Chamber Materials Challenges for Inertial Fusion Energy

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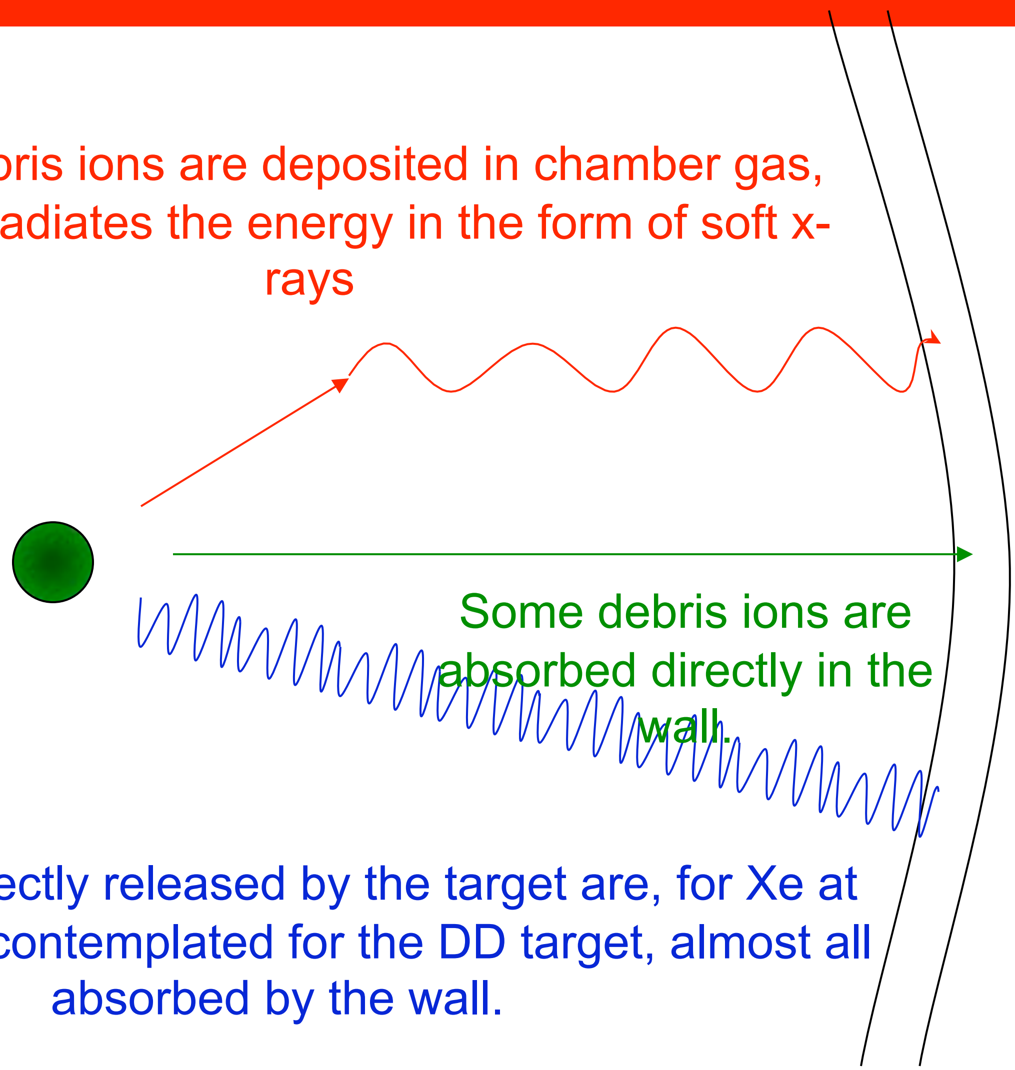
Oak Ridge National Laboratory

Outline

- **Overview of inertial fusion energy chamber materials environment**
- **Surface and bulk radiation damage mechanisms in materials**
  - **Example: Radiation hardening and flow localization**
- **Strategies for designing resilient IFE chambers**
  - **Liquid walls (minimize harsh environment threats)**
  - **Chamber gas and/or magnetic deflection of ions**
  - **Radiation-resistant materials**
  - **Rapid changeout**

The threat spectrum can be thought of as arising from three contributions: fast x-rays, unstopped ions, and re-radiated x-rays

Some debris ions are deposited in chamber gas, which re-radiates the energy in the form of soft x-rays



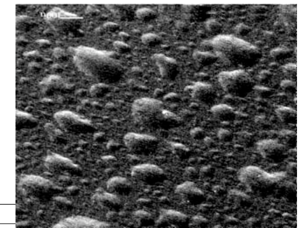
The x-rays directly released by the target are, for Xe at the pressures contemplated for the DD target, almost all absorbed by the wall.

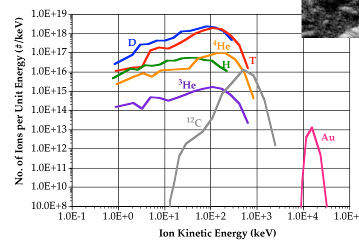
The wall (or armor) reacts to these insults in a manner largely determined by its thermal conductivity and stopping power.

R.R. Peterson et al., ARIES study (2001)

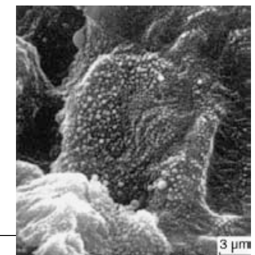
IFE Chamber Materials may be exposed to multiple threats

- **Surface blistering and exfoliation**
  - **Due to implanted He, H ions**

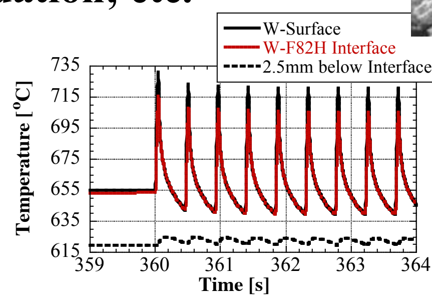




- **Near-surface ion damage**
  - **Sputtering, radiation damage, implanted gas**

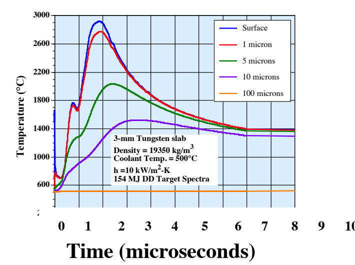


- **Dust creation and material redeposition**
  - **Tritium retention and release; mirror degradation; etc.**



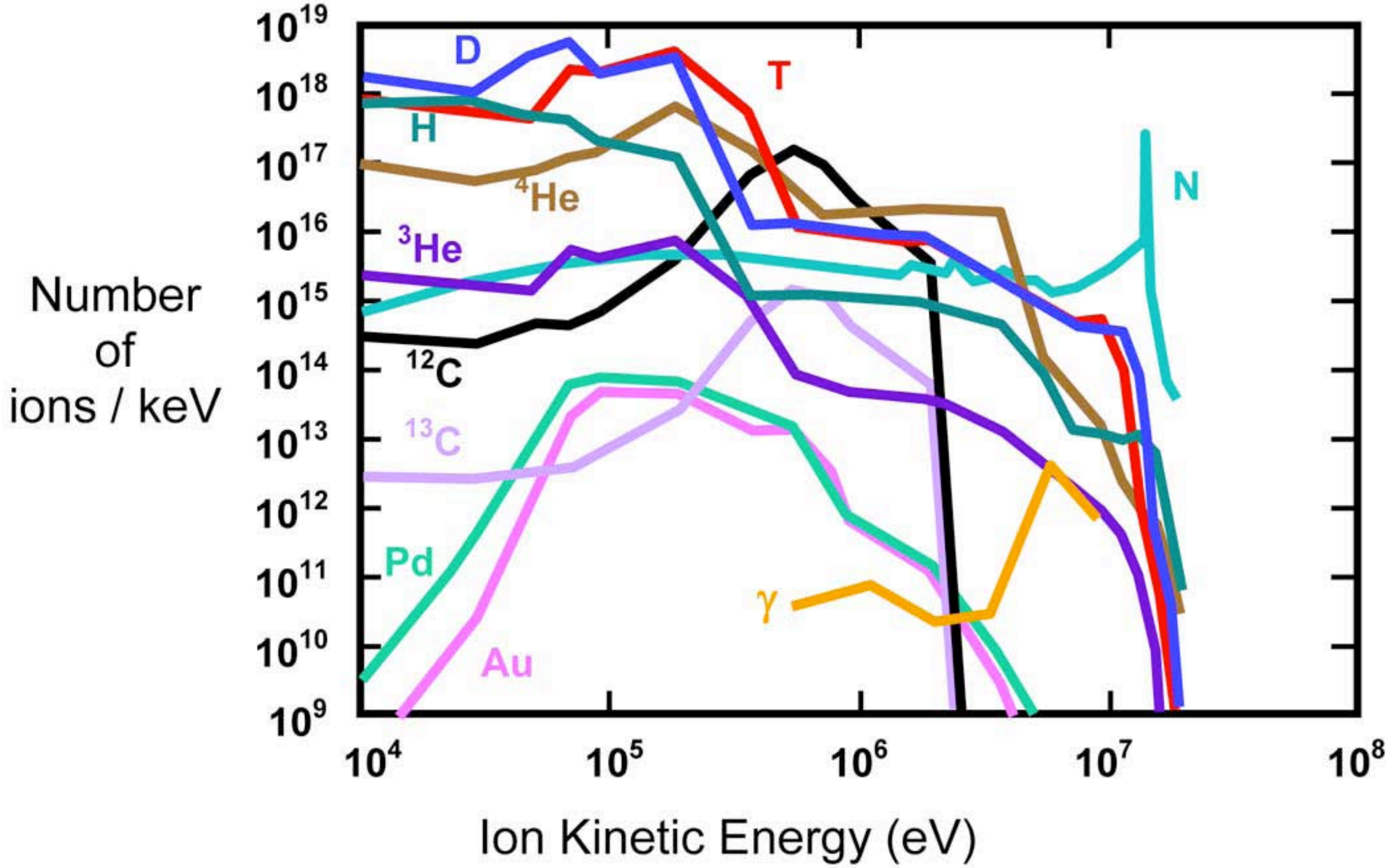
- **Cyclic thermomechanical stress**

- **Volumetric fusion neutron and gamma ray damage**
  - **Embrittlement, dimensional instability**



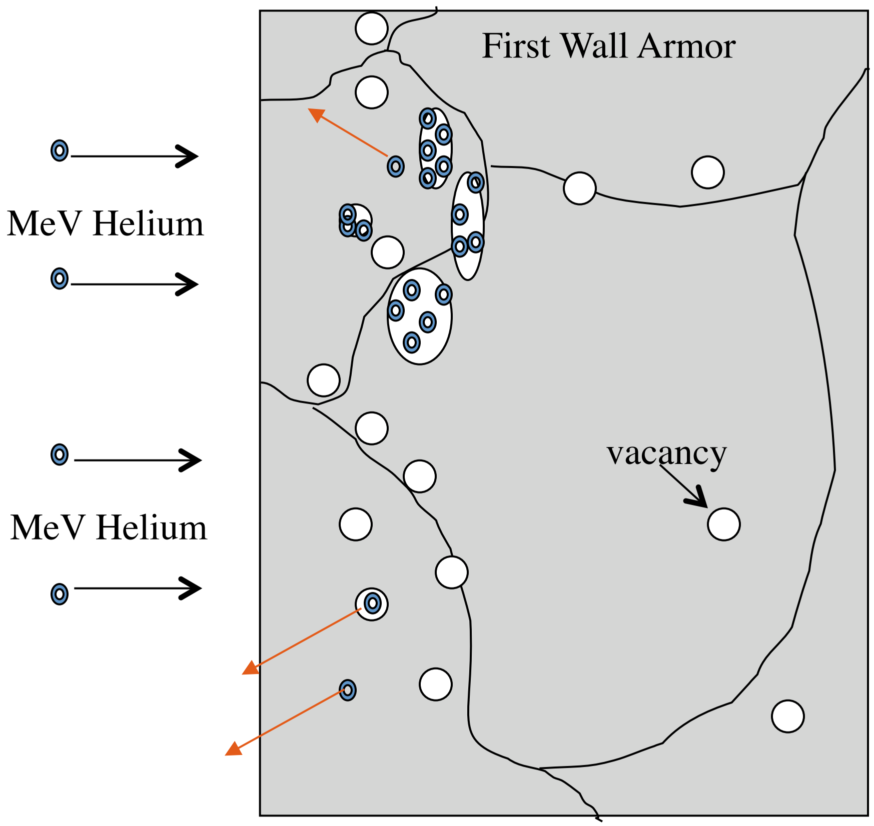
- **Nuclear heating (γ, n, ions)**

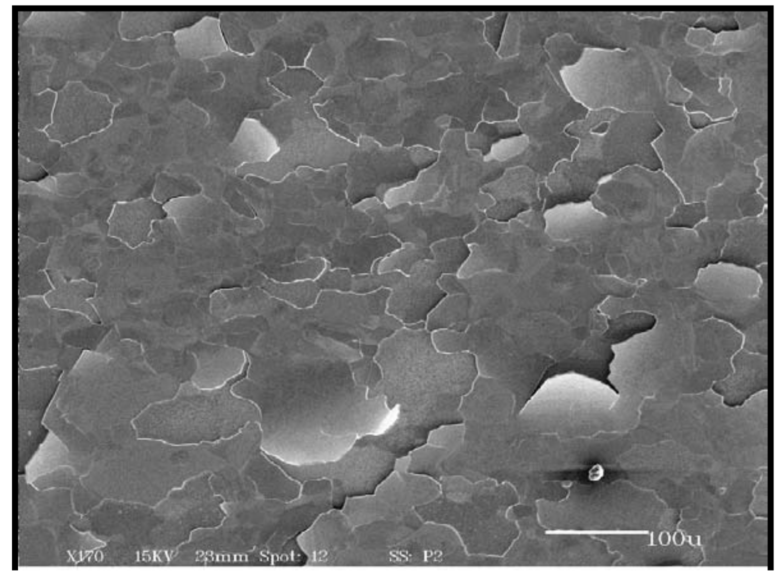
Summary of Threat Spectra for conventional direct drive



J. Sethian et al., IEEE Trans. Plasma Sci. 38 (2010) 690

Helium Blistering and Exfoliation

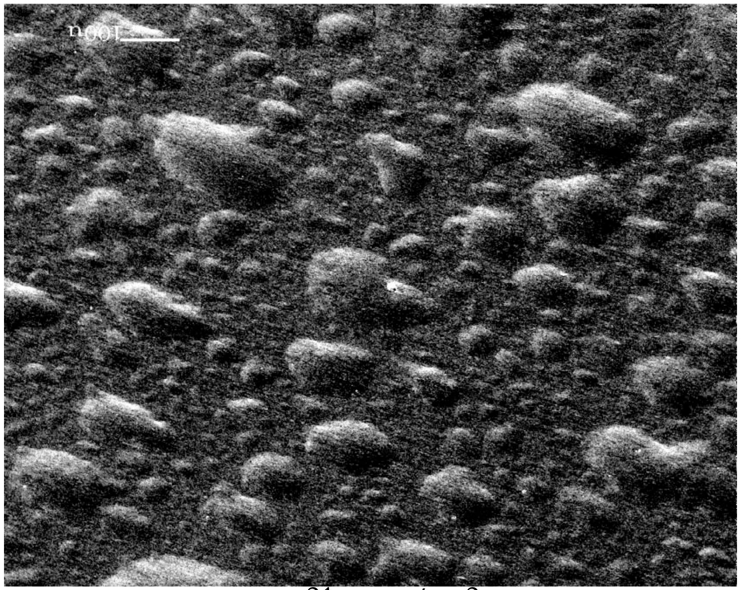




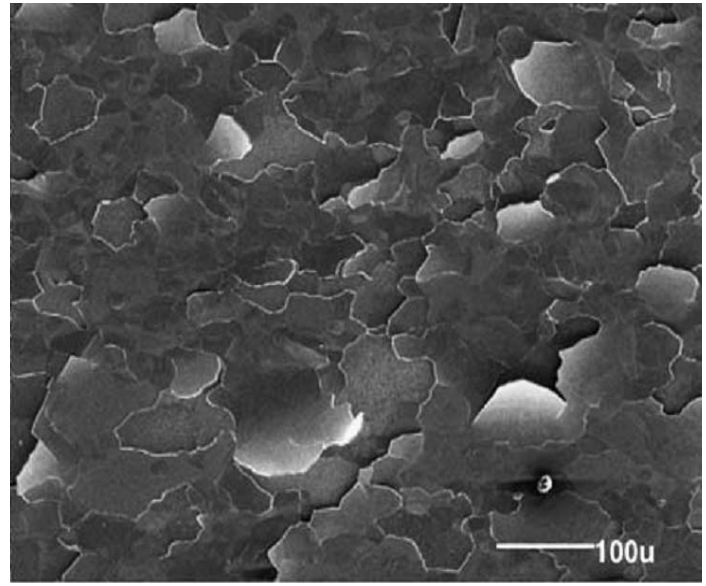
- **Growth of He bubbles beneath the surface causes blistering at ~3x10^{21}/m^2 and surface exfoliation at ~10^{22}/m^2**
  - ***weak dependence on material type***

- **For IFE power plant, unprotected first wall He fluence >>> 10^{22}/m^2**
  - ***One strategy to mitigate blistering and exfoliation is to enhance He migration to free surfaces***
    - ***High temperature operation and/or use of nanoscale FW architectures***

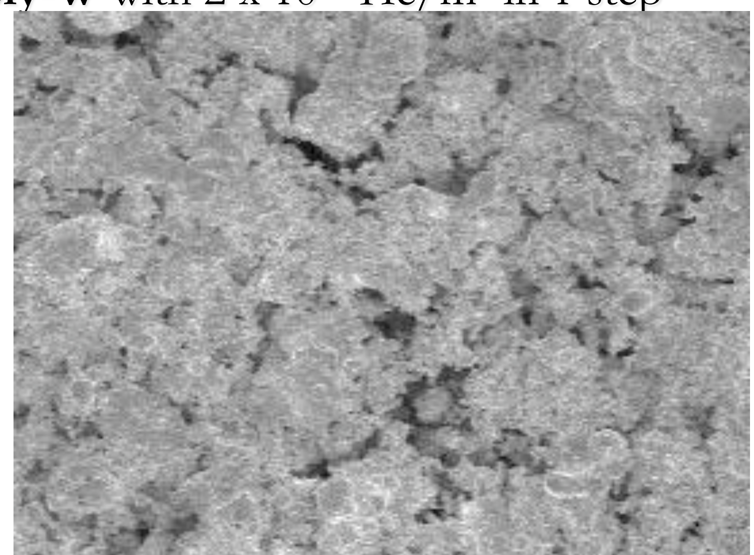
Exfoliation- Poly-W vs. Nano-Cavity W



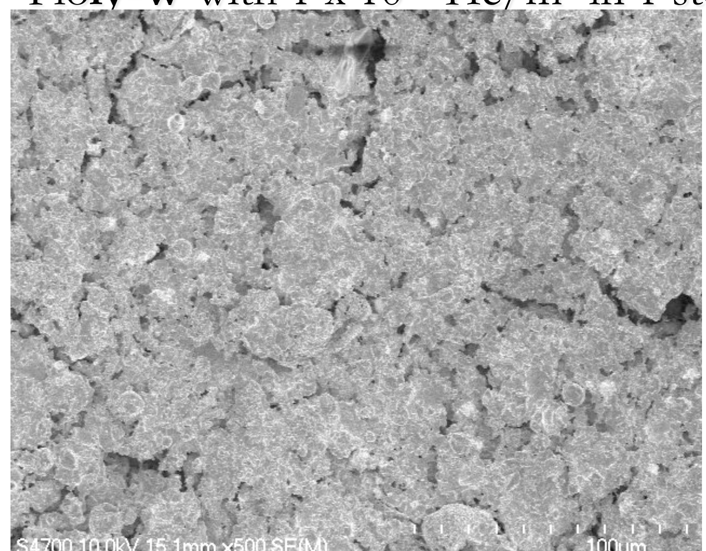
Poly-W with 2 x 10^{21} He/m^2 in 1 step



Ploly-W with 1 x 10^{22} He/m^2 in 1 step



nano-W unimplanted

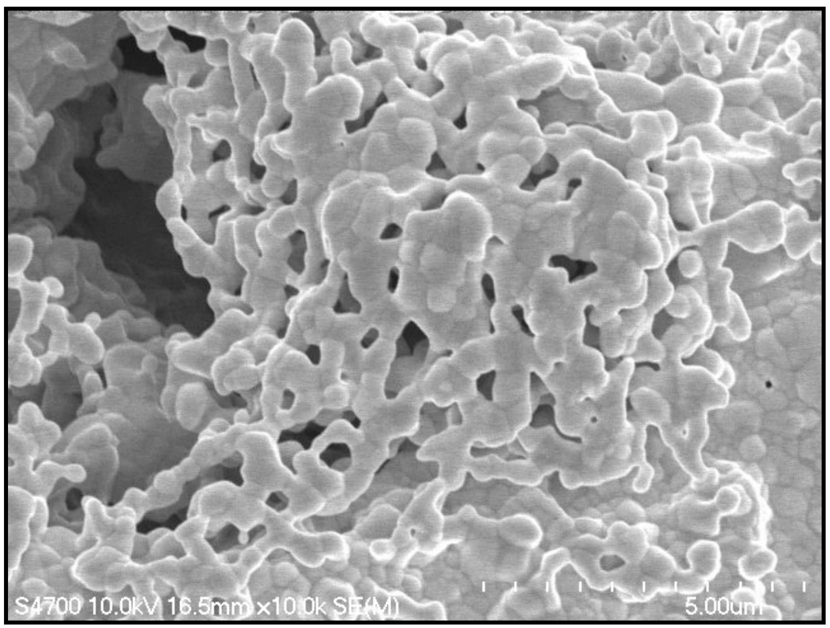


nano-W with 5e21 He/m^2 in 1 step

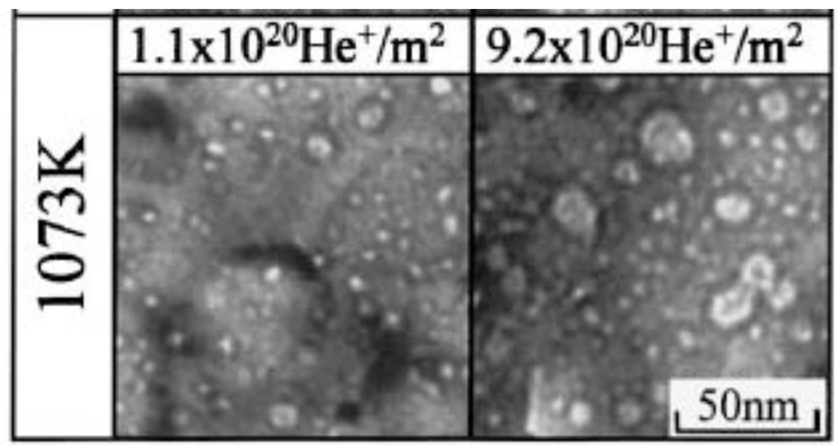
(>100 hrs)

