Challenges in Developing Materials for Fusion Technology–Past, Present and Future

Steven J. Zinkle

Oak Ridge National Laboratory, Oak Ridge, TN, USA

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Outline

- Brief review of fission and fusion chronologies
- Three overarching challenges to materials for fusion technology
  - Plasma materials interactions
  - Nuclear degradation to materials and structures
  - Fuel cycle & power conversion challenges to harnessing fusion energy
- Emerging trends for structural materials
  - Computational thermodynamics (integrated computational materials engineering/ materials genome initiative)
  - Direct/additive manufacturing techniques
- Overview of unresolved grand challenges

Timeline of some key events for nuclear energy and materials and computational science

CP-1

Graphite reactor

1^{st} stellarator & Tokamak

Shippingport

Tokamak era begins

Nuclear >10% US electricity

TFTR: Q=0.27

JET: Q=0.65, 0.5s

NIF

JT-60: Q_{eq}=1.25

ITER

1940 1950 1960 1970 1980 1990 2000 2010

Development of Mat. Sci. as an academic discipline

1 Gflops achieved; high performance computing centers established

1 Tflops

1 Pflops

1^{st} MD simulation of radiation damage (500 atoms, 1 min. time step)

multimillion atom MD simulations (~1 fs time step)

The development of fission energy faced numerous technological barriers (e.g., Zr alloy cladding)

- **1950: US annual production of Zr was ~200 lbs (~10^6 lbs/yr needed by late 1950s); $240/lb cost was ~30x higher than economical limit**
- **"At the time of this decision there was no assured source of Zr, no estimate of how much would be needed, no certainty that any known or conceivable process could produce the required amount, and no specifications for the nuclear, mechanical, or corrosion qualities the metal had to possess." (Nautilus launched Jan. 17, 1955 using Zry2 cladding that was first specified in Aug. 1952)**

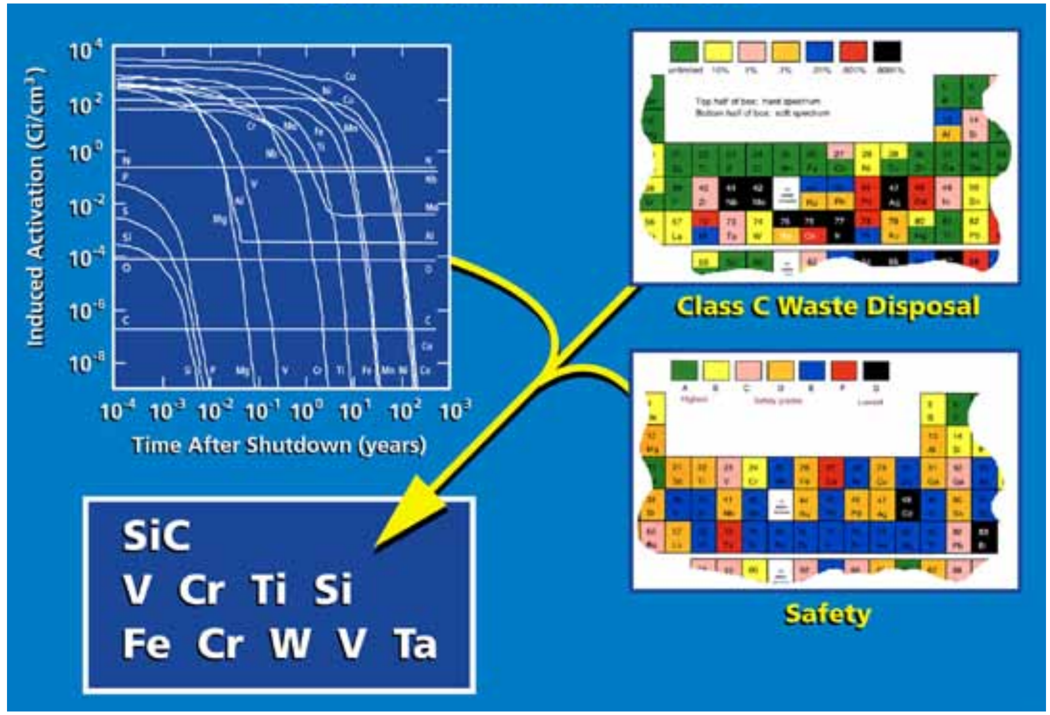
H.G. Rickover, History of the development of Zr alloys for use in nuclear reactors, NR:D:1975

Evolution in materials for fusion technology

- 1970s: conceptual design studies and initial R&D
  - Stainless steel first wall and blanket structure (UWMAK-I, Starfire, etc.); most designs assume pulsed operation
  - Refractory alloys (Mo, Nb, V) considered as backup options; ferritic steels emerge as a backup in the late 1970s
  - Worldwide fusion materials R&D activities initiated
- 1980s: 14MeV neutron source; Rise of PFC tiles and low-activation mandate
  - RTNS-II irradiation source used to explore fundamentals of low-dose 14 MeV neutron damage; fission reactors and ion accelerators used to study high dose effects
  - Graphite tiles and carbonization used improve plasma performance
  - 1983: Low activation materials panel report (Conn et al.)
    - Simultaneous consideration of long-term waste disposal, maintenance, and decay heat/volatization safety issues

The Overarching Goals for Fusion Power Systems Narrow the Choices and Place Significant Demands for Performance of Structural Materials

- **Safety**
- **Minimization of Rad Waste (& suitability for recycling)**
- **Economically Competitive**
  - High thermal efficiency (high temperatures)
  - Acceptable lifetime
  - Reliability

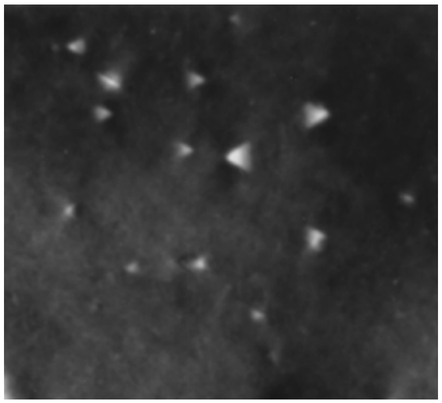


Multidisciplinary Fusion Materials Research has Demonstrated the Equivalency of Displacement Damage Produced by Fission and Fusion Neutrons

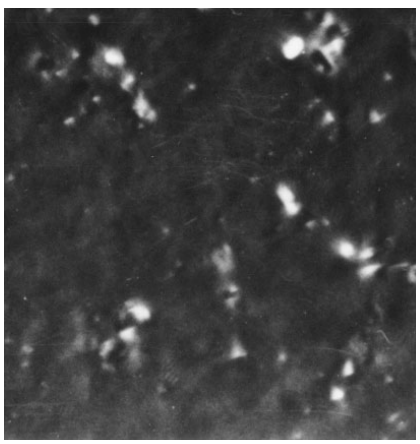
Similar defect clusters produced by fission and fusion neutrons as observed by TEM

Fission

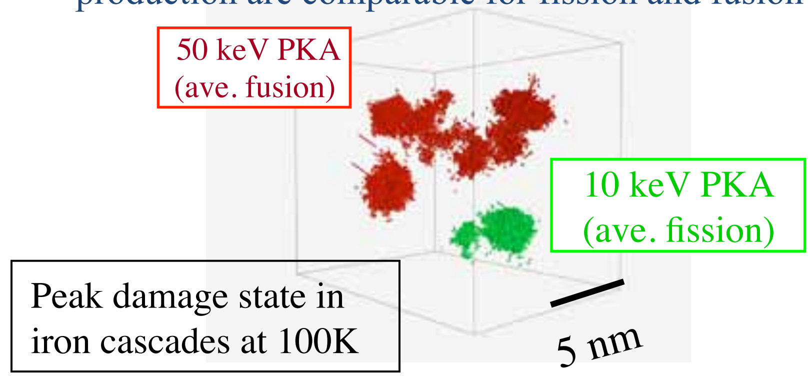
(0.1 - 3 MeV)



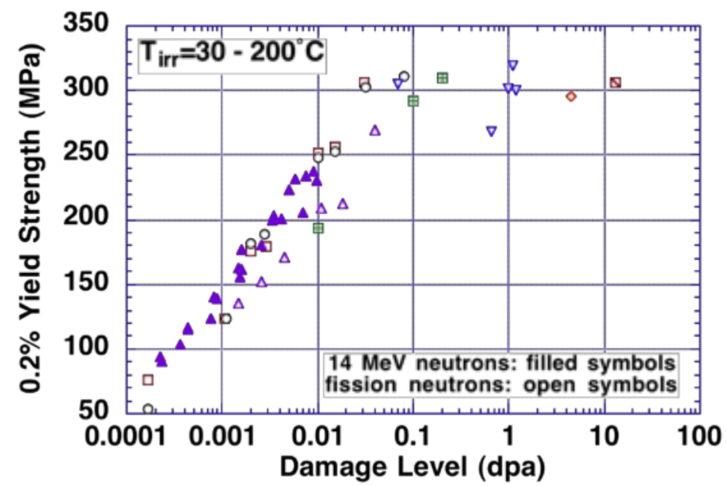
Fusion
(14 MeV)



MD computer simulations show that subcascades and defect production are comparable for fission and 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

