

  (Shell thickness (in cm) / Resistivity (in Ohm.cm)) > 15,000
- **Tungsten**: preferred material for ARIES stabilizing shells:
  - Reasonable resistivity (ρ) and shell thickness (**~0.08 cm** for ρ= 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.

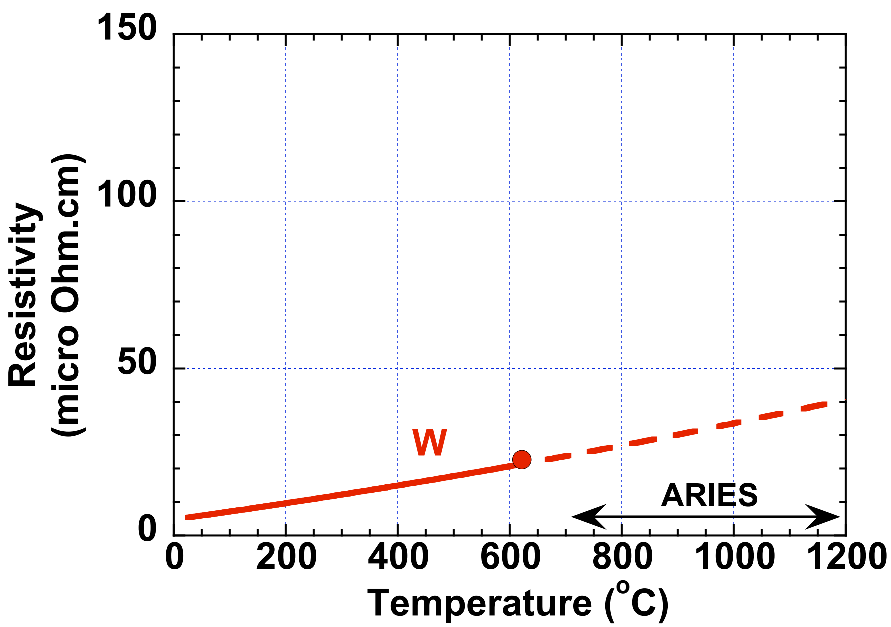
- **Concerns**:
  - **Impact on TBR**
  - Temperature gradient within shell
  - Thermal stresses
  - Feasibility of radiative cooling?

Unirradiated W:
Variation of Resistivity with Temperature*

Ref: M. Billone's memo to ARIES Team on "Electrical Resistivity of Tungsten," (5/27/1996).
Available at: http://www-ferp.ucsd.edu/LIB/PROPS/w.html

- Electric resistivity of **unirradiated** W is well established.
- W resistivity (in micro Ohm.cm):

$$\rho_W = 4.8\,(1 + 4.8297e\text{-}3\ T + 1.1663e\text{-}6\ T^2) \qquad \text{for } 25^oC < \mathbf{T} < 625^oC$$

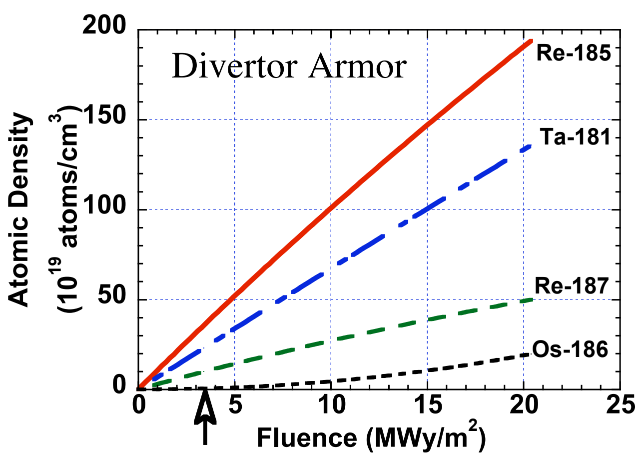


At 1000°C, ρ_W increases 6 times, requiring ~0.5 cm thick W shell (> 0.08 cm thick shell at RT).

