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

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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

      } Preferred options
    - 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

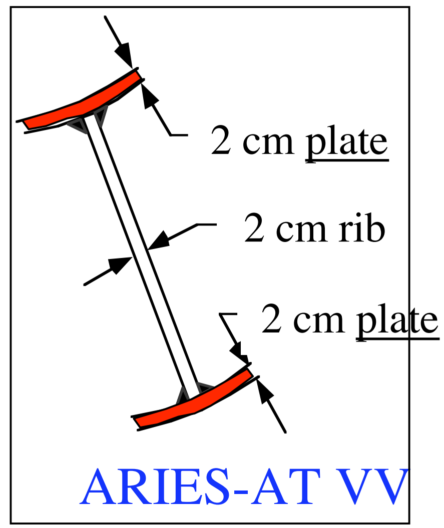
- What is new?
- Neutron-induced swelling vs dpa
- VV Activation assessment:
  - Specific activity (Ci/m^3)
  - Radwaste management schemes:
    - Clearance - release to commercial market to fabricate as consumer products
    - Recycling - Reuse within nuclear industry
    - Geological disposal classification:
      - 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**):

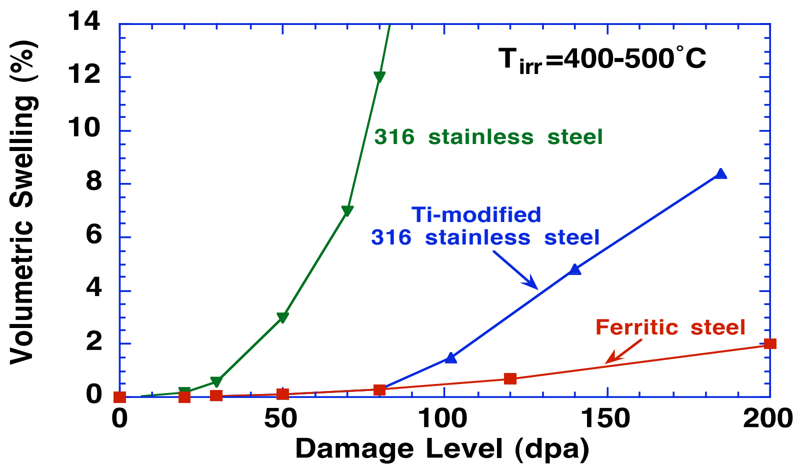
- Well-developed technology for nuclear and other advanced technology applications
- High long-term activation due to 2.5 wt% Mo (alloying element)
- Susceptible to swelling at high dose
- High He production
- Poor thermal conductivity and low thermal stress parameter
- Non ferromagnetic
- New alumina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

Ferritic/Martensitic Steels (such as **F82H FS**):

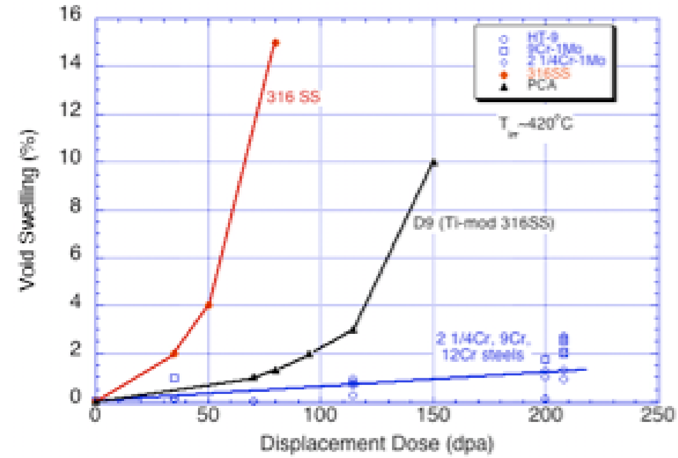
- Well-developed technology for nuclear and other advanced technology applications
- Low long-term activation
- Resistance to swelling at high dose
- Good thermal conductivity and thermal stress parameter
- Ferromagnetic
- Heat treatable
- ODS versions offer route to better high-temperature strength, improved He management, and mitigate displacement damage.

* R.J.Kurtz and R.E. Stoller, "Performance Limits for Austenitic & RAFM Steels,"UCLA Meeting, August 12-14, 2008.

Higher Swelling in 316-SS than in FS



Fission reactor, low He data



Gelles 1996; Garner & Toloczko 2000; Klueh & Harries 2001

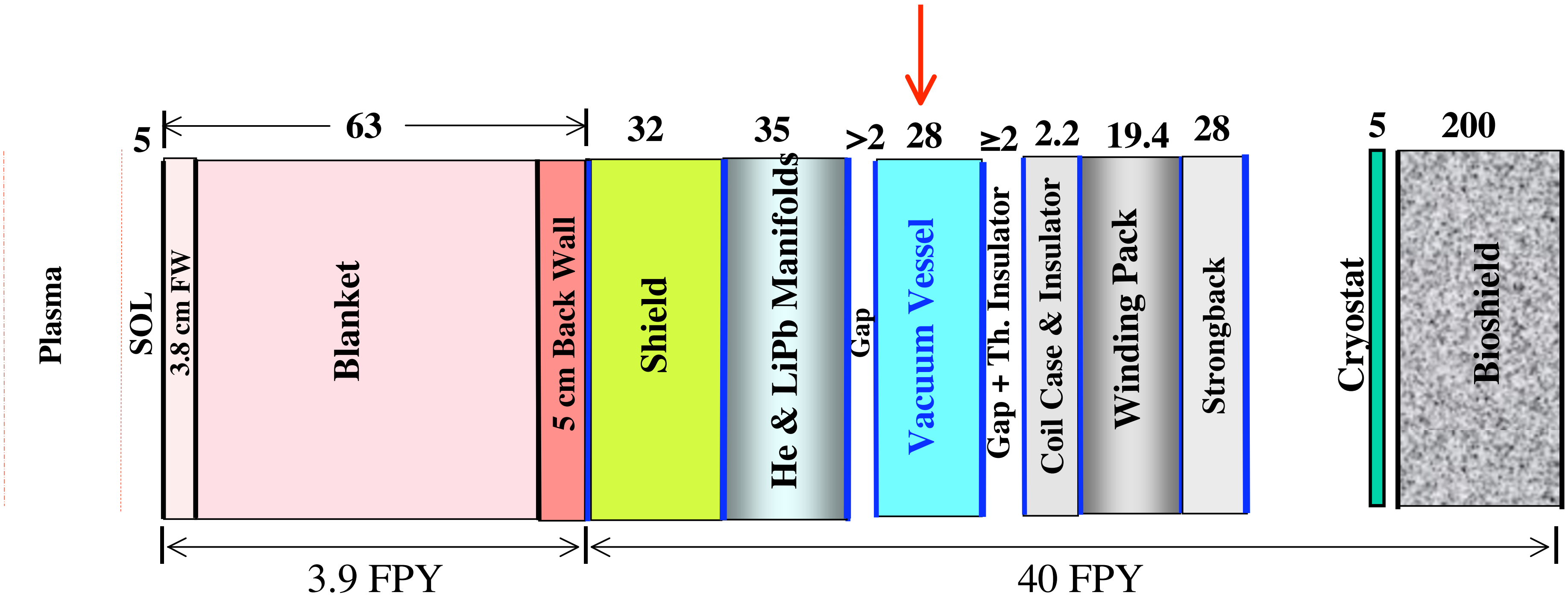
VV dpa @ 40 FPY	IB	OB
ARIES-AT	~ 30*	~ 5*
ARIES-DB	~ 10*	~ 5*