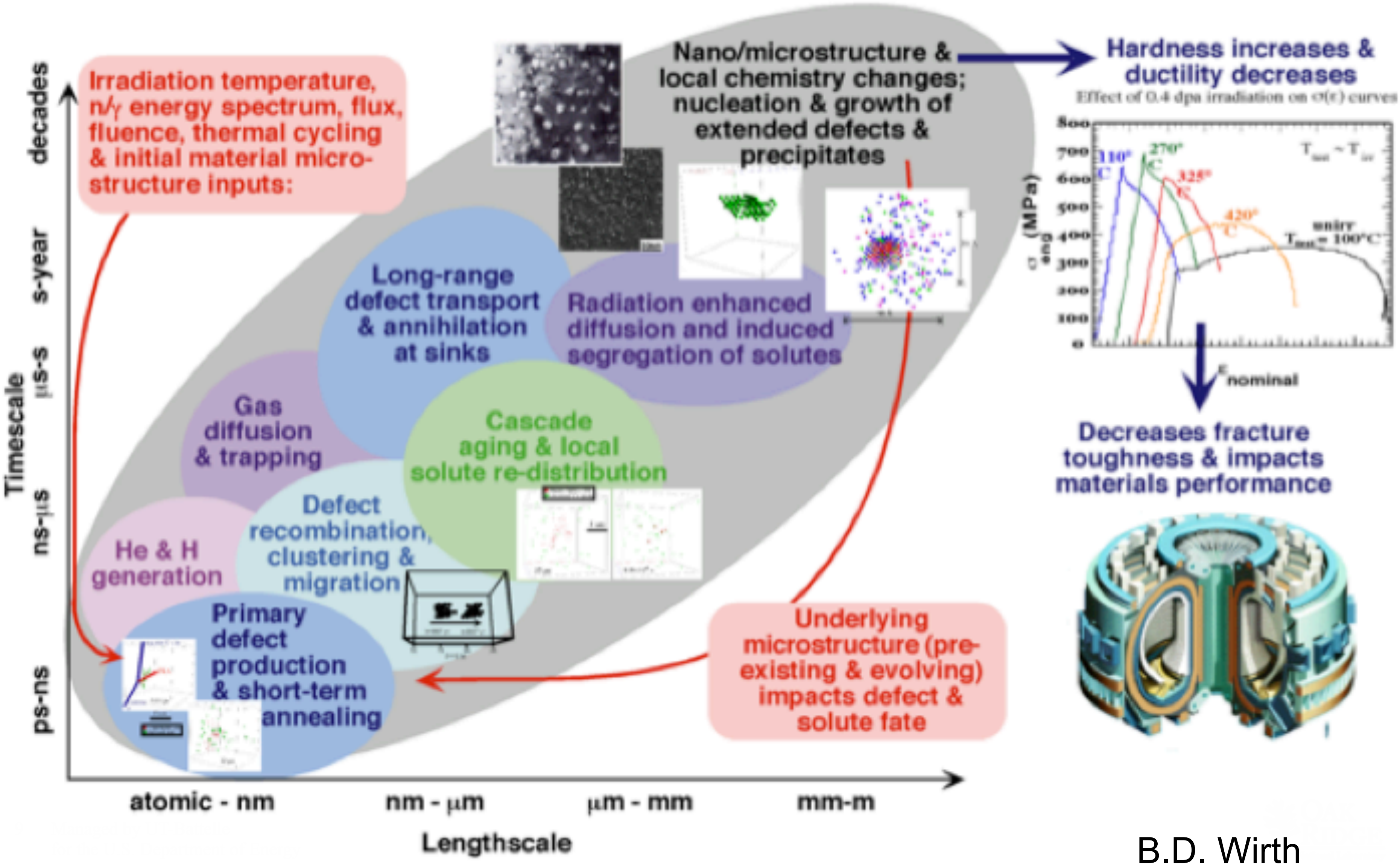
S.J. Zinkle, M. Victoria & K. Abe, J. Nucl. Mater. 307-311 (2002) 31

Evolution in materials for fusion technology, cont’d

- 1990s: exploration of high-performance compositions, ITER R&D, and innovative engineering designs
  - Decay heat issues with Mn-stabilized stainless steel leads to termination of reduced-activation austenitic steel R&D
  - 9%Cr ferritic/martensitic steels emerge as leading structure choice; V alloys and SiC/SiC
  - ITER materials R&D (316SS, Cu alloys, C/Be/W PFCs)
    - Fabrication/joining, low temperature radiation hardening and embrittlement, etc.
  - Initiation of liquid wall and other high-performance concepts (ARIES, APEX, ALPS, etc.)
- 2000s: Predictive computational modeling and improved structural material options
  - Tungsten PFC technology for high-performance plasmas
  - Multiscale, multiphysics coupled models
  - Comprehensive knowledge and database acquired for key materials (9%Cr FM steel, etc.)
  - ODS ferritic steels and new alloys designed by computational thermodynamics
  - Waiting for ITER site and IFMIF construction decisions

Identification of Grand Science Challenges Provided the Scientific Foundation for the Evaluation

Examples for Conquering Degradation to Materials and Structures



B.D. Wirth

Three overarching challenges to materials must be resolved for steady state fusion energy devices

- Plasma-materials interactions
  - Sputtering and redeposition (including tritium entrapment)
  - High heat flux
  - Varying thermomechanical stress
- Nuclear degradation to materials and structures
  - Structural stability to intense fusion neutron exposure (incl. H/He)
  - Radiation-enhanced corrosion
  - Reduced activation mandate
- Harness fusion energy (fuel cycle & power conversion)
  - Minimize tritium inventory in blanket structures, etc.
  - Efficiently extract tritium fuel from hot coolant
  - Thermohydraulic and MHD instabilities

MHD forces in flowing liquid metal coolants in MFE blankets can exceed normal viscous and inertial forces by >5 orders of magnitude

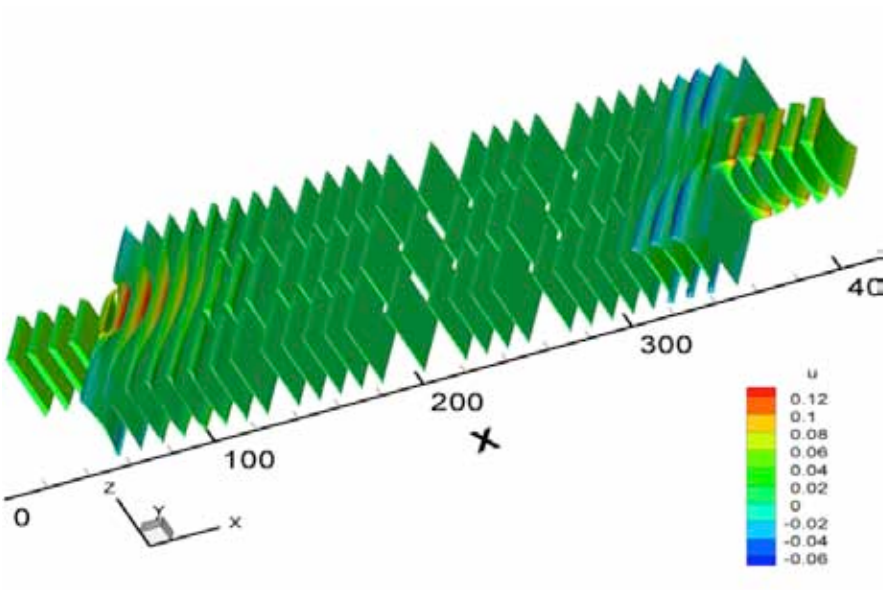
3D MHD simulation of flow distribution to 3 blanket channels from a common manifold

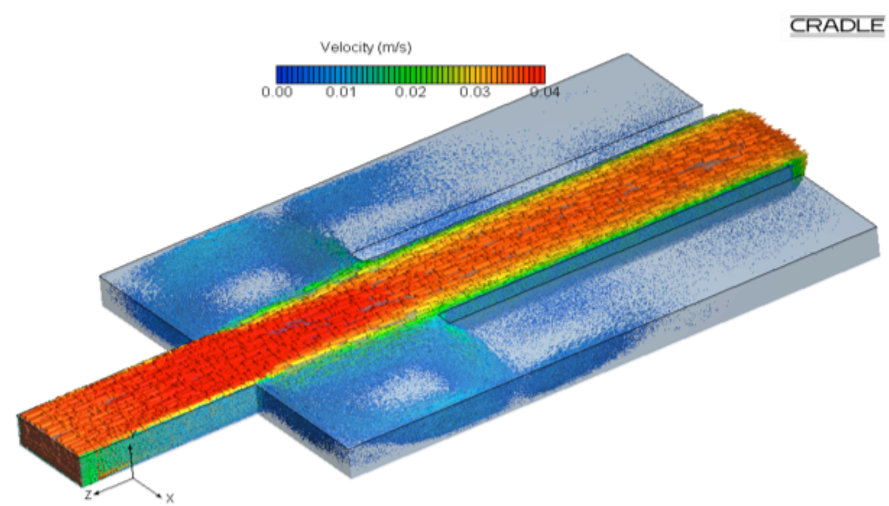
With B field

- **Coolant flow is uniform within three channels**

No B field

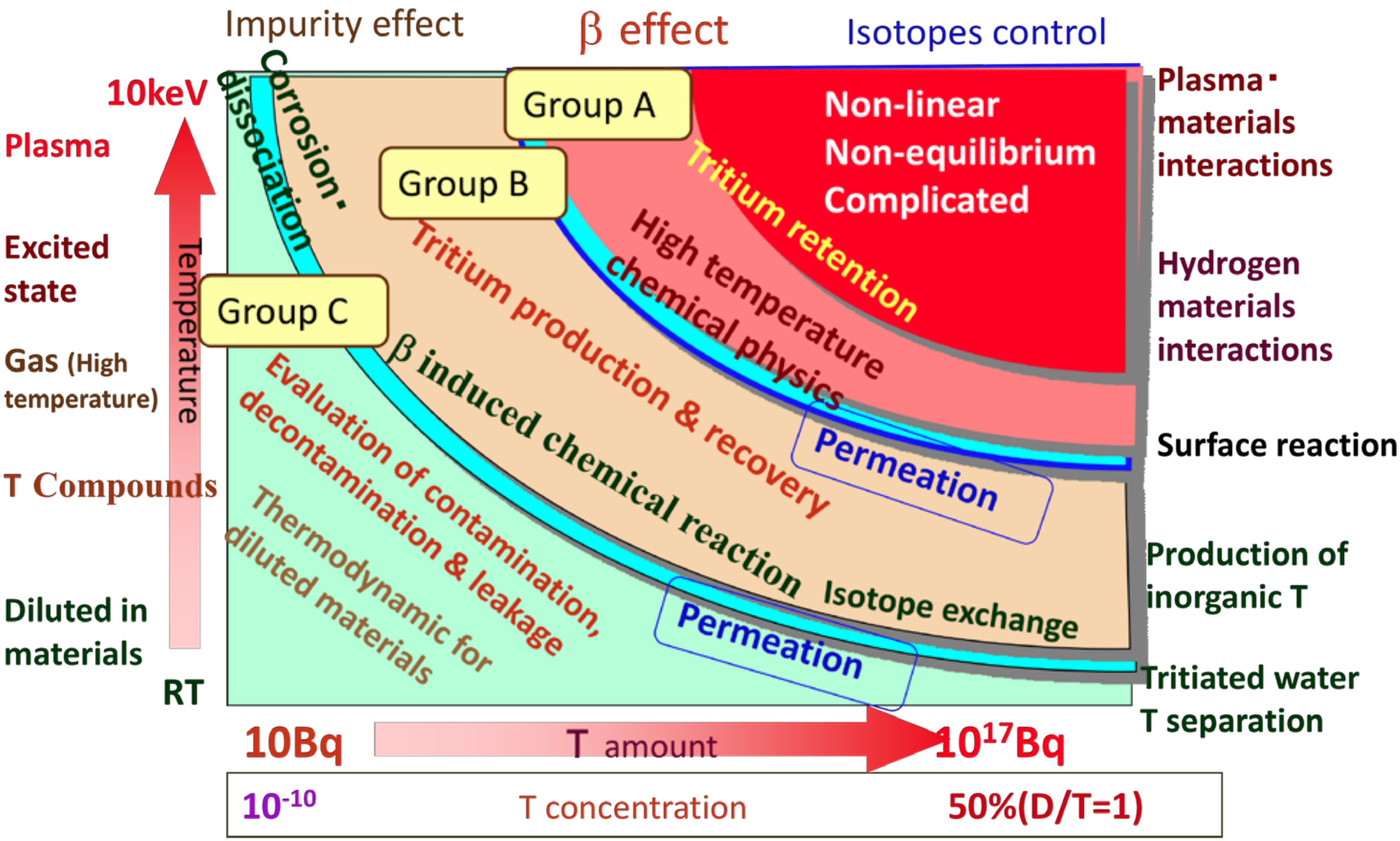
- **Coolant flow is concentrated in center channel**