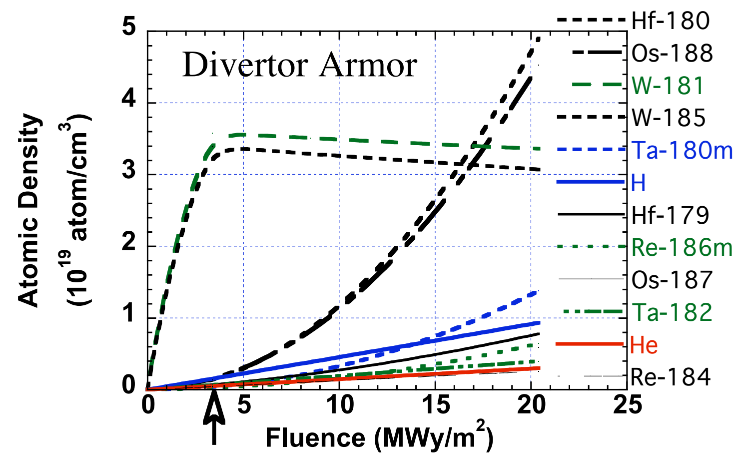
Tungsten Composition Changes with Neutron Irradiation

- 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 :

> 90% of W Transmutation Products



< 10% of W Transmutation Products



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

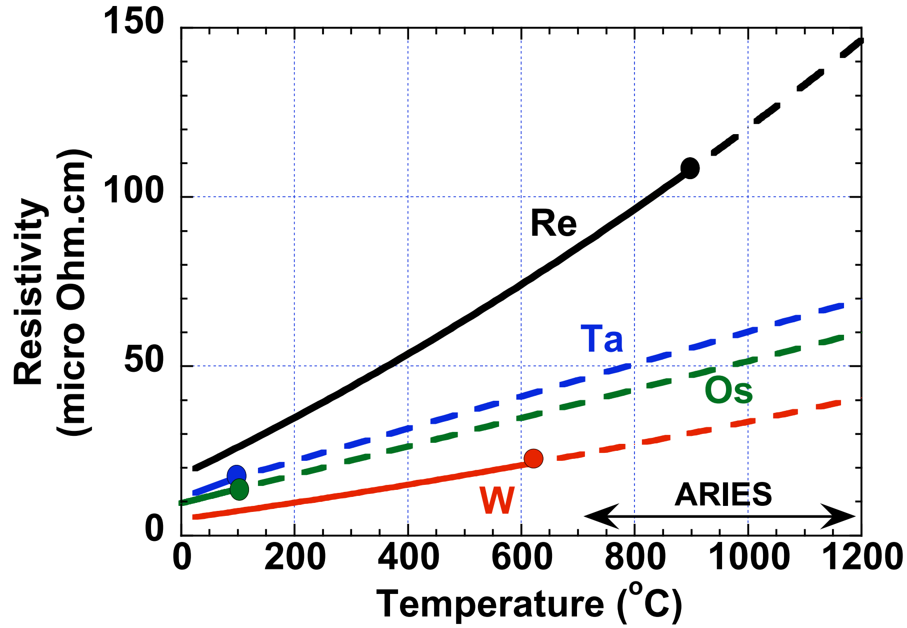
Variation of Resistivity of Transmutation Products with Temperature*

Refs.: 1- M. Billone's memo to ARIES Team on "Electrical Resistivity of Tungsten," (5/27/1996). Available at: http://www-ferp.ucsd.edu/LIB/PROPS/w.html
2- CRC Handbook of Chemistry and Physics - 66th Edition (1985-1986).

- W, Re, Os, Ta resistivities (in micro Ohm.cm):

W	$\rho_W = 4.8\,(1 + 4.8297\text{e-}3\ T + 1.1663\text{e-}6\ T^2)$	for $25^oC < T < 625^oC$
Re	$\rho_{Re} = 17.7\,(1 + 4.5585\text{e-}3\ T + 1.2447\text{e-}6\ T^2)$	for $25^oC < T < 900^oC$
Os	$\rho_{Os} = 9.49\,(1 + 4.425\text{e-}3\ T)$	for $0^oC < T < 100^oC$
Ta	$\rho_{Ta} = 12.45\,(1 + 3.83\text{e-}3\ T)$ - Ref. 2 -	for $25^oC < T < 100^oC$

Note errors in Billone's memo: marked in red



W and Re exhibit parabolic variations with temperature.

