Transmutation and phase stability of tungsten armour in fusion power plants

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Plan of talk

- Introduction
- EU Power Plant Conceptual Study (PPCS) Models A, B and AB with W armour
- Fusion power-plant (FPP) conditions: required plasma facing material (PFM) properties
- Neutron spectra (MCNP code)
- Tungsten transmutation with neutron resonance self-shielding to W-Re-Os alloys (EASY-2003 code)
- Trajectories in W-Re-Os thermodynamic phase diagram
- Discussion and Conclusions

Assumed armour conditions

	First Wall	Divertor
Temperature (K)	~ 750	< 1500
Mean heat flux (MW m^{-2})	< 0.5	< 15
Neutron load (MW m^{-2})	2 - 2.2	~ 1
Flux CX atoms (m^{-2} s^{-1})	$< 10^{18}$	$< 10^{24}$
<E> CX atoms (eV)	< 10000	< 5
Plasma quiescence	Some PMI	Steady
Service life (y)	5	2.5

W transmutation

- W186(n,γ)W187 strong resonances at E_n~20 eV
- Calculated in continuous-energy representation in MCNP
- Calculations of the W transmutation are complex and sensitive to neutron spectra
- Geometry - effect of nearby neutron-moderating materials

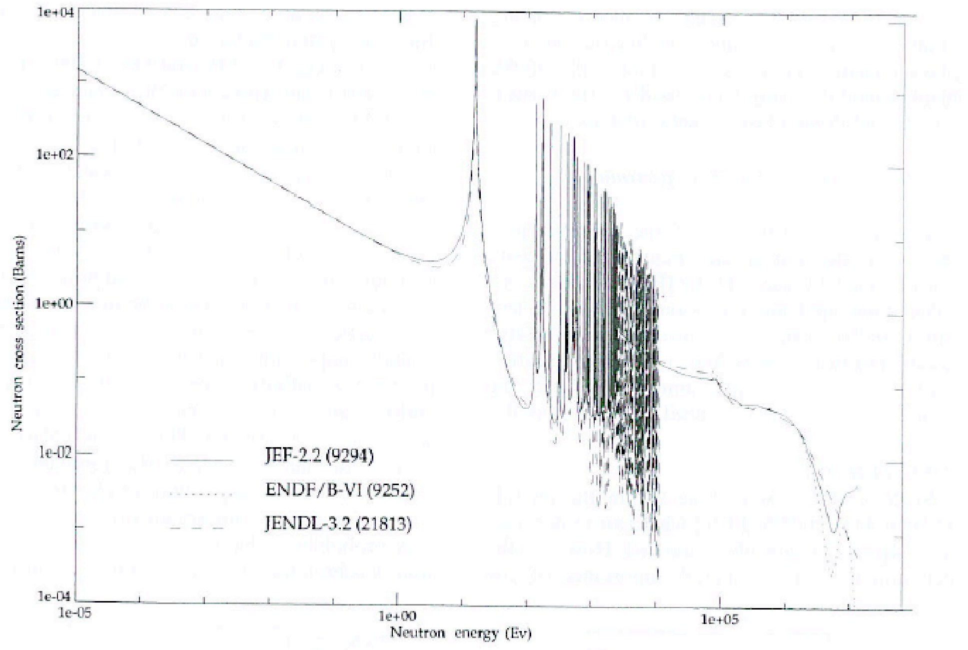

Fig. 1. Transport libraries ^{186}W(n, g)W^{187} cross-section.

Alloy composition is time and plant design sensitive

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PPCS features & materials

	Model A	**Model B**	**Model AB**
Fusion Power (GW)	5.00	3.60	4.29
Divertor Peak load (MW.m^{-2})	15	10	10
Average neutron wall load	2.2	2.0	1.8
Major Radius (m)	9.55	8.6	9.56
Blanket			
Structural material	Eurofer	Eurofer	Eurofer
Coolant / Toutlet (C)	**H_2O / 325**	**He / 500**	**He / 500**
Breeder / neutron multiplier	**LiPb**	**Li4SiO4 pebble bed / Be**	**LiPb (no Be)**
Divertor			
Structural material	**[CuCrZr]**	**W alloy**	**W alloy**
Armour material	W alloy	W alloy	W alloy
Coolant	**H_2O**	**He**	**He**