Tritium Science & Technology for Fusion Reactor

Scientific Research in Priority Areas
Tritium for Fusion
2007 - 2011



T. Tanabe, ISFNT, Portland, 2011

OAK RIDGE National Laboratory

There are (too) numerous viable fusion blanket technology options, all of which are at a relatively immature TRL

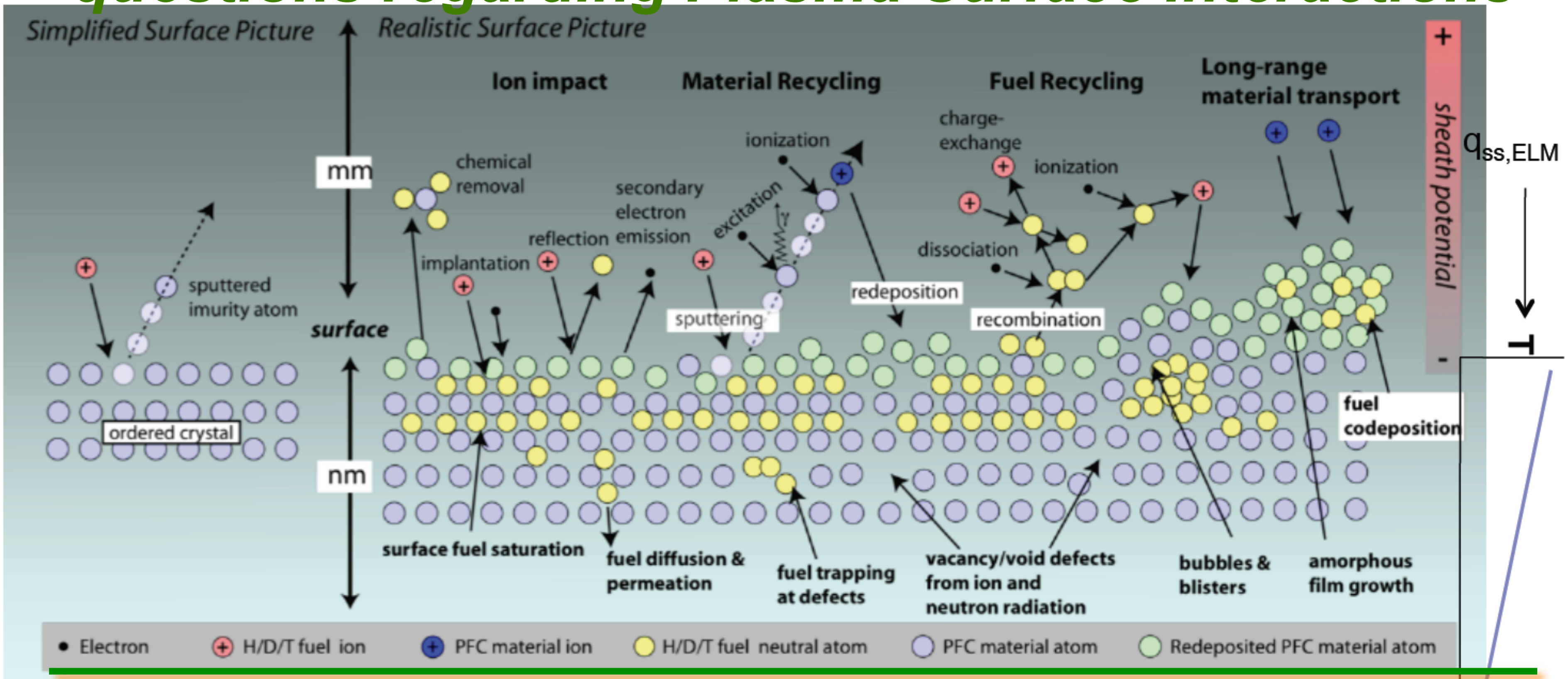
- **Key issues include tritium recovery/transport, coolant compatibility, safety, waste disposal/recycling, radiation damage effects, and lifetime limits**
- **These blanket concepts would utilize a variety of conceptually interesting (but unproven on engineering scale) tritium recovery processes**

Structural Material	**Coolant/Tritium Breeding Material**					
	Li/Li	He/PbLi	H_2O/PbLi	He/Li ceramic	H_2O/Li ceramic	FLiBe/FLiBe
Ferritic steel						
V alloy						
SiC/SiC						

Several materials-tritium issues require additional investigation

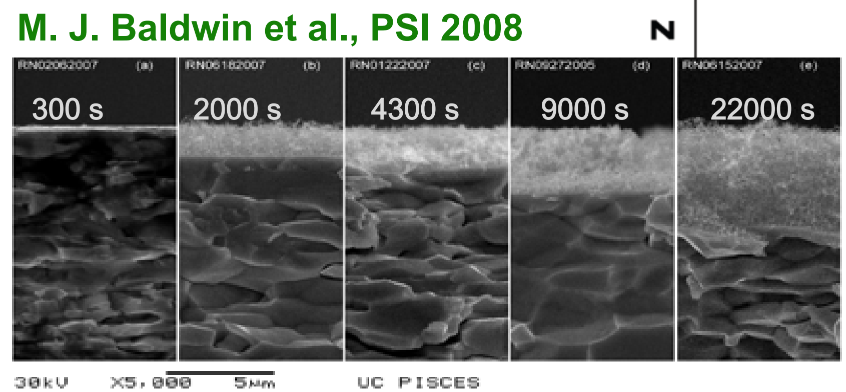
- Identification of a robust, efficient and economic method for extraction of tritium from high temperature coolants
  - Large number of potential tritium blanket systems is both advantageous and a hindrance
- Current materials science strategies to develop radiation-resistant materials may (or may not) lead to dramatically enhanced tritium retention in the fusion blanket
  - Fission power reactors (typical annual T_2 discharges of 100-800 Ci/GW_e; ~10% of production) are drawing increasing scrutiny
  - A 1 GW_e fusion plant will produce ~10^9 Ci/yr; typical assumed releases are ~0.3 to 1×10^5 Ci/yr (<0.01% of production)
  - Nanoscale cavity formation may lead to significant trapping of hydrogen isotopes in the blanket structure
  - Tritium trapping efficacy of precipitates and nanoscale solute clusters (blanket & piping) is poorly understood from a fundamental perspective

There are numerous fundamental scientific questions regarding Plasma Surface Interactions



Wirth, Nordlund, Whyte and Xu, *MRS Bulletin* (2011).

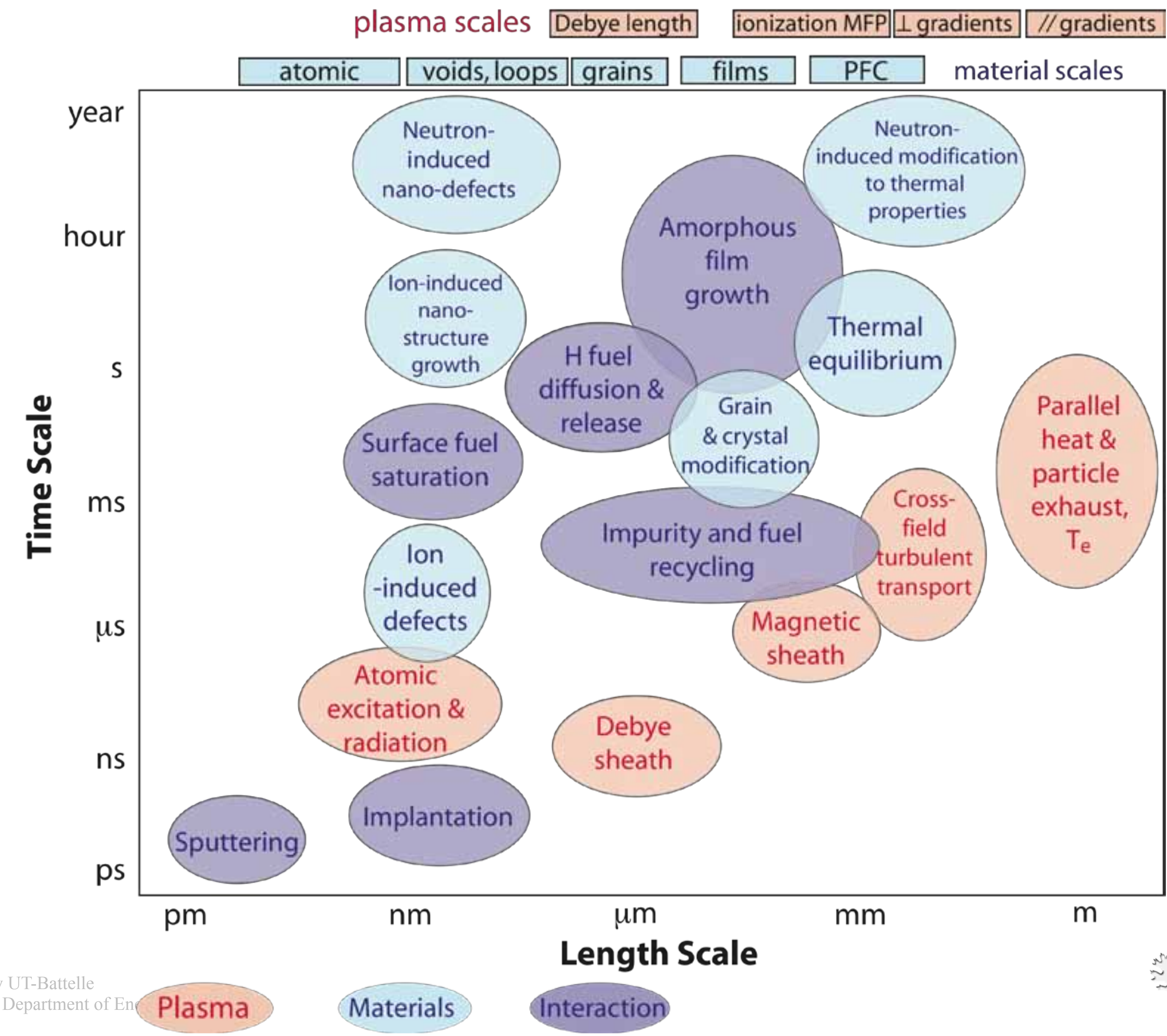
M. J. Baldwin et al., PSI 2008



T_s = 1120 K, Γ_{He+} = 4–6×10^{22} m^{-2}s^{-1}, E_{ion} ~ 60 eV

Recent observations of tungsten 'nano fuzz' highlight the complexity & importance of plasma surface interactions in controlling plasma performance (plasma impurity generation) & safety (tritium inventory, dust)