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

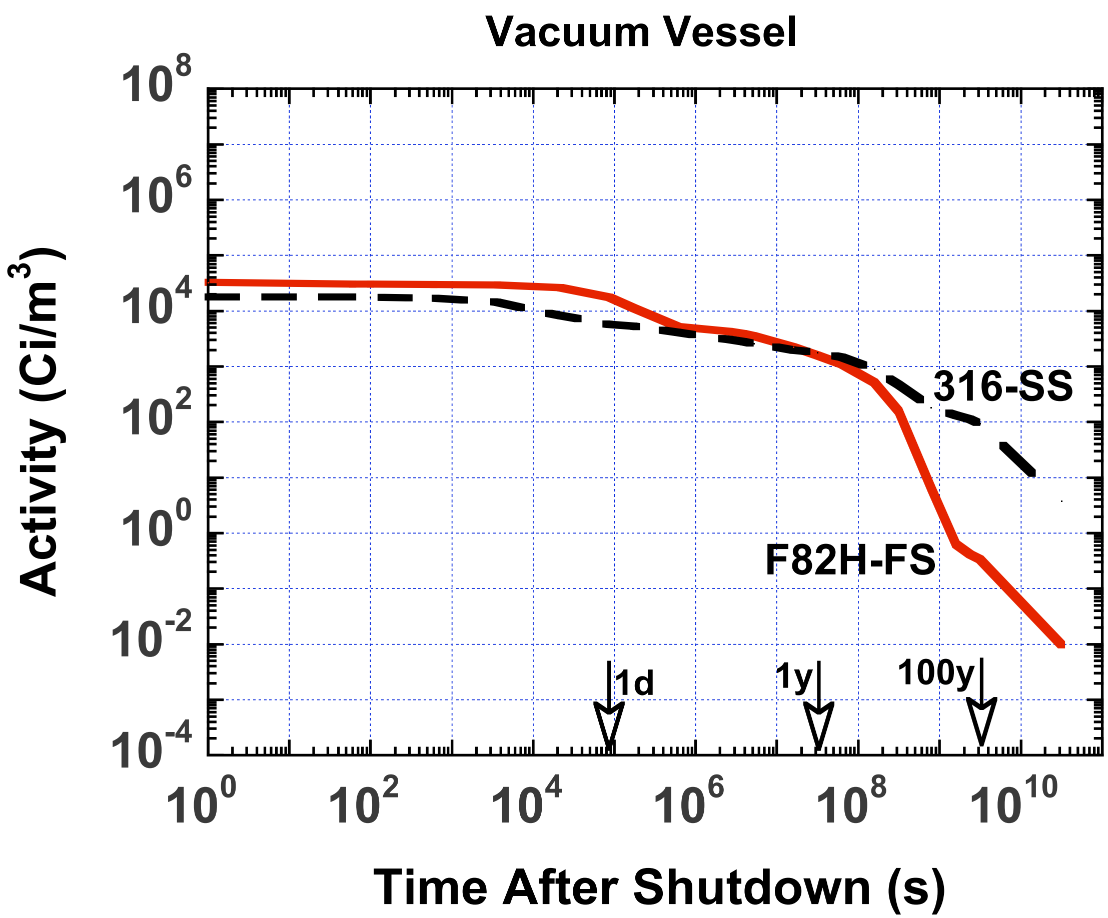
Neutron-induced swelling is not significant at low dpa of ARIES VV

VV Activation

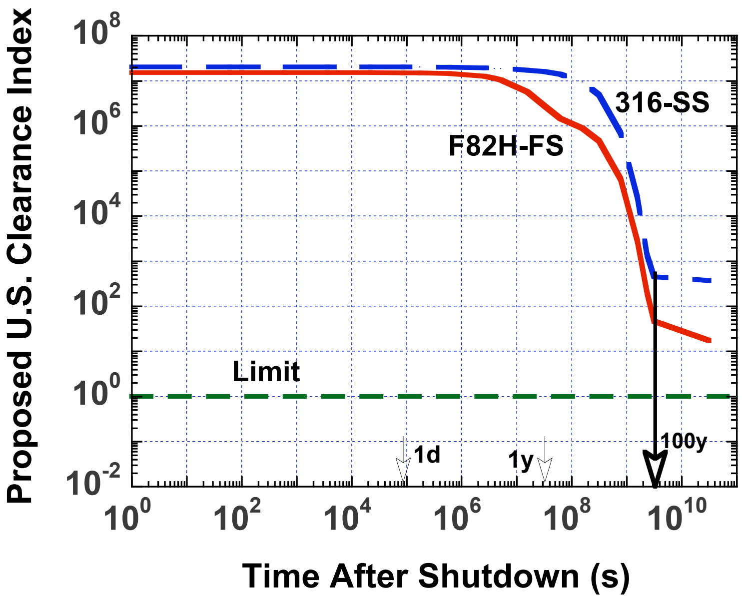
- **ARIES-CS geometry and parameters**:
  - 2.6 MW/m^2 average NWL
  - 40 FPY VV lifetime
  - 85% availability.