Surface Exfoliation Results of Polycrystalline vs. Nano-porous W

- **Polycrystalline-W with showed blistering ($2x10^{21}$ He/m^2) and exfoliation ($1x10^{22}$ He/m^2)**
- **Nano-porous W with 5x 10^{21} He/m^2 did not show surface blistering or exfoliation**
- **Modeling suggests He retention should be dramatically reduced for size scales <50nm (UCSD)**

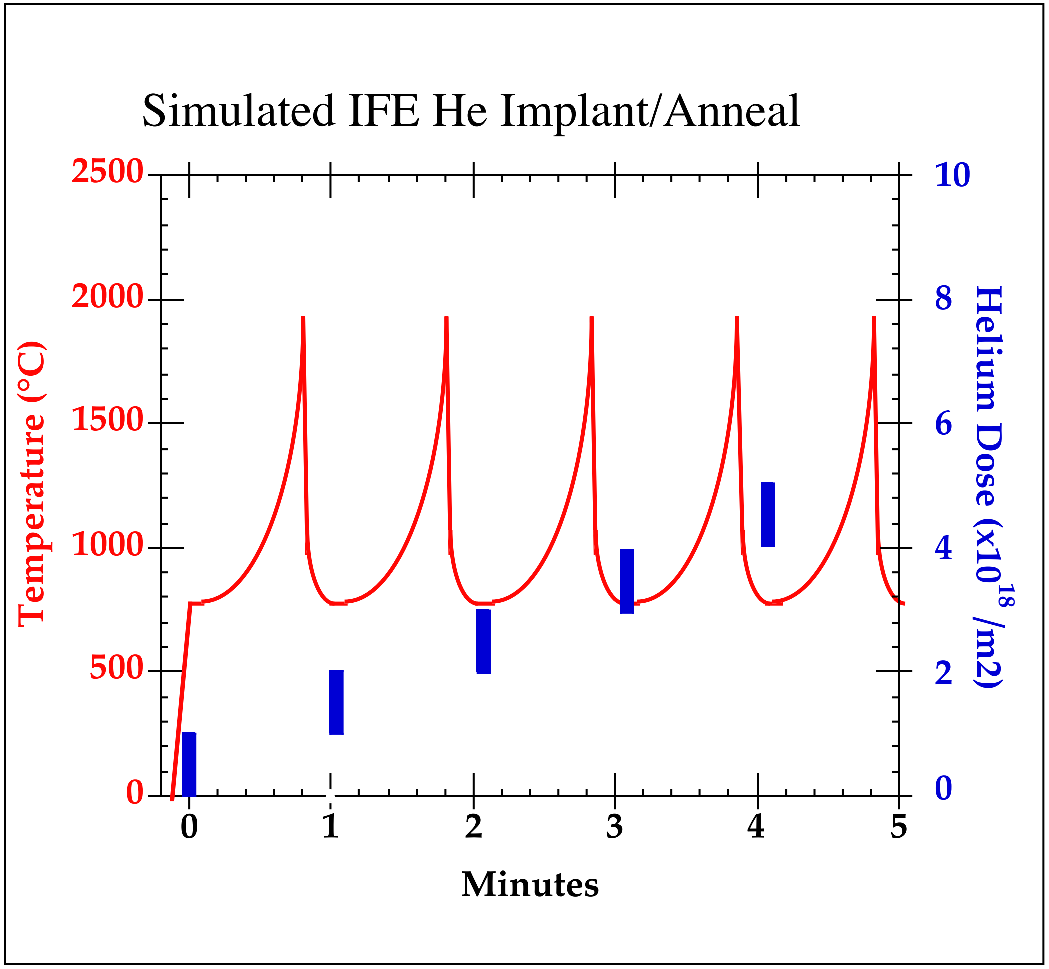


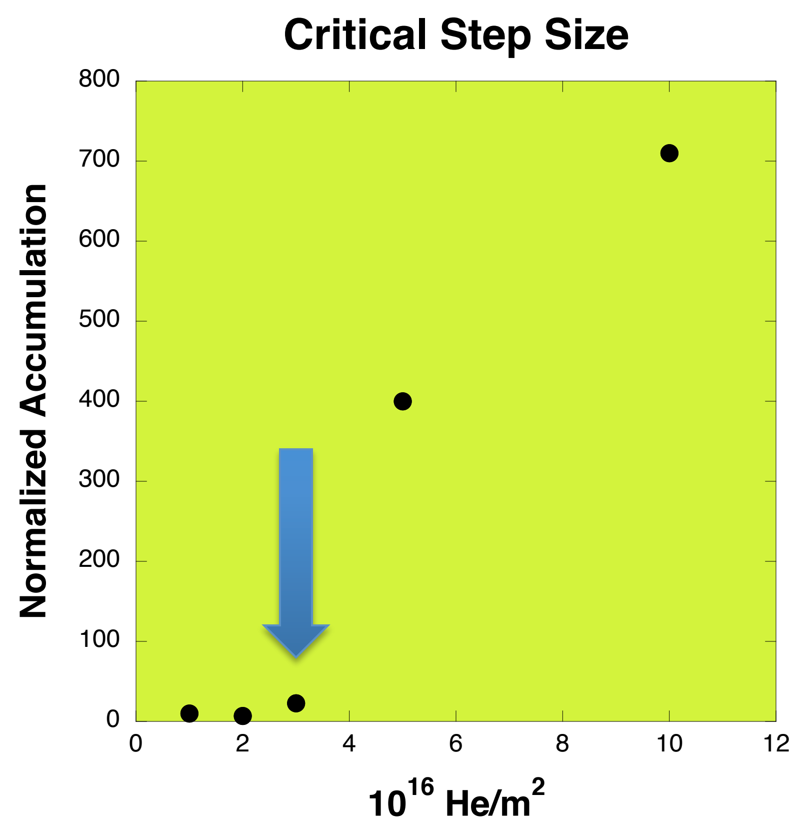
5000 nm



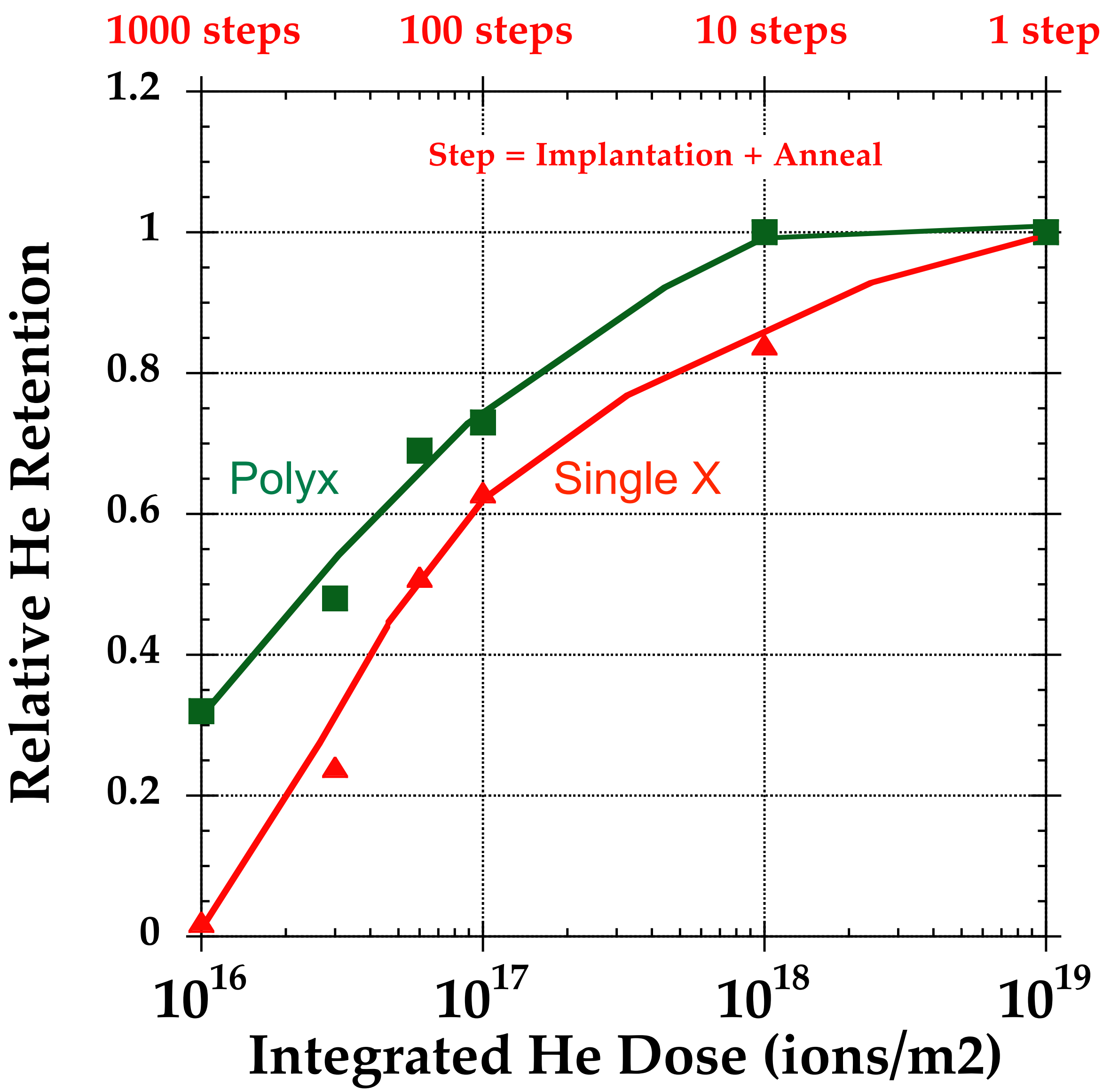
Iwakiri 2000

Minimum Dose for Helium Accumulation
Is IFE Below Threshold?

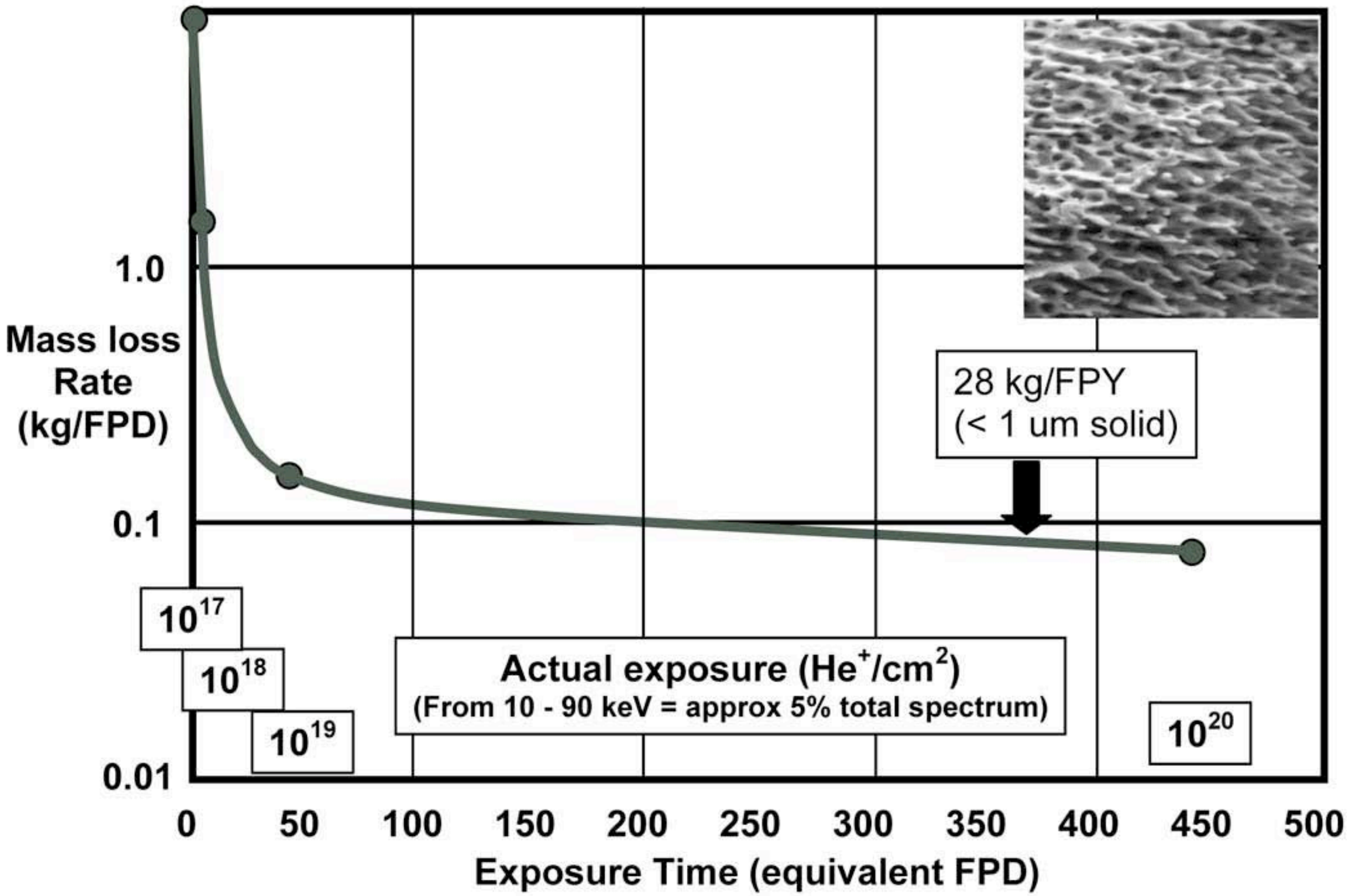




Retained He concentration is minimal if injected fluence prior to annealing is less than 3×10^{16} He/m^2 (for single crystal W)


1000 steps
100 steps
10 steps
1 step
Step = Implantation + Anneal
Polyx
Single X
1.2
1
0.8
0.6
0.4
0.2
0
Relative He Retention
10^{16}
10^{17}
10^{18}
10^{19}
Integrated He Dose (ions/m2)

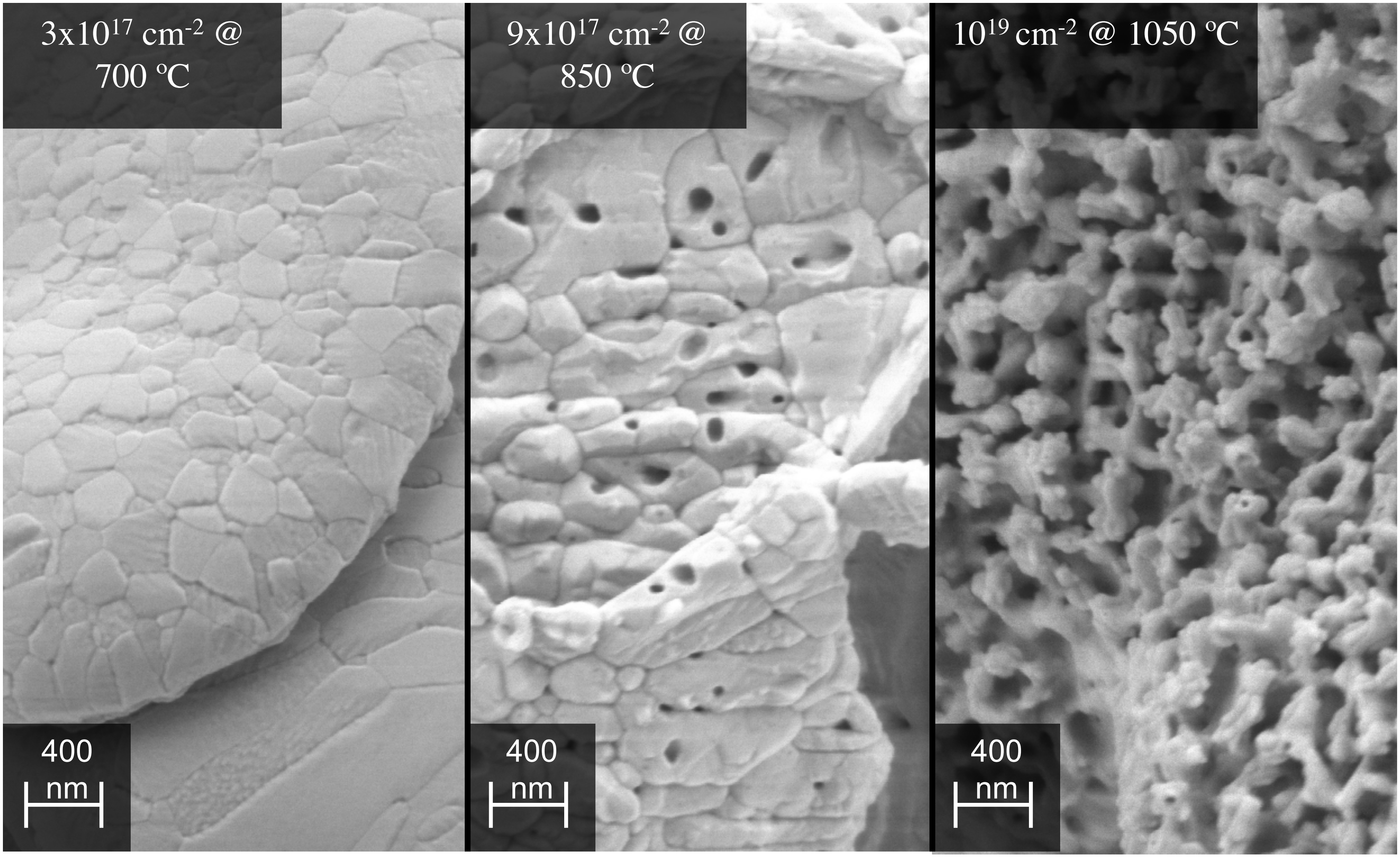
FW tungsten erosion due to He cavity exfoliation



J. Sethian et al., IEEE Trans. Plasma Sci. 38 (2010) 690

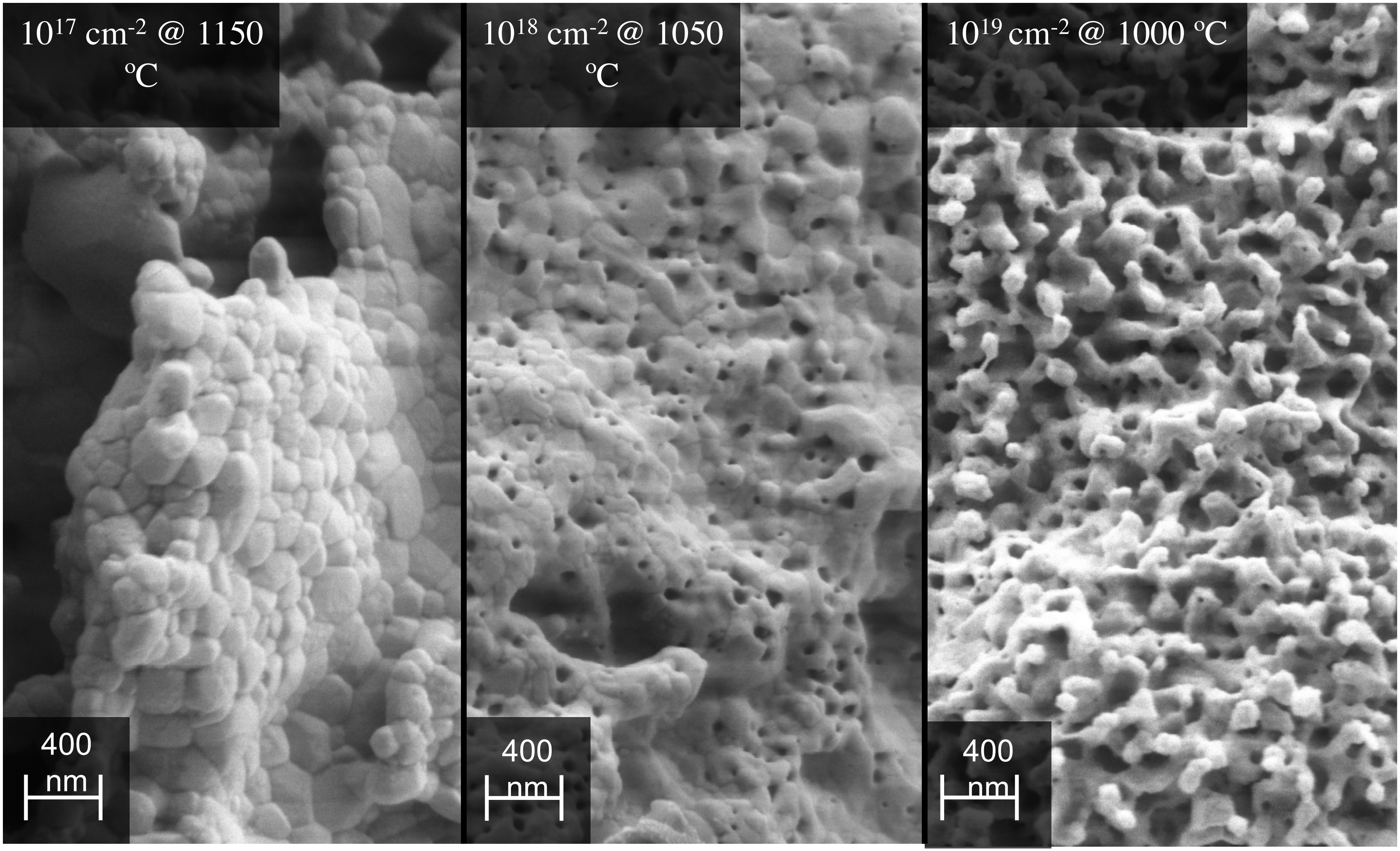
SEM Analysis Reveals Pore Formation Threshold In *Fine-Grained W* Is Near ~10^{18} He^+/cm^2