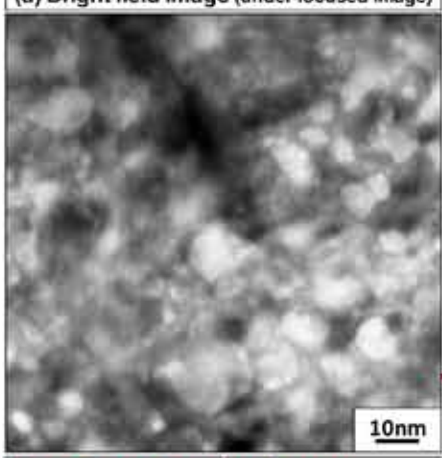
Plasma-material interactions are multiscale and interactive



W Temperature & PMI are coupled

~ 600 - 700 K | ~ 900 – 1900 K | > 2000 K

(a) Bright field image (under focused image)



PISCES-A: D_2-He plasma

M. Miyamoto et al. NF (2009) 065035

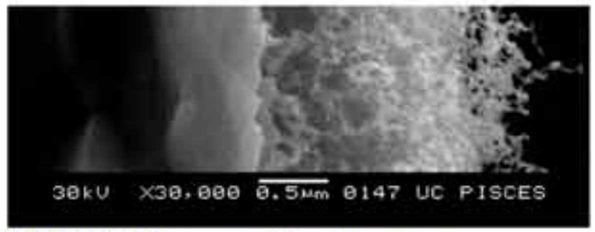
600 K, 1000 s, 2.0x10^{24} He$^+$/m^2, 55 eV He$^+$

- Little morphology
- He nanobubbles form
- Occasional blisters

PISCES-B: mixed D-He plasma

M.J. Baldwin et al, NF 48 (2008) 035001

1200 K, 4290 s, 2x10^{26} He$^+$/m^2, 25 eV He$^+$

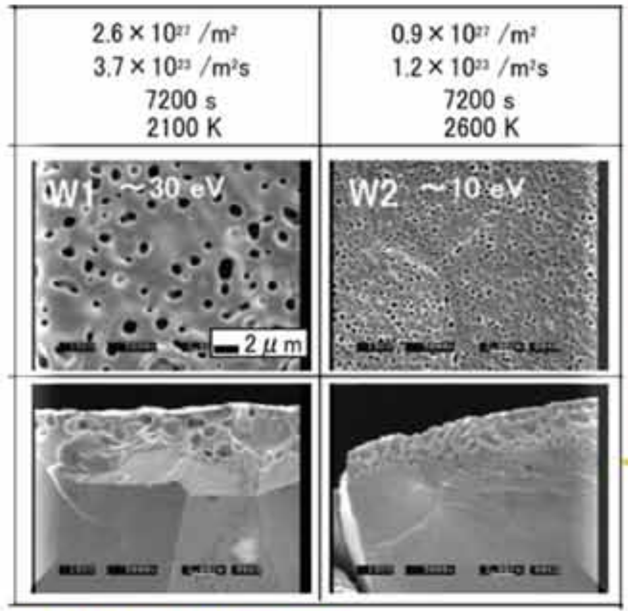


NAGDIS-II: pure He plasma

N. Ohno et al., in IAEA-TM, Vienna, 2006

1250 K, 36000 s, 3.5x10^{27} He+/m^2, 11 eV He+

- Surface morphology
- Evolving surface
- Nano-scale 'fuzz'



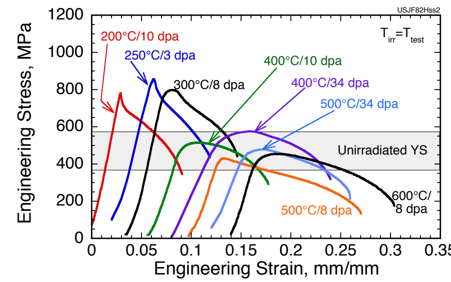
NAGDIS-II: He plasma

D. Nishijima et al. JNM (2004) 329-333 1029

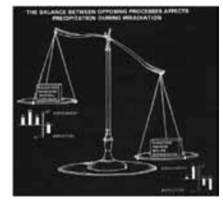
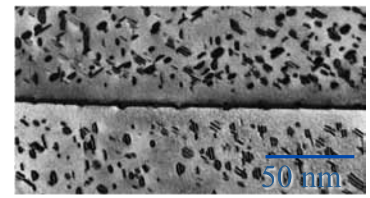
- Surface morphology
- Shallow depth
- Micro-scale

Radiation Damage can Produce Large Changes in Structural Materials

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

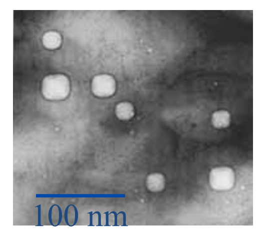


- **Phase instabilities from radiation-induced precipitation (0.3-0.6 T_M, >10 dpa)**

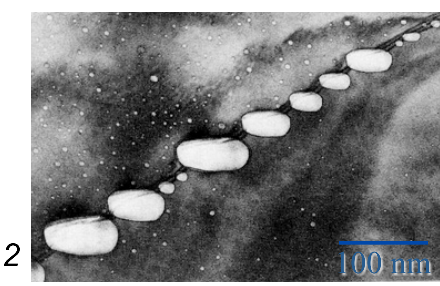



- **Irradiation creep (<0.45 T_M, >10 dpa)**

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



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

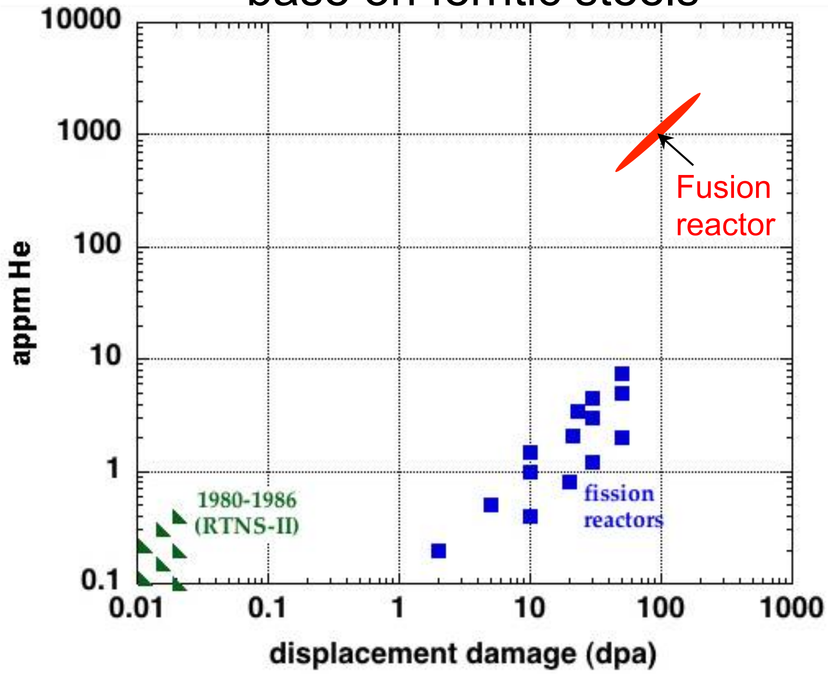


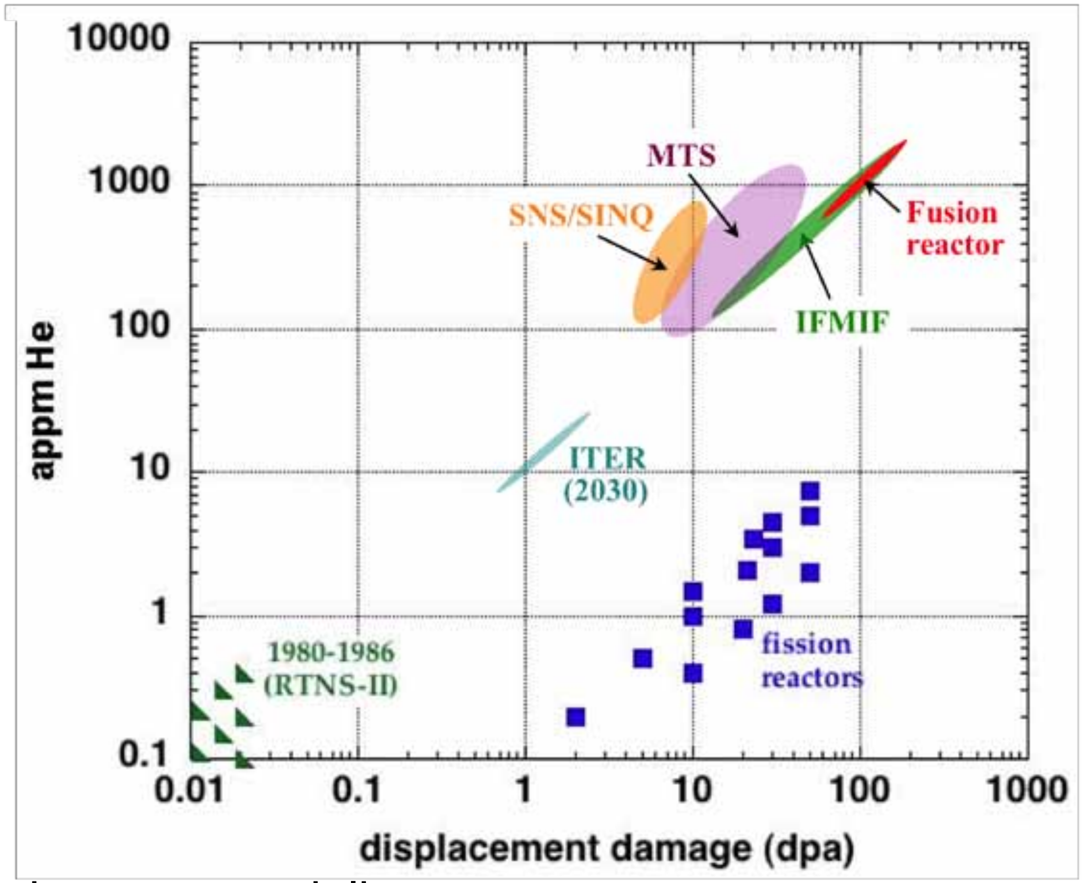
S.J. Zinkle, *Phys. Plasmas* 12 (2005) 058101; Zinkle & Busby, *Mater. Today* 12 (2009) 12