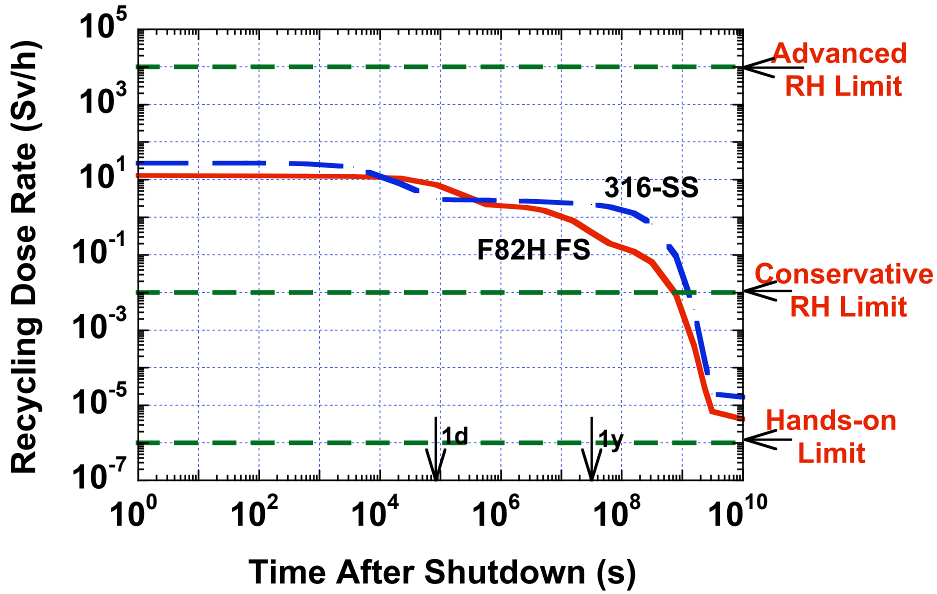


Long-term Activity of 316-SS is higher Relative to F82H-FS



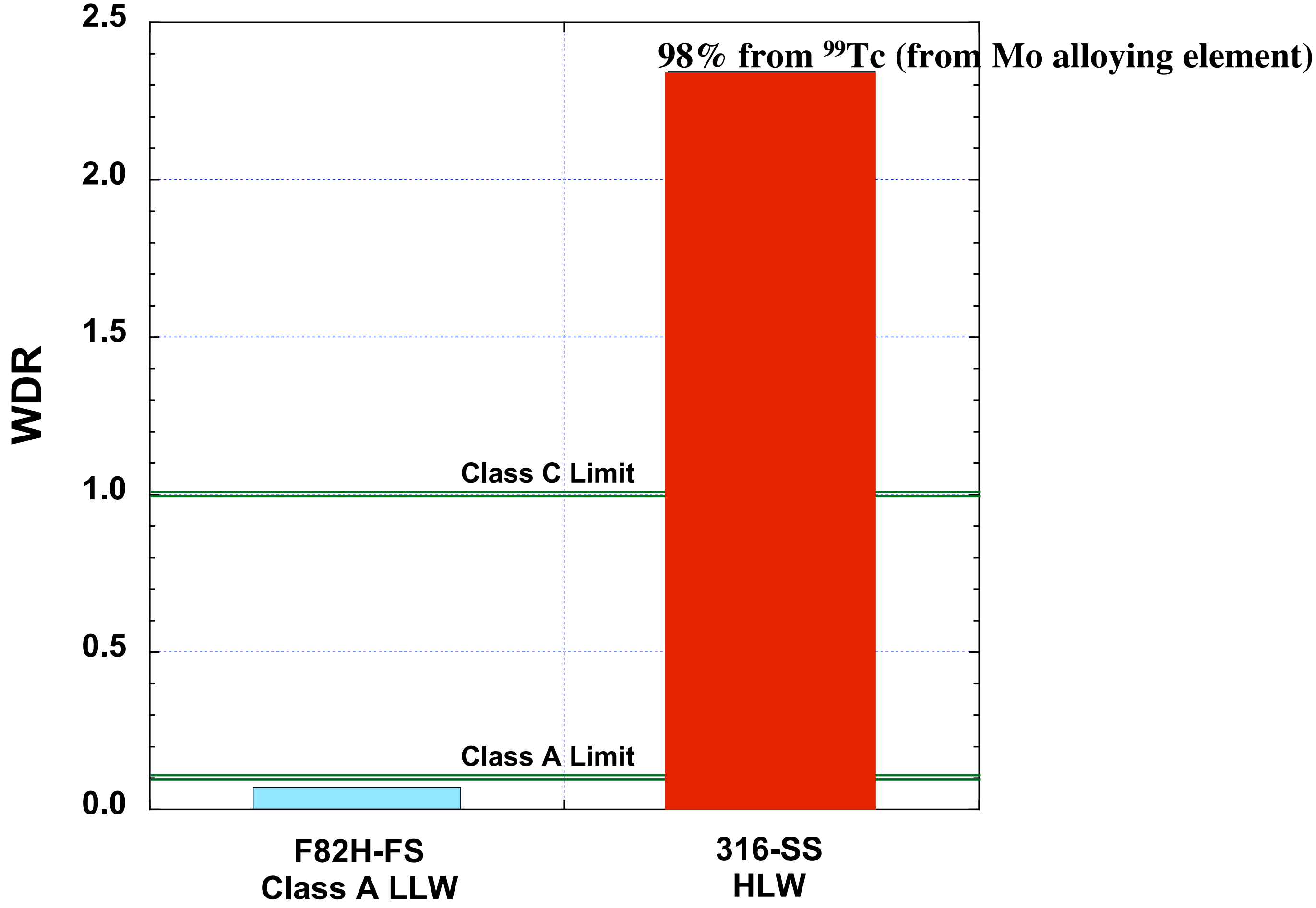
Both Materials are Not Clearable, but Recyclable with Advanced RH Equipment





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/m^3)
  - 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.**

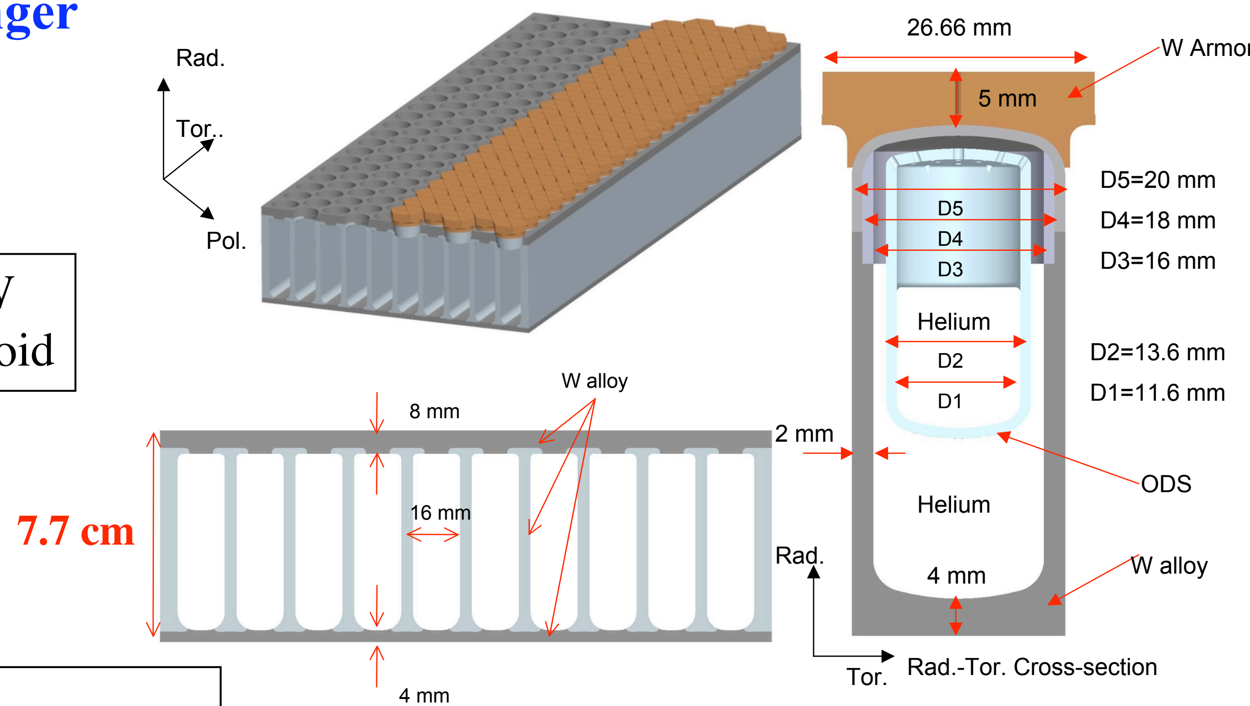
- **Radiation damage** to W:
  - Atomic displacement (dpa)
  - He production (in appm)
  - H production (in appm).

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 ?!

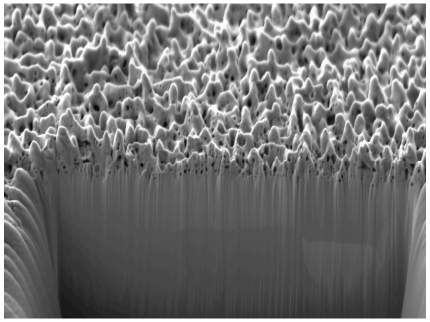
Status of W Alloy Development

(R. Kurtz - 5/4/2010)

- 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^{o}C) $\Rightarrow$ 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^{o}C
    - Need He spectrum and angular distribution.



W-Based Materials and Alloys

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- **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:**

with impurities

- **W-Re** (74 / 26 wt%)
- **W-Ni-Cu** (90 / 6 / 4 wt%)
- **W-Ni-Fe** (90 / 7 / 3 wt%)
- **W-La_2O_3** (99 / 1 wt%) - for EU divertor, per Rieth (Germany).
- **W-TiC** (98.9 / 1.1 wt%) - nano-composited alloy developed by Japan.

Commercial Products

Optimized for fusion divertors to improve ductility and fracture toughness

W-TiC Alloy for Fusion Applications

Reference: H. Kurishita, S. Matsuo, H. Arakawa, T. Sakamoto, S. Kobayashi, K. Nakai, T. Takida, M. Kato, M. Kawai, N. Yoshida, "Development of Re-crystallized W–1.1%TiC with Enhanced Room-Temperature Ductility and Radiation Performance," Journal of Nuclear Materials, Volume 398, Issues 1-3, March 2010, Pages 87-92.

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} m^{-2} s^{-1}), high fluence (4.5 x 10^{26} m^{-2}) ion bombardment at moderate temperature (573 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} 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].

[13] M. Miyamoto, D. Nishijima, Y. Ueda, R.P. Doerner, H. Kurishita, M.J. Baldwin, S. Morito, K. Ono, J. Hanna: Nucl. Fusion 49 (2009) 065035.