S. Zenobia et al. 2008



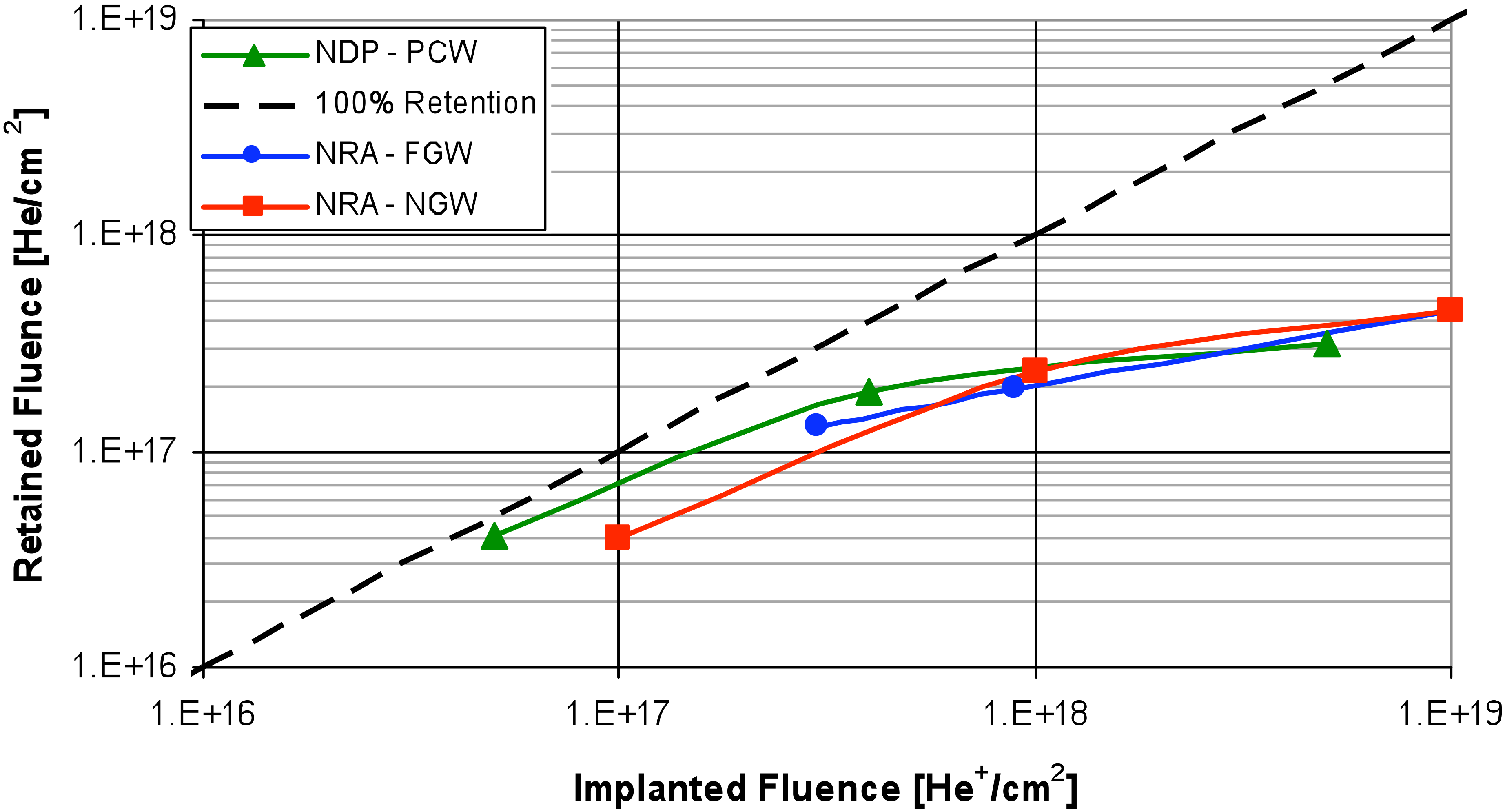
SEM Analysis Reveals Pore Formation Threshold In *Nano-Grain W* Is Near ~10^{18} He^+/cm^2

S. Zenobia et al. 2008



NRA* & NDP* Gives Retained Helium Fluence In *Poly-Crystal W, FGW* & *NGW* (700 – 1150 ºC)

S. Zenobia et al. 2008

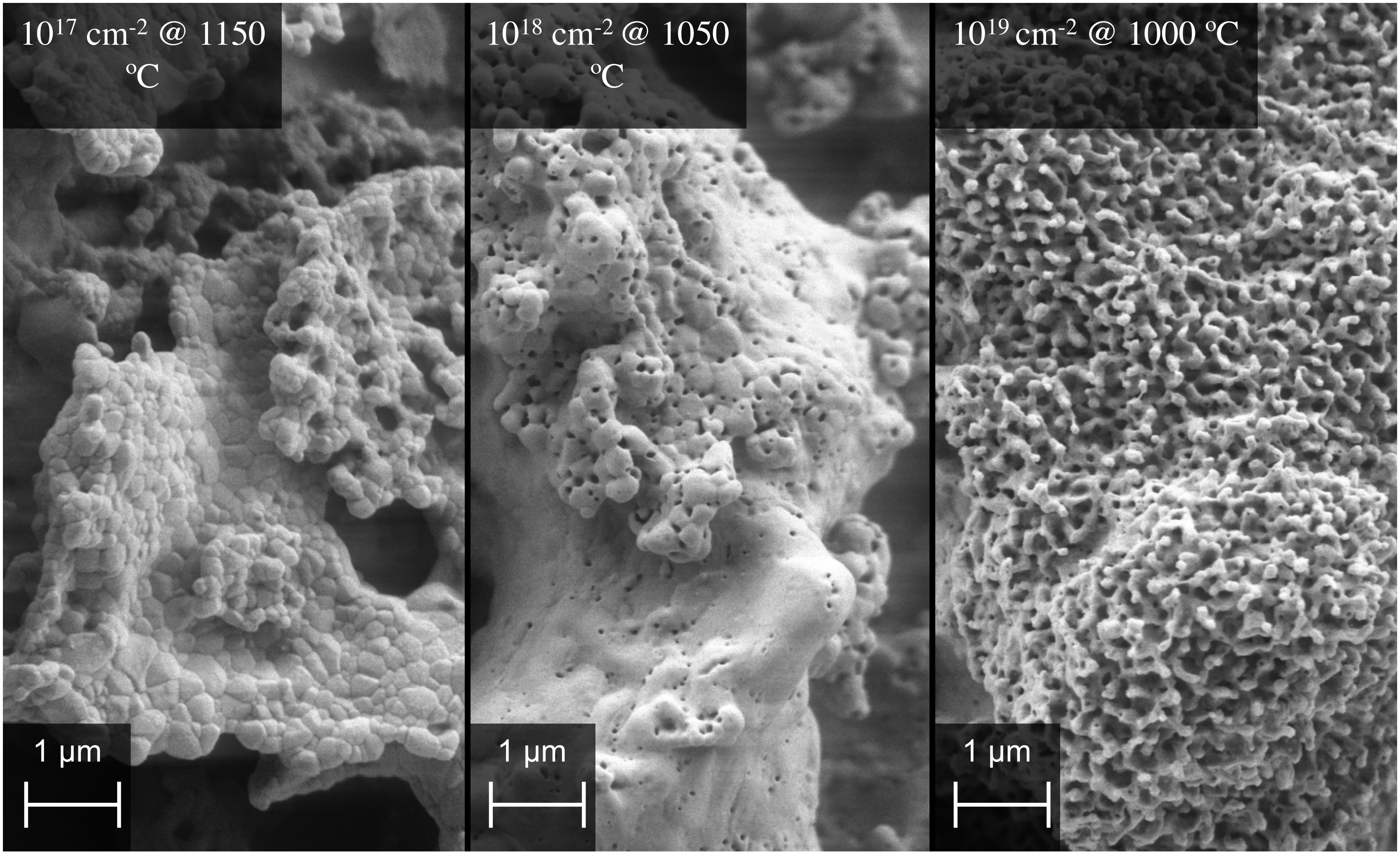


*NRA = Nuclear Reaction Analysis

*NDP = Neutron Depth Profiling

SEM Analysis Reveals Pore Formation Threshold In *Fine-Grained W* Is Near ~10^{18} He^+/cm^2

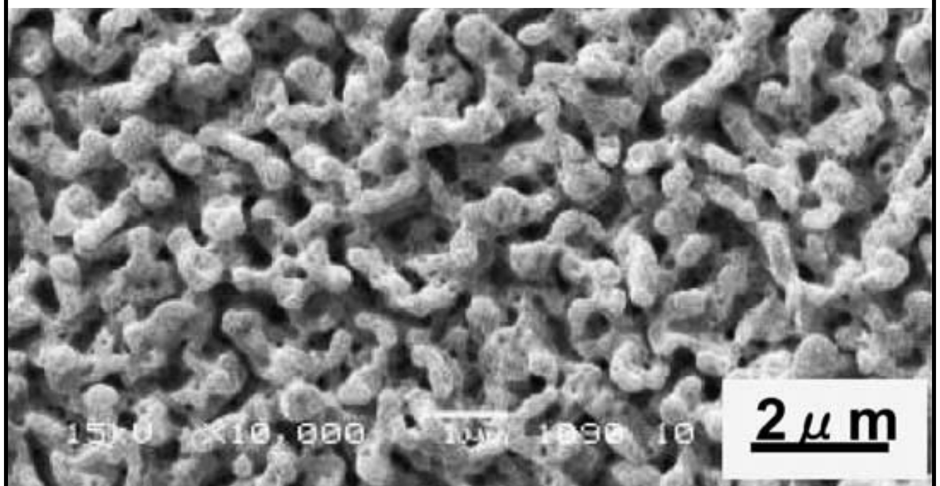
S. Zenobia et al. 2008

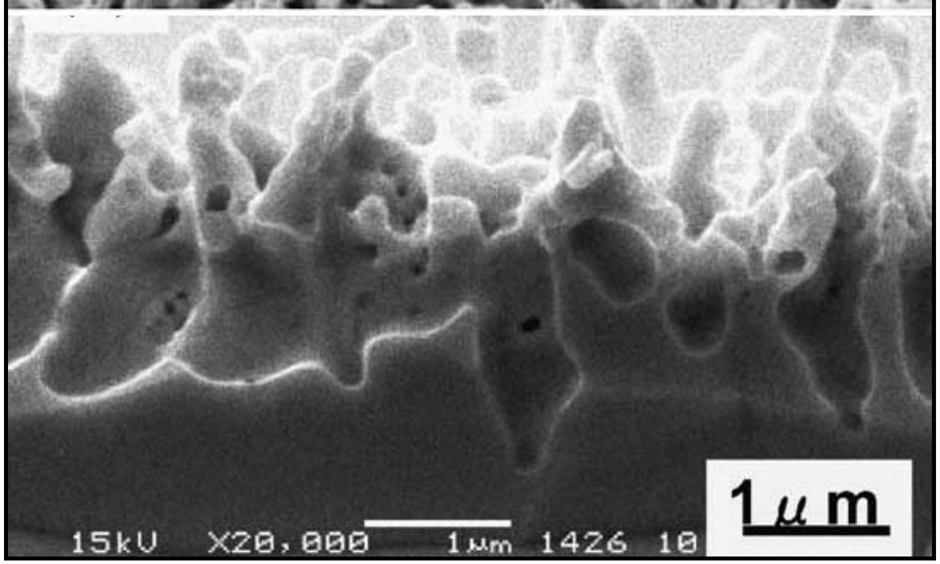


Coral Spires & Extended Porous Layers in FGW & NGW Consistent w/ Literature Findings

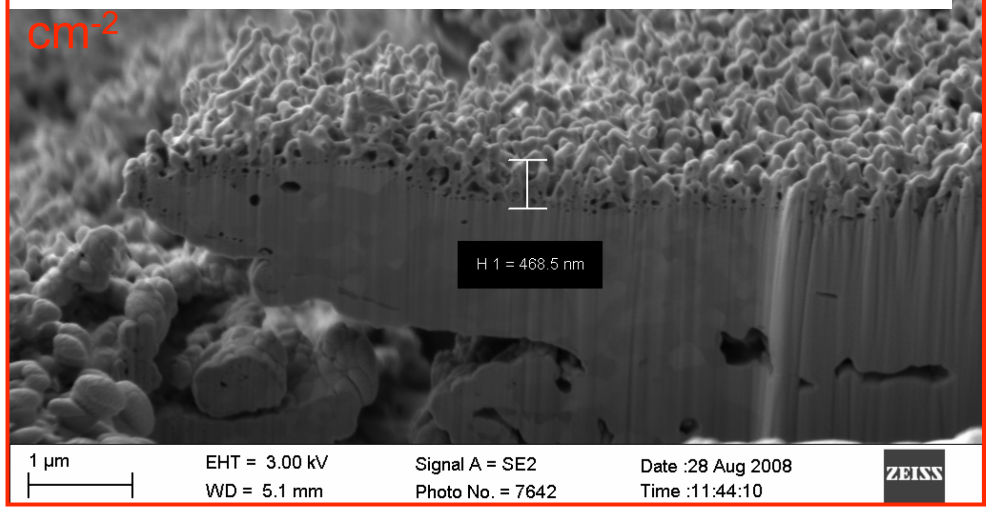
S. Zenobia et al. 2008

Tokunaga, et al. (2004) PCW – 15 keV He^+ @ 2600 ºC and 3.23×10^{19} cm^{-2}

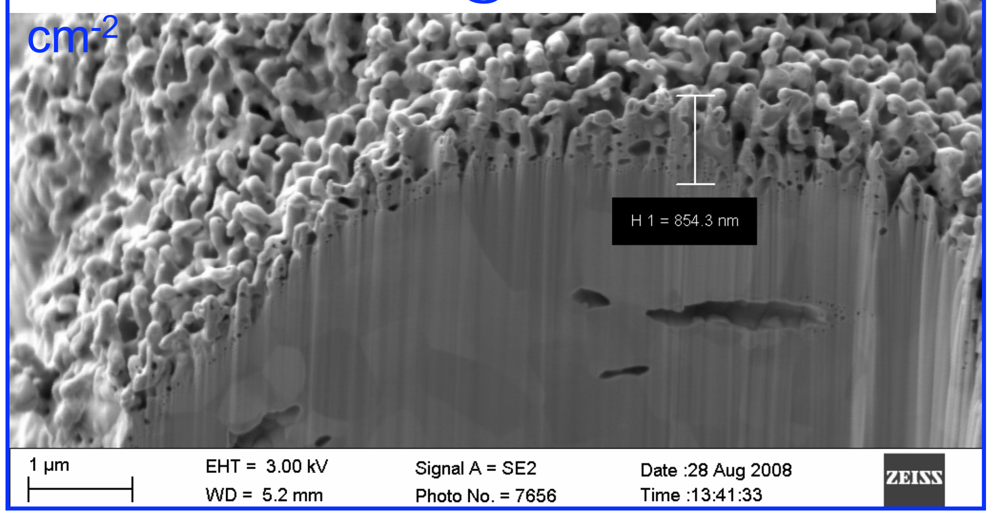




NGW – 30 keV He^+ @ 1010 ºC and 10^{19} cm^{-2}

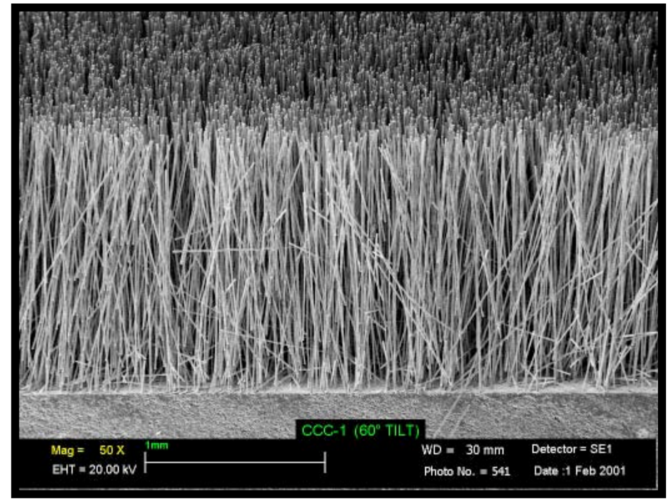


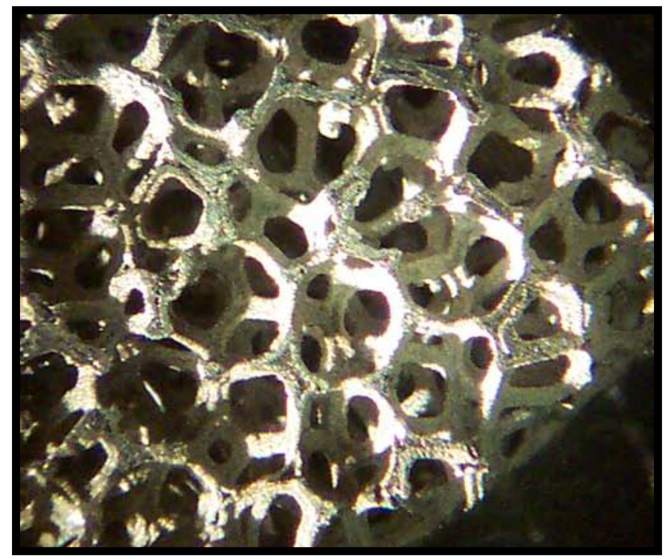
FGW – 30 keV He^+ @ 1050 ºC and 10^{19} cm^{-2}

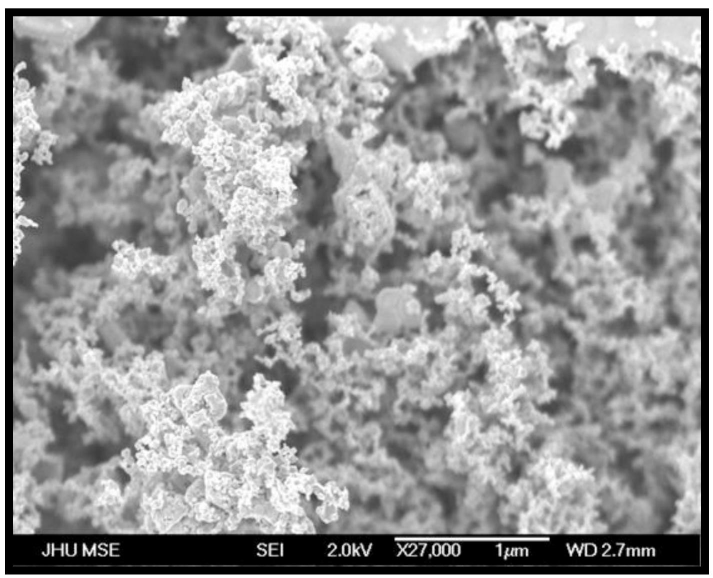


IFE Solid First Wall Materials Options

- **Graphite and refractory metals (e.g. tungsten)**
  - Reasonably high thermal conductivity at high temperature (~100-200 W/m-K)
  - Sublimation temperature of carbon ~ 3370°C
  - Melting point of tungsten ~3410°C
- **In addition, possibility of an engineered surface to provide better accommodation of high energy deposition is considered**
  - tungsten coated ferritic or SiC
  - carbon brush structures
  - tungsten foam or vacuum plasma sprayed nanoporous W

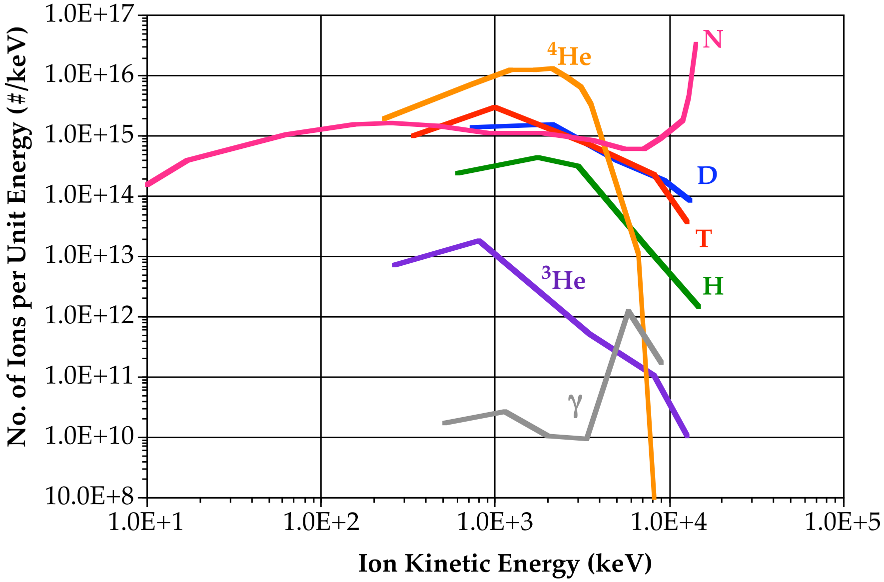




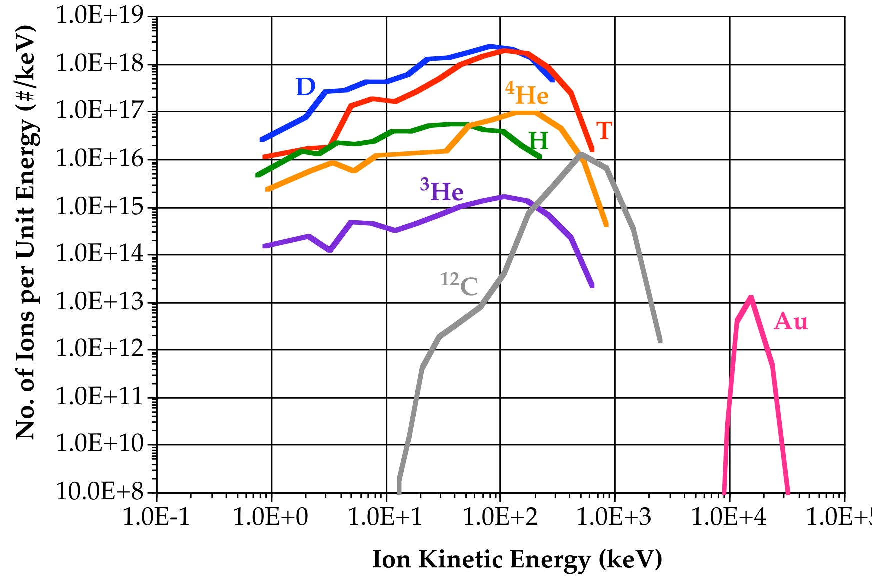


IFE First Wall Ion Spectra involves numerous ion species

Fast Ions



Debris Ions



- Potential synergistic near-surface ion damage effects due to sputtering, implanted ions, and displacement damage need further analysis
    - To date, only limited single-effects studies have been performed (e.g., He implantation)

Ion sputtering mechanisms are well known

Energy dependence of ion sputtering

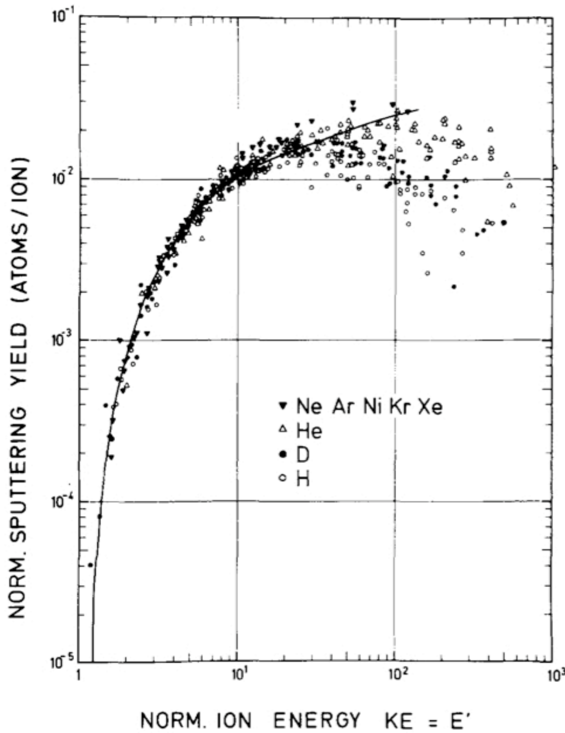
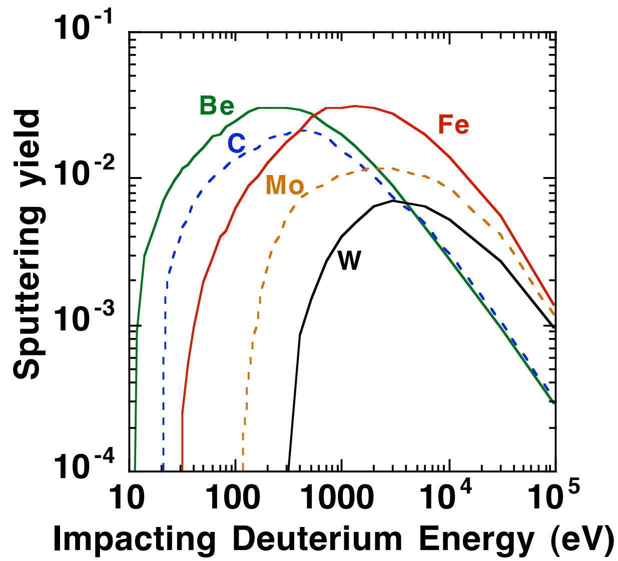
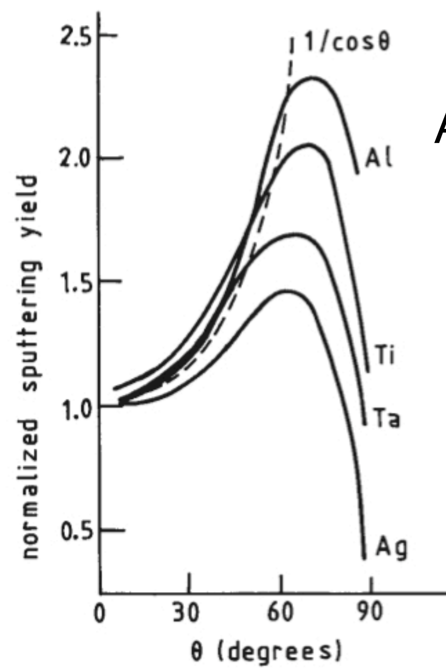


FIG. 1. Normalized yield data as a function of $E' = KE$. The solid line represents Eq. (4).