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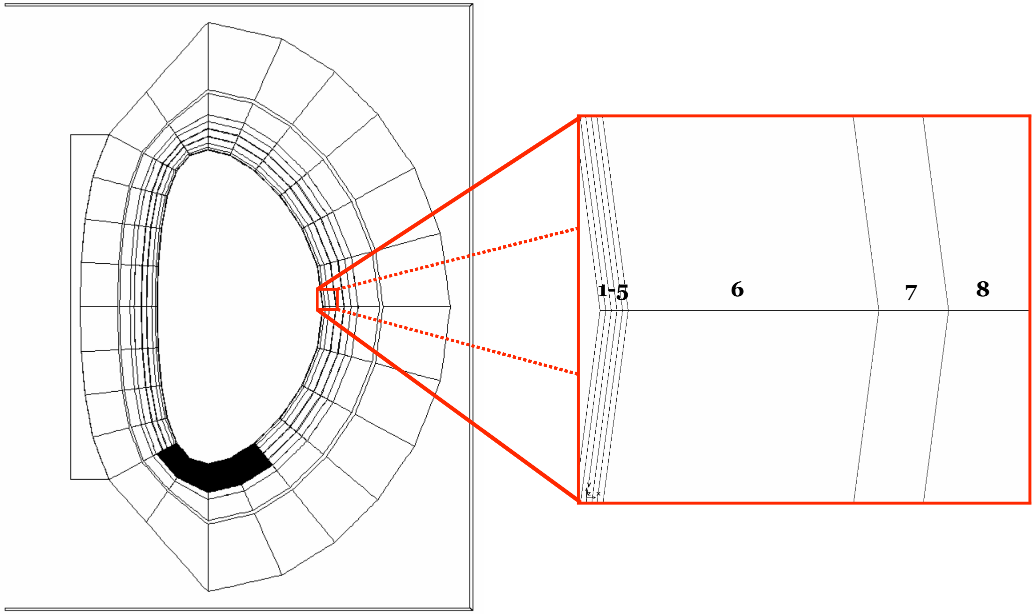
PPCS: First wall model



	1-5 Armour	6 FW	7 FW	8 Breeder Zone
A	W	Eurofer + H_2O	Eurofer	Eurofer + H_2O + $Li_{17}Pb_{83}$
B	W	Eurofer + He	Eurofer	Eurofer + He + Be + Li_4SiO_4
AB	W	Eurofer + He	Eurofer	Eurofer + He + $Li_{17}Pb_{83}$

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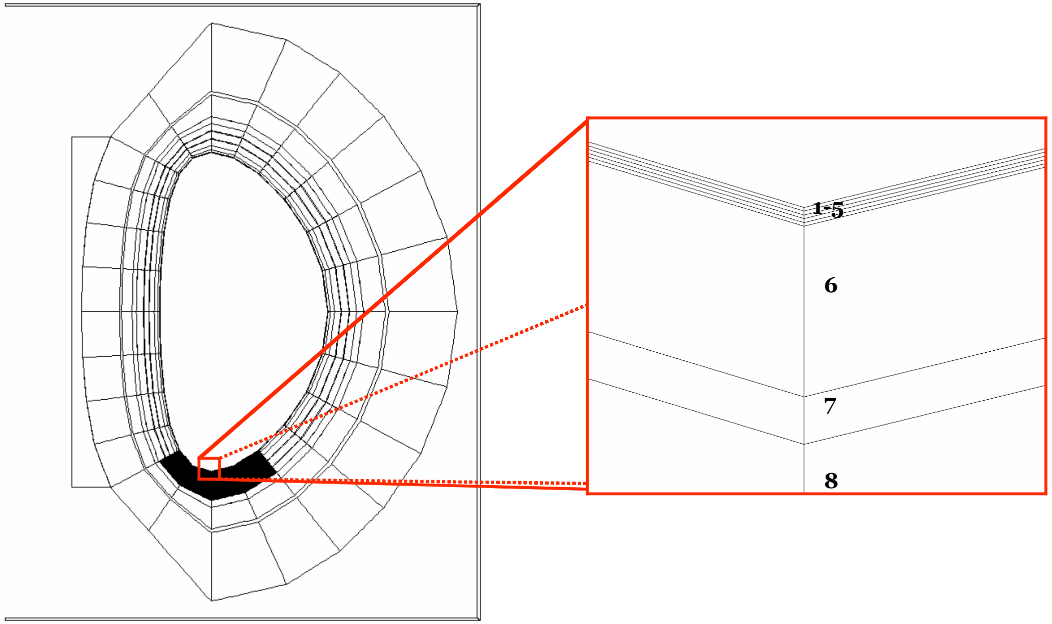
PPCS: Divertor model



	1-5 Armour	6-7 Heat Sink	8 Structure
A	W	Eurofer + W + CuCrZr +OFHC+H_2O	Eurofer +H_2O
B	W	Eurofer + W + He	Eurofer + He
AB	W	Eurofer + W + He	Eurofer + He