There are several options to close the current knowledge gap in fusion-relevant radiation effects in materials

- An intense neutron source (in concert with enhanced theory and modeling) is needed to improve understanding of basic fusion neutron effects and to develop & qualify fusion structural materials

Current knowledge base on ferritic steels



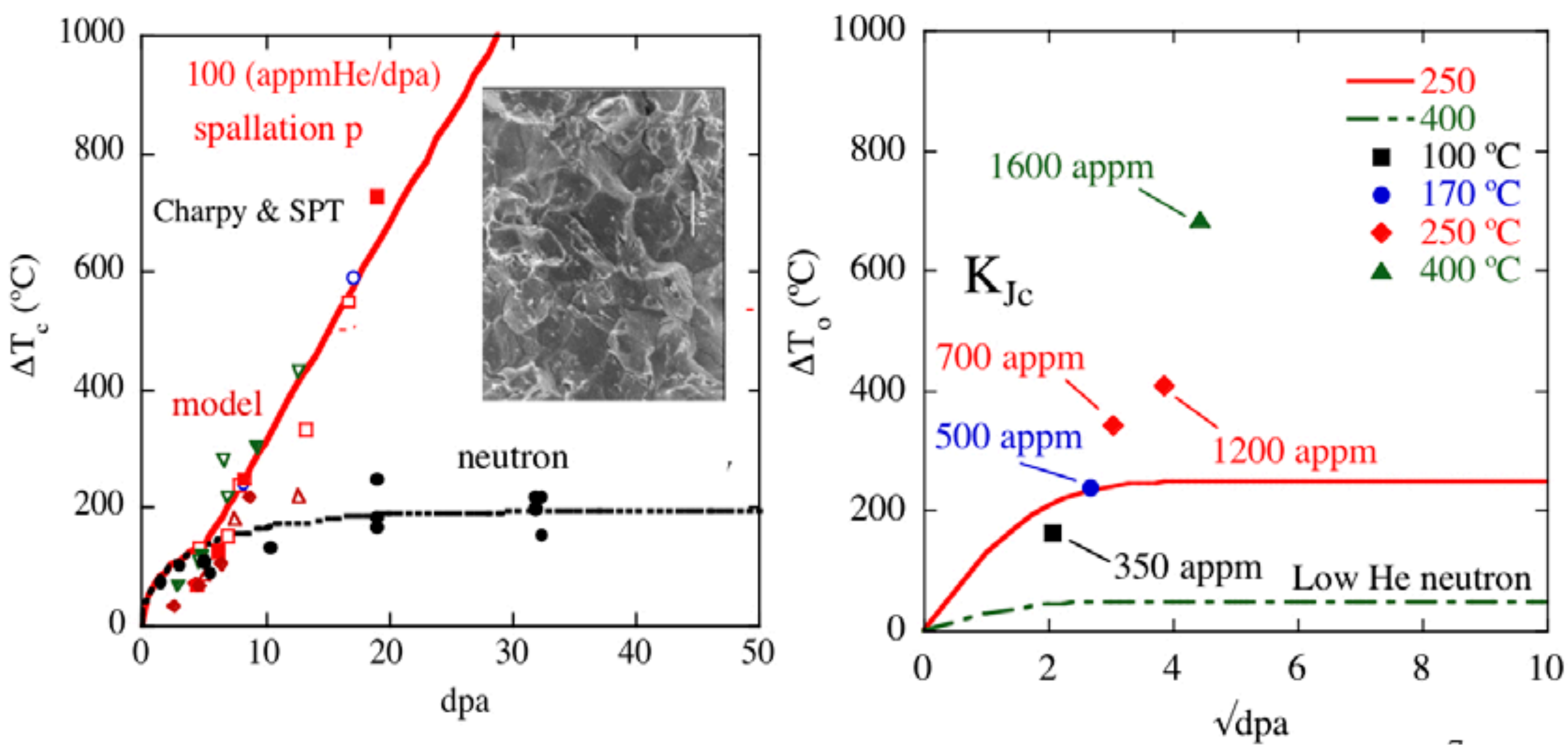


Option A: IFMIF + fission reactors +ion beams + modeling
Option B: robust spallation (e.g., MTS) + fission reactors + ion beams + modeling
Option C: modest spallation (e.g.,SNS/SINQ) + fission reactors + ion beams + modeling

Helium production during irradiation causes increased hardening and increase in DBTT in 9Cr steels

Helium Effects on Fast Fracture

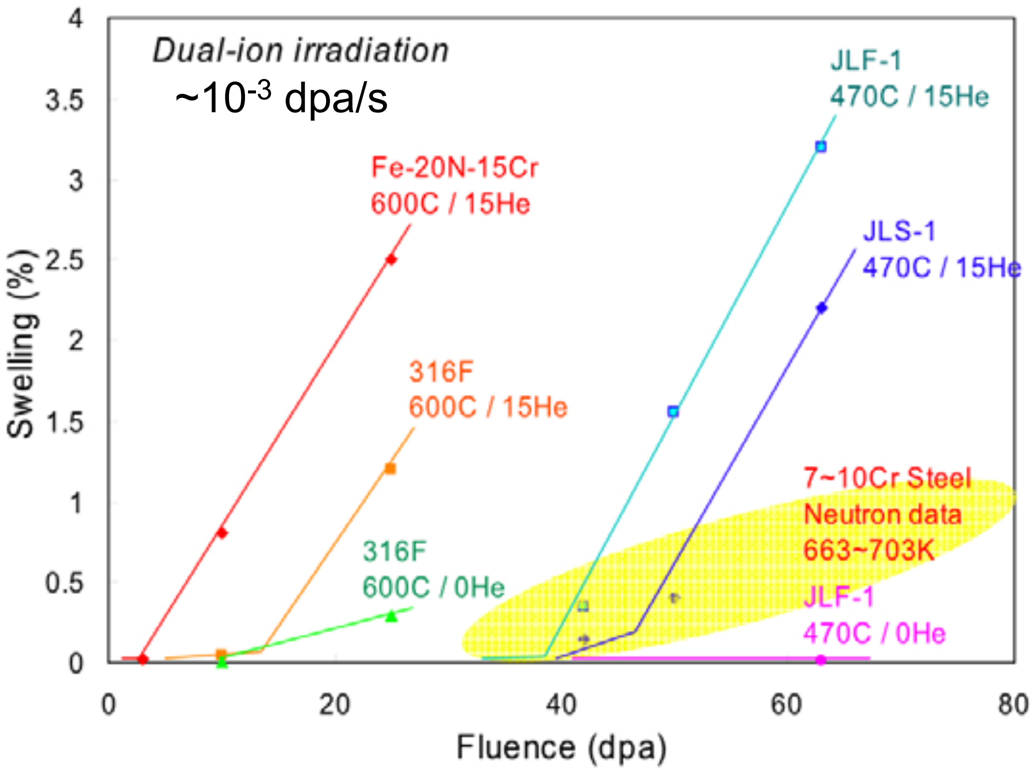
- Recent data confirm previous UCSB predictions of severe $\Delta\sigma_y$-He embrittlement & IG fracture > 500 appm He – high He data SPN irradiations Y. Dai



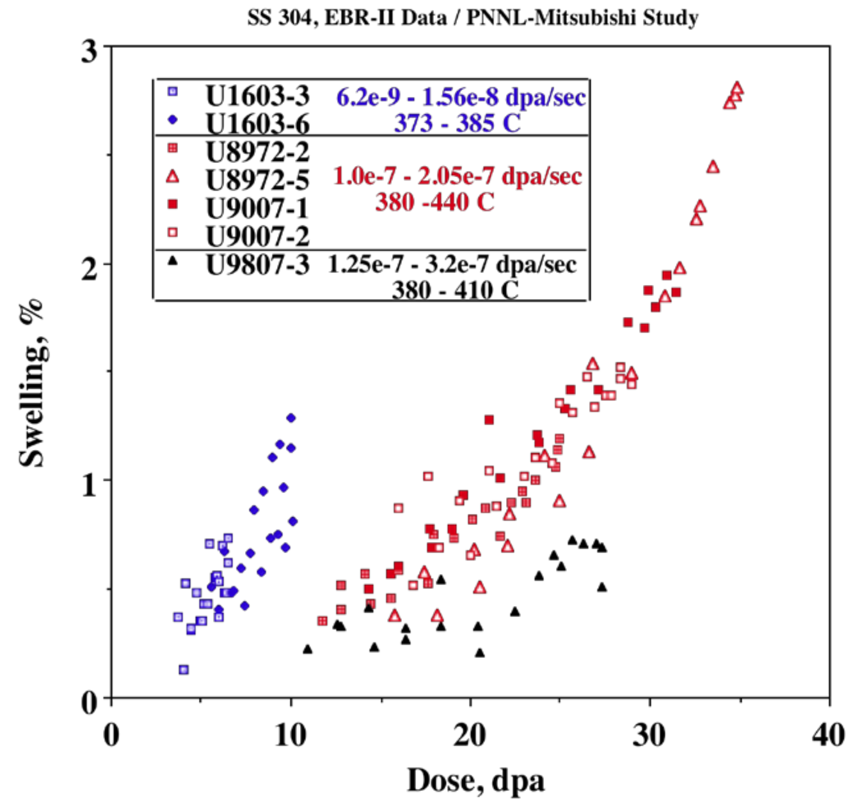
G.R. Odette et al., UCSB

Swelling of Ferritic/martensitic Steel is a Concern for Fusion-relevant He/dpa ratios

The onset of void swelling typically decreases with decreasing dose rate



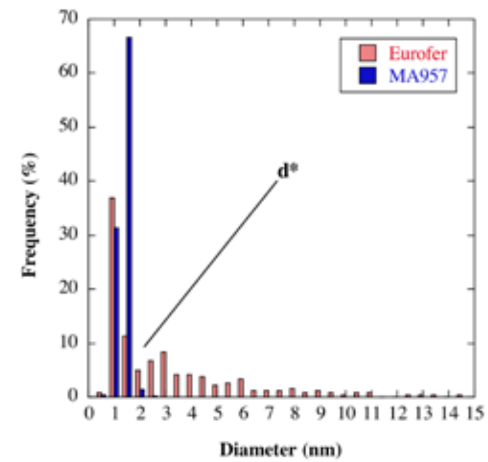
Y. Katoh et al., J.Nucl.Mat. 323 (2003) 251
H. Ogiwara et al. J.Nucl.Mat. (2002)