J. Bohdansky et al., JAP 51 (1980) 2861



Angular dependence of sputtering



Ar ions

Figure 1. The sputtering yield, normalized to unity for ion incidence normal to the surface, as a function of the polar angle of incidence θ with respect to the surface normal for 1.05 keV Ar^+ ion bombardment of polycrystalline Al, Ti, Ta and Ag. (Adapted from

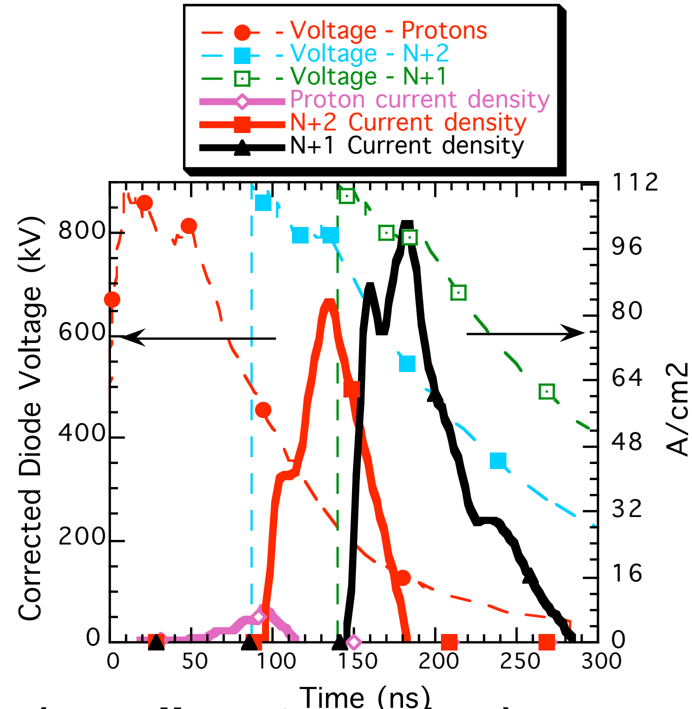
G. Carter, J.Phys. D 34 (2001) R1

Numerous surface ripple structures occur due to angle dependence

Pulsed Ion Effects

RHEPP-1 delivers pulses of intense ion irradiation with selectable species

T. Renk



Above: Marx tank with pulse-forming line
Right: treatment chamber

N++, N+ beam (small proton pulse)

Peak voltage = 1.7 MV N++Peak current density (total) ~145 A/cm^2

Total pulse width ~ 200 ns

< 10 J/cm2 /pulse

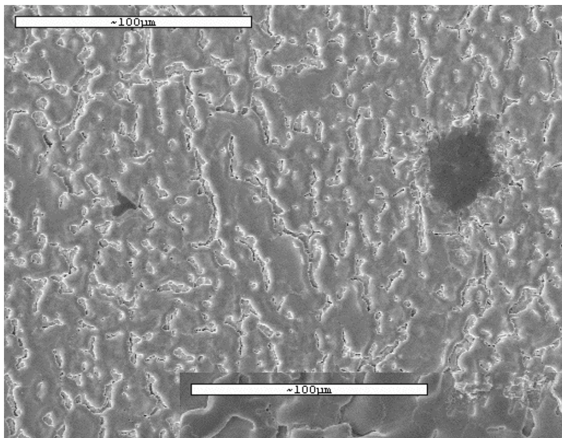
Ion range (TRIM):
N+ 0.9 μm, N++ 1.2 μm

Sandia National Laboratories

Pulsed Ion Effects - Tungsten

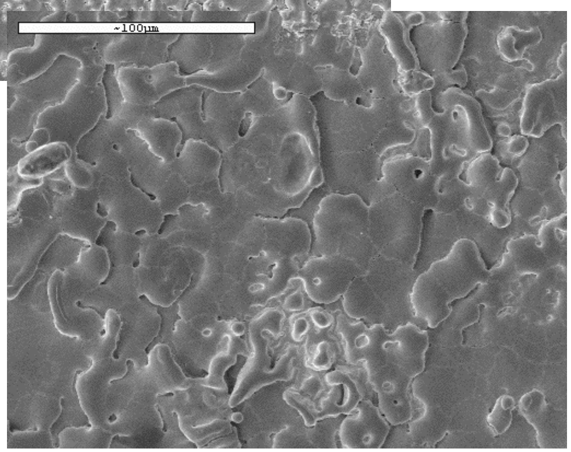
PowderMet W develops high relief and deep cracking that evolves over hundreds of pulses

T. Renk

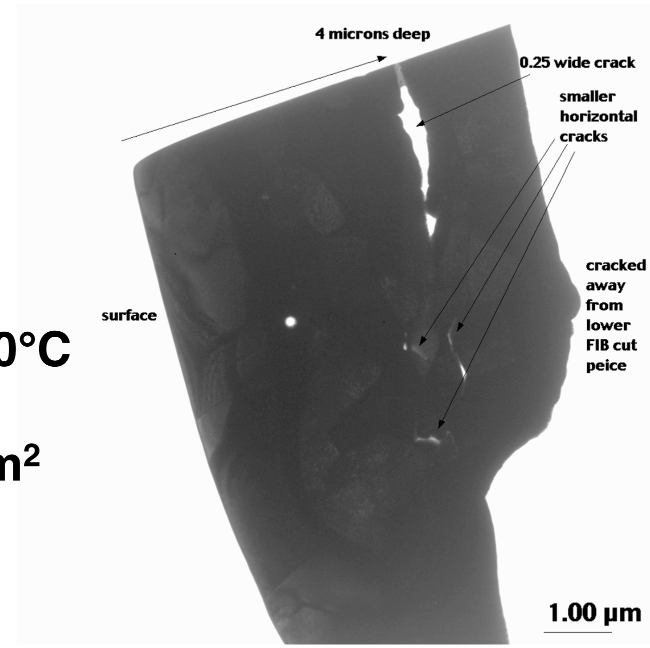


SEM, W
250 pulses @
2.5 J/cm^2 MAP N
R_a < 0.5 μm

W heated to 600°C
Melt: 2.3 J/cm^2
Ablation: 6 J/cm^2



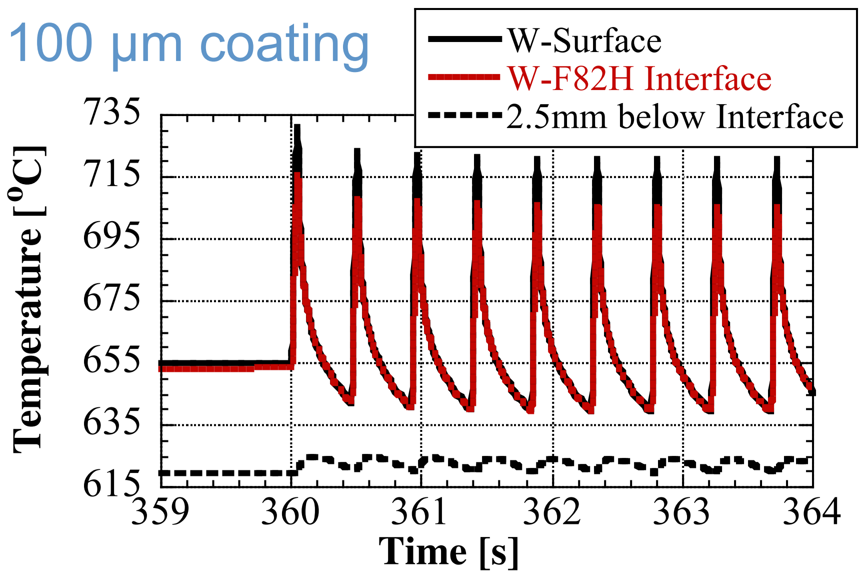
SEM, W
1000 pulses @
2.5 J/cm^2 MAP N
R_a ~ 4 - 5 μm
P - V ~ 35 μm



FIB/XTEM of 1000-pulse W, showing deep cracks evidently caused by fatigue, no surface melt

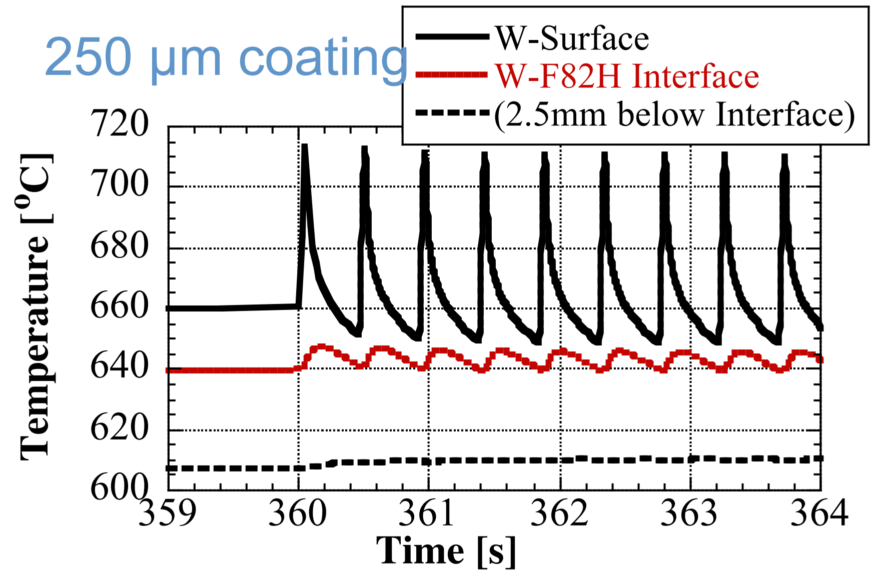
Calculated temperature profiles for 100 & 250 μm thickness W coatings on ferritic steel

100 μm coating



ΔT = 60ºC

250 μm coating



ΔT = 10ºC

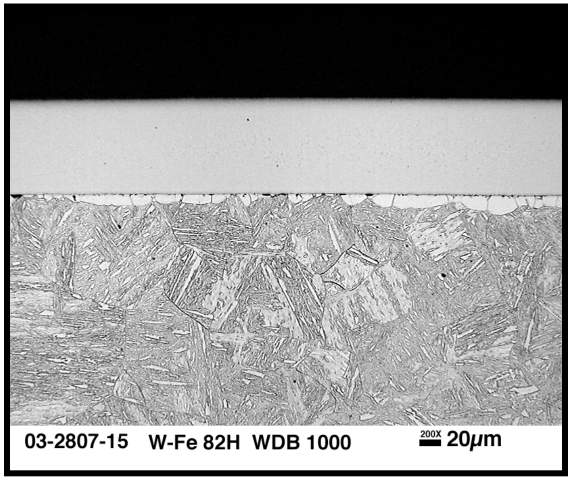
Variation of IR pulse conditions and coating thickness allows for control of the thermo-mechanical condition at the W/steel interface.

Fabrication Process : W/F82H ferritic steel

- Two processes for bonding low activation ferritic to tungsten are being studied: Diffusion Bonding and Plasma Spray:

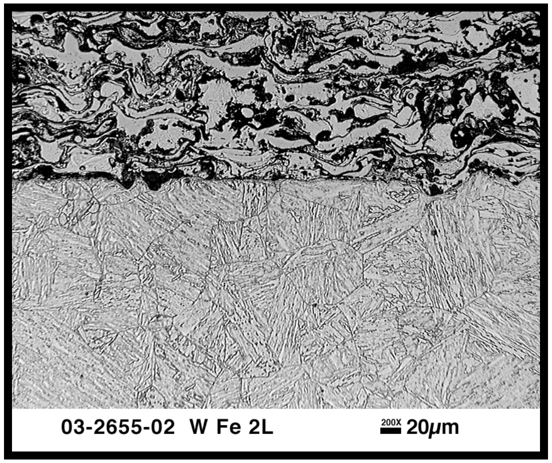
I. Diffusion-bonded tungsten foil (0.1 mm thickness)

- Allows the best possible mechanical properties and surface integrity
- Tungsten will remain in the un-recrystallized state
- No porosity

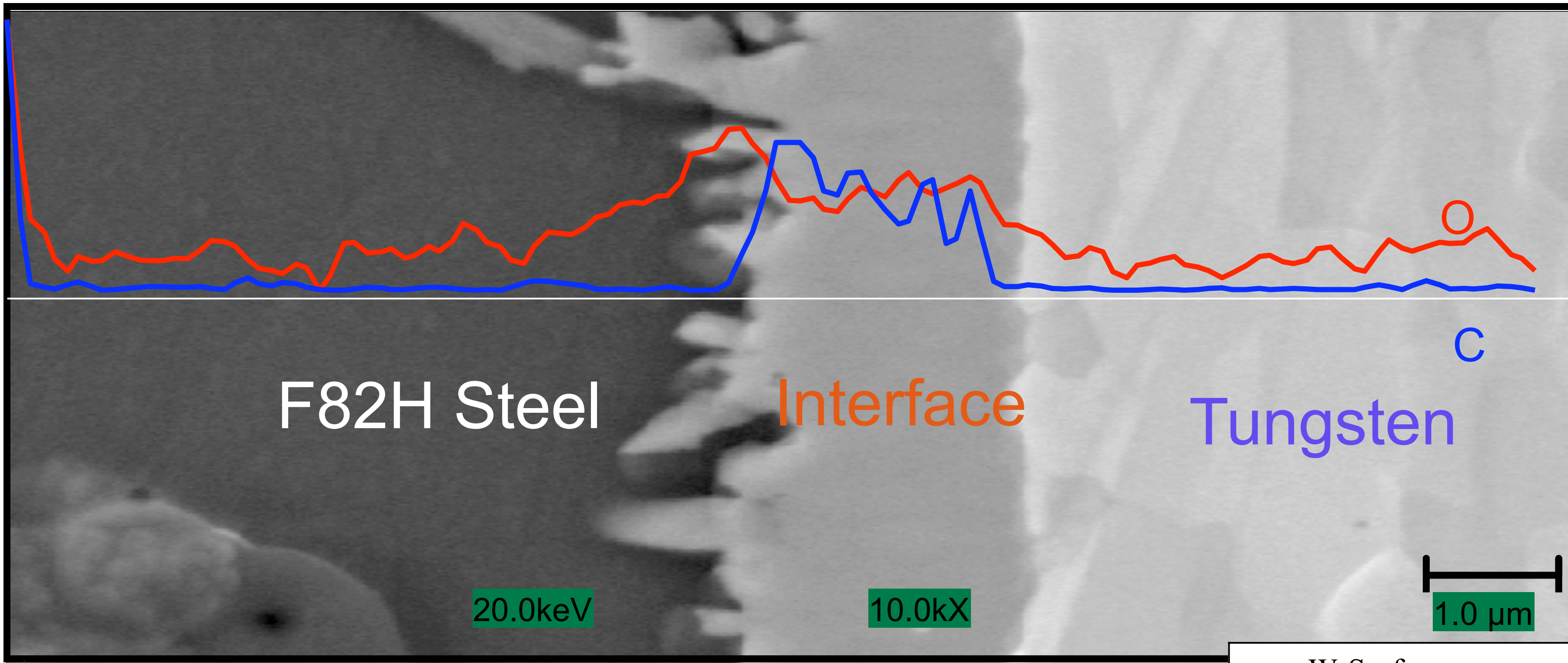


II. Plasma-sprayed tungsten transition coatings

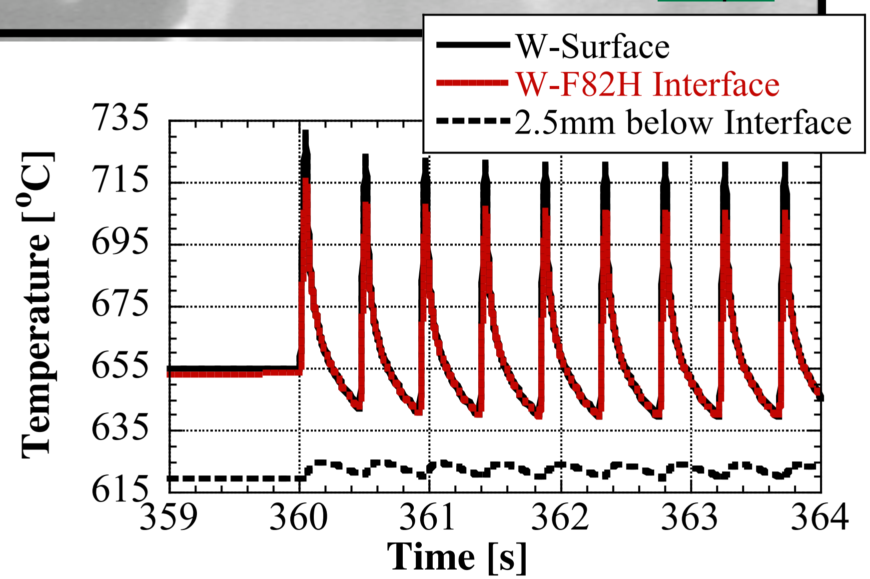
- Allows for a graded transition structure by blending tungsten and steel powders in an intermediate layer to accommodate CTE mismatch.
- Resulting microstructure is recrystallized but small grain size
- May be spayed in vacuum or under a cover gas (wall repair)
- Variable porosity



Development of VPS W/steel

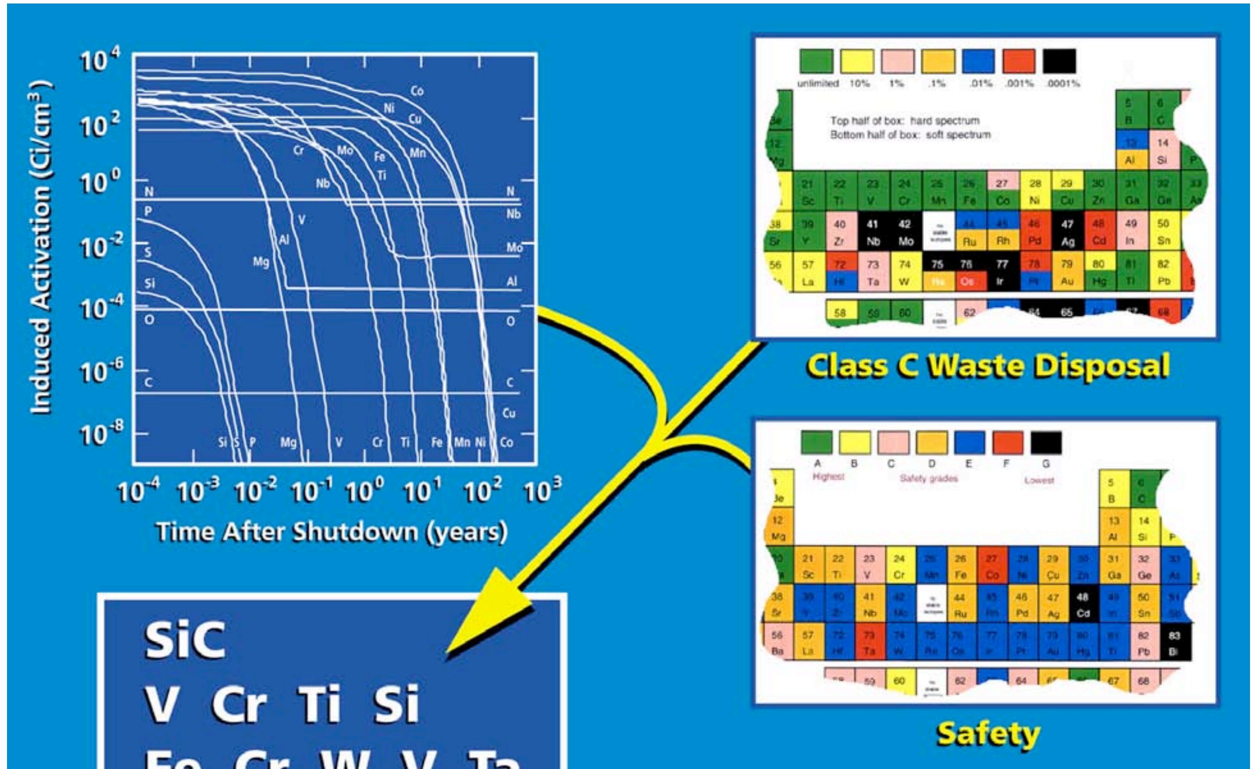


- VPS W/steel has withstood 10,000 thermal cycles.
- Long term aging of bonded materials (> 10,000 h)



The overarching goals for fusion power systems narrow the choices and place significant demands for performance of structural materials