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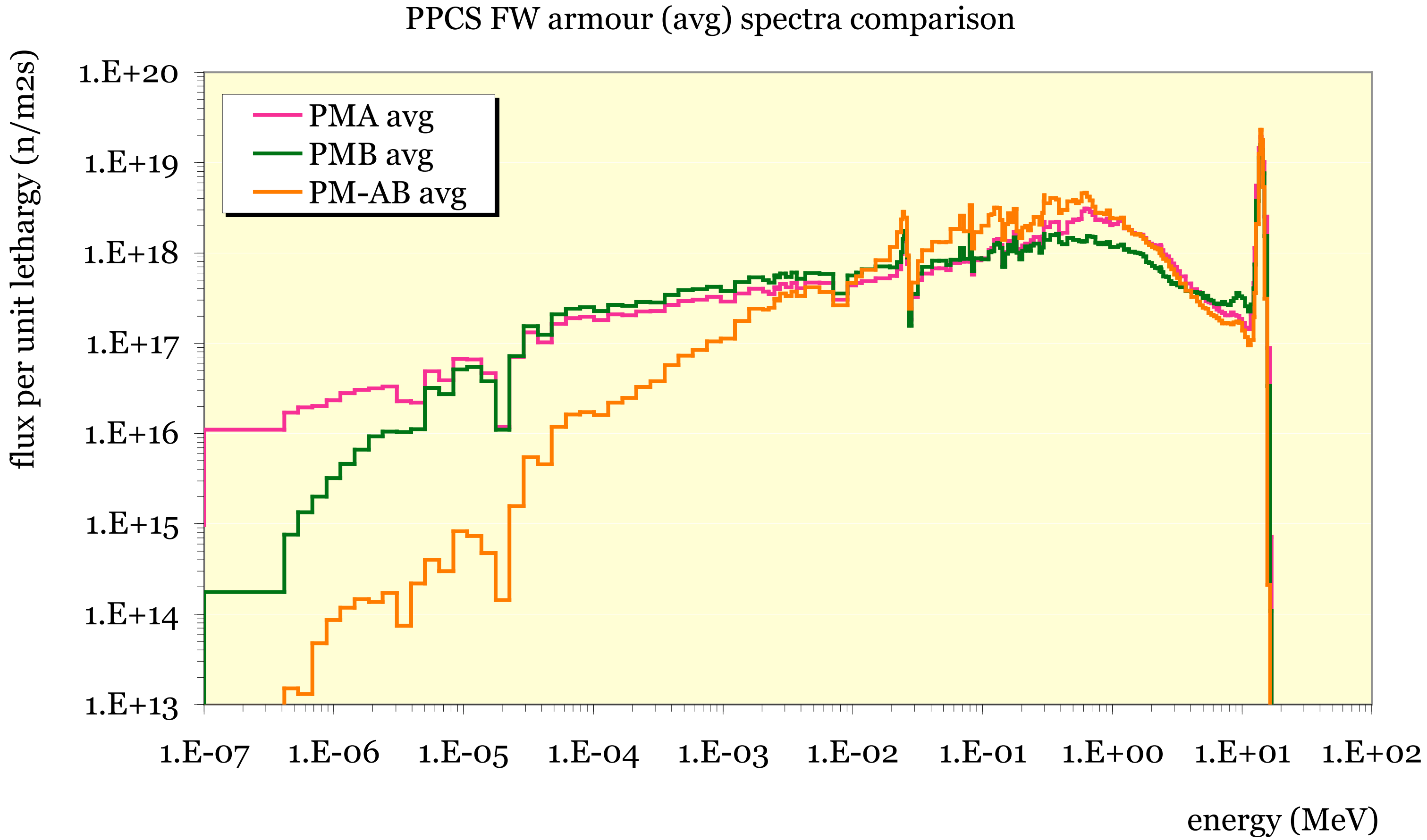
Neutron spectra: first wall armour



