Road mapping Plasma Facing Materials for Fusion Pilot Plants: Solid and Liquid

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and with many helpful discussions with

M. Baldwin, J. Guterl, A. Hassanein, A. Lasa, J. Marian, J. Rapp, L. Snead, Z. Unterberg, and K. Woller

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DEPARTMENT OF NUCLEAR ENGINEERING

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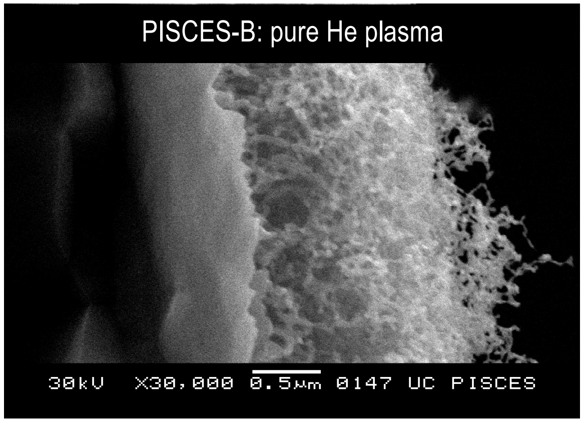
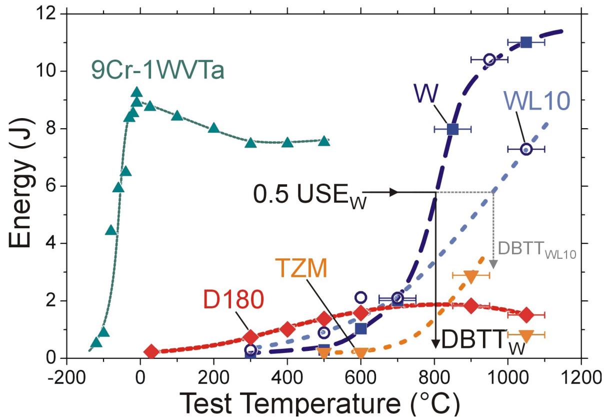
Plasma Facing Materials must tolerate extreme heat, neutron and particle fluxes

Baldwin, Nishijima, Doerner, et. al, courtesy of Center for Energy Research, UCSD, *La Jolla, CA*



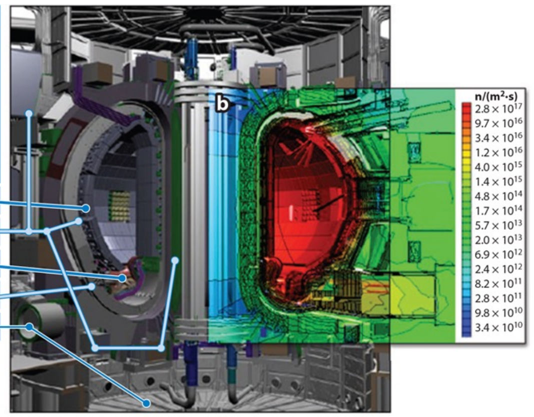
M. Rieth, A. Hoffmann, HHFC, 2008



- Typical materials considered for PFM include graphite, beryllium and tungsten -- although this list has been modified by considerations at ITER
- Tungsten alloys leading candidates as divertor structural materials due to their excellent thermo-physical properties.
- However, critical issues need to be addressed:
  - Creep strength
  - Fracture toughness (DBTT)
  - Microstructural stability (Recrystallization)
  - Low & high cycle fatigue
  - Oxidation resistance
  - Effects of neutron irradiation (hardening & embrittlement, composition changes, He, H)
- Several computational and experimental efforts to explore ways to predict & improve the performance of tungsten PFCs are now underway