- **Safety**
- **Minimization of Rad. Waste**
- **Economically Competitive**
  - **High thermal efficiency (high temperature capability)**
  - **Acceptable lifetime**
  - **Reliability**

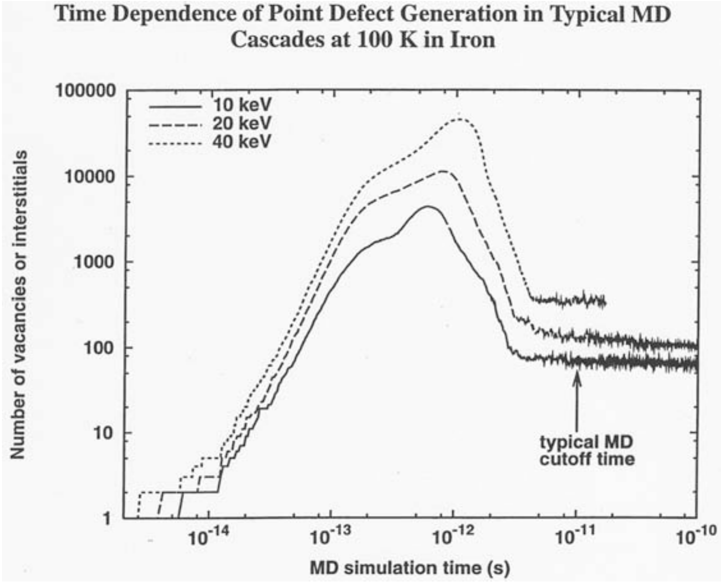


Based on
Piet et al., Fusion Tech. 17 (1990) 636

Fe-9Cr steels: builds upon 9Cr-1Mo industrial experience and materials database (9-12 Cr ODS steels are a higher temperature future option)
V-4Cr-4Ti: Higher temperature capability, targeted for Li self-cooled blanket designs
SiC/SiC: High risk, high performance option (early in its development path)
W alloys: High performance option for PFCs (early in its development path)

Advanced nuclear energy systems impose harsh radiation damage conditions on structural materials

- 1 displacement per atom (dpa) corresponds to stable displacement from their lattice site of all atoms in the material during irradiation near absolute zero (no thermally-activated point defect diffusion)
  - Initial number of atoms knocked off their lattice site during fast reactor neutron irradiation is ~100 times the dpa value
    - Most of these originally displaced atoms hop onto another lattice site during "thermal spike" phase of the displacement cascade (~1 ps)



R.E. Stoller

- Requirement for structural materials in advanced nuclear energy systems (~100 dpa exposure):
  - ~99.95% of "stable" displacement damage must recombine
    - ~99.9995% of initially dislodged atoms must recombine
- Two general strategies for radiation resistance can be envisioned:
  - Noncrystalline materials
  - Materials with a high density of nanoscale recombination centers

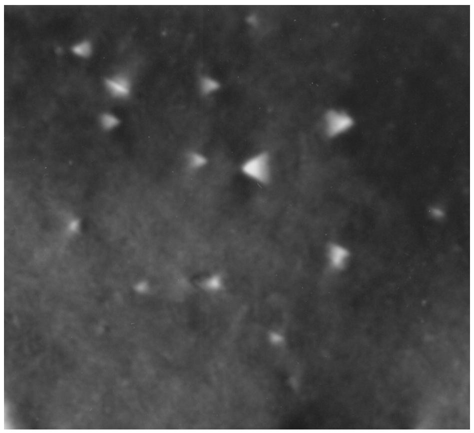
after S.J. Zinkle, Phys. Plasmas 12 (2005) 058101

Multidisciplinary Fusion Materials Research has Demonstrated the Equivalency of Displacement Damage Produced by Fission and Fusion Neutrons

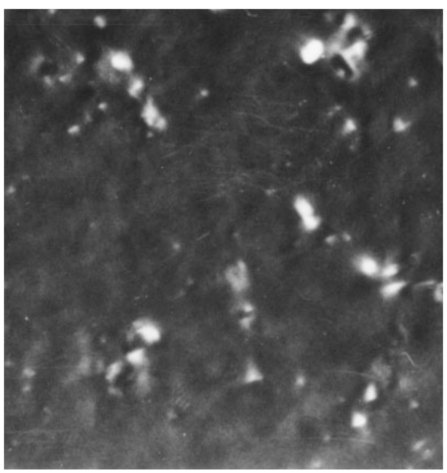
Similar defect clusters produced by fission and fusion neutrons as observed by TEM

Fission

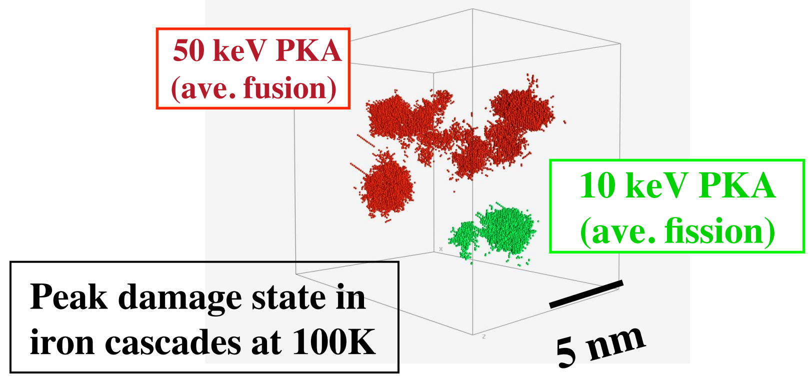
(0.1 - 3 MeV)



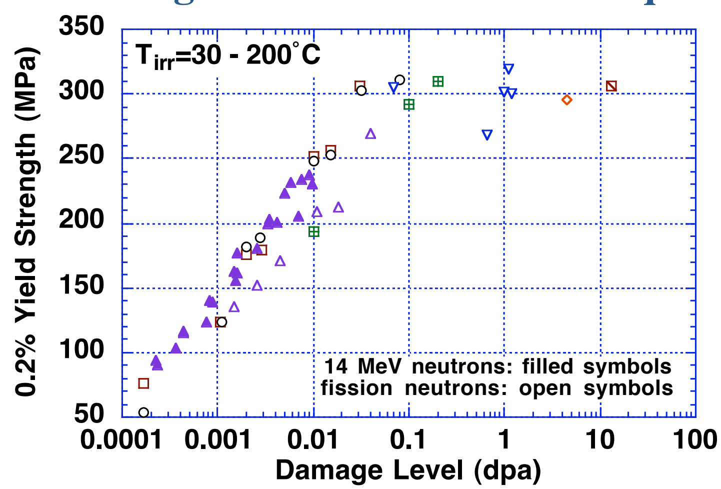
Fusion
(14 MeV)



MD computer simulations predict comparable subcascades and defect production for fission, fusion



Similar hardening behavior confirms the equivalency



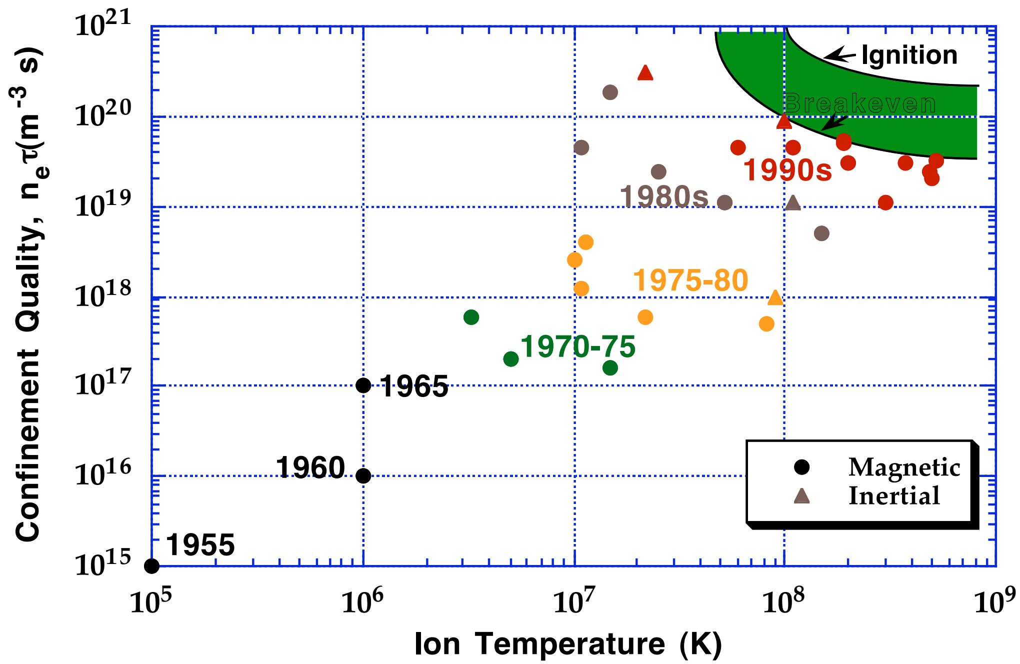
A critical unanswered question is the effect of higher transmutant H and He production in the fusion spectrum

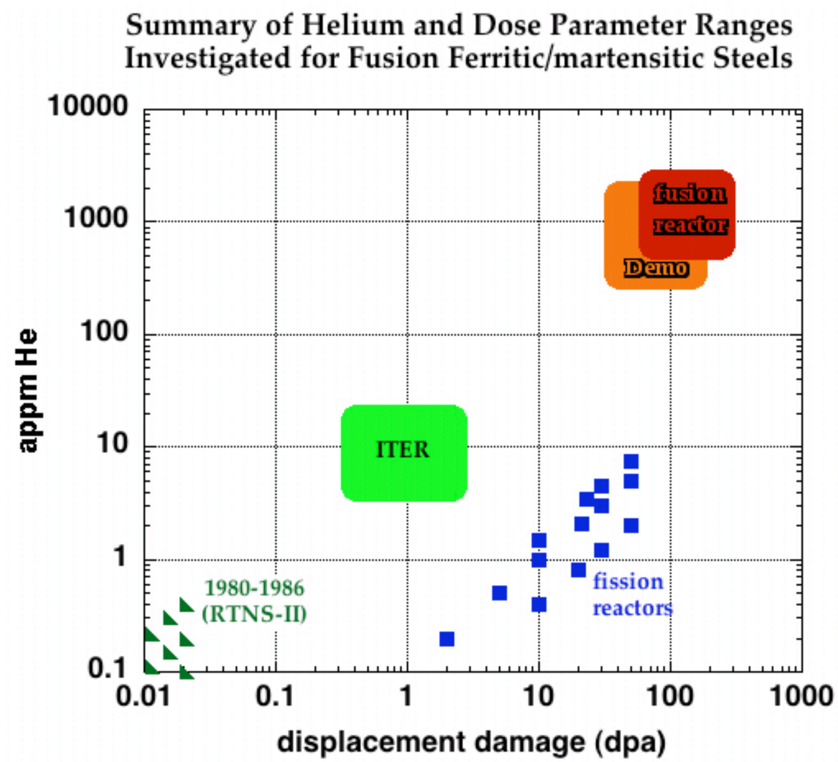
Zinkle et al., J. Nucl. Mater. 307-311 (2002) 31

Fusion materials research must rely heavily on modeling due to inaccessibility of fusion-relevant operating regime

- **Extrapolation from currently available parameter space to fusion reactor regime is much larger for fusion materials than for plasma physics issues**
- **An intense neutron source such as IFMIF will be needed to develop and qualify fusion structural materials**

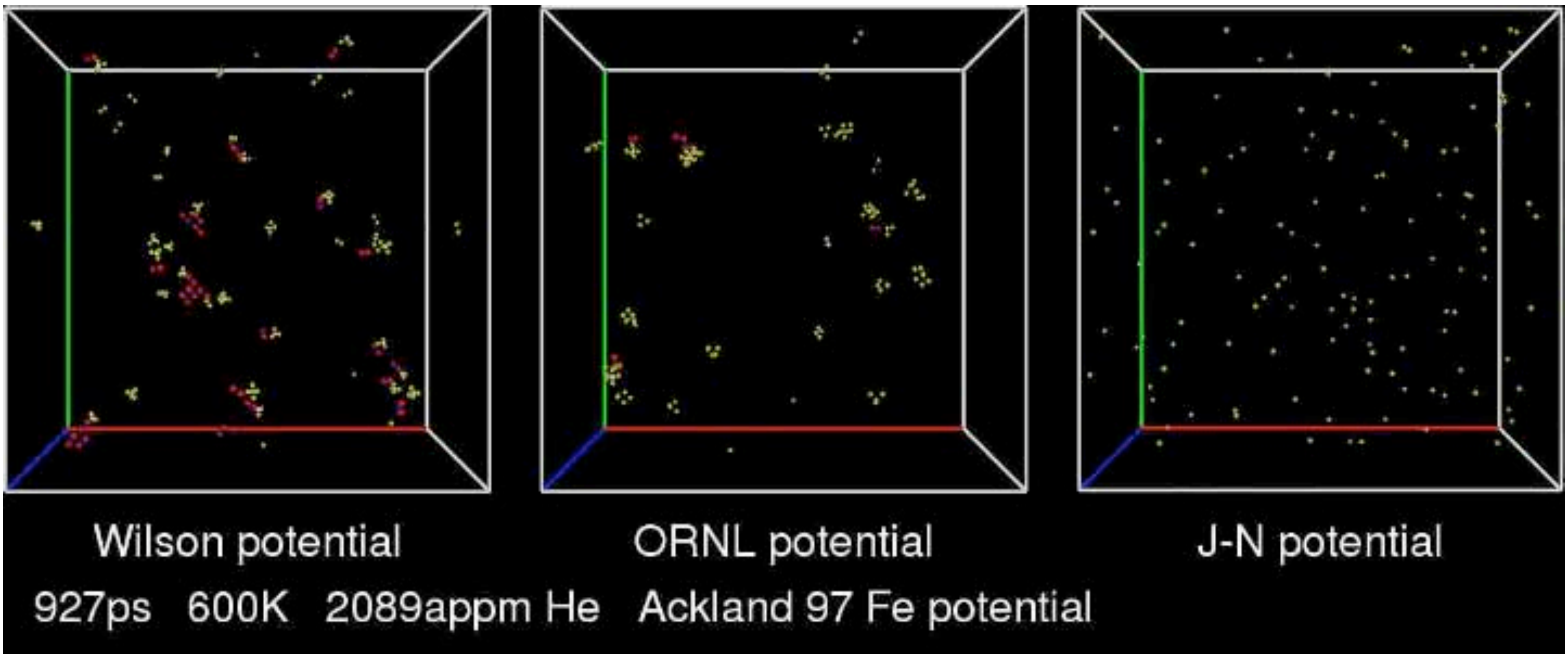
Plasma physics (IFE & MFE) experimental achievements





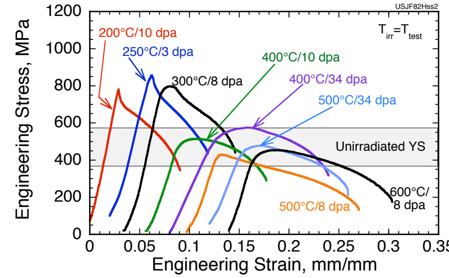
Investigation of He diffusion and clustering behavior

- Three different He-Fe potentials predict radically different behavior
  - Wilson potential creates FP (SIA emission) more quickly than ORNL potential, higher He binding energy.
  - Juslin-Nordlund potential does not form He clusters or create FP above ~400°C.
- Accurate knowledge of fundamental diffusion and clustering is essential to provide parameters for mesoscale microstructural models

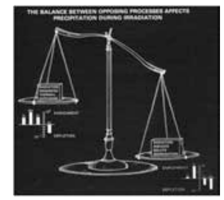


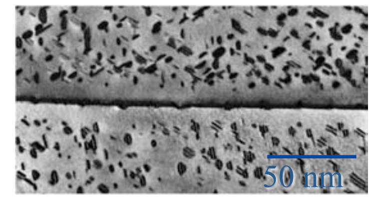
Radiation Damage can Produce Large Changes in Structural Materials

- **Radiation hardening and embrittlement (<0.4 T_M, >0.1 dpa)**



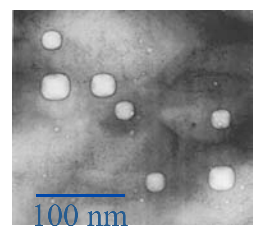
- **Phase instabilities from radiation-induced precipitation (0.3-0.6 T_M, >10 dpa)**





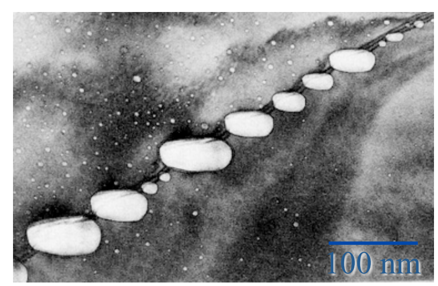
- **Irradiation creep (<0.45 T_M, >10 dpa)**

- **Volumetric swelling from void formation (0.3-0.6 T_M, >10 dpa)**



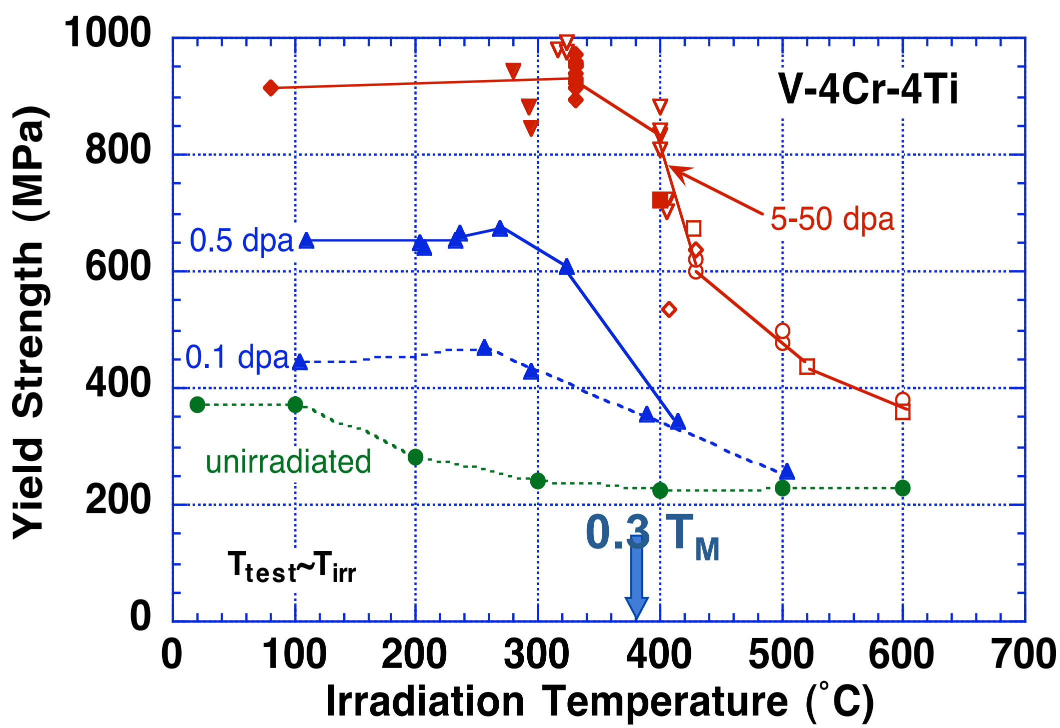
- **High temperature He embrittlement (>0.5 T_M, >10 dpa)**

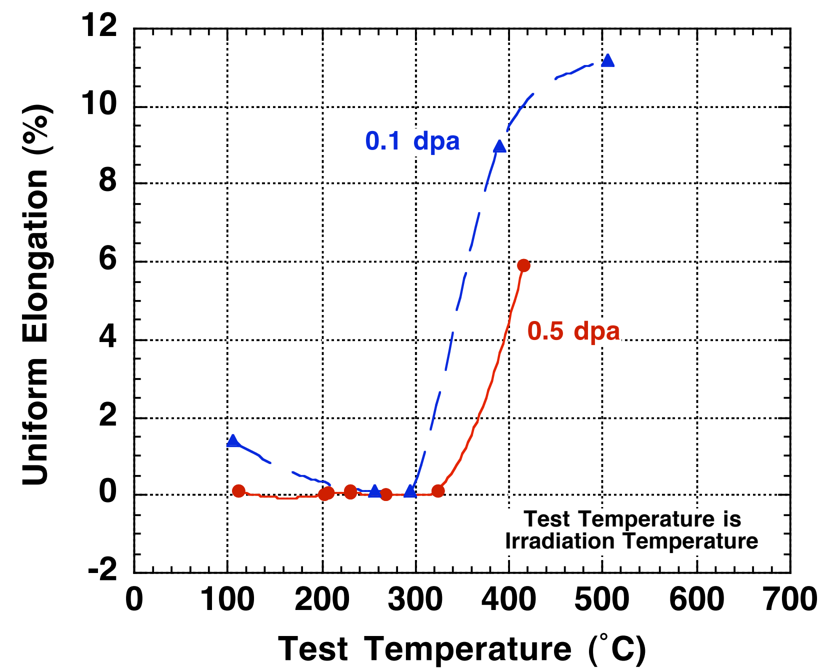
after S.J. Zinkle, Phys. Plasmas 12 (2005) 058101