W absorption dip at ~ 20 eV visible for all three PPCS models studied

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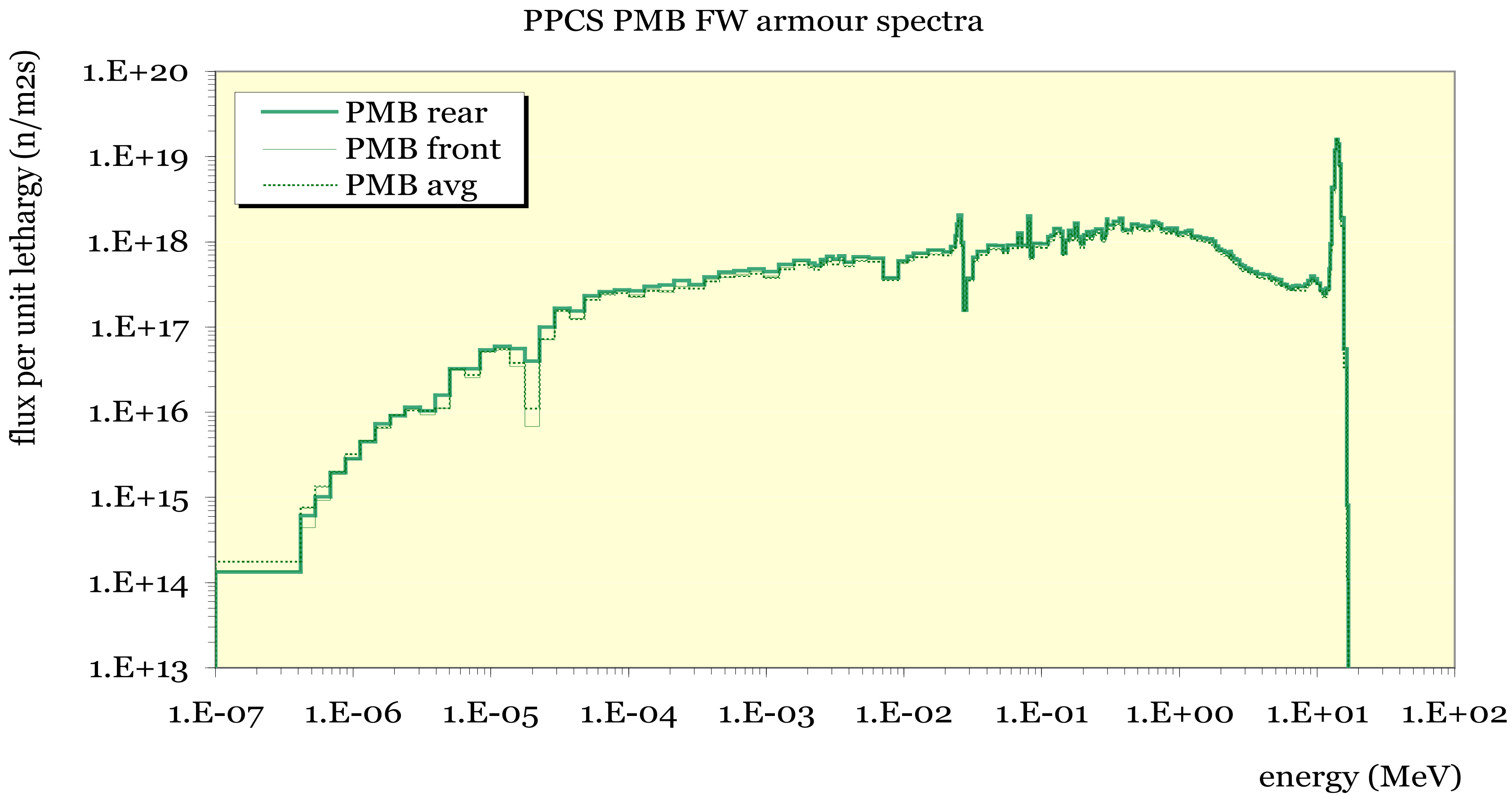
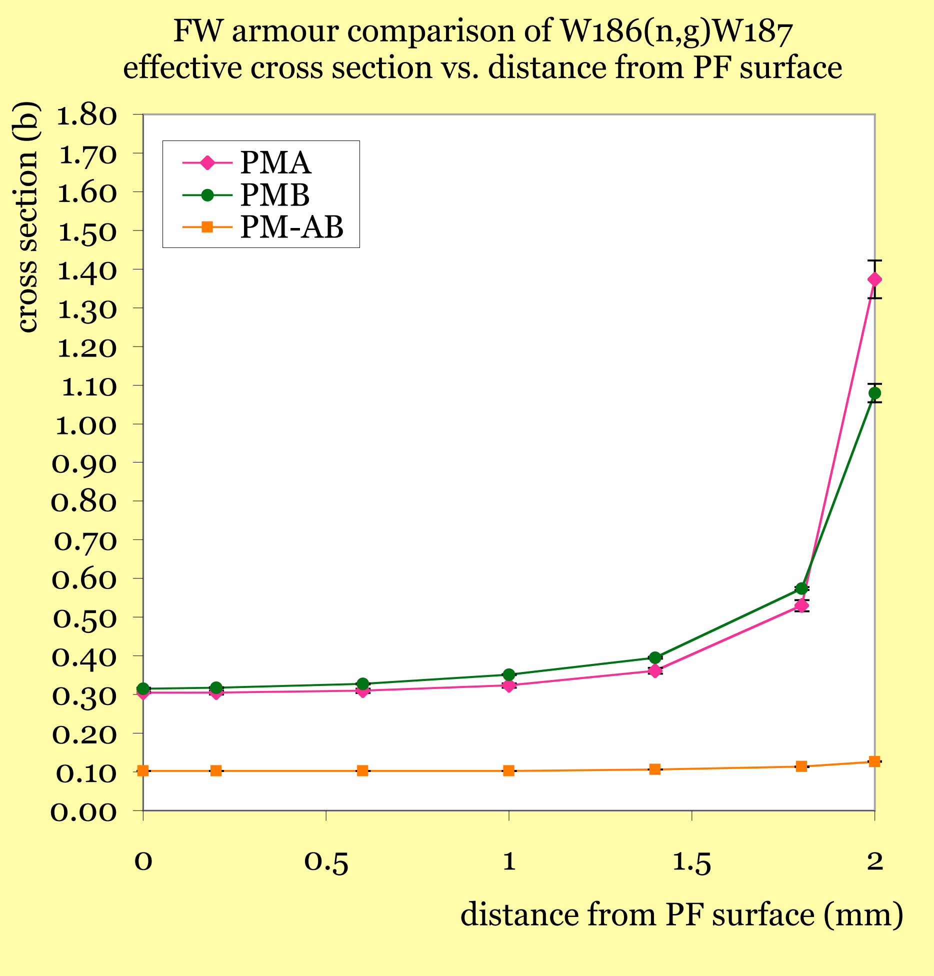
Neutron resonance self-shielding



2mm thick W FW armour: self-shielding at ~ 20 eV

Difference between front and rear faces

W self-shielding in wall armour



Effective cross-section

$$\sigma_{eff} = \frac{RR}{N_W \bullet \phi}$$

Reaction rate RR calculated with continuous energy

Water / Be behind armour in models A and B moderate neutron spectrum → large σ_{eff}