- 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 (0.01wt%)
(M. Rieth - Germany)

Undesirable impurity for geological disposal → Nb

Chemical specification of solid metallic tungsten

Element Element	Garantierte Analyse max. [µg/g] Guaranteed analysis max. [µg/g]	Typische Analyse [µg/g] Typical analysis [µg/g]
Ag	10	< 5
Al	15	5
As	5	< 2
Ba	5	< 2
Ca	5	< 2
Cd	5	< 2
Co	10	< 2
Cr	20	< 5
Cu	10	< 5
Fe	30	10
K	10	5
Mg	5	< 2
Mn	5	< 2
Na	10	< 2
Nb	10	< 5
Ni	5	< 2
Pb	5	< 2
Ta	20	< 10
Ti	5	< 2
Zn	5	< 2
Zr	5	< 2
Mo	100	20
W	**min. 99.97 % *)**	**99.99 % *)**

*) metallische Reinheit ohne Mo / metallic purity excluding Mo

C	30	10
H	5	2
N	5	< 2
O	20	5
P	20	< 10
S	5	< 2
Si	20	5

Key Parameters for Nuclear Analysis

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

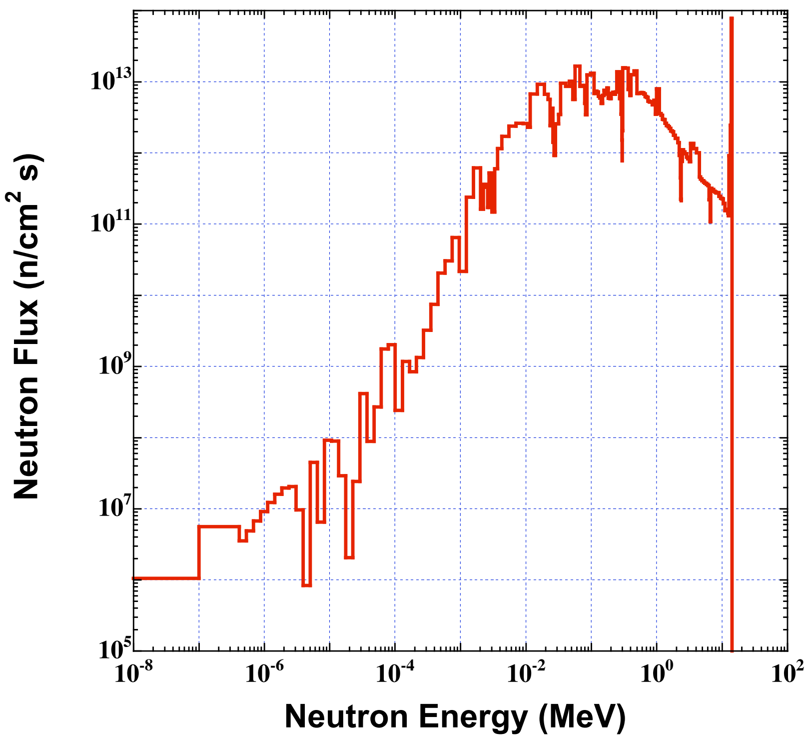
- Divertor replaced with blanket on same time scale
  ⇒ ~ 4 y of operation (3.4 FPY with 85% availability)

- 1 MW/m^2 NWL and 3.4 FPY ⇒ 3.4 MWy/m^2 fluence

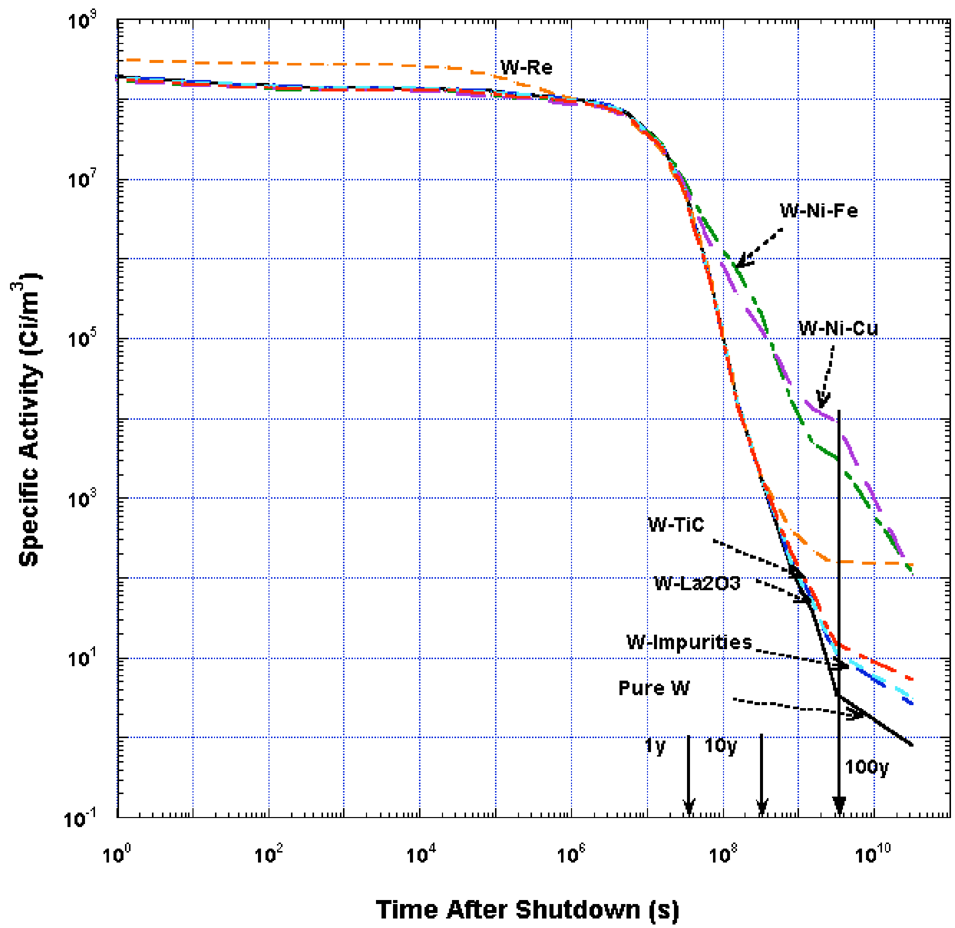
- Other fluences examined (up to 20 MWy/m^2).