Radiation hardening in V-4Cr-4Ti

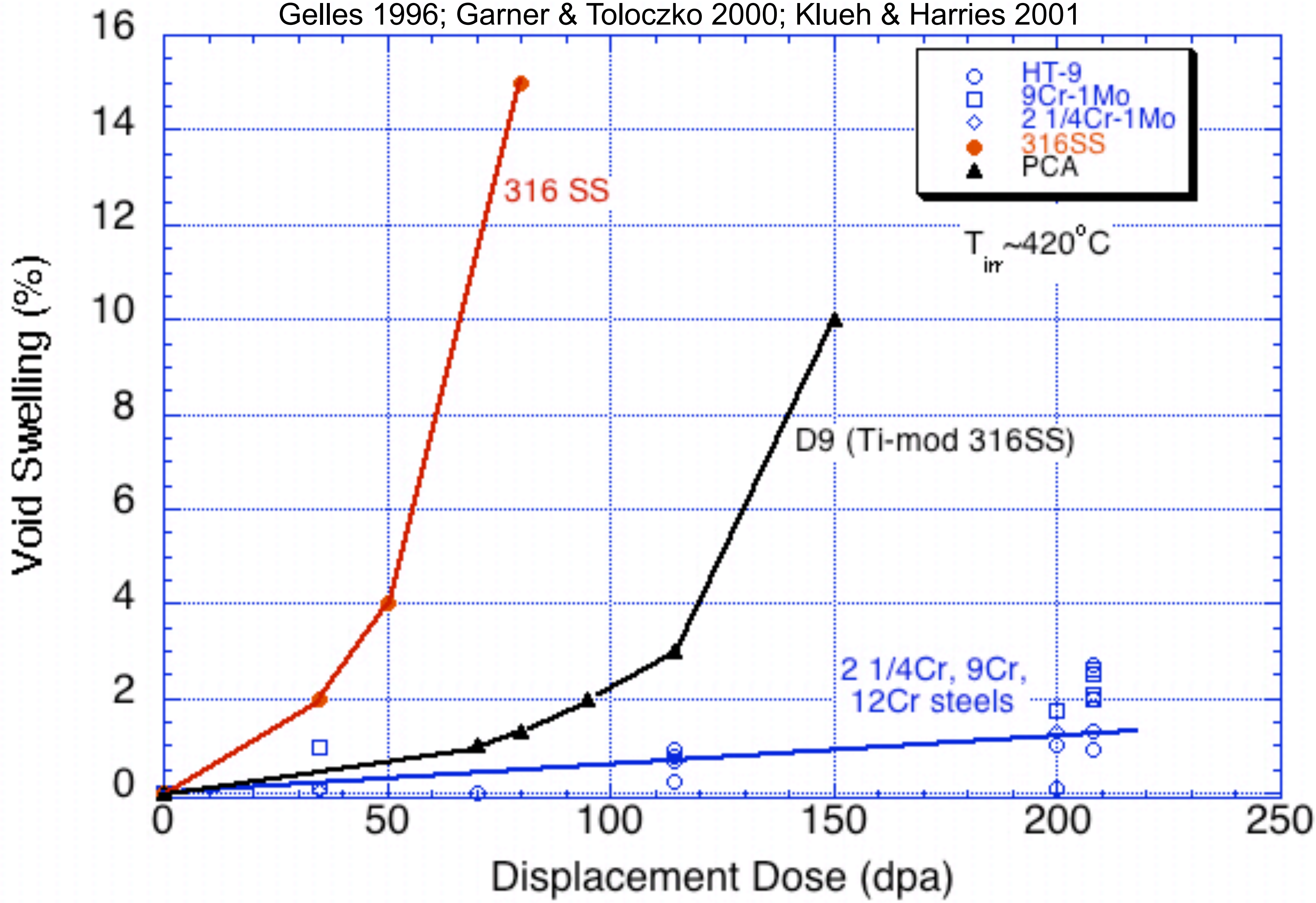
High hardening and loss of uniform elongation occurs for irradiation and test temperatures <0.3 T_M





Comparison of Void Swelling Behavior in Neutron Irradiated Austenitic and Bainitic/ferritic/martensitic Steels

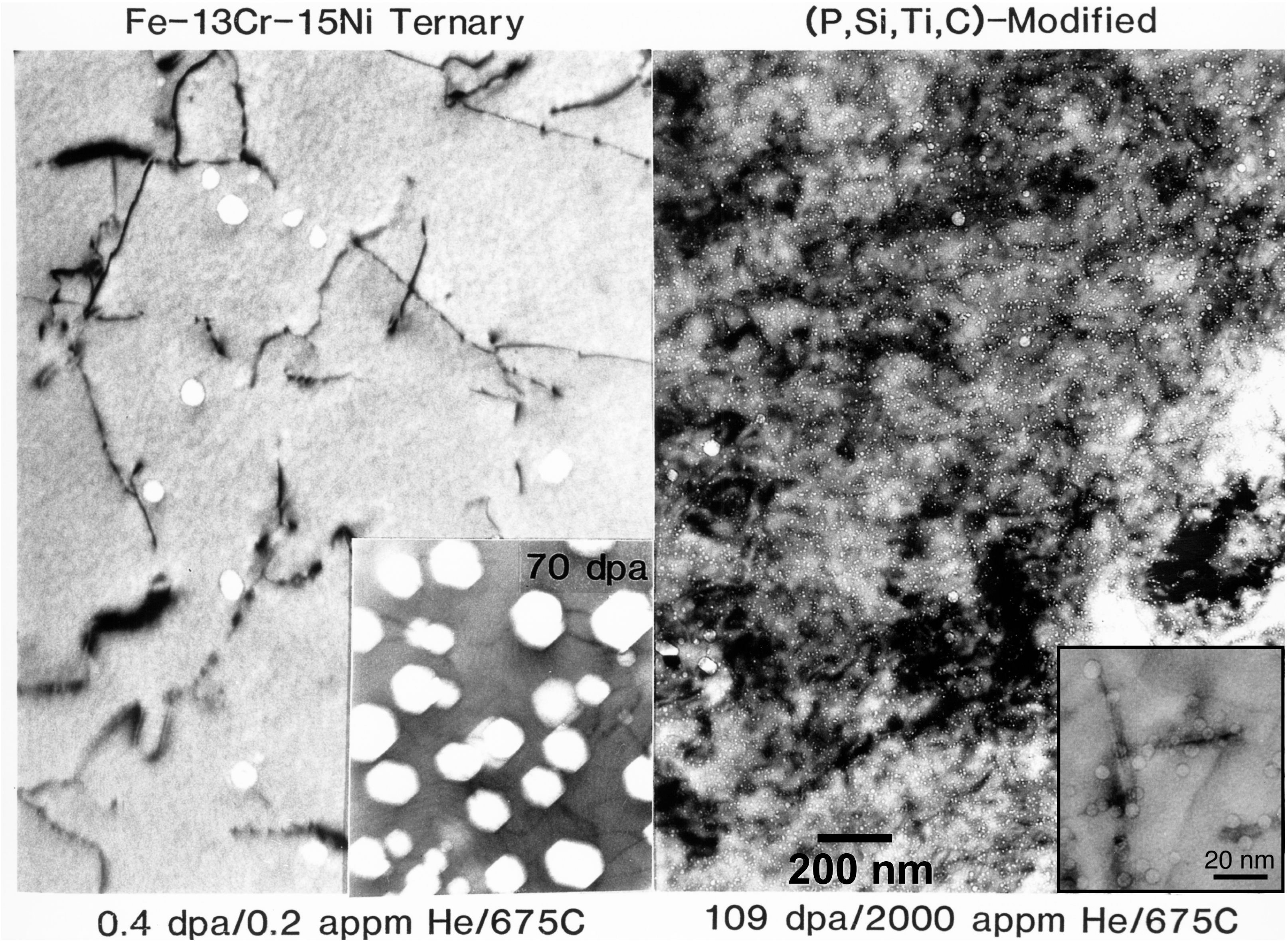
Gelles 1996; Garner & Toloczko 2000; Klueh & Harries 2001



 Managed by UT-Battelle
for the U.S. Department of Energy

OAK RIDGE National Laboratory

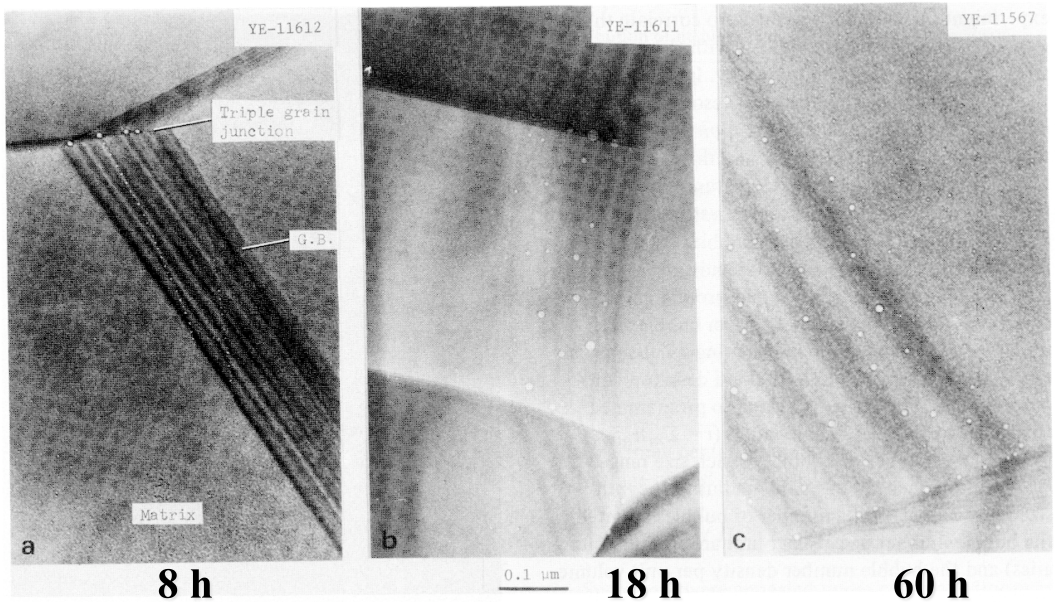
Swelling Resistant Alloys can be developed by Controlling the He Cavity Trapping at Precipitates



Mansur & Lee J. Nucl. Mat. 179-181 (1991) 105

These nanoscale precipitates also typically provide improved thermal creep strength

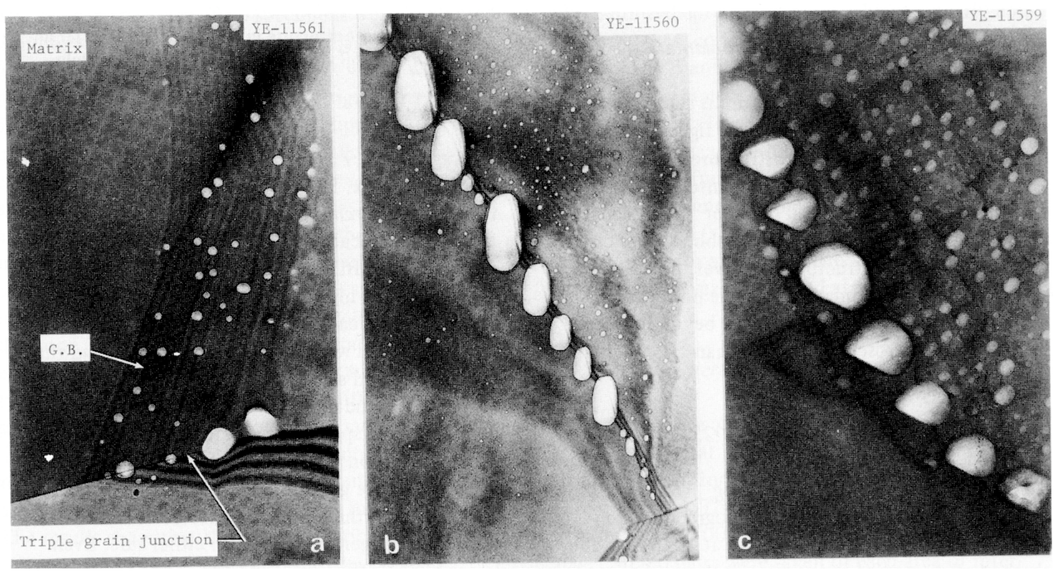
High temperature He embrittlement in austenitic stainless steel: Effect of annealing time and applied stress at 750˚C on grain boundary cavities



8 h **18 h** **60 h**

0 MPa

Fig. 2. Growth of helium bubbles in unstressed Fe–17 Cr–17 Ni specimens after annealing at 1023 K for (s) 2.88×10^4 s, (b) 6.48×10^4 s and (c) 21.60×10^4 s.



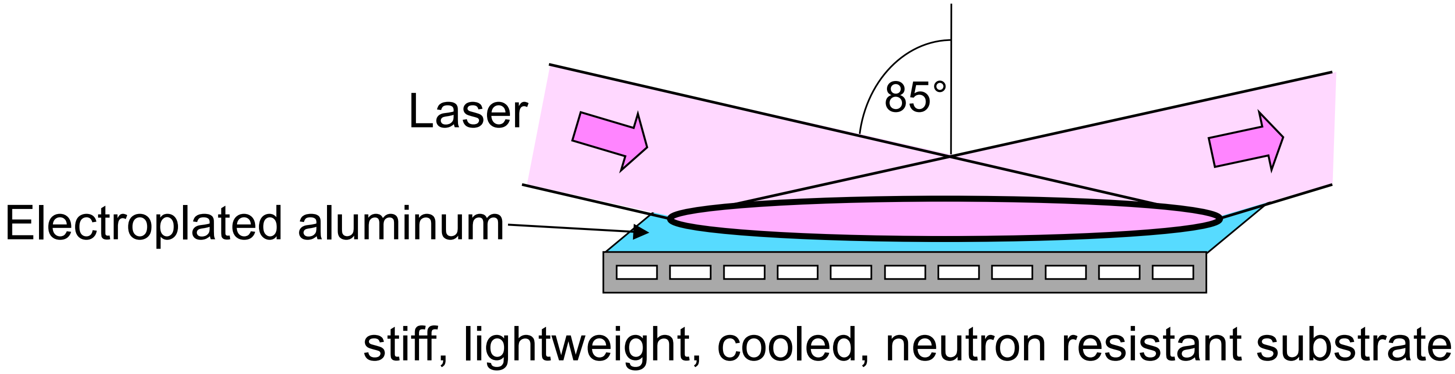
19.6 MPa

D.N. Braski et al.
J. Nucl. Mat. 83 (1979) 265

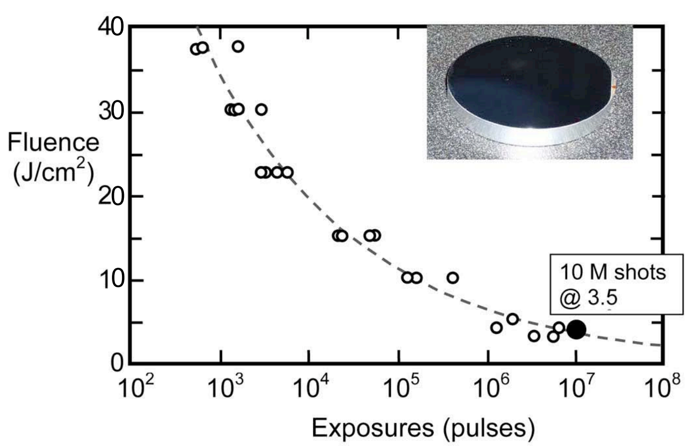
Optics

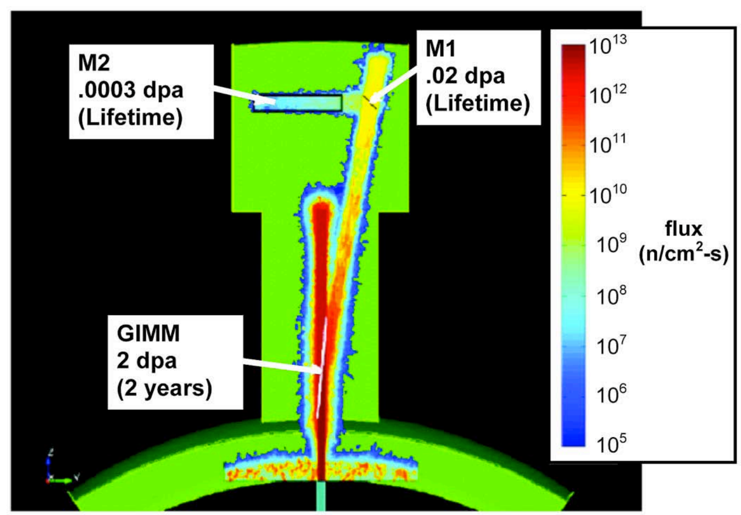
Grazing Incidence Aluminum Mirror meets IFE requirements for reflectivity (>99% @ 85°) & damage threshold (5 J/cm²)

Concept



Results

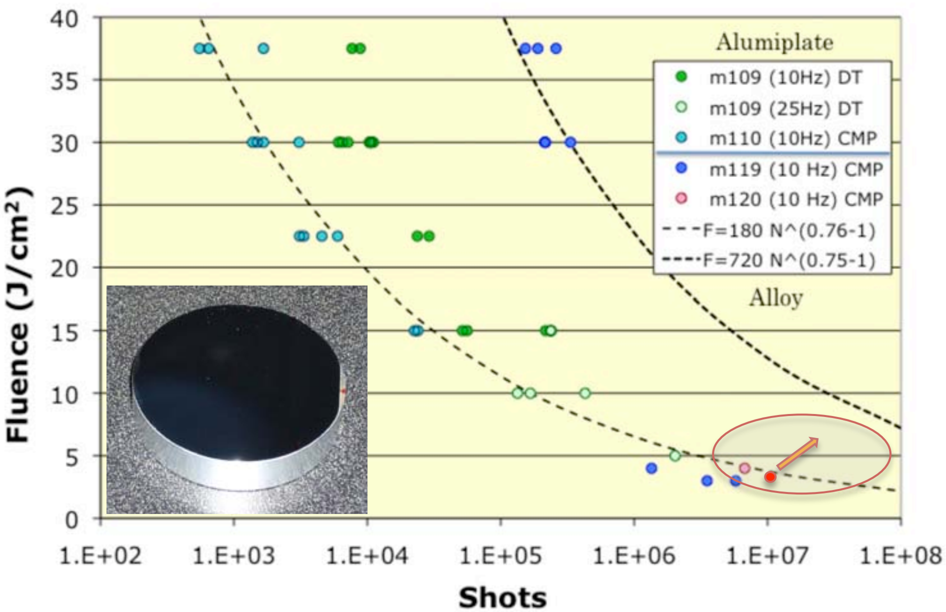




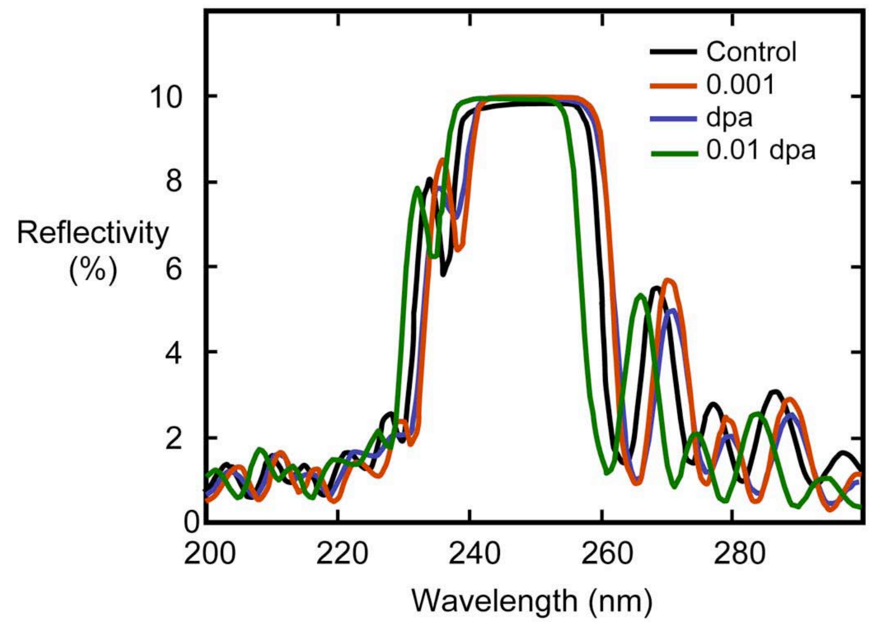
J. Sethian et al., IEEE Trans. Plasma Sci. 38 (2010) 690

Scoping studies suggest materials systems can be engineered for IFE chambers
(single-effects studies in non-fusion environments)

Laser damage threshold measured for a variety of metal mirrors (in the absence of neutron and ion damage)

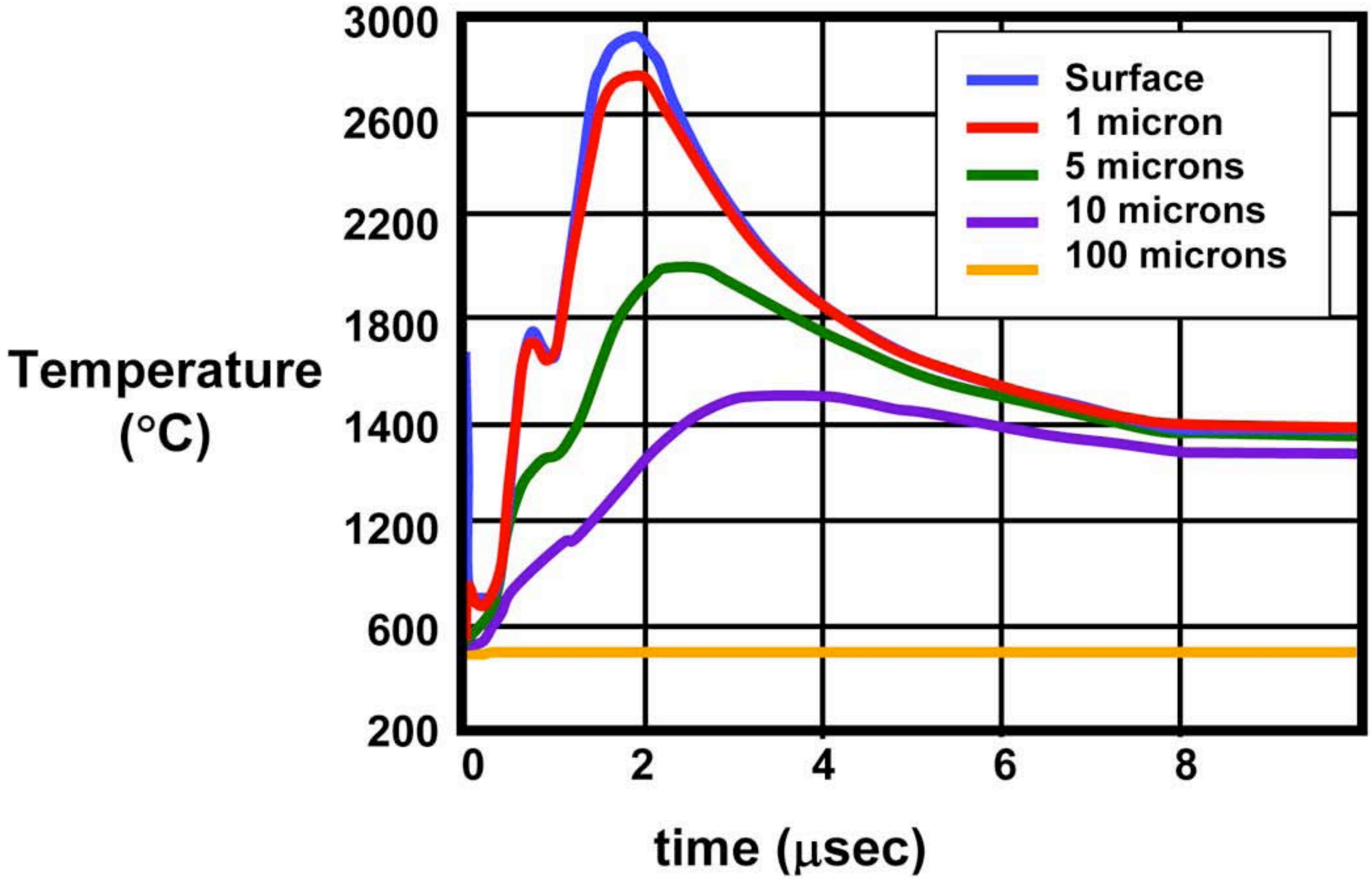


Al_2O_3/SiO_2 dielectric mirrors retain good reflectivity after fission neutron irradiation