Shielding smallest at rear face

He coolant in model AB → harder neutron spectrum → smaller σ_{eff}

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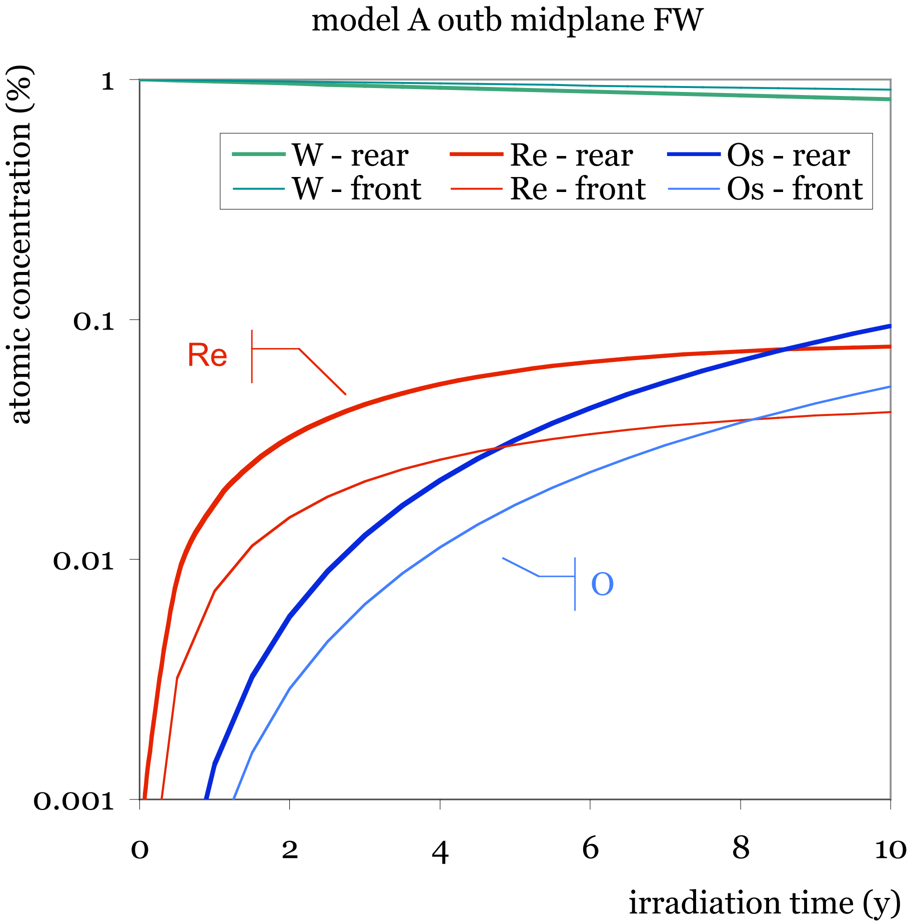
W-Re-Os Alloy composition model A FW armour



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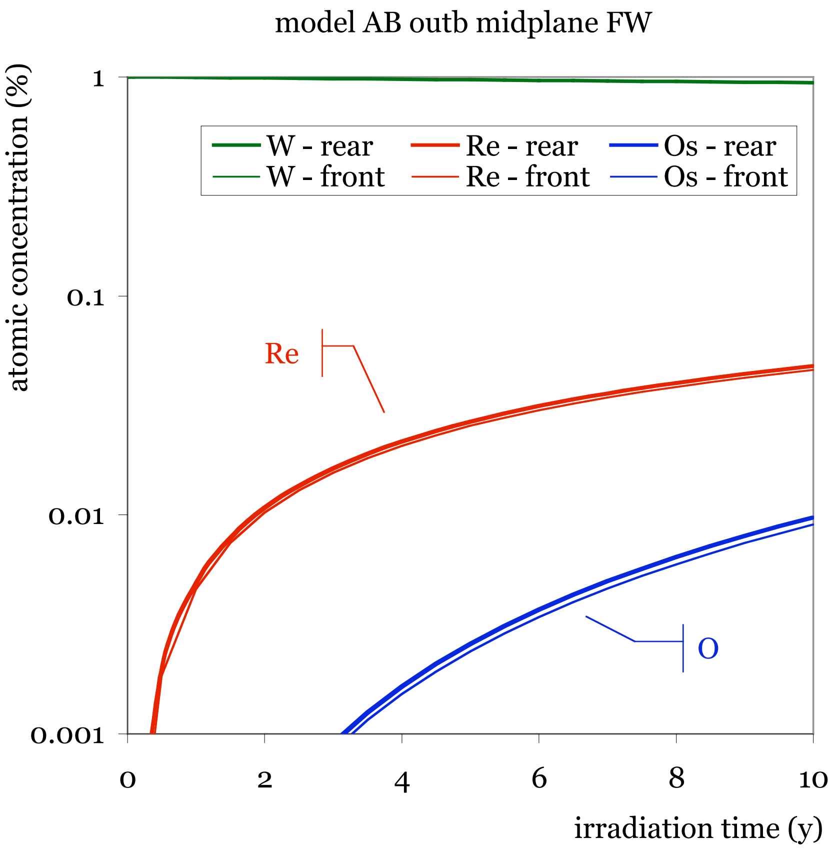
after	face	W At%	Re At%	Os At%
5 y	**rear**	**90.8**	**6.1**	**3.2**
	front	**95.3**	**3.0**	**1.7**
10 y	rear	82.9	7.7	10.0
	front	90.6	4.1	5.2

Model B is similar

W-Re-Os Alloy composition
model AB FW armour



after	face	**W** At%	**Re** At%	**Os** At%
5 y	**rear**	**97.1**	**2.7**	**0.3**
	front	**97.2**	**2.6**	**0.2**
10 y	rear	94.2	4.8	1.0
	front	94.5	4.6	1.0