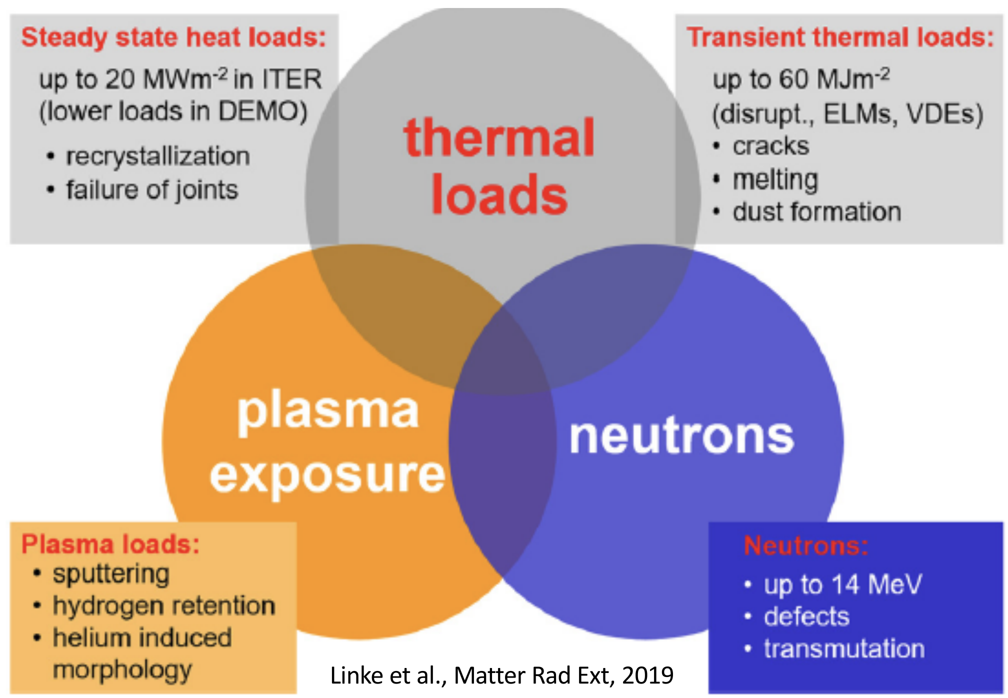
Plasma facing materials are a grand challenge for fusion reactors

ITER: lifetime fast neutron fluence (n/m^2; $E > 0.1$ MeV)	DEMO fusion power reactor: annual fast neutron fluence (n/m^2; $E > 0.1$ MeV)	Component
3.7×10^{21}	5×10^{22}	Blanket
5.1×10^{14}	7×10^{15}	Magnet
1.9×10^{21}	2.6×10^{22}	Divertor
1.1×10^{19}	1.5×10^{20}	Vacuum vessel
3.4×10^{11}	4.5×10^{12}	Cryostat



Zinkle and Snead, Annual Reviews 2014

PFM requirements ultimately require engineered forms of W with mechanistically driven stability.