Source Terms for Nuclear Analysis: Neutron Flux and Specific Activity

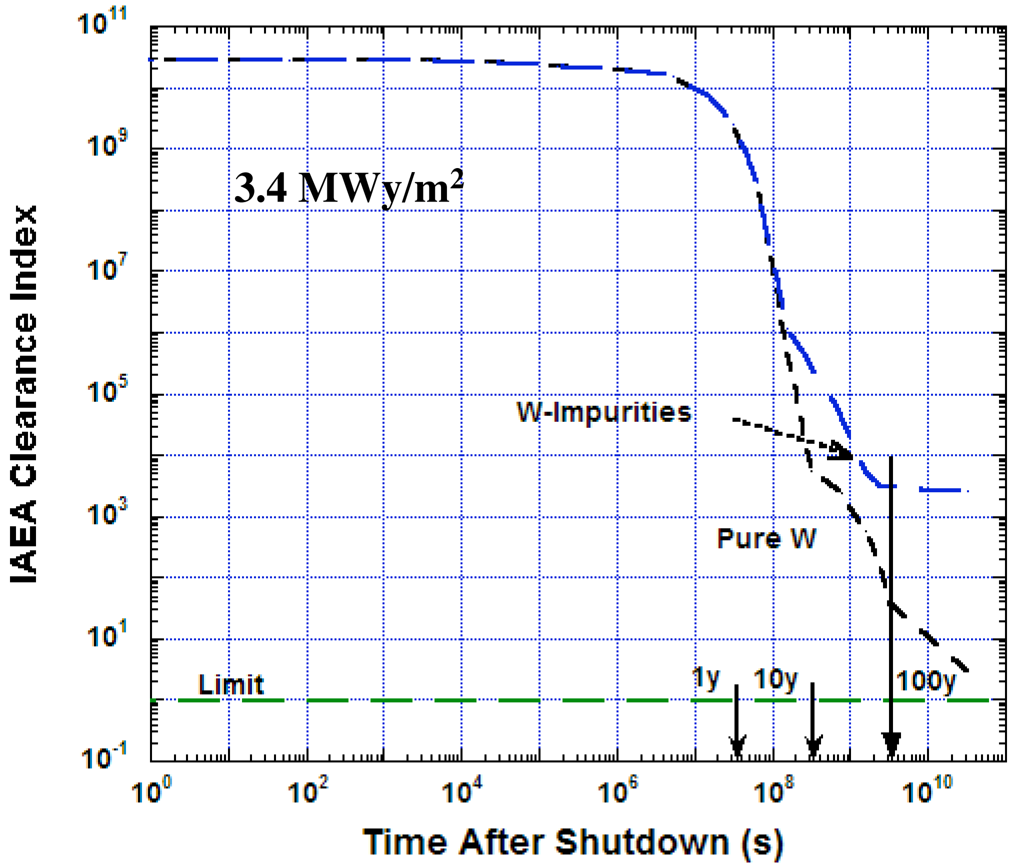
Neutron Spectrum at Divertor Surface



Specific Activity of W Alloys in Cooling Channel

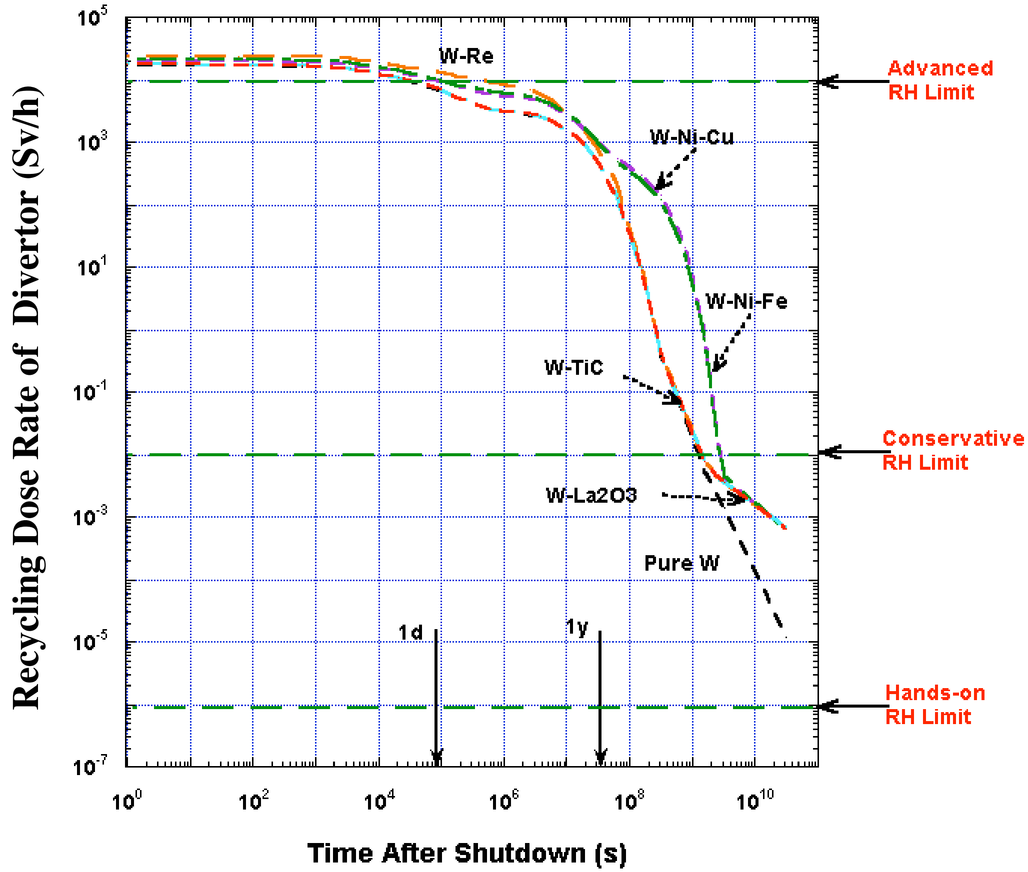


Divertor is Not Clearable



- Even highly pure W cannot be cleared after 100 y following shutdown.
- Divertor should preferably be recycled or disposed of.

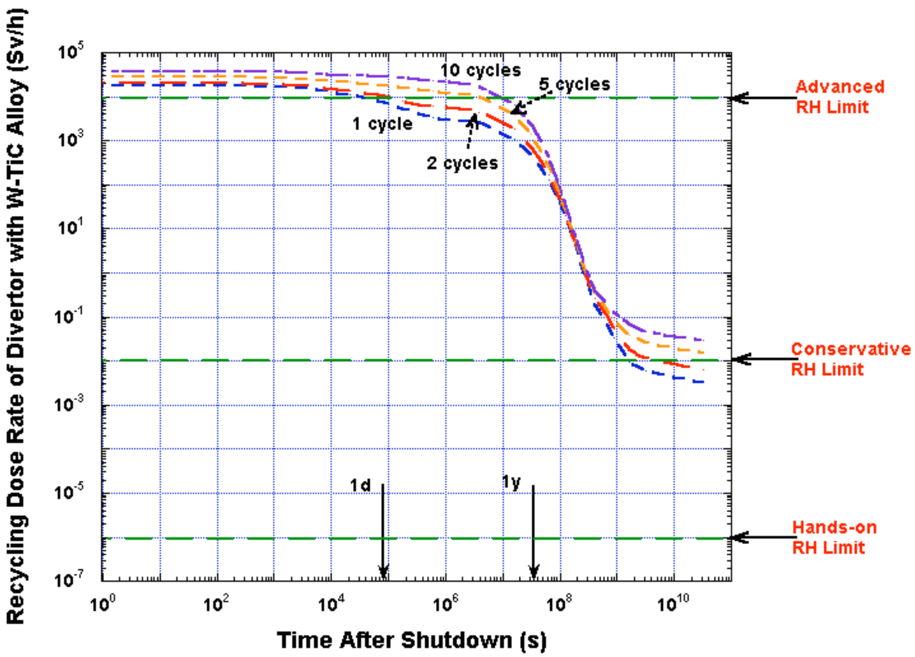
Candidate W Alloys are Recyclable with Advanced Remote Handling Equipment



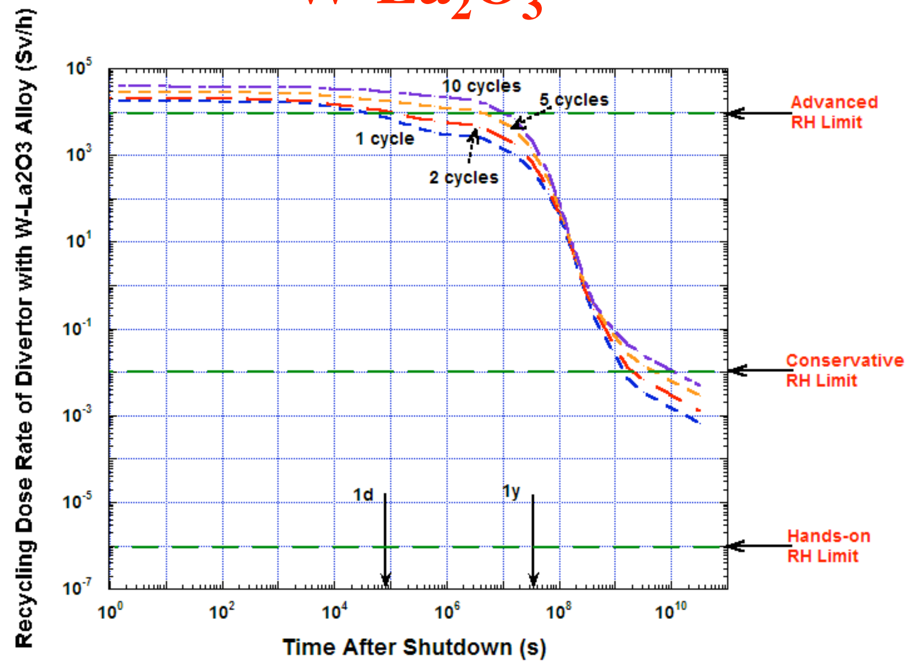
- All W alloys can be recycled after few days with advanced RH equipment.
- W-TiC and W-La_2O_3 alloys exhibit lowest recycling dose.
- All W-based components require active cooling during recycling to remove decay heat.
- Conventional RH equipment cannot be used during plant life (~50 y).

Candidate W Alloys are Recyclable with Advanced RH Equipment (Cont.)

W-TiC



W-La_2O_3



- 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.