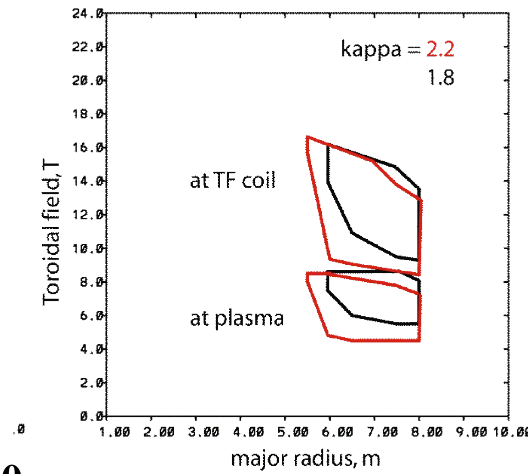
Linear variations assumed for Ta and Os at T > 100°C. Parabolic variation yields higher resistivity.

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

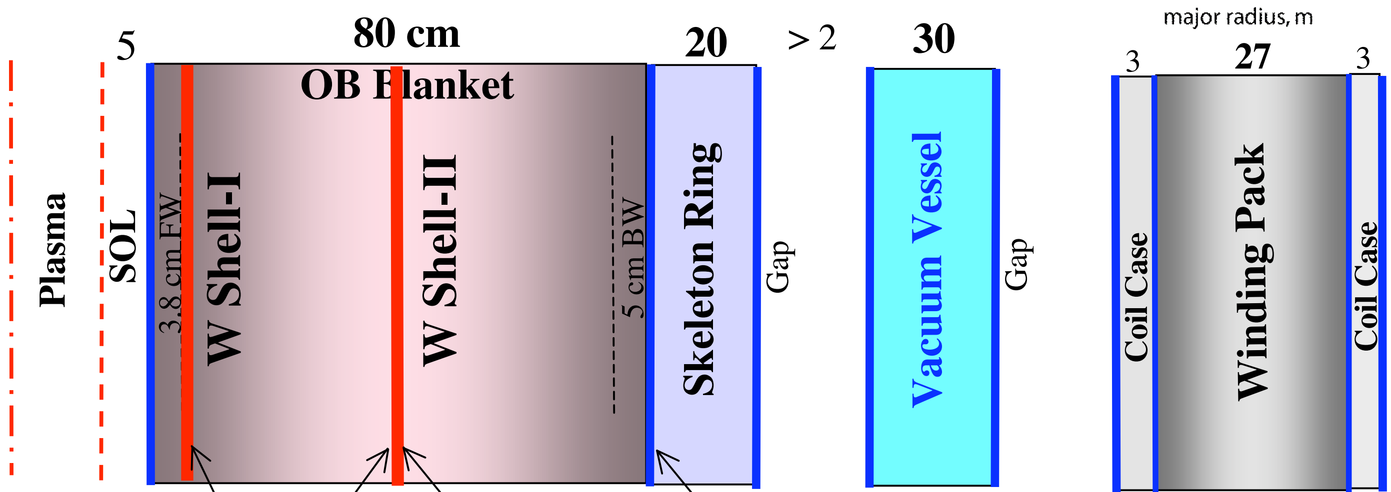
Re, Ta, Os Atomic Fractions Estimated using ALARA Activation Code