Linke et al., Matter Rad Ext, 2019

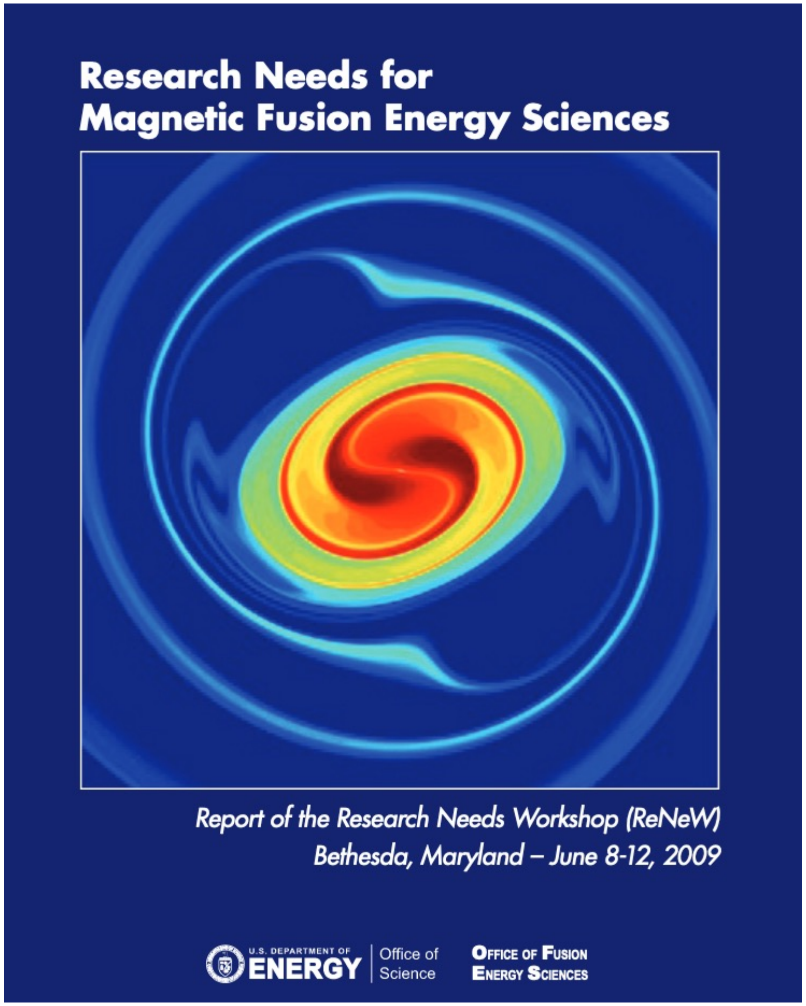
An eye toward a fusion pilot plant

- 14.1 MeV neutron flux >10^{14} n/(cm^2·s)
- First wall power load: 2 MW/m^2
- Divertor: 10-20 MW/m^2

C. Bachmann et al., FED, 2015; G. Federici et al., FED 2014

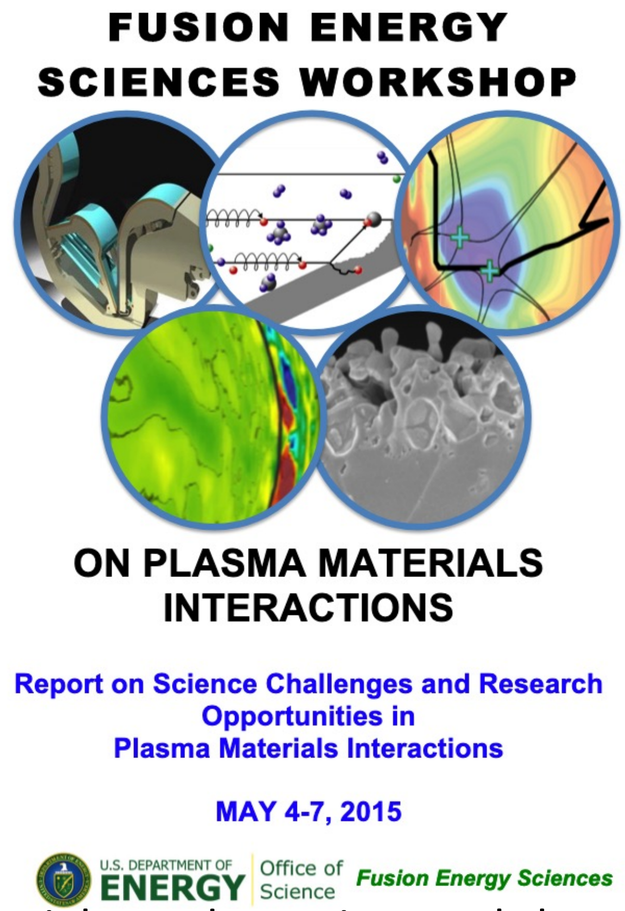
For essentially all ITER components, current materials systems **<u>will not survive</u>** the anticipated DEMO (or a compact FPP) lifetime.

PMI Challenge has been well recognized



Research Theme (3 of 5): Taming the plasma-material interface

- Thrust to decode & advance the science and technology of plasma-surface interactions
- Thrust to improve power handling
- Thrust to demonstrate an integrated solution for PMI with optimized core plasma