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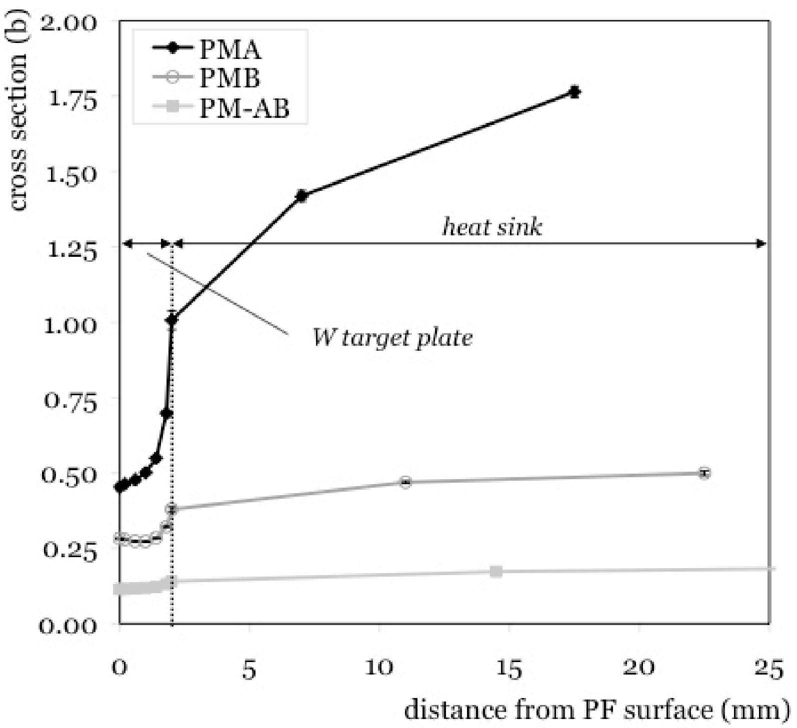
Self-shielding in 25mm W divertor armour



Shielding again smallest at rear face of armour

Model B has lower neutron moderation than Model A in the divertor because it has He and not water coolant

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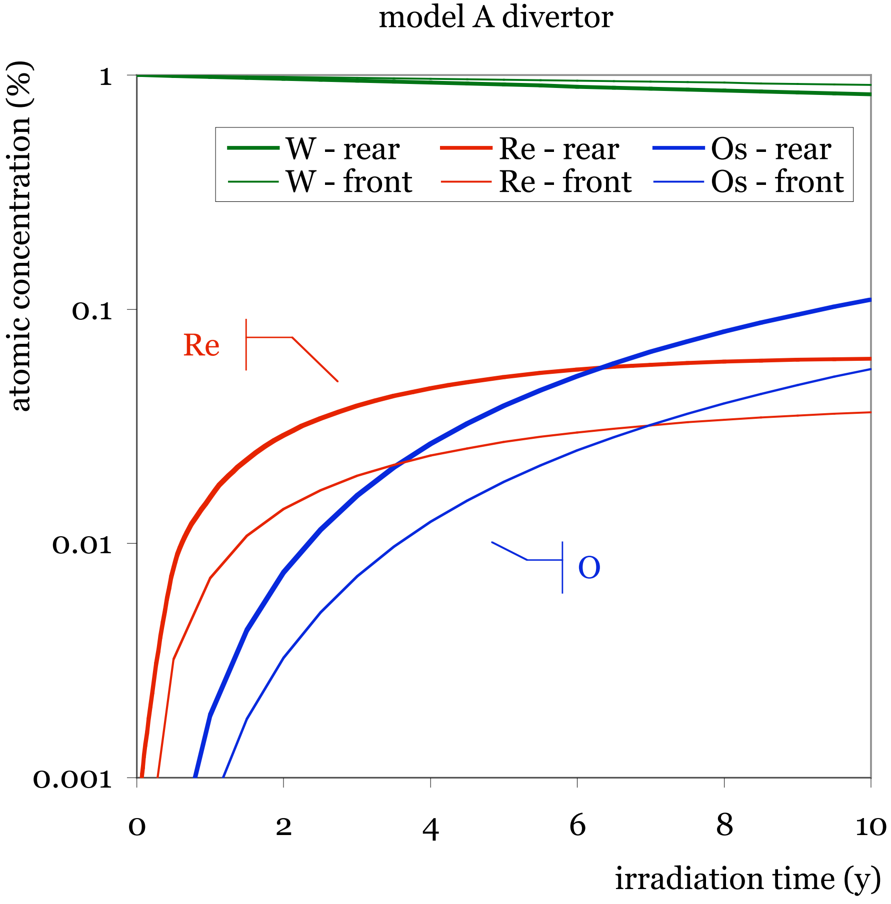
W-Re-Os Alloy composition model A divertor armour



after	face	W At%	Re At%	Os At%
2.5 y	**rear**	**95.4**	**3.4**	**1.2**
	front	**97.8**	**1.7**	**0.5**
5 y	rear	91.0	5.1	3.9
	front	95.5	2.7	1.8