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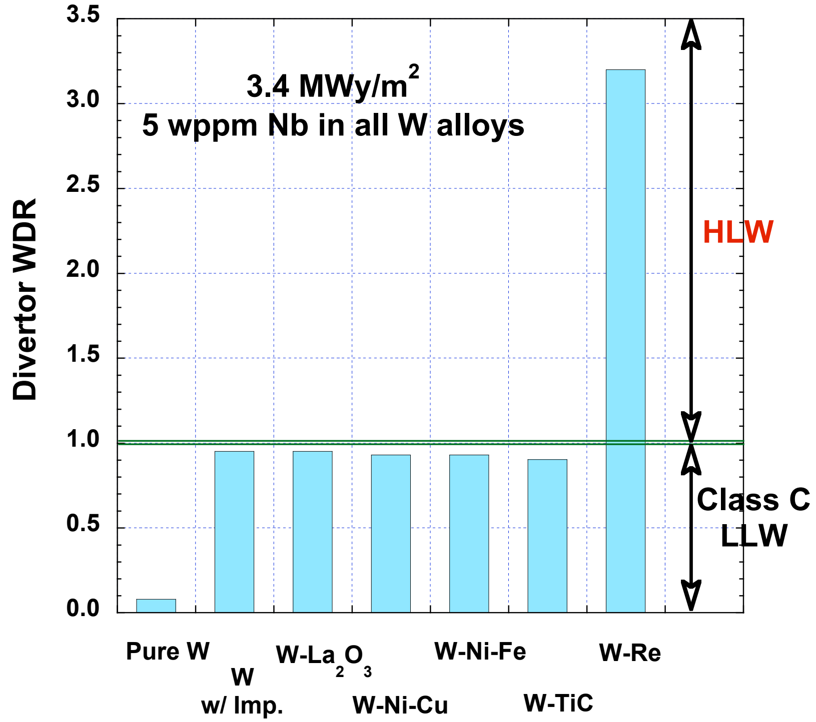
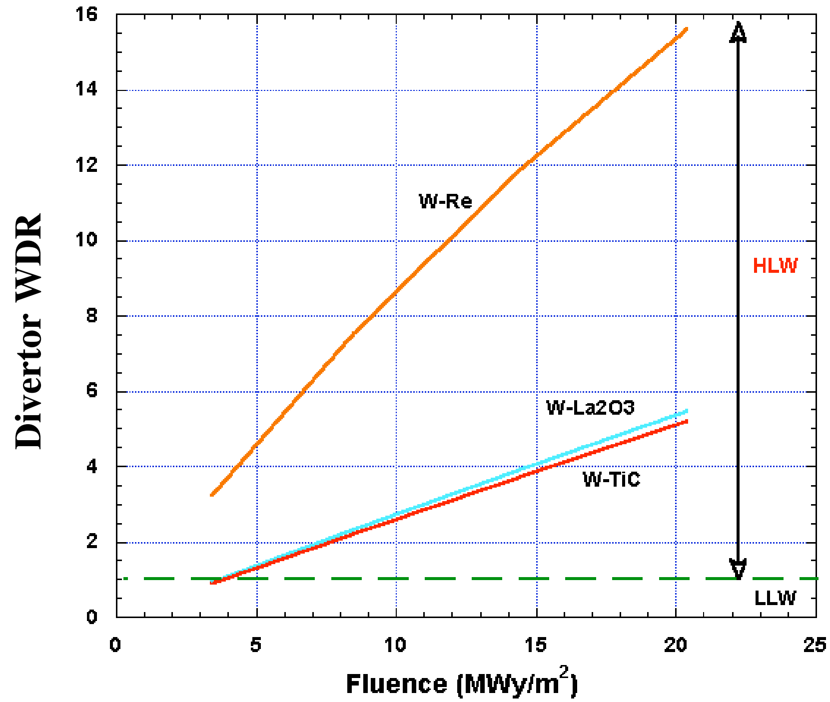
Classification of W-Based Divertor for Geological Disposal

Group	Material	WDR*	Classification
Armor	Pure W	0.08 (99% from ^{186m}Re)	Class C LLW
Armor	W + impurities	0.95 (50% from ^{94}Nb)	Class C LLW
Structural Components	W-La_2O_3	0.95 (50% from ^{94}Nb)	Class C LLW
Structural Components	W-Ni-Cu	0.93 (46% from ^{94}Nb)	Class C LLW
Structural Components	W-Ni-Fe	0.93 (46% from ^{94}Nb)	Class C LLW
Structural Components	W-TiC	0.9 (54% from ^{94}Nb)	Class C LLW
Structural Components	W-Re	3.2 (74% from ^{186m}Re)	HLW

* Divertor averaged WDR evaluated at 100 y using Fetter's limits.

Classification of W-Based Divertor for Geological Disposal (Cont.)





- For 3.4 MWy/m^2 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/m^2.
- "W alloys with 5 wppm Nb" generate HLW if fluence exceeds 3.6 MWy/m^2.
- Operating at higher fluences (> 4 MWy/m^2) mandates:
  - Controlling Nb to 1 wppm or less
  - Removing Mo from W-TiC alloy.

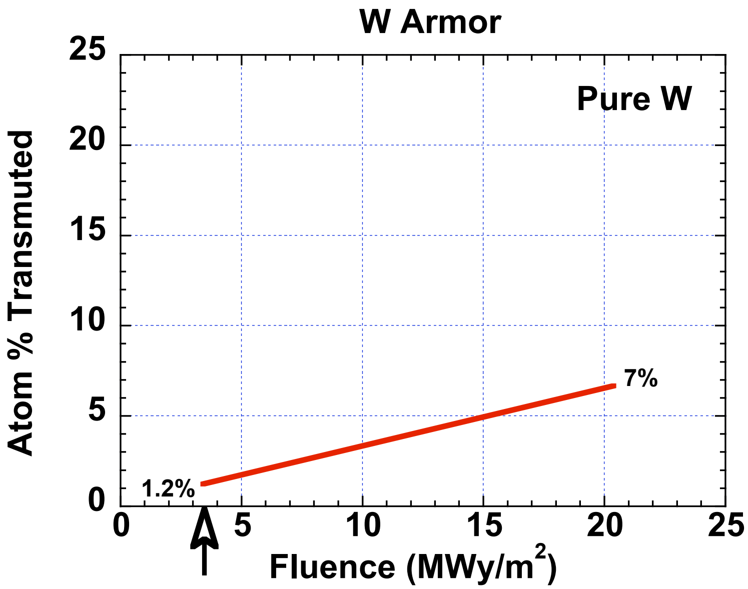
Transmutation of W

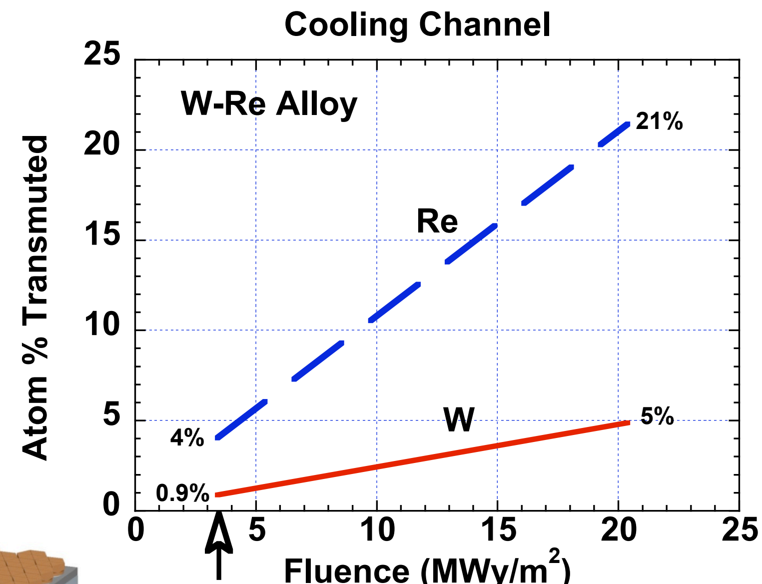
- Unlike Fe, W transmutes at higher rate.
- W transmutes into Re, Ta, Os, and other radioisotopes, producing He and H gases.
- In W-Re alloy, Re transmutes into Ta, Os, W, and other radioisotopes, producing He and H gases.
- Per R. Kurtz:
  - Transmutation of Re into Os is expected to adversely affect 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

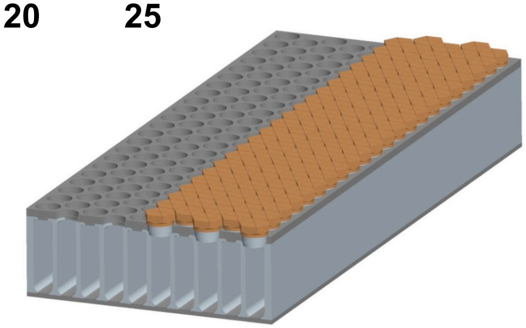
  ⇒ W armors on divertor and FW and W of stabilizing shells transmute differently.