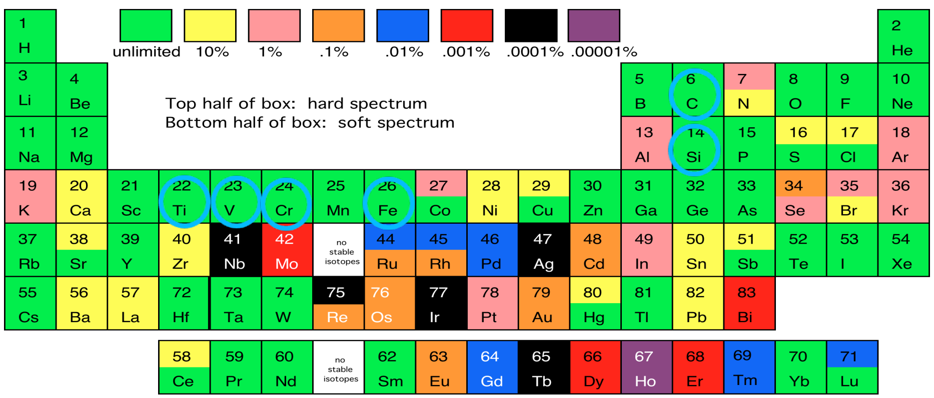


Report from Fall 2023 Materials roadmapping workshop expected this summer

Safety & Waste considerations

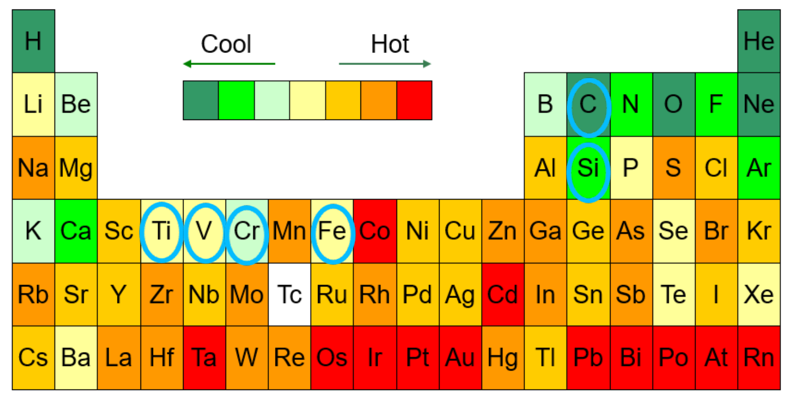
Activation considerations are essential for worker/public safety, maintainability, waste management, and public acceptance of fusion energy

- For Class C waste qualification (after 5 MW/m2 neutron wall loading for 4 years)



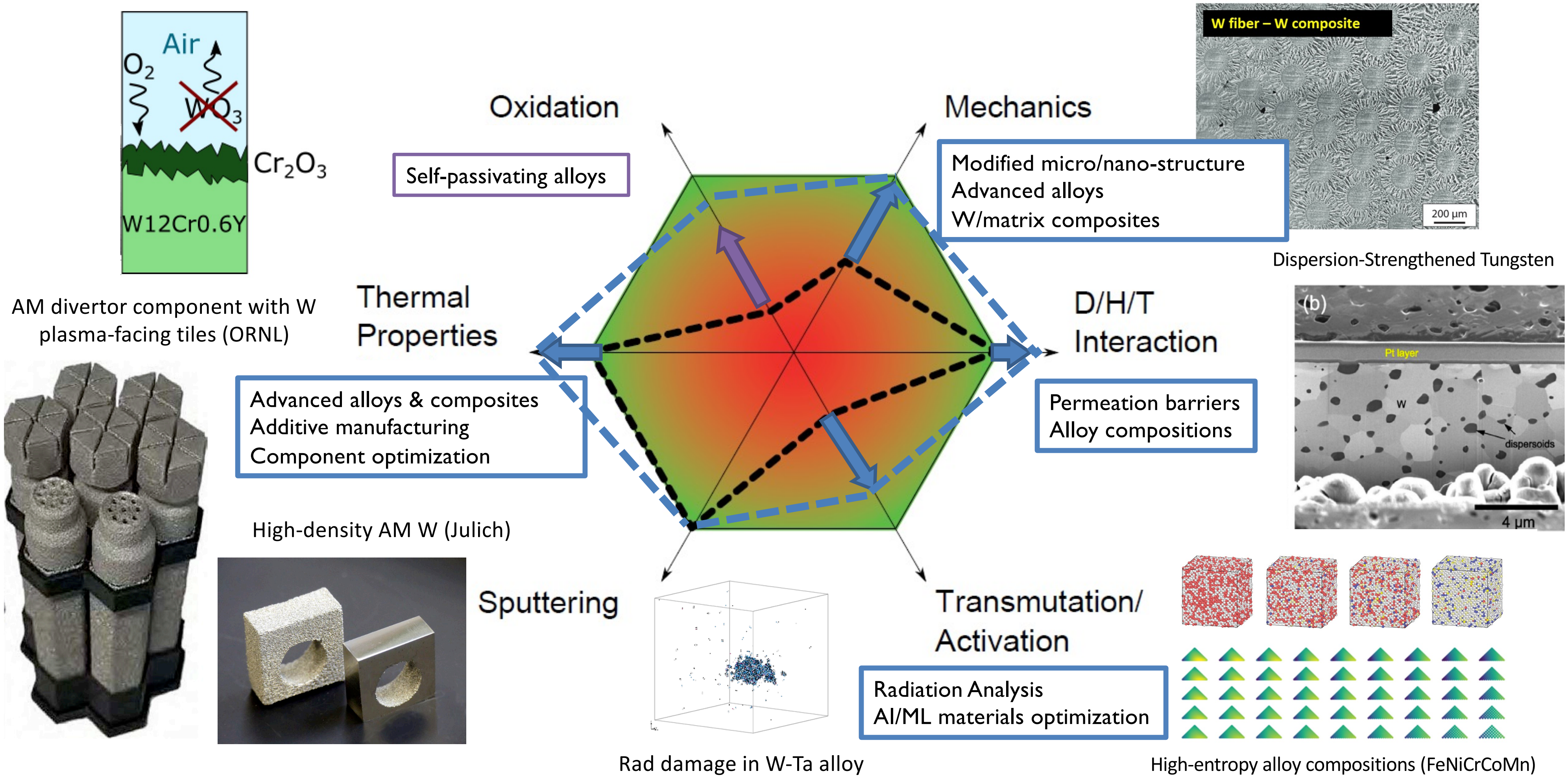
S. Piet, et al., Fusion Technology, Vol. 19, Jan. 1991, pp. 146-161; and E. T. Cheng, "Concentration Limits of Natural Elements in Low Activation Materials", ICFRM-8, Sendai, Japan, October 1997, J. Nucl. Mat.