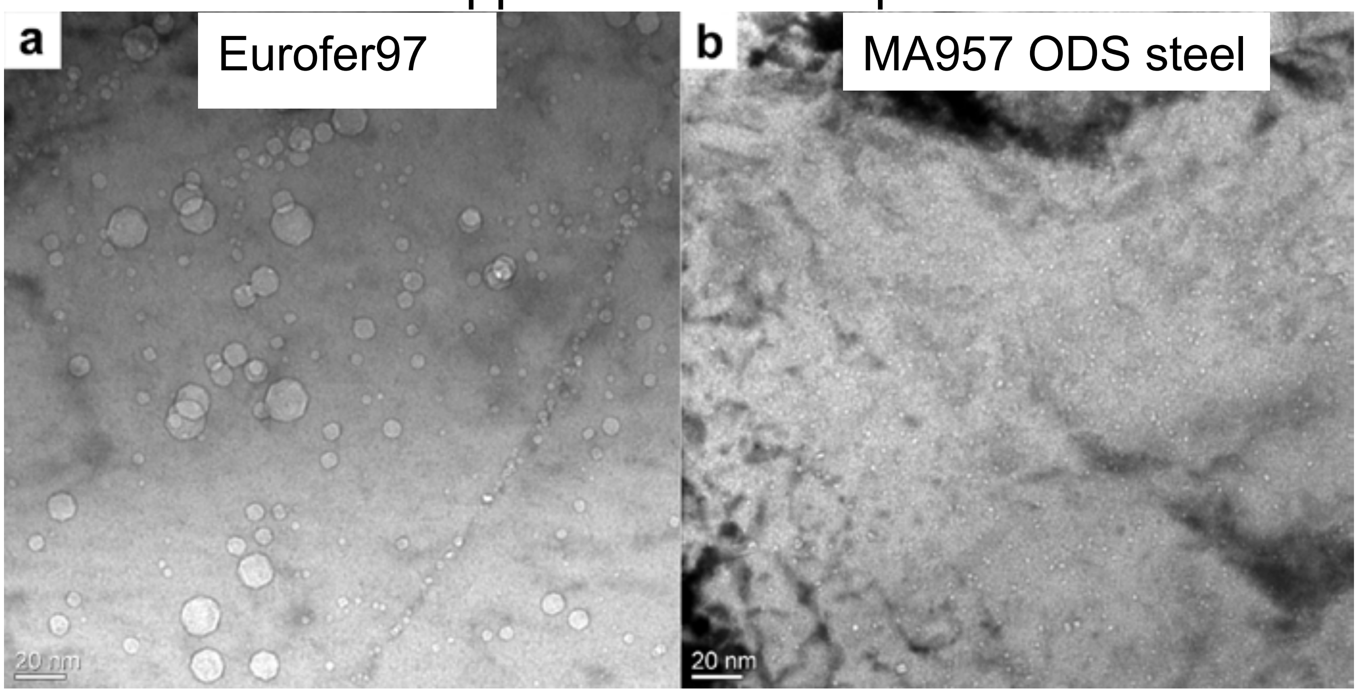
F.A. Garner, PNNL

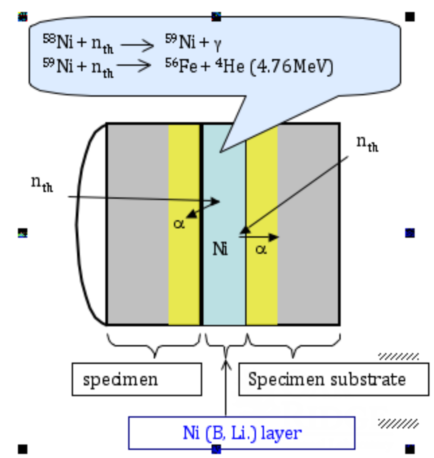
In situ He injector study during fission reactor (HFIR) irradiation

- MA957 (ODS steel) and Eurofer97 9%Cr ferritic/martensitic steel
- Eurofer97: 7.5×10^{22} cavities/m^3 with bimodal size distribution (1.3 nm bubbles & 5 nm voids - precursor to significant swelling)
- MA957: 7.8×10^{23} bubbles/m^3 & no voids



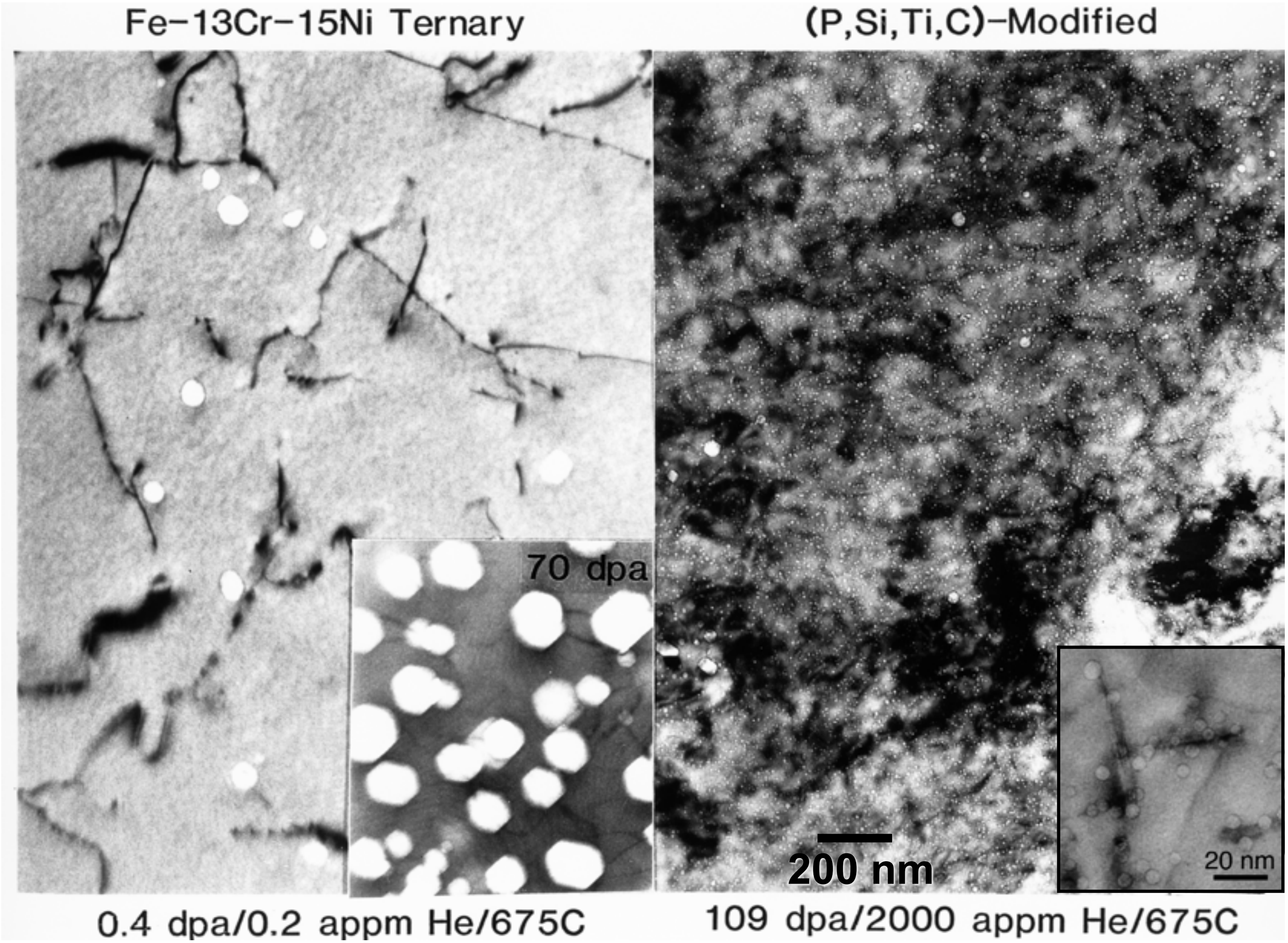
1400 appm He and 25 dpa at 500°C





Odette et al. ICFRM-15, Charleston, South Carolina

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

Materials science strategies to improve radiation resistance may lead to enhanced tritium retention