Model B is similar

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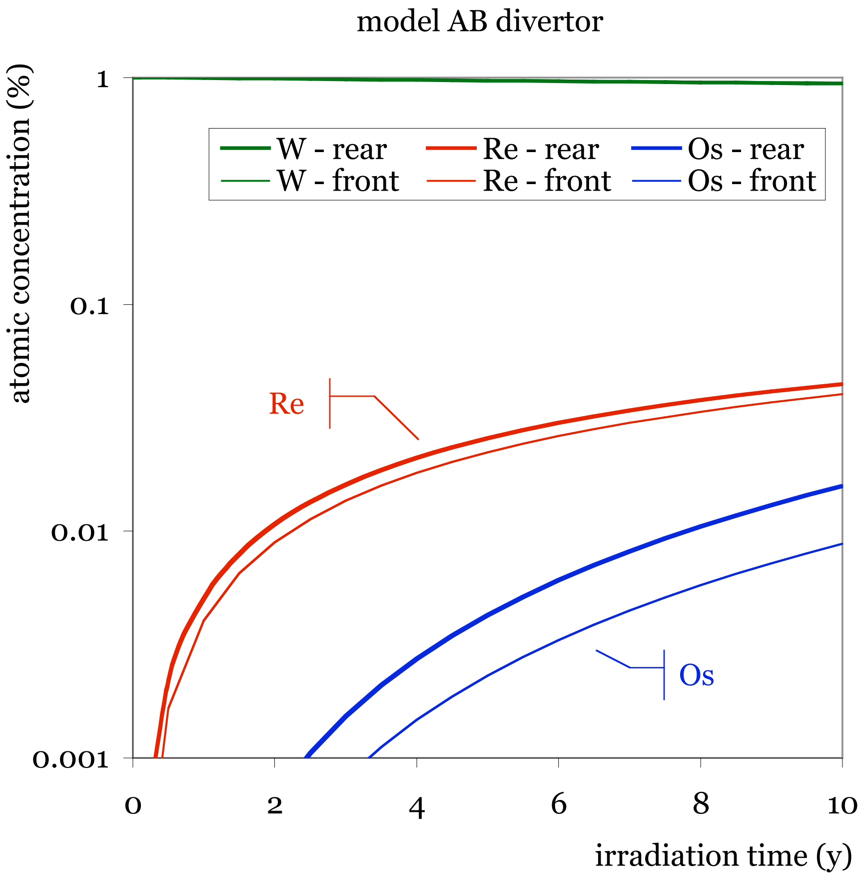
W-Re-Os Alloy composition model AB divertor armour



after	face	W At%	Re At%	Os At%
2.5 y	**rear**	**98.6**	**1.3**	**0.1**
	front	**98.8**	**1.1**	**0.06**
5 y	rear	97.0	2.6	0.4
	front	97.5	2.2	0.2

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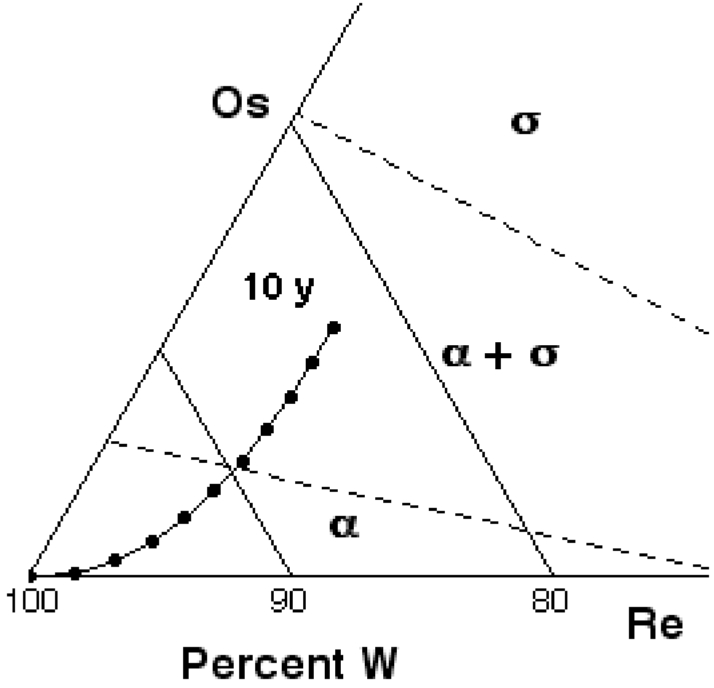
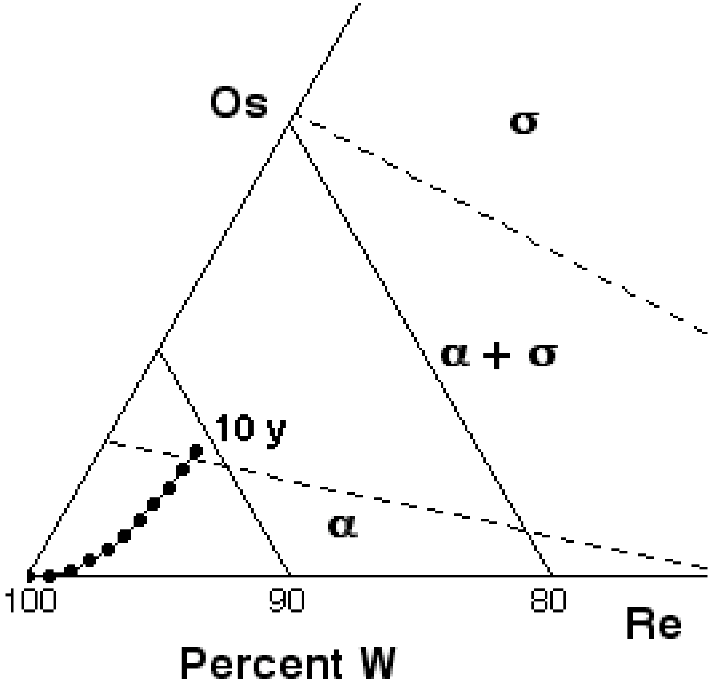
Phase stability: model A Divertor