* White paper for Fusion Materials Program by A. Rowcliffe, "Tungsten-Based Materials for Divertor Applications," (2009).

Transmutation of W in Divertor Armor and Cooling Channel







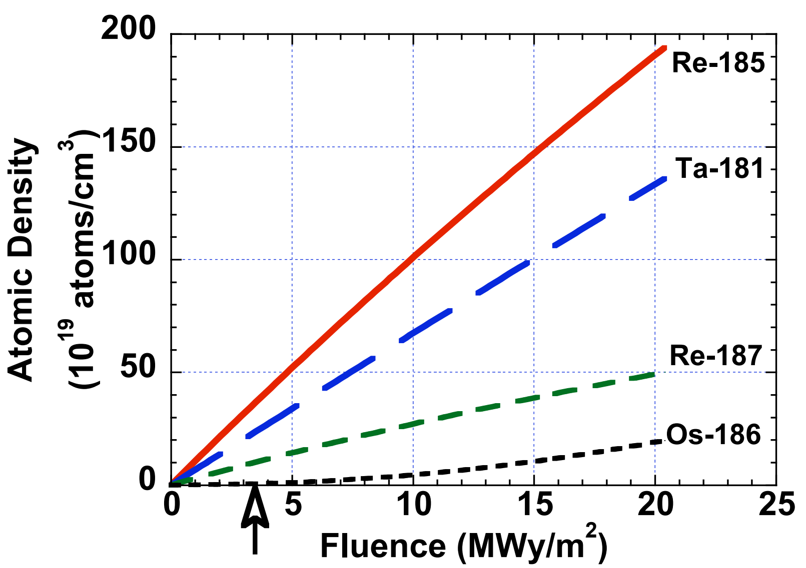
- 1-2% transmutation of W at ARIES irradiation conditions (3.4 MWy/m^2 for single-use divertor).
- Re transmutes at faster rate than W.
- Excessive Re transmutation (21%) at 20 MWy/m^2 fluence.

Example of Transmutation Products

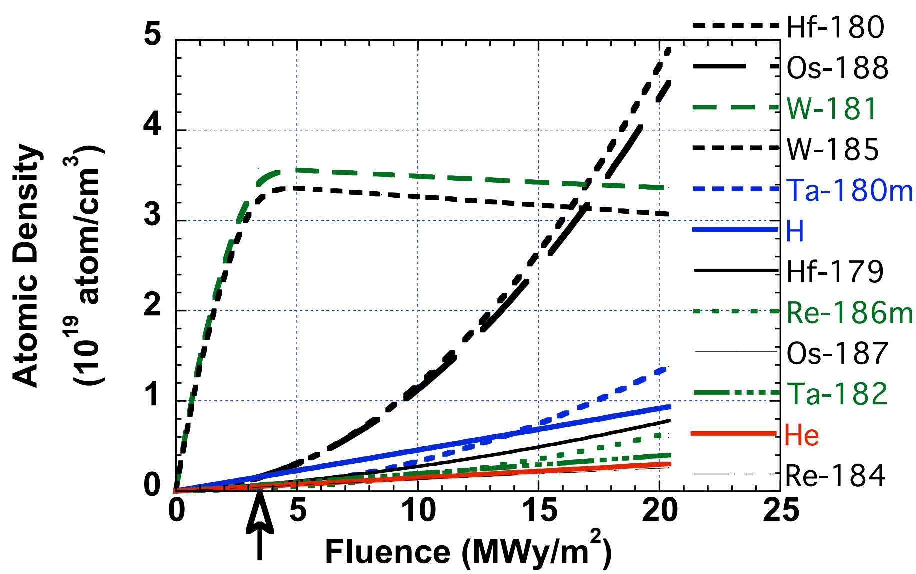
W Armor of ARIES Divertor

(Pure W)

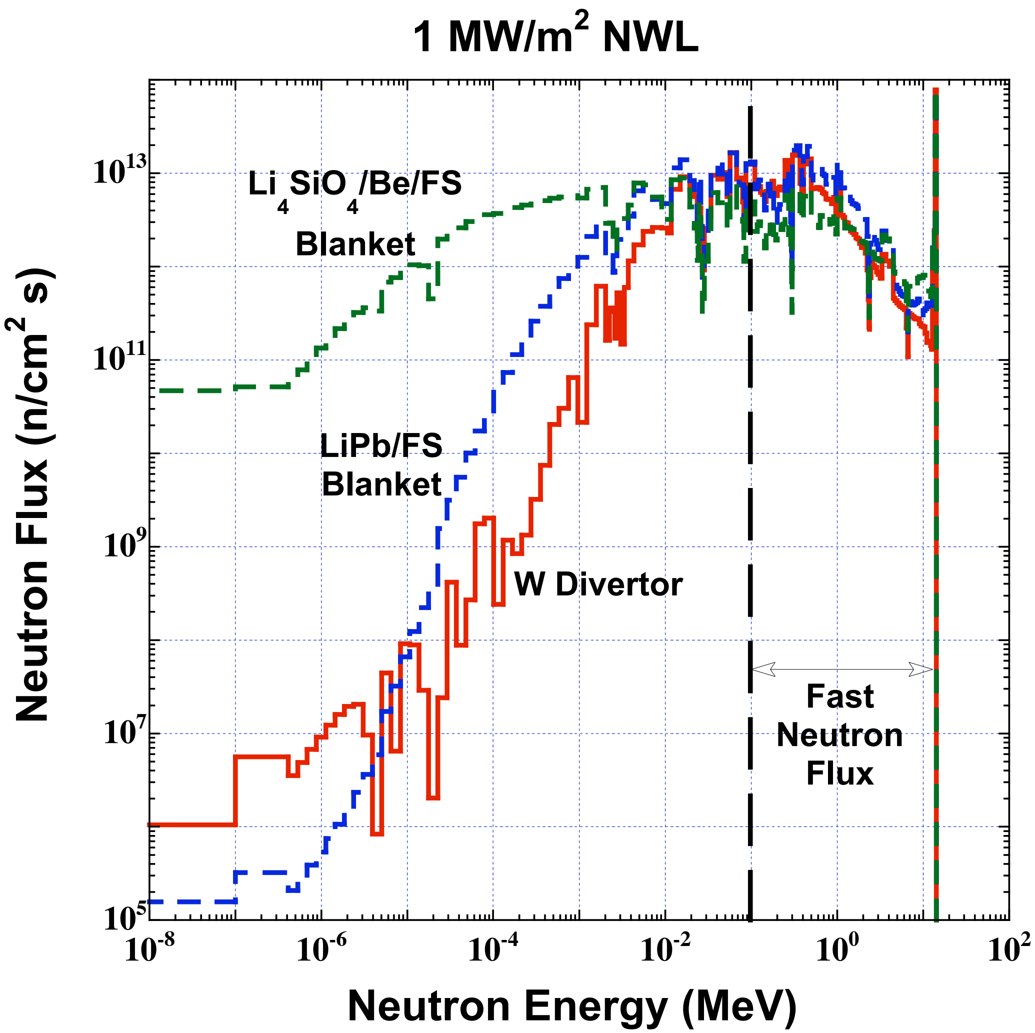
> 90% of W Transmutation Products



< 10% of W Transmutation Products



Will FW Spectrum Make a Difference to Armor Transmutation?