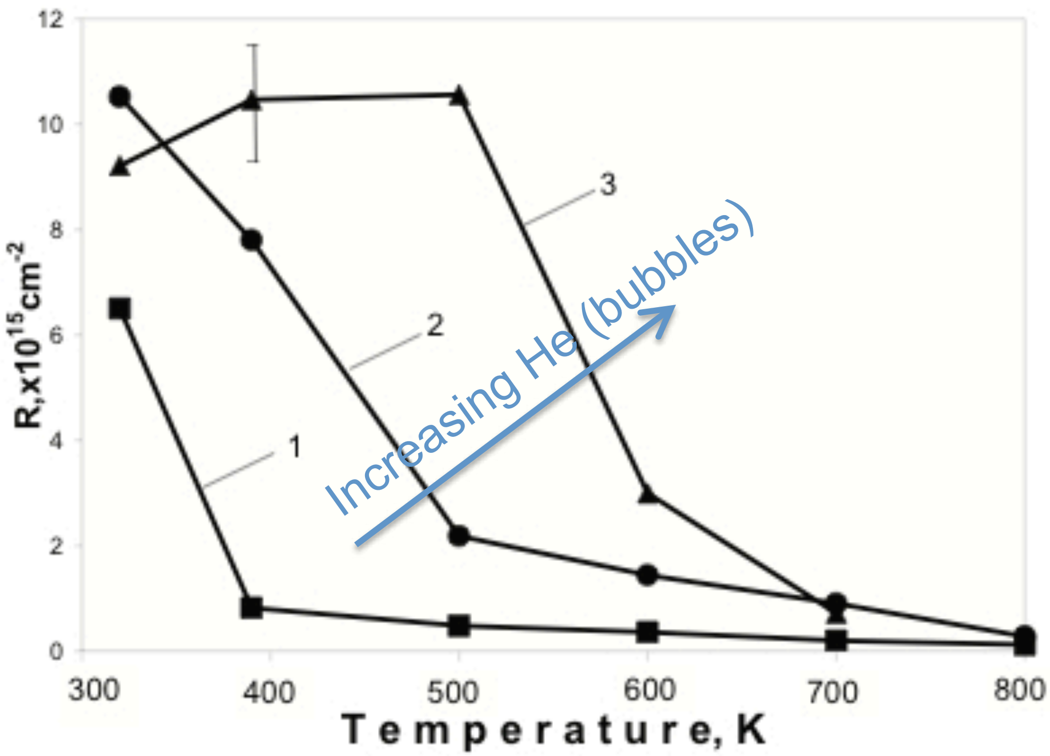
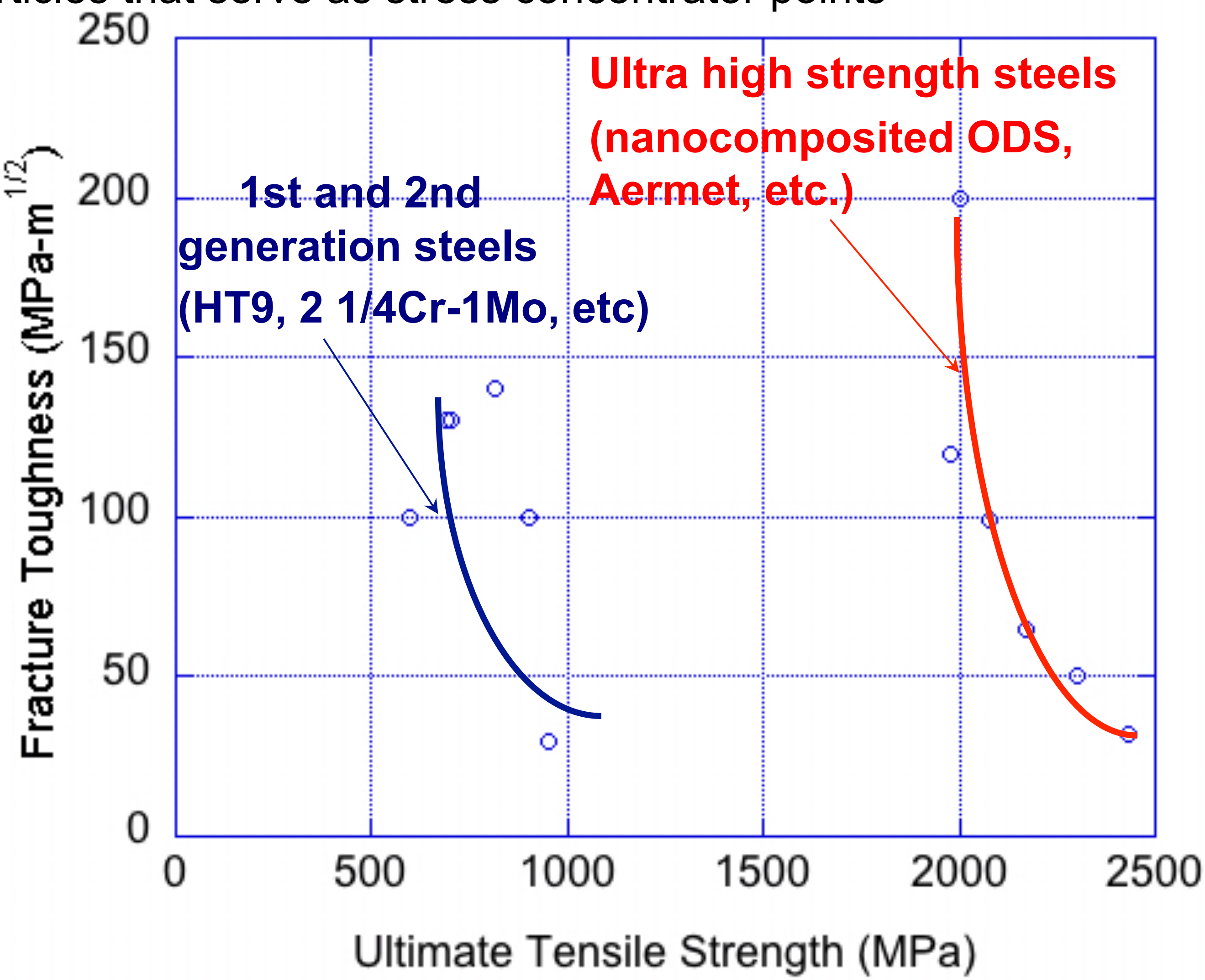


Fig. 8 Deuterium retention in 18Cr10NiTi steel implanted to $1x10^{16}$ cm^{-2} without helium (1) and with helium to $5x10^{15}$ (2) and to $5x10^{16} cm^{-2}$ (3).

G.D. Tolstolutskaya et al., 12th Int. Conf. on Environmental Degradation of Materials in Nucl. Power System (TMS, 2005), p. 411

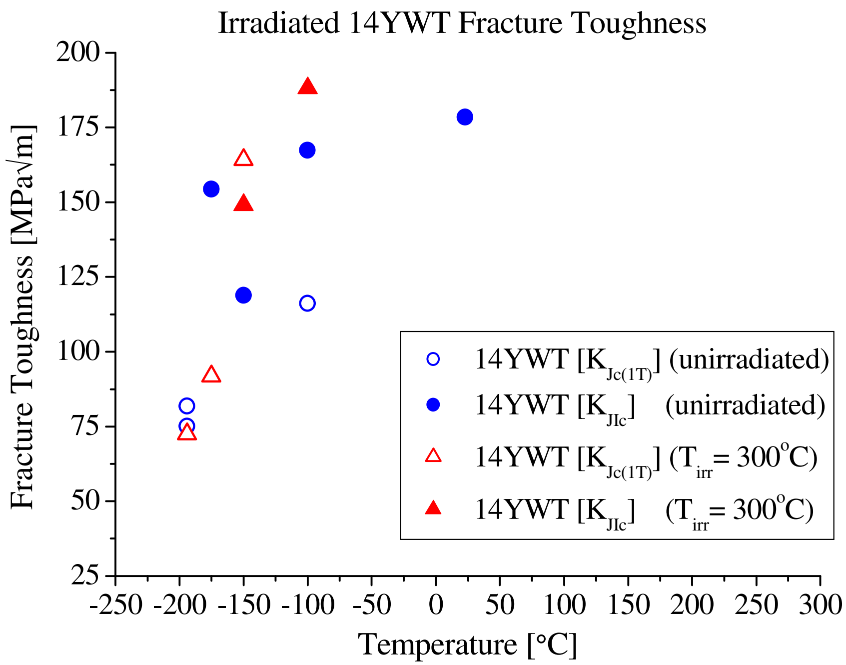
Recent progress in developing high-strength steels that retain high-toughness has been remarkable

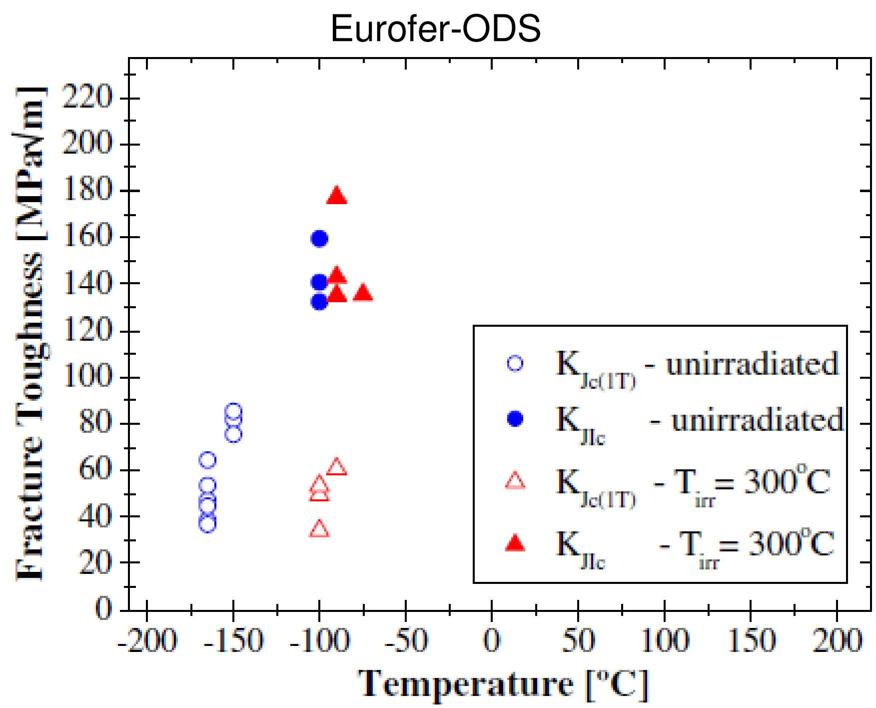
- Generally obtained by producing high density of nanoscale precipitates and elimination of coarse particles that serve as stress concentrator points



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

High Fracture Toughness Achieved in 14YWT ODS steel



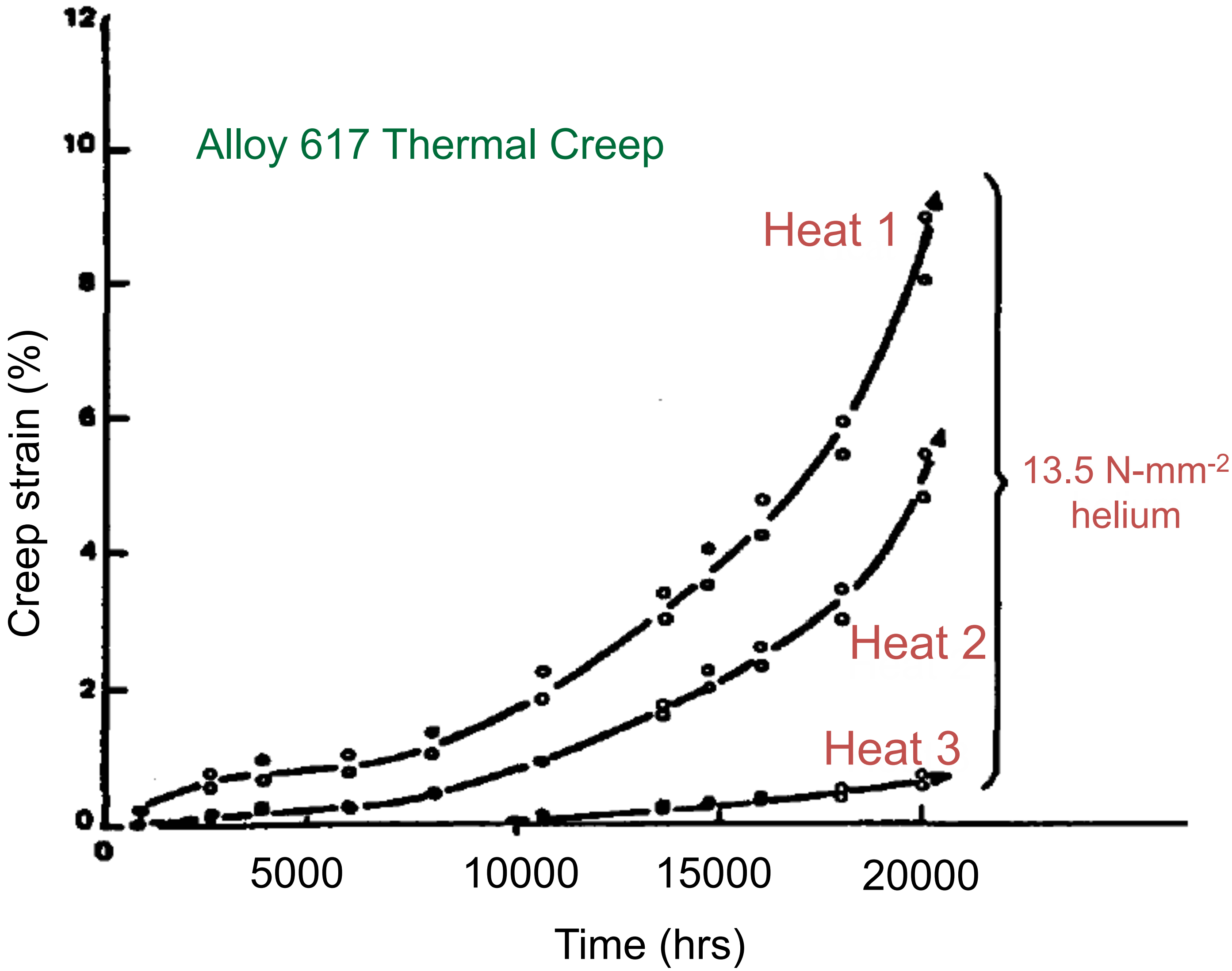


- Neutron irradiation to 1.5 dpa at 300ºC did not degrade the fracture toughness of 14YWT (vs. 85º shift in DBTT for EUROFER-ODS steel