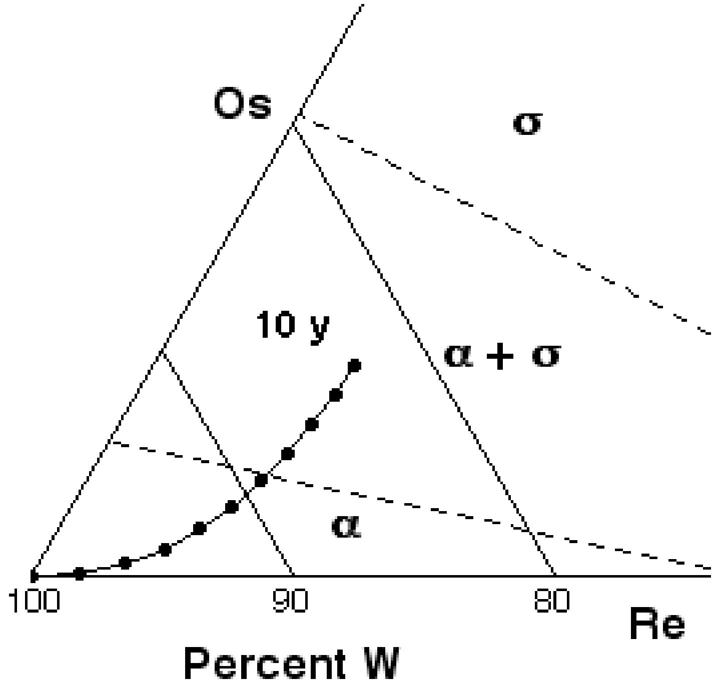
Rear



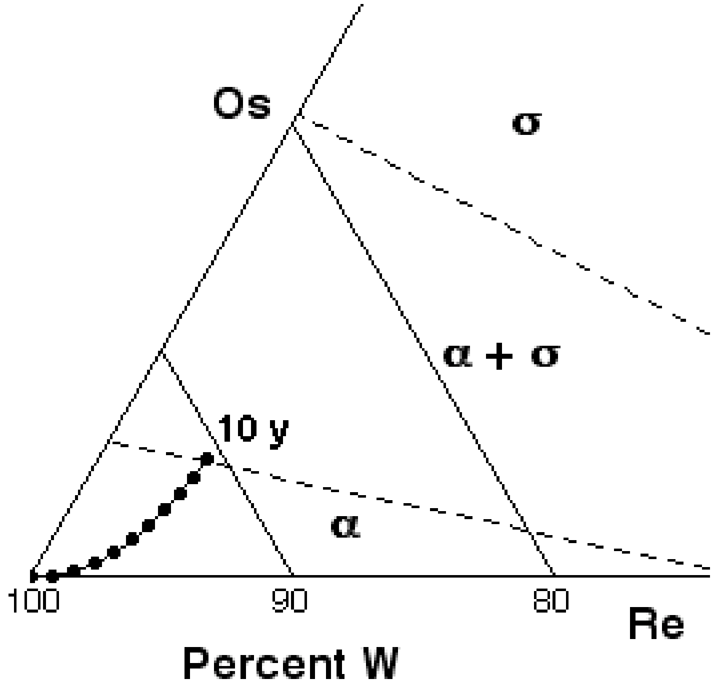
Front

Armour remains in bcc α field for service life

Phase stability: model A First wall



Rear



Front

Armour remains in bcc α field for service life

W-Re precipitates

•Despite the alloys remaining in the single bcc field for their service lifetimes, the end-of-service concentrations of transmutant elements Re and Os are significant

•Several previous neutron irradiation studies show *homogeneously* nucleated W-Re and W-Re3 precipitates in W alloyed with as little as 5%Re, i.e. in the 100% bcc field, in disagreement with the phase diagram

•Such precipitates harden, raise the DBTT and embrittle the armour and need further study

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Conclusions I

- The W-Re-Os alloy composition is sensitive to the neutron spectrum and therefore to the choice of breeder/coolant materials
- Important to include the large tungsten neutron resonance for the self-shielding
- The W-Re-Os alloys in the first wall and divertor armour remain in the bcc field for their required service lifetimes
- After 5 y, the W first wall armour becomes an alloy with a composition close to the $\alpha + \sigma$ field of the phase diagram
- Such alloys should be thermodynamically stable

Conclusions II

- However, neutron irradiation induced precipitates of W-Re, W-Re3 nucleate in W alloyed with as little as 5%Re, i.e. in the 100% bcc field
- The mechanism for this is not understood
- The hardening and DBTT increase could embrittle FW armour, particularly at joints
- Suggest new neutron irradiation experiments on W-Re-Os alloys, in the concentration ranges calculated here, to check mechanical properties