J. Sethian et al., IEEE Trans. Plasma Sci. 38 (2010) 690

Time-dependence of Temperature near the First Wall for W-coated SiC



3 mm W armor, 154 MJ direct drive target spectra, 500 C coolant temperature

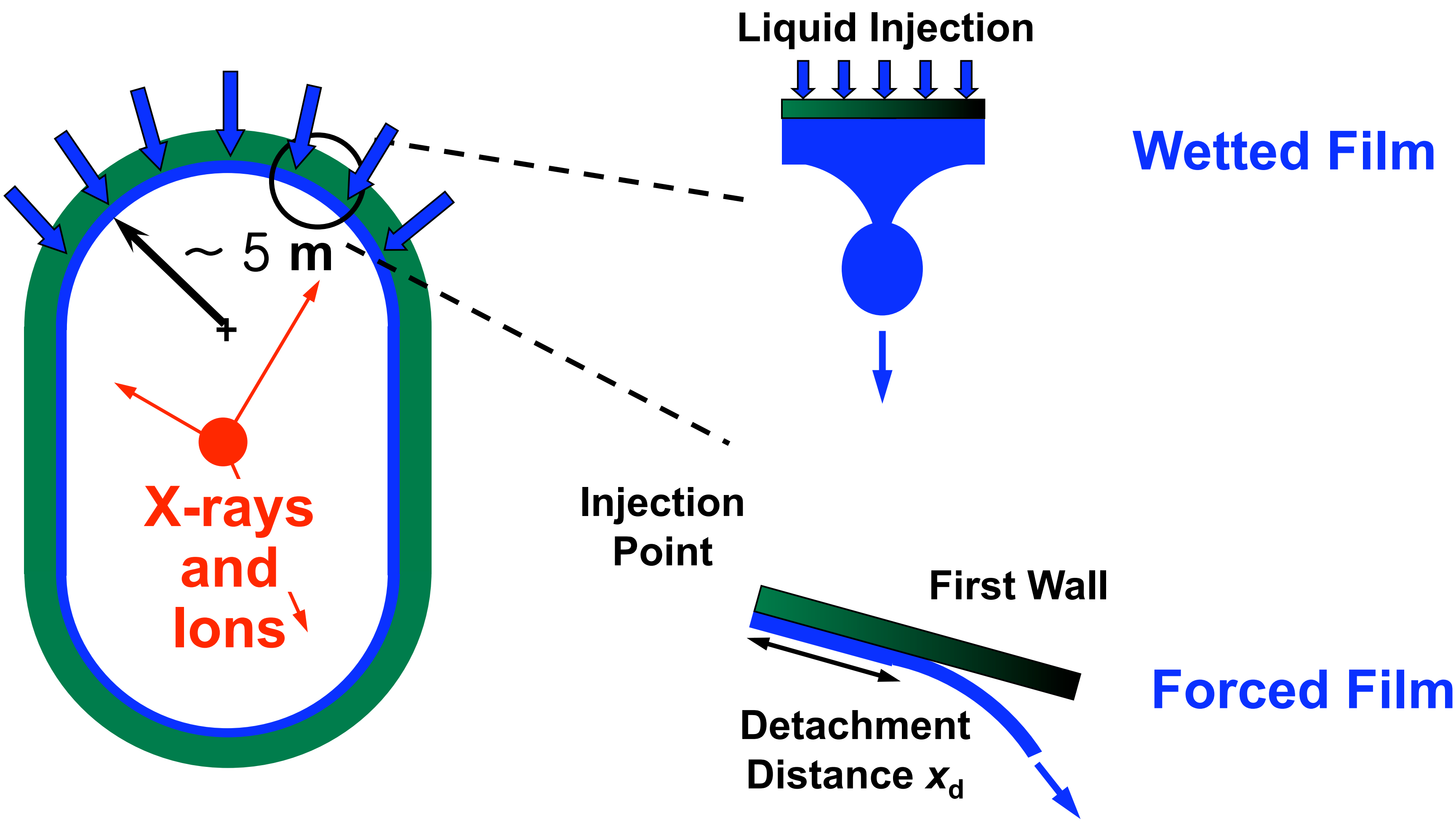
J. Sethian et al., IEEE Trans. Plasma Sci. 38 (2010) 690

Overview of IFE Chamber concepts

Concept	Advantages	Challenges
Solid wall/vacuum	Simplest Easier laser/target issues	Numerous materials issues
Magnetic intervention/ vacuum	Smallest chamber Eliminates FW thermal load	Ion dumps
Replaceable wall/vacuum	Easier laser/target issues	Operational complexity
Solid wall/chamber gas	Smaller chamber	Laser/target issues Chamber recovery (hot gas and residual plasma)
Thin liquid wall	Minimizes FW thermal load	Liquid coverage near penetrations
Thick liquid wall	No materials issues	Chamber recovery Droplet formation Difficult to modify

after J. Sethian et al., IEEE Trans. Plasma Sci. 38 (2010) 690

Two Methods for Establishment of Thin-Liquid Walls Have Been Proposed



S.I. Abdel-Khalik, (2003)

Aerosol Generation and Transport is the Key Issue for Thin-Liquid Wall Concepts

A renewable thin-liquid protection resolves several issues:

- ➢ It can handle a much higher heat fluxes compared to solid surfaces;
- ➢ It will eliminate damage to the armor/first wall due to high-energy ions.

A renewable thin-liquid protection, however, introduces its own critical issues:

- ➢ Fluid-dynamics aspects (establishment and maintenance of the film)
  - ✓ "Wetted wall:" Low-speed normal injection through a porous surface
  - ✓ "Forced film:" High-speed tangential injection along a solid surface
- ➢ Chamber clearing (recondensation of evaporated liquid)
  - ✓ "Source term:" both vapor and liquid (e.g., explosive boiling) are ejected
  - ✓ Super-saturated state of the chamber leads to aerosol generation
  - ✓ Target injection and laser beam propagation lead to severe constraints on the acceptable amount and size of aerosol in the chamber.

Design Windows have been Developed for Establishment and Stability of the Protective Film

"Wetted-wall" concept:

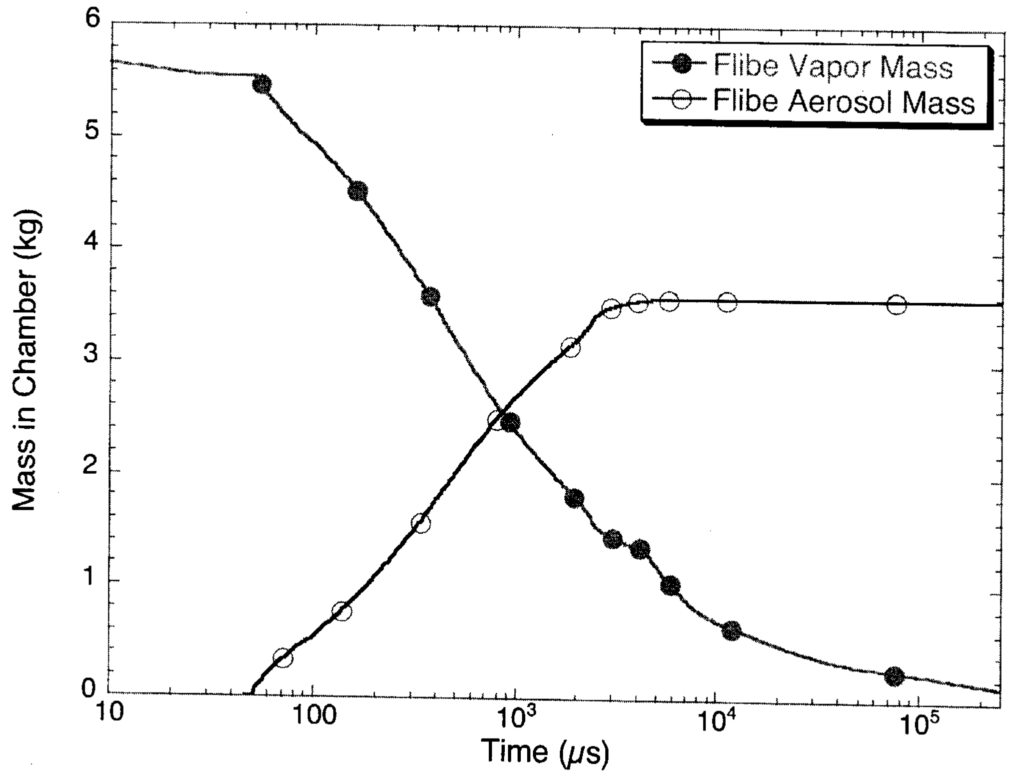
- General non-dimensional charts for film stability over a wide variety of candidate coolants and operating conditions have been developed.
- Model predictions are closely matched with experimental data.
- It will eliminate damage to the armor/first wall due to high-energy ions.

"Forced-flow" concept:

- Non-dimensional design widows for longitudinal spacing of injection/coolant/removal slots to maintain attached protective film have been developed;
- A wetting first wall surface requires fewer injection slots than non-wetting surface – Wetting surfaces are more desirable.

Most of Ablated Material Would Be in The Form of Aerosol

- FLiBe aerosol and vapor mass history in a 6.5-m radius following a target explosion (ablated thickness of 5.5 μm)
- Most of ablated material remains in the chamber in aerosol form;
- Only homogeneous nucleation and growth from the vapor phase.

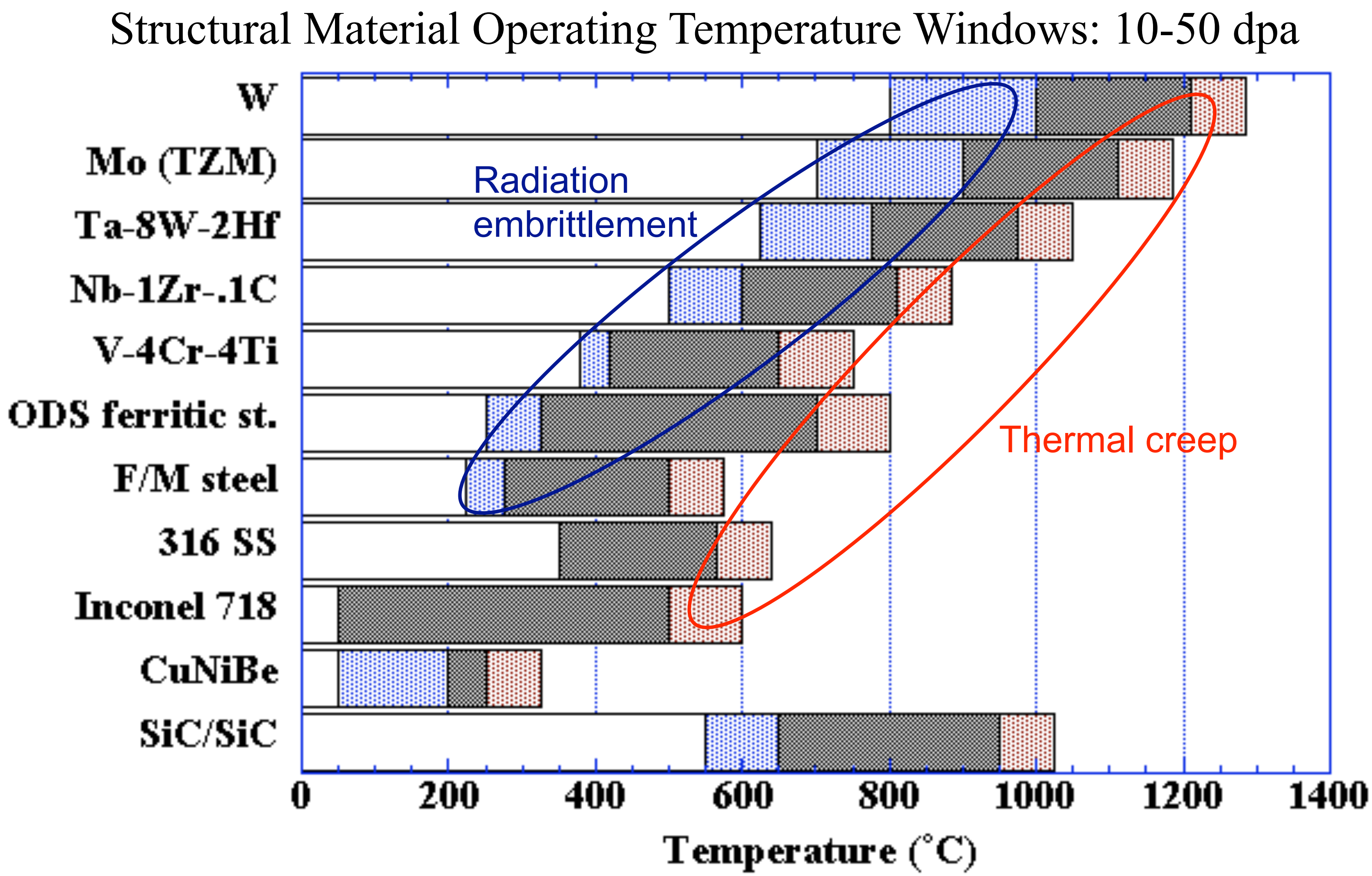


R. Raffray et al., Fusion Sci & Technol. 46 (2004) 438

There Are Many Mechanisms of Aerosol Generation in an IFE Chamber

- Homogeneous nucleation and growth from the vapor phase
  - ✓ Supersaturated vapor
  - ✓ Ion seeded vapor
- Phase decomposition from the liquid phase
  - ✓ Thermally driven phase explosion
  - ✓ Pressure driven fracture
- Hydrodynamic droplet formation (may be critical in thick-liquid wall concepts)

Can we break the shackles that limit conventional structural materials to ~300^{o}C temperature window?



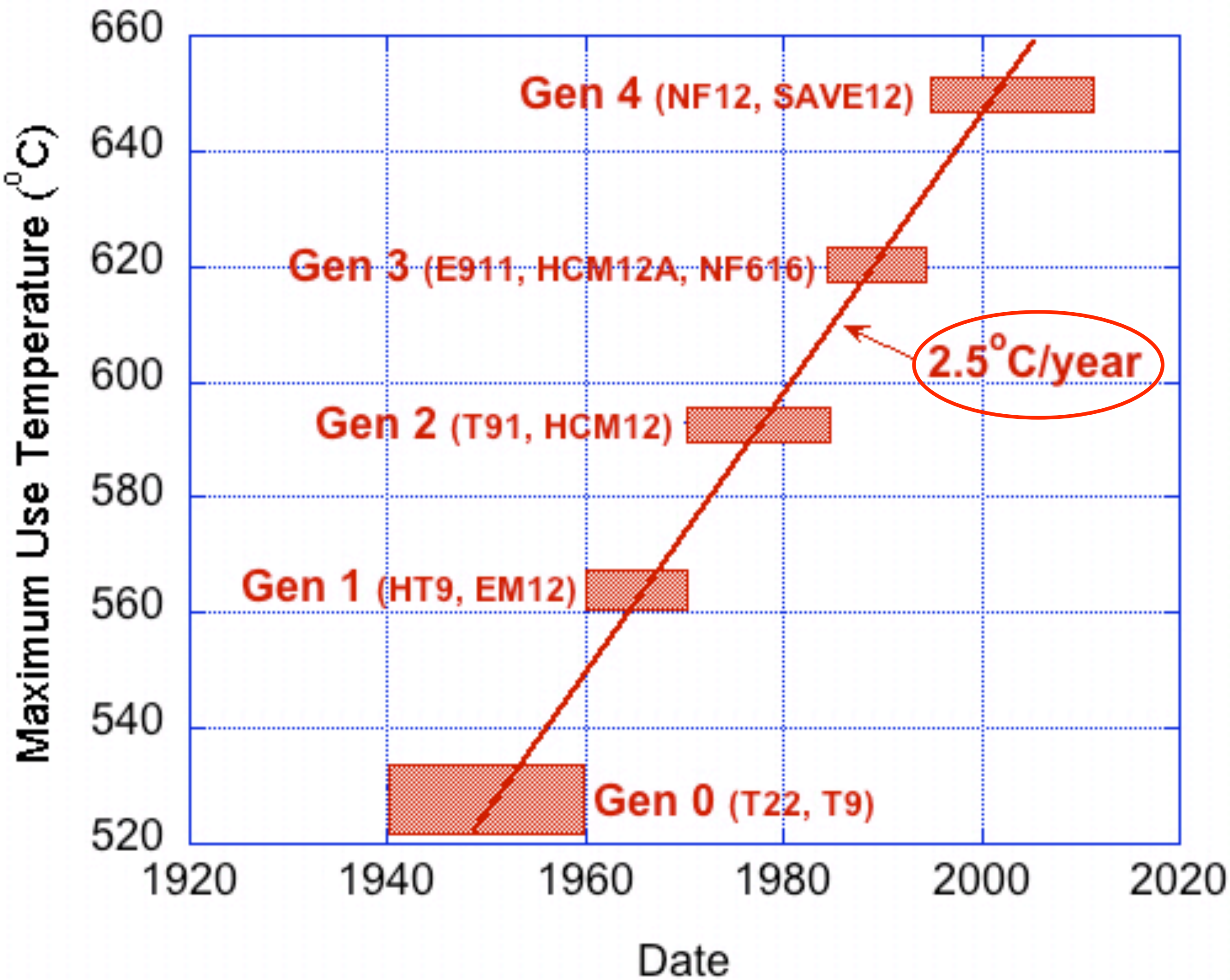
$\eta_{Carnot}=1-T_{reject}/T_{high}$

Additional considerations such as He embrittlement and chemical compatibility may impose further restrictions on operating window

Zinkle and Ghoniem, Fusion Engr. Des. *49-50 (2000) 709*

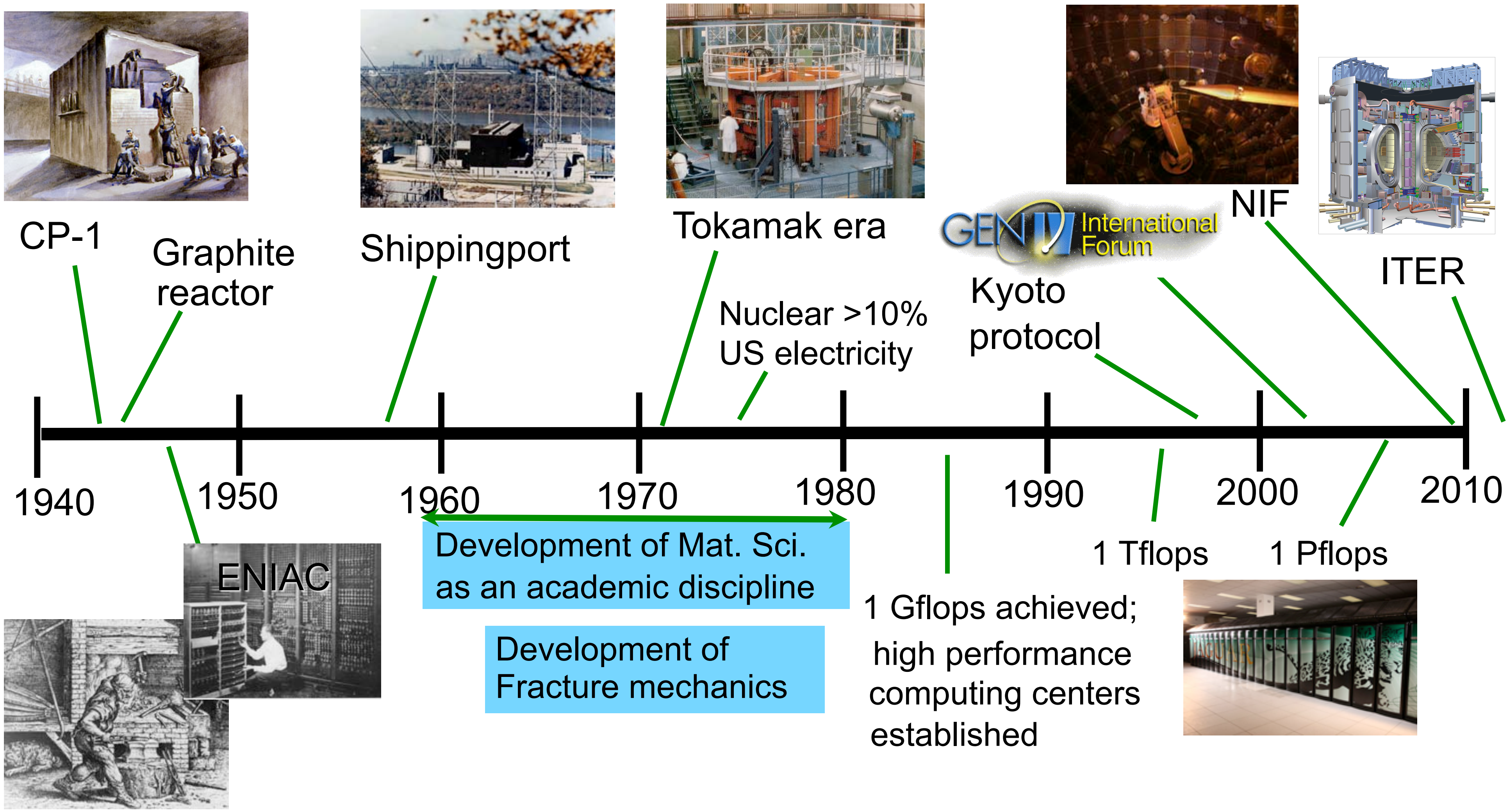
Historical development of improved high-temperature steels has exhibited slow and steady progress

Based on R. Viswanathan, Adv. Mat. Proc. 162 (2004) 73



S.J. Zinkle & J.T. Busby, Mater. Today 12 (2009) 12

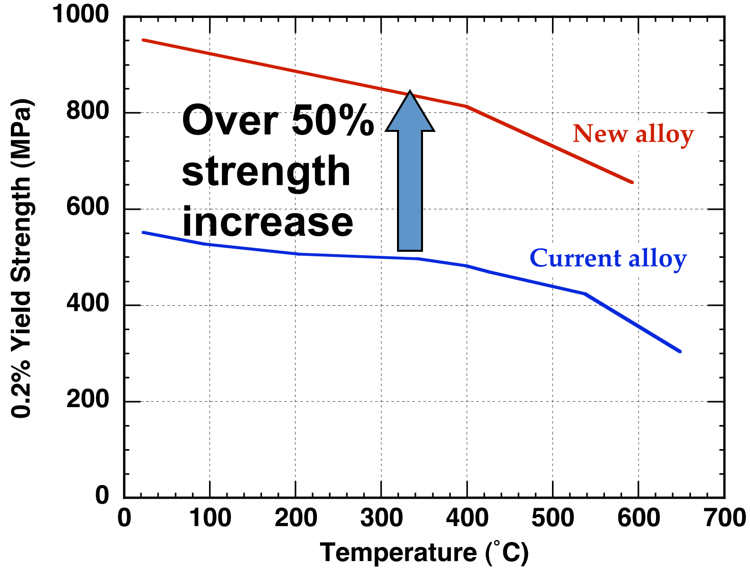
The Launching of Nuclear Energy Largely Preceded the Development of Modern Materials Science