- 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 MW/m²

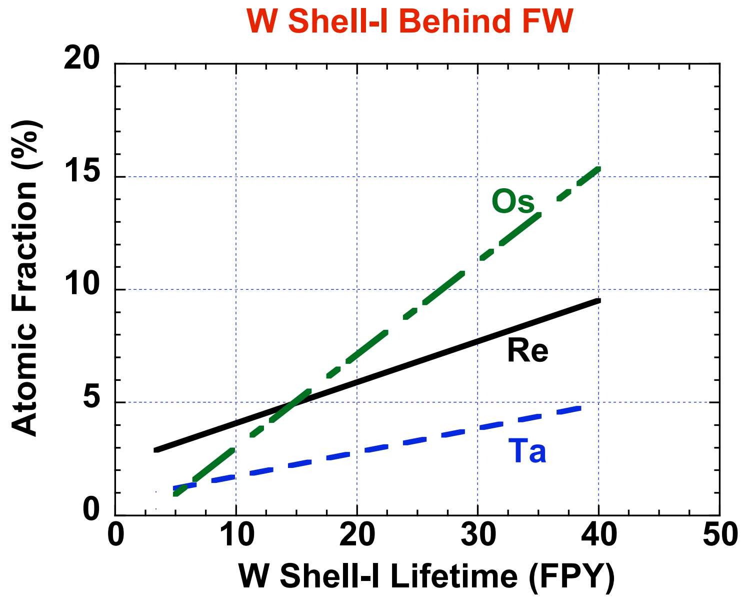


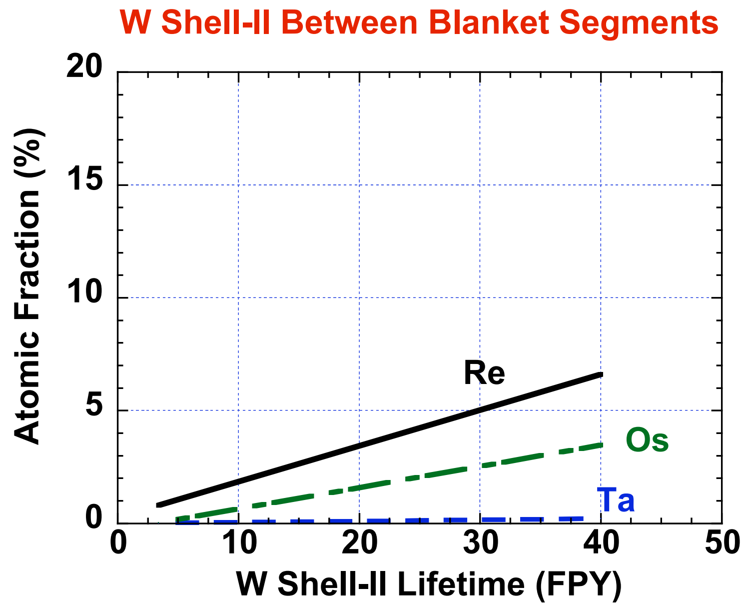
Potential Locations for Kink Shell (discrete toroidally)

Kappa = 2.2 **Kappa = 1.8**

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.

Change of W Electrical Resistivity with Transmutation Products

- Experimental data for **irradiated** W with 14 MeV neutrons does not exist.

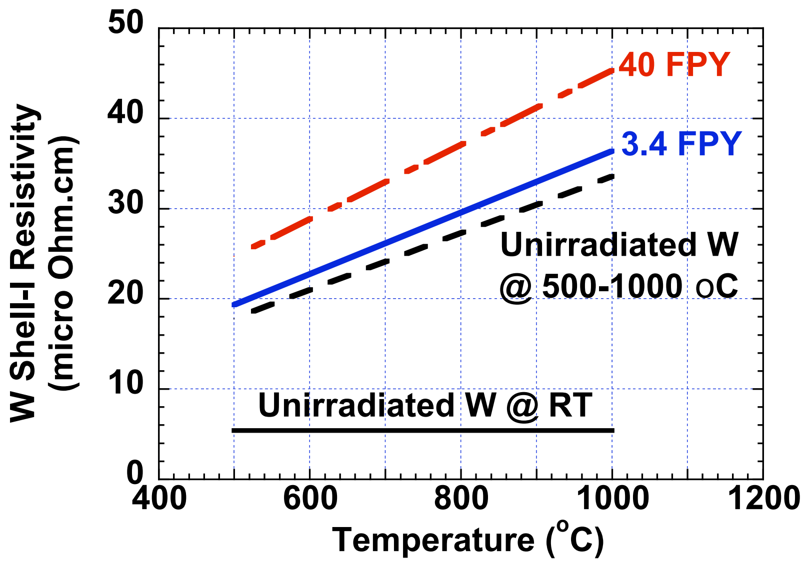
- **Per Billone**, electrical resistivity of irradiated W can be estimated by *law of mixtures*:

$$\rho = f_W \rho_W + f_{Re} \rho_{Re} + f_{Ta} \rho_{Ta} + f_{Os} \rho_{os}$$

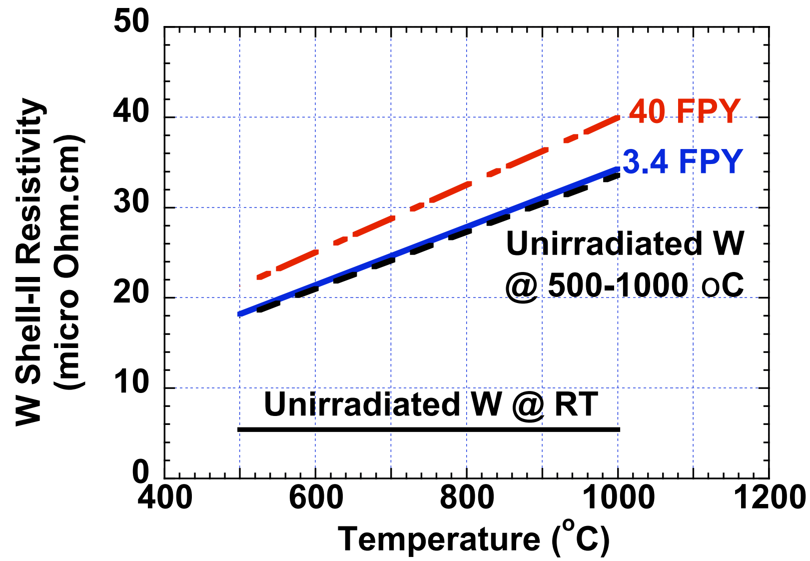
where f = atomic fraction.