- Similar safety criteria based on short-term activation and after-heat



Based on T. Noda, et al., Journal of Nuclear Materials 155-157, 1988, 581.

W PMI roadmap: Current R&D to address W performance gaps



Proposed W R&D, including complementary modeling & testing

Gaps that must be closed to move the material beyond TRL 3 (near-term R&D):

- Erosion, redeposition, material migration
  - Understand effects of preferential sputtering, material transport in the machines
  - Use linear plasma devices to study erosion under different exposure conditions / tokamak studies to understand material transport within the machine
- Recrystallization: How do we stabilize the microstructure?
  - Laboratory testing: High temperature UHV furnaces, e-beam facilities, microscopy with HT stages
  - Integrated testing: Exposure specimens to H mode plasmas w/ ELMs
- Interfacial stability
  - Microscopy: SEM / TEM during heating / ion irradiation
- Insufficient data for W materials with the relevant n-spectrum at relevant temperatures.
  - Long-term community need for FPNS facility for fusion materials testing
- Effects of neutron-irradiation (topics that can be addressed with existing ion beam / fission facilities):
  - Hydrogen isotope trapping / diffusion / permeation within damaged materials
  - How does transmutation affect embrittlement at low doses?
  - Need to assess thermal conductivity loss at high fluence n-damage
- Understanding the effects of the complex chemical environment
  - Use “single effect” experiments to study effects of B, N, and other impurities on surface chemistry
  - Develop interatomic potentials for models to address more complex chemical environment