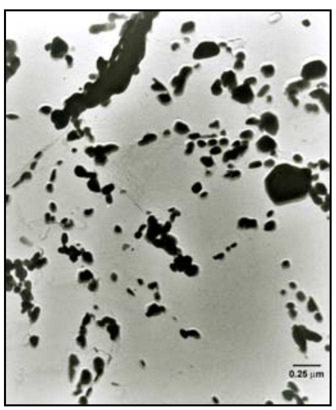


- Fusion and Gen IV fission energy systems should take maximum advantage of current and emerging materials and computational science tools

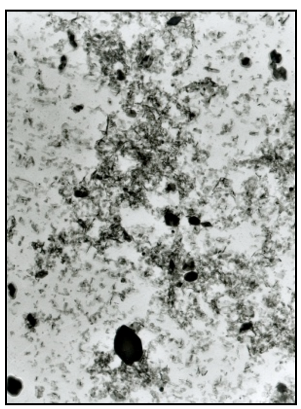
Modern materials science methods can yield dramatic improvements in structural materials such as steels

Example: 2 1/4%Cr steel for pressure vessels





2 1/4 Cr-1Mo



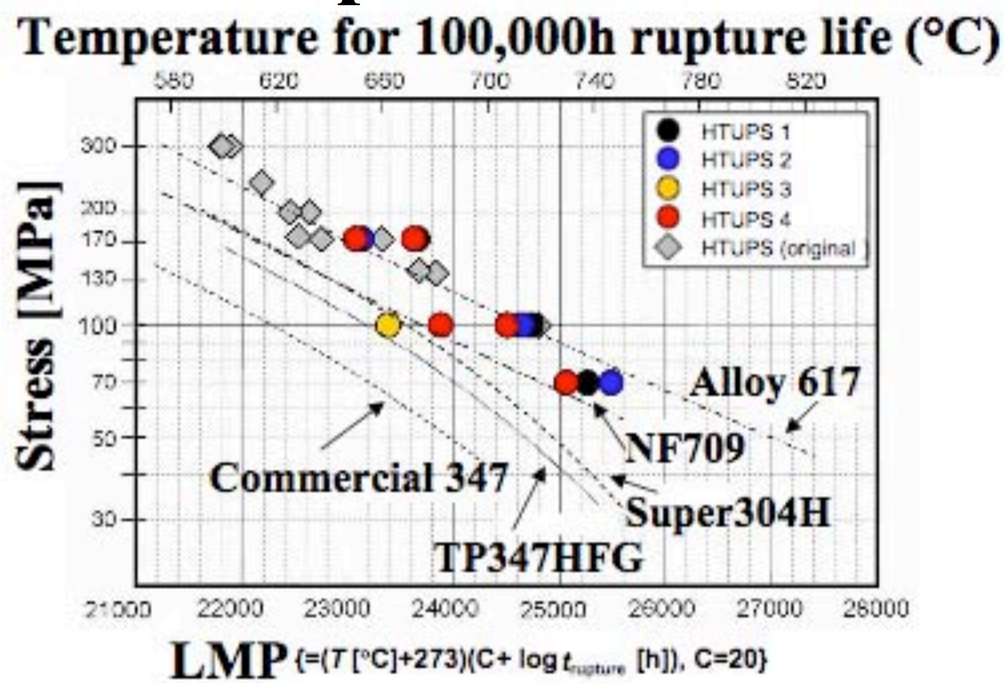
New 2 1/4 Cr-2WV

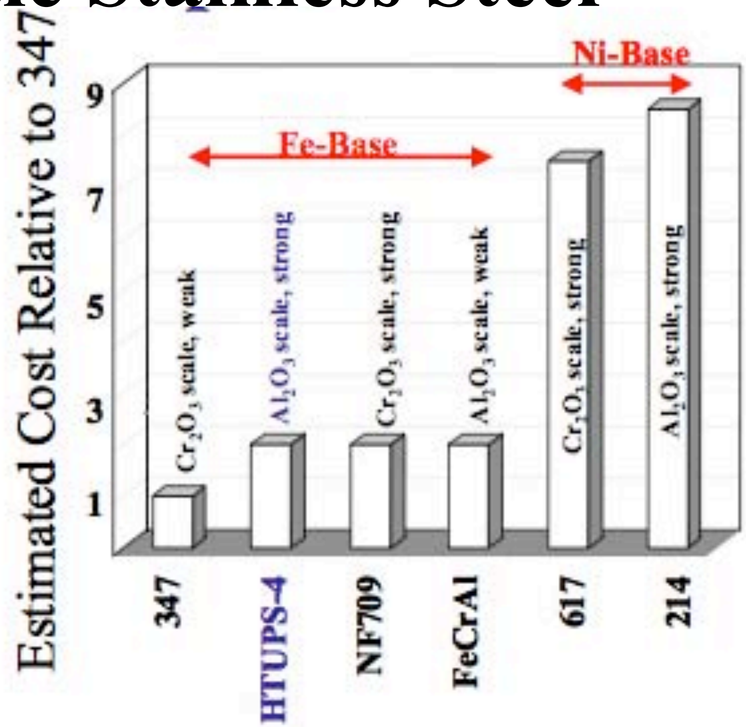
CF8C-Plus cast stainless steel: 10x improvement in thermal creep lifetime; 2 years from start of project to fabrication of components by industry

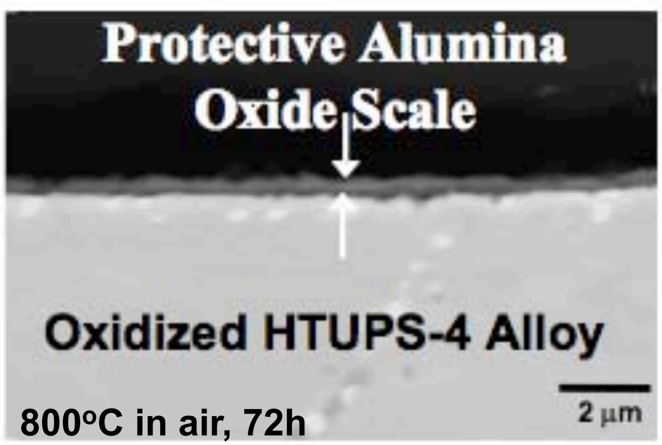
- 2 1/4 Cr steel properties better than HT9 and as good or better than modified 9Cr-1Mo steel
  - Two 50 ton heats procured by industry are awaiting final ASME code approval

R.L. Klueh and P.J. Maziasz, ORNL

Development of New Alumina-Forming, Creep Resistant Austenitic Stainless Steel



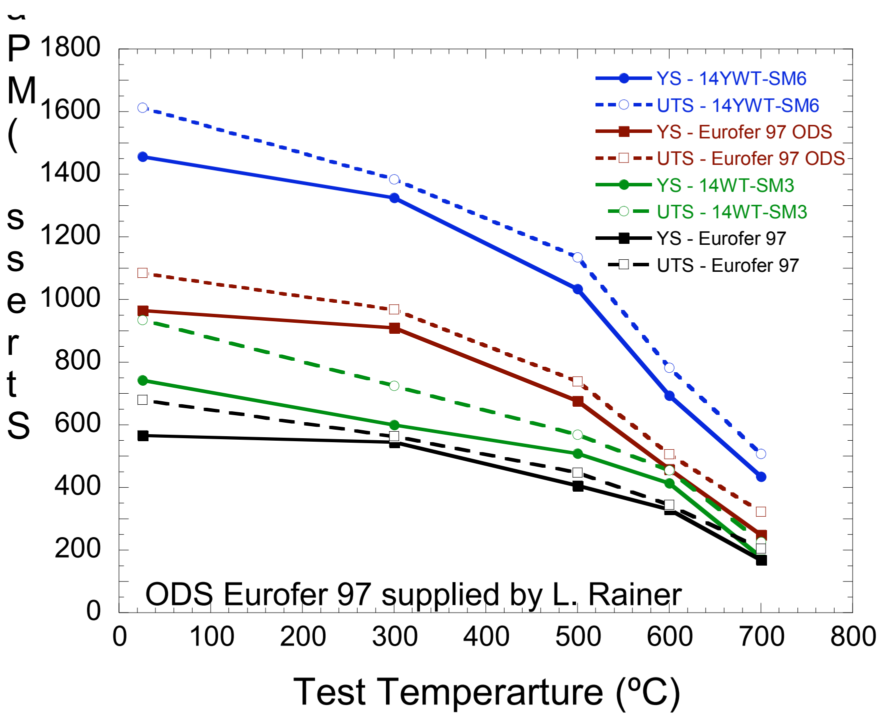


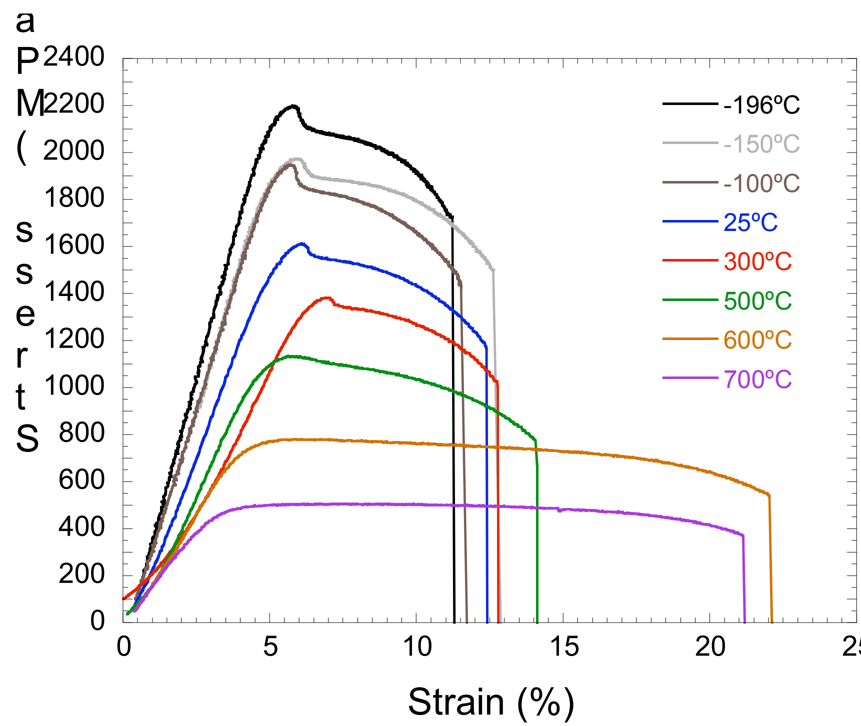


- Designed for 600-800°C structural use under aggressive oxidizing conditions
  - -superior oxidation resistance to conventional chromia-forming alloys
- Comparable cost to current heat-resistant austenitic stainless steels

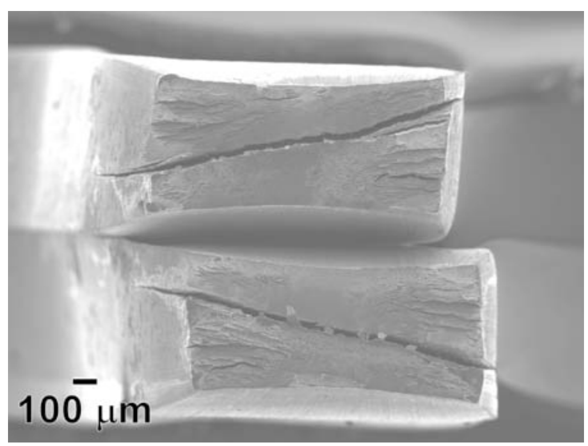
Y. Yamamoto, M.P. Brady et al., Science 316 (2007) 433

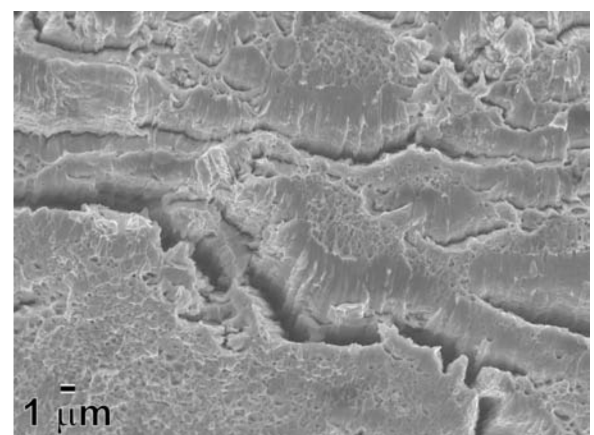
14YWT Nanocluster-strengthened ferritic steel shows high tensile strength and some ductility to -196ºC





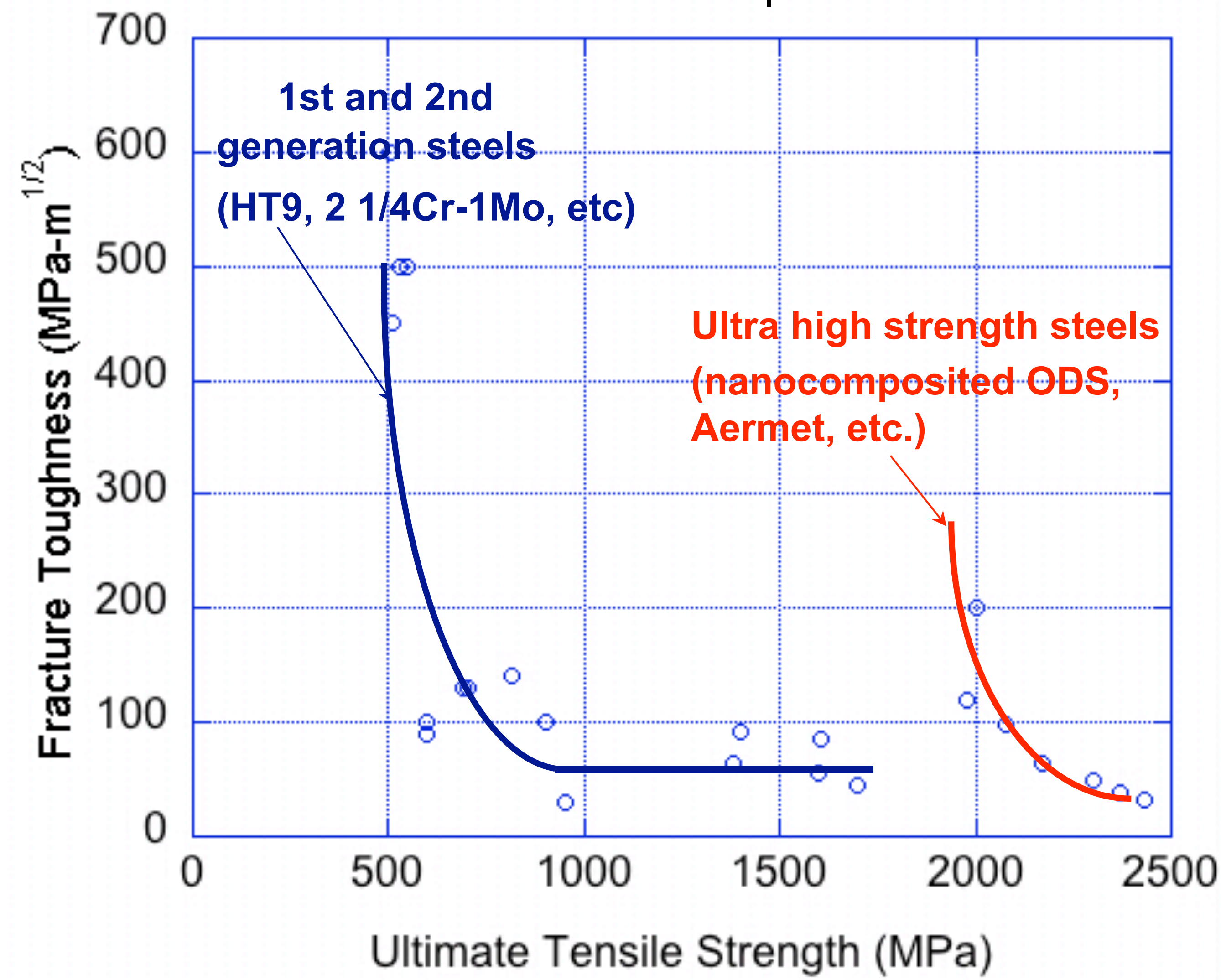
- At -196ºC ($\varepsilon = 10^{-3}s^{-1}$)
  - mixed mode dimple rupture-cleavage failure
  - reduction in area = 43%
  - σ_f = 3.0 GPa
  - T.E. = ~7%





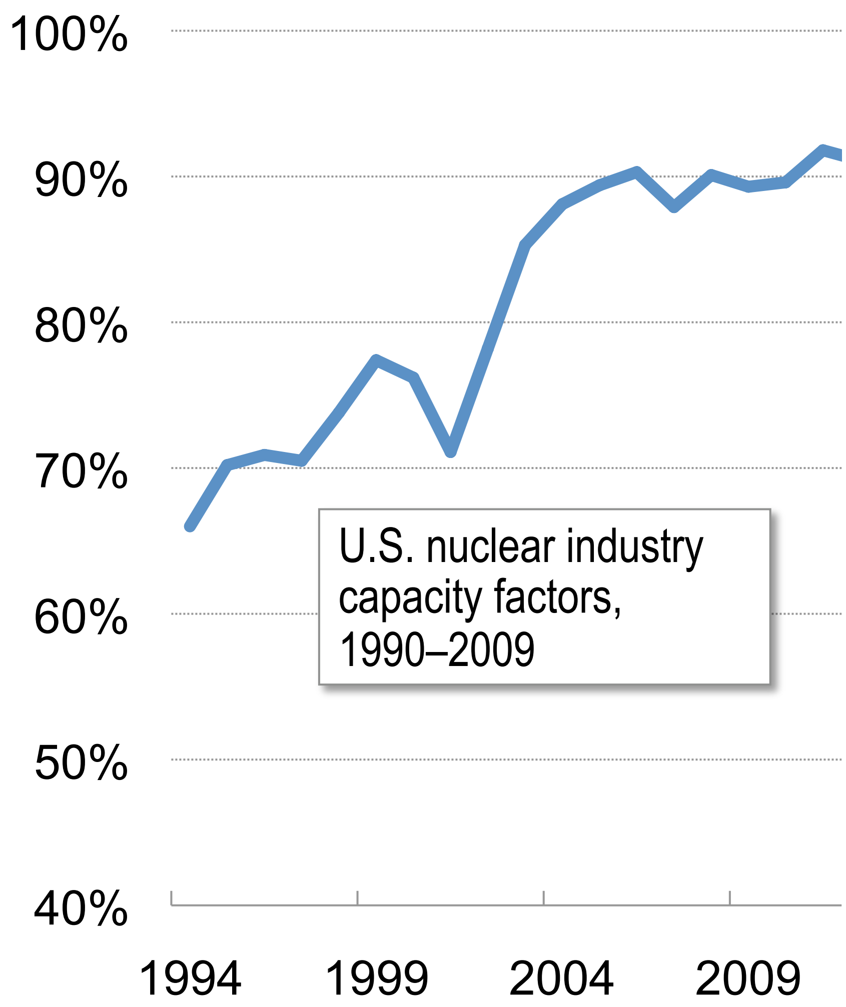
Recent research suggests high-strength steels that retain high-toughness are achievable

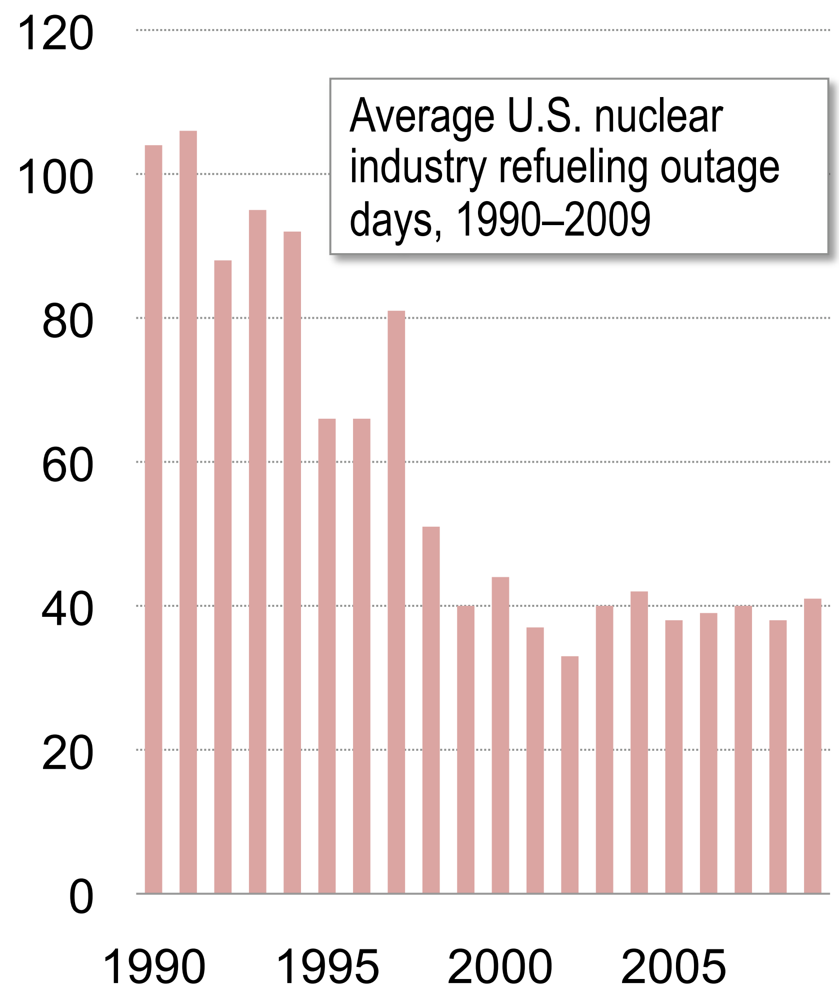
- Generally obtained by producing high density of nanoscale precipitates and elimination of coarse particles that serve as stress concentrator points



S.J. Zinkle & J.T. Busby, Mater. Today 12 (2009) 12

U.S. nuclear fission industry has developed procedures to rapidly return to full power production





Similar rapid-maintenance procedures should be achievable in fusion energy plants

Conclusions

- Several plausible methods have been proposed to mitigate IFE chamber damage due to sputtering, ion and neutron damage, and cyclic stresses
  - e.g., liquid walls
  - None of these mitigation techniques have been demonstrated on an engineering scale
- Improved materials may be designed in a timely manner with a science-based approach
  - Design of nanoscale features in structural materials confers improved mechanical strength and radiation resistance
- Improved rapid change-out techniques have traditionally been implemented by knowledge-sharing among utilities
  - A concerted effort is needed to transfer relevant aspects to IFE fusion energy power plant conditions