- L-T Orientation
- Pre-cracked: crack length to width (a/w) ratio of 0.5
- Tested using the unloading compliance method (ASTM 1820-06)
- K_{Jc} for brittle cleavage calculated from critical J-integral at fracture, adjusted to 1-T reference specimen $K_{Jc(1T)}$
- K_{JIc} for ductile deformation behavior calculated from critical J-integral at onset of stable crack growth

D.A. McClintock et al., J. Nucl. Mater. 392 (2009) 353

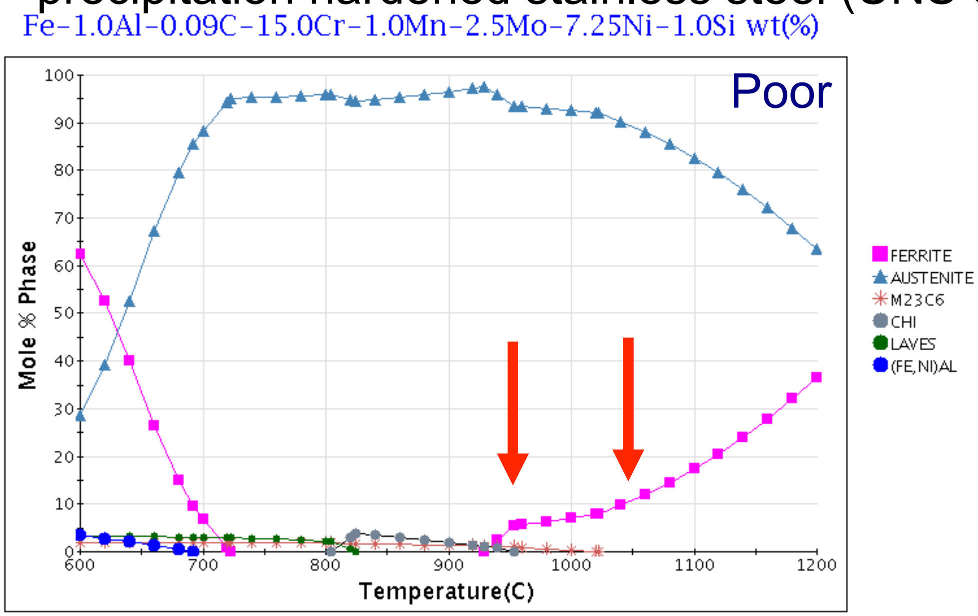
Heat to Heat Variability has been a Common Feature of Structural Alloys



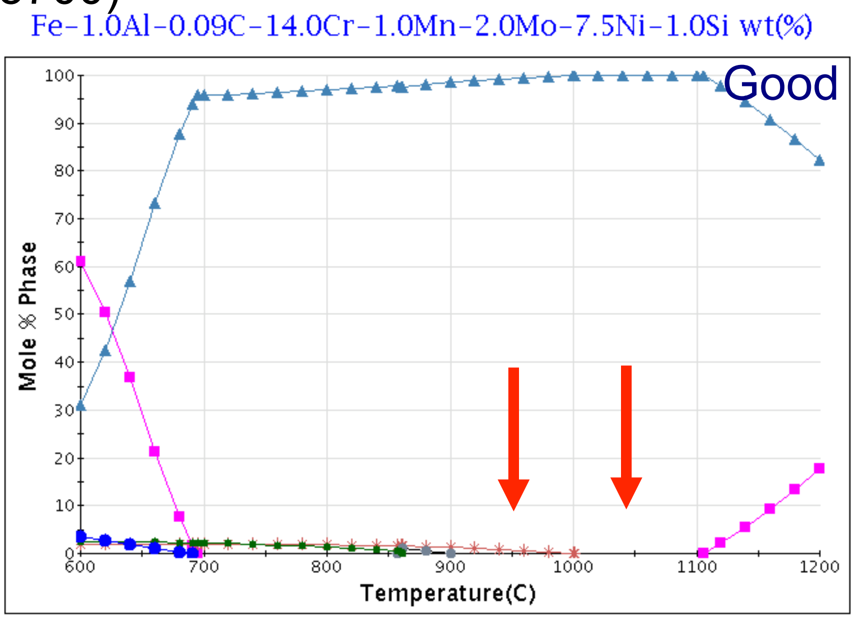
P.J. Ennis et al. 1984

Computational thermodynamics analysis indicates many commercial alloys are not optimized: example for precipitation hardened stainless steels

Both 15%Cr-7%Ni alloys are within allowable chemical composition for PH15-7 Mo precipitation hardened stainless steel (UNS S15700)



“average” Cr, Mo, Ni



“low” Cr, Mo and “high” Ni

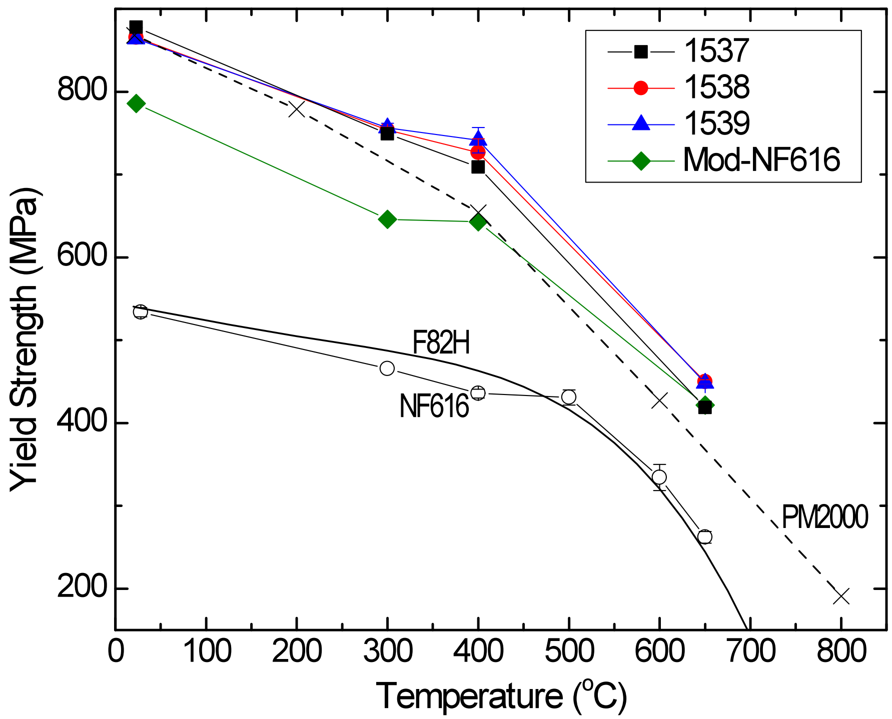
UNS S15700: 14.0-16.0 Cr, 6.50-7.75 Ni, 2.0-3.0 Mo

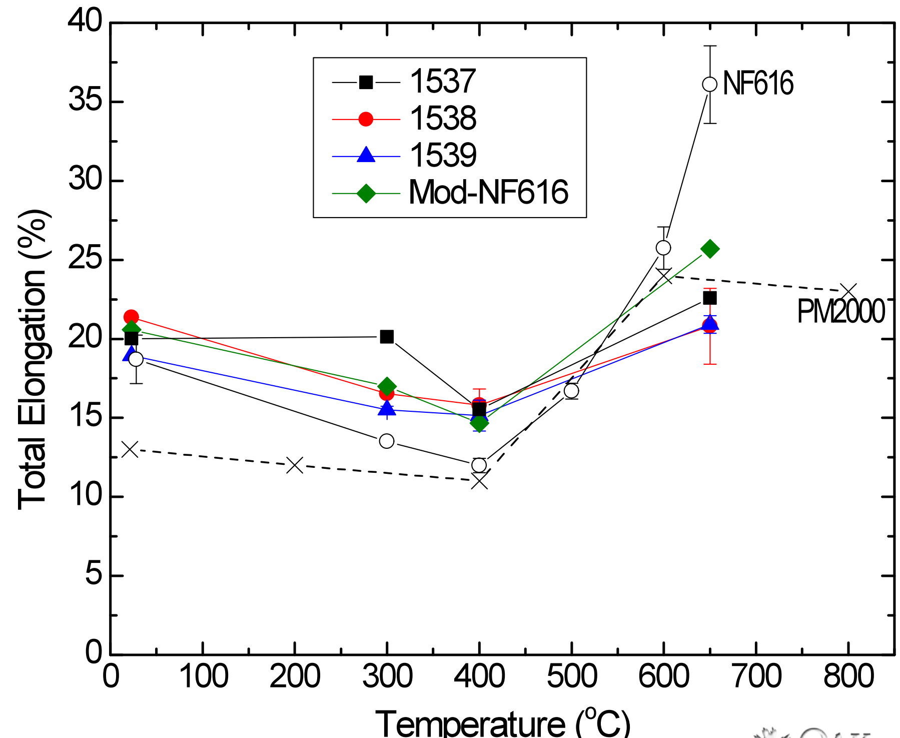
- **Within alloy specifications, large differences can be expected with standard heat treatment**
- **Computational thermodynamics calculations can lead to composition and heat treatment optimization**

J.M. Vitek

Tensile properties of new reduced activation ferritic martensitic steel