Comparison of W alloys, CFC/graphite and SiC

Functional Requirement	Relevant Material Properties	Tungsten (Alloys)	Graphite/CFC	Silicon Carbide
Minimize impact on plasma core	**Erosion (sputtering, evap., arcing, melt, dust, etc.), Atomic physics (cooling)**	Low phys. sputtering, no chem. sputtering, some concern of leading edge melting/droplets, high core radiation	Moderate phys+chem sputter (T-dependent). Ablation at high temp., low core radiation, dilution probably OK	Phys & chem. sputtering somewhat lower (2-10x) than carbon, needs more study. Ablation at high T., low core radia.
Exhaust heat	**Thermal Conductivity**	High, some degradation under irradiation, ODS-W?	High for unirradiated, but substantial degradation < 1 dpa	Moderate unirradiated, some degradation at high dpa, OK for FW
Minimize H/D/T retention	**H diffusivity/permeability, trapping, co-deposition**	Implantation/diffusion acceptable, saturates a low dpa at low temp, (high temp?). low sputtering = low codep	Codep-dominated, likely unacceptable for safety/TBR except maybe at very high-T and/or O baking	Codep-dominated, needs more study
Maximize He pumping	**He diffusivity/permeability, trapping probability**	Some nano-bubbles but generally acceptable	Can review literature, but not really relevant	Low He permeability
Transparent to neutrons	**Nuclear cross sections**	High-Z, Acceptable for thin coatings on FW	Acceptable	Acceptable
Sufficient lifetime	**Erosion, neutron damage**	Low sputtering. n-embrittlement at low temp, creep at high temp. -> melt damage?	Not as bulk materials. Perhaps as thin film, but high chem. erosion unless T very high/low	Bulk material in areas of ~low heat flux, or thin coating. Erosion better than C, more study

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Exhaust heat	**Thermal Conductivity**	High, som… degrada… der irradiation, …DS-W?	High for u…diated, but subs… degrada… < 1 dpa	Moderate u…irradiated, some de…ion at high dpa, …or FW
Minimize H/D/T retention	**H diffusivity/permeability, trapping, co-deposition**	Implantation/diffusion acceptabl… aturates a low dpa … temp, (high temp…, low sputtering = low codep	Codep-dominated, likely un…ptable for safety/T… ept maybe a… very high-T and/or O baking	Codep-dominated, needs more study
Maximize He pumping	**He diffusivity/permeability, trapping probability**	Some nan… bbles but generally …ptable	Can revi…rature, but not r… elevant	Low He p…ability
Transparent to neutrons	**Nuclear cross sections**	High-Z, Ac…able for thin coati… FW	Accept…	Acceptab…
Sufficient lifetime	**Erosion, neutron damage**	Low sputtering, n-embrittle…t low temp, cre… high temp. -> melt damage?	Not as bul…aterials. Perhaps … film, but high che…osion unless T very high/low	Bulk material in areas of ~low heat flux, or thin coating. Erosion better than C, more study

Solid Walls – W challenges and advantages

Code	Name[1]	Key Advantages	Key Challenges
W/ AMW	Tungsten/ AM Tungsten	• High melting temperature • Resistant to sputtering • Chemical compatibility with tritium • High thermal conductivity	• Recrystallization • Limited fracture toughness and high DBTT • Severe embrittlement at low doses due to transmutation • Difficulty in producing crack-free AM components
WX	Solution Stabilized Tungsten Alloys	• High melting temperature • Resistant to sputtering • Increased recrystallization temperatures • Enhanced radiation stability • Fine grains lead to improved mechanical performance	• Reduction in thermal conductivity • Additional solid transmutants • Preferential sputtering of alloying elements • Embrittlement at low doses due to transmutation
WP	Particle Stabilized Tungsten Alloys	• High melting temperature • Resistant to sputtering • Increased recrystallization temperatures • Enhanced radiation stability via interfacial sink effects • Fine grained microstructures lead to improved mechanical performance	• Reduced thermal conductivity • Unknown effects due to transmutation of the solute • Preferential sputtering of alloying elements • Embrittlement at low doses due to transmutation • Loss of precipitates under irradiation
WHA	Tungsten Heavy Composites	• Simple fabrication via liquid sintering, commercially available and cheaper than W • High fracture toughness and ductility at RT, readily machinable • Potential PFC material if used with an armor material to avoid sputtering of the ductile phase	• Relatively low melting temperature of the ductile phase • Void swelling of the ductile phase • Neutron activation of Ni
W/W	Tungsten-tungsten MMC	• Tungsten fibers are commercially available from different vendors in large quantities for relatively cheap • Tungsten fibers are ductile and might be ductile after neutron irradiation • Tungsten is the preferred first wall material due to several reasons	• CVI process limits matrix thickness, which will be a challenge to industry-scale production of nuclear grade components. • Joining parts (also a challenge to scale-up of components)