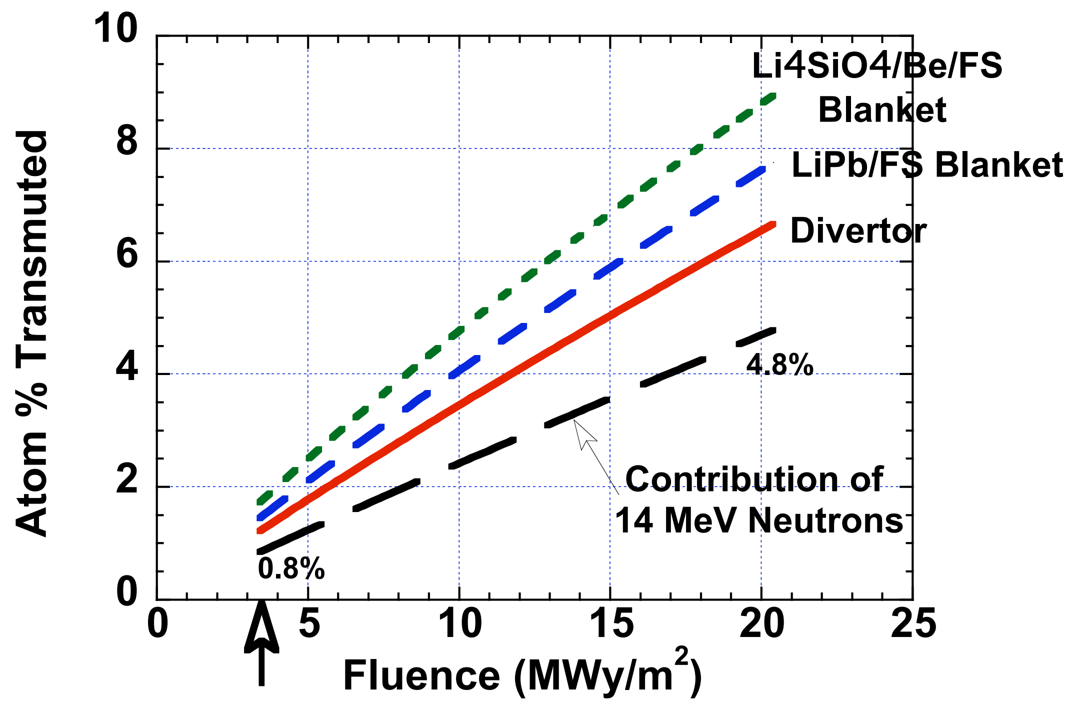
Neutron Flux @ Surface	Total	$E_n < 0.1$ MeV
Divertor	6e14	25%
LiPb/FS Blanket	7.5e14	29%
Li_4SiO_4/Be/FS Blanket	5e14	43%

Softer Spectrum Results in Higher Transmutation of W

1 MW/m^2 NWL.

0.5 cm pure W armor attached to:

- W-based divertor
- FW of LiPb/FS blanket
- FW of Li_4SiO_4/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

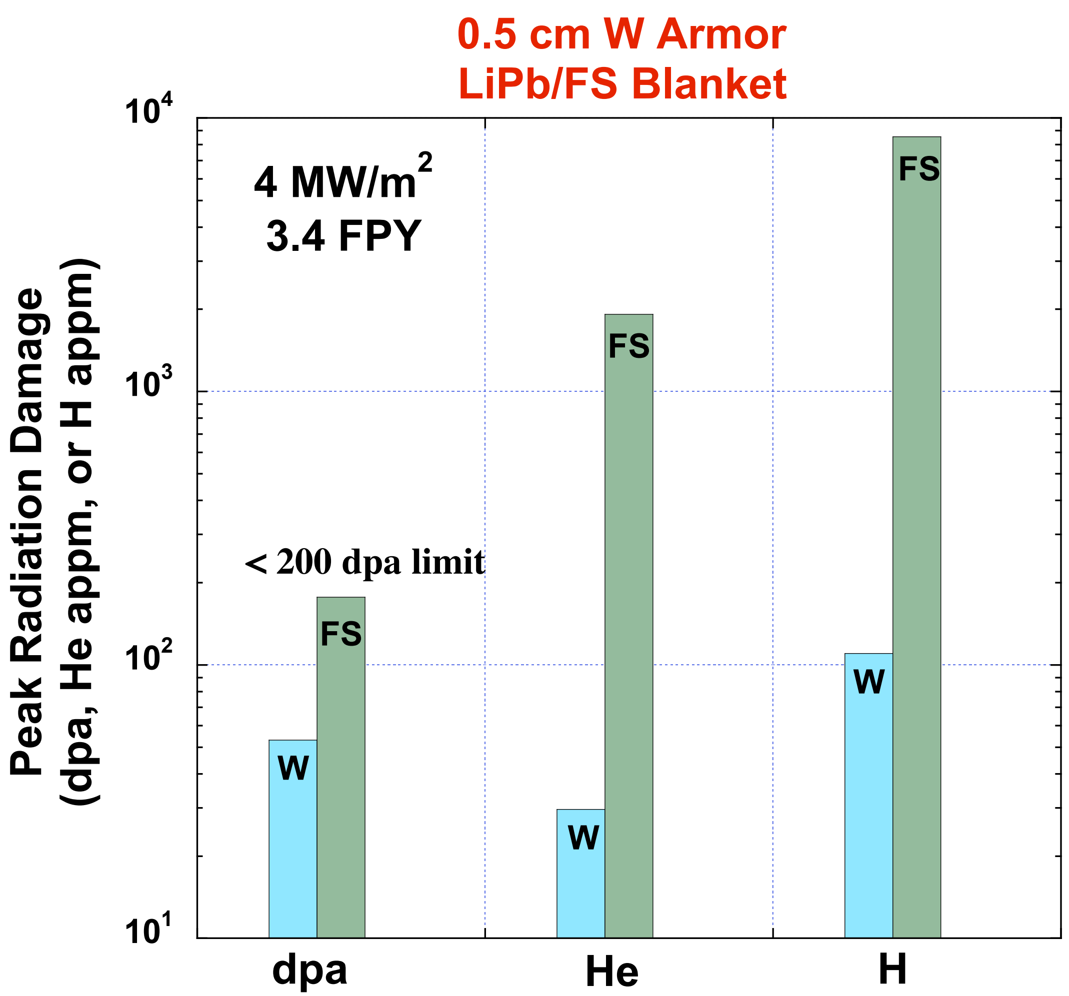
Damage/FPY @ 1 MW/m^2	dpa (dpa/FPY)	He* (appm/FPY)	H* (appm/FPY)
Divertor	3	1.9	7.1
LiPb/FS Blanket	3.9	2.2	8.1
Li_4SiO_4/Be/FS Blanket	3.1	2.16	8

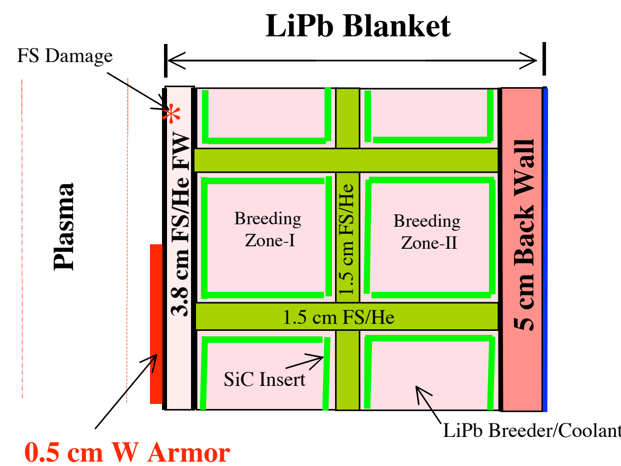
For same fluence, materials behind W armor change damage to W by only 10-30%

Realistic Designs Peak Damage @ 3.4 FPY	dpa	He*	H*
Divertor @ 2 MW/m^2	20	13	49
OB LiPb/FS Blanket @ 4 MW/m^2	53	30	110
OB Li_4SiO_4/Be/FS Blanket @ 4 MW/m^2	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





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_2O_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_2O_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 resistivety.