Change of W Shell Resistivity with Irradiation and Temperature

W Shell-I behind OB FW



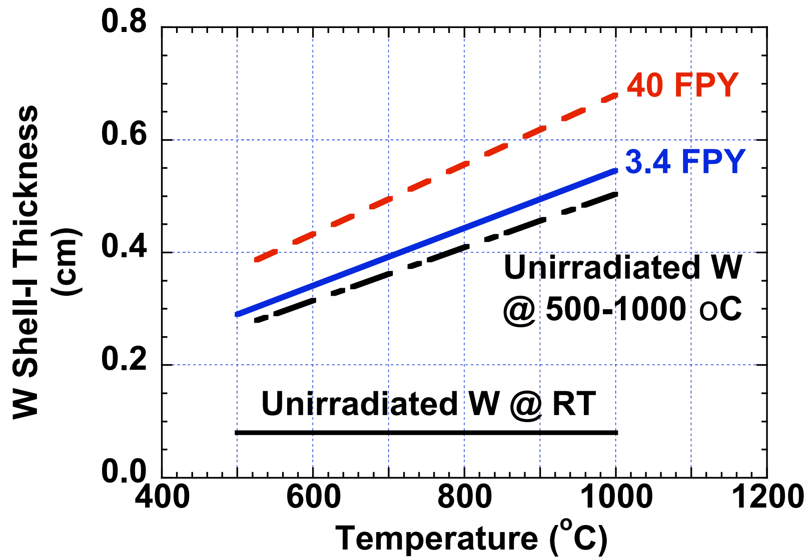
W Shell-II between OB Blanket Segments



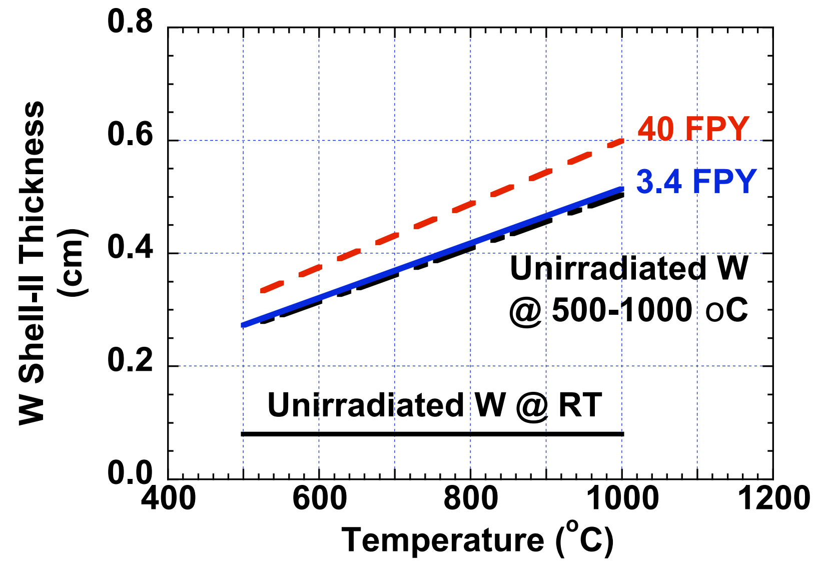
Impact of Change in W Resistivity on W Shell Thickness

$$\Delta_{shell} = 15{,}000\ \rho_{shell}$$

W Shell-I behind OB FW

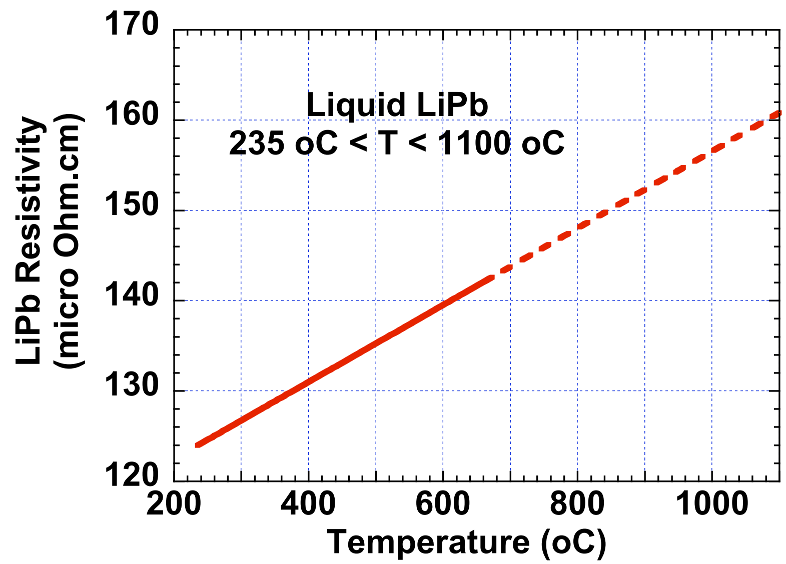


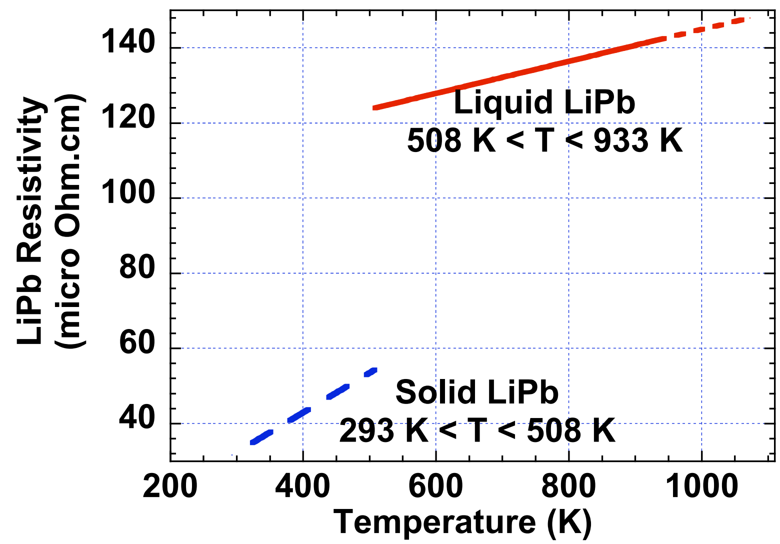
W Shell-II between OB Blanket Segments



Could LiPb Serve as Stabilizing Shell?

- At 700 °C, ρ_{LiPb} ~150 micro Ohm.cm* ⇒ 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 dominent .
- 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?