Solid Walls – critical feasibility & performance issues for W

Code	Description	W	AM-W	WX*	WP*	WH*	W/Wf
1B-1	Recrystallization under static thermal loading scenarios	3	1	2	2	2	2
1B-2	Thermophysical properties and effects of thermal cycling	3	2	2	2	1	2
1B-3	Mechanical properties including tensile response, fracture toughness, and ductile-to-brittle transition temperature	3	1	2	2	2	2
1B-4	Transmutation induced chemical changes, irradiation defect microstructures, and their implications for phase stability, recrystallization, and volumetric swelling	1	1	1	1	1	1
1B-5	Net erosion (sputtering and He effects) and redeposition	2	1	1	2	1	2
1B-6	Hydrogen isotope permeation and retention for D/T and mixed D/T+He plasma conditions	2	1	1	2	1	1
1B-7	Near net shape manufacturing and repeatability	3	2	2	2	2	1
1B-8	Recrystallization under cyclic thermal loading with an evaluation of thermal shock and thermal fatigue	2	1	2	2	2	1
1B-9	Degradation under transient disruption thermal loading scenarios	2	1	1	1	1	1
1B-10	Impact of neutron irradiation (defect populations and transmutation products) on thermal and mechanical properties	2	1	2	1	1	1
1B-11	Combined effects of neutron irradiation and high heat flux on defect microstructures and overall phase stability and swelling	1	1	1	1	1	1
1B-12	Effects of plasma exposure on irradiation induced embrittlement	1	1	1	1	1	1
1B-13	Creep strength, time-to-rupture, and effects of neutron irradiation	1	1	1	2	1	1
1B-14	Oxidation behavior under fusion relevant accident scenarios	1	1	2	2	1	1

mTRL Ranking Scale

1	2	3	4	5	6

Motivation for Ultra High Temperature Ceramics (UHTCs)

• Lacking a perfect plasma facing material that can withstand the multiple operation exposure extremes & materials design requirements

High Heat flux

- High thermal conductivity
- Thermal stress

Surface morphological changes

- PFC erosion
- Tritium retention
- He/H implantation (blister formation)
- Dust/debris release

Neutron irradiation induced property changes

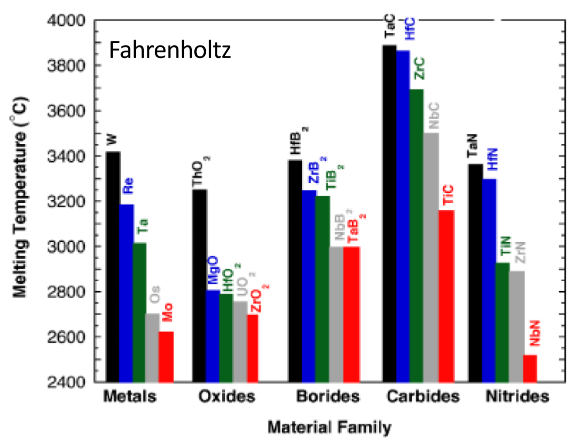
- Thermal conductivity
- Mechanical properties
- Grain growth and cavity swelling

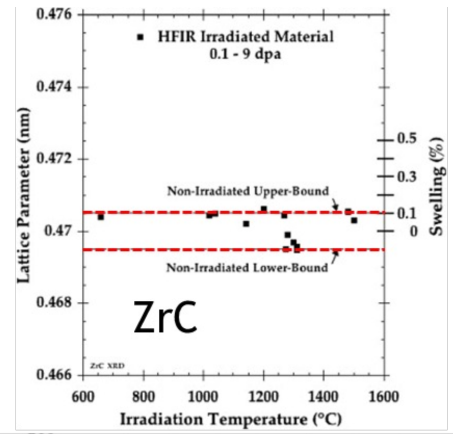
Plasma interactions and sputtering

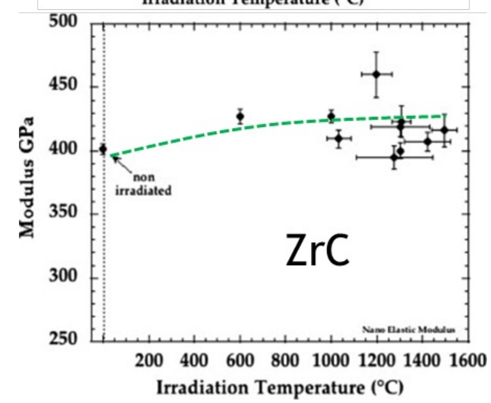
- Plasma compatibility (low-Z preferred)
- Surface erosion and redeposition (high-Z preferred)

UHTCs are a potential PFM solution

- High melting points
- stable microstructures
- Minor radiation-induced swelling
- Some evidence suggests very minor changes in mechanical properties after neutron irradiation Snead





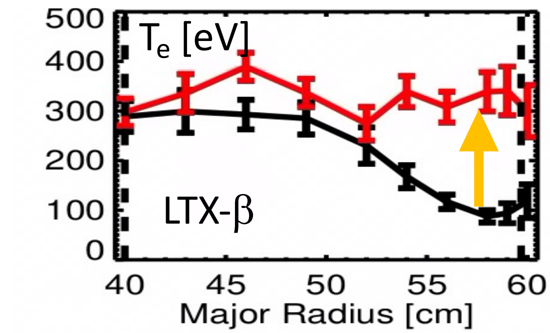


Conductive Liquid metals: sparingly tested in present-day devices

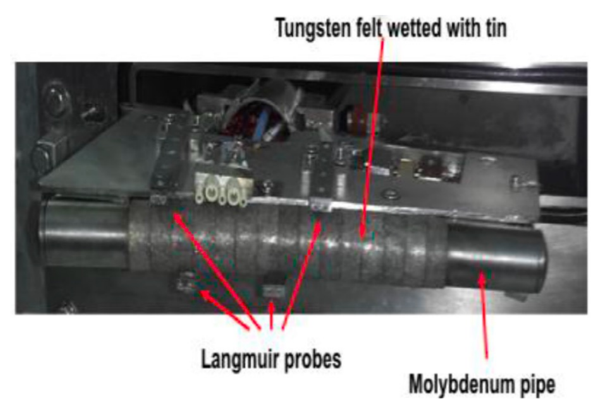
- Liquid Li used in NSTX (divertor), EAST (insertable limiter), FTU (limiter), LTX and LTX-beta (limiter), COMPASS (divertor insert), HIDRA (limiter) and MAGNUM-PSI (target)

- Liquid Sn PFCs have been tested in FTU (limiter) and ASDEX-Upgrade (divertor)

- Lead-Lithium is untested as a PFM, but is being considered by private companies



Boyle NF 2023



Mazzitelli NF 2019

Wall changeout discussion agenda – PMI/first wall/divertor

Breakout groups (5 scheduled, 3 materials-related & 2 plasma-related) will discuss (90 minutes) first wall changeout options/opportunities – Tyler Abrams will provide more specific instructions

- I will co-lead the Fusion Materials Science & Technology breakout (with Greg Sinclair)
- Adam McLean and Jonathan Yu will co-lead Divertor/SOL breakout
- Florian Effenberg and Aritra De will co-lead

10:30 AM	07	A. Garofalo C. Holcomb	Core Physics/AT Scenarios Breakout (Room 15-019, Zoom Link)
		A. McLean J. Yu	Divertor/SOL Breakout (Room 15-018, Zoom Link)
		B. Wirth G. Sinclair	Fusion Materials & Technology Breakout (Room 13-301, Zoom Link)
		H. Wang S. Zamperini	Pedestal/Core-Edge Breakout (G34 CR Conf. Room, Zoom Link)
		F. Effenberg A. De	Plasma-Materials Interactions Breakout (Room 13-530, Zoom Link)
12:30 PM			Breakout Groups Adjourn

Martin Nieto-Perez	Pennsylvania State University	Fusion Materials Science & Technology	Multi-species materials sputtering studies in IGNIS-2
Mitra Taheri	Johns Hopkins University and (Joint) Pacific Northwest National Lab	Fusion Materials Science & Technology	Next generation candidate fusion materials systems: complex refractory alloys
Robert Kolasinski	Sandia National Laboratories	Fusion Materials Science & Technology	PMI and materials science considerations for tungsten plasma-facing components in DIII-D
~~Zeke Unterberg~~	~~ORNL~~	~~Fusion Materials Science & Technology~~	~~TBD~~
Lance Snead	Stony Brook	Fusion Materials Science & Technology	Limitations of tungsten as a HHF material and where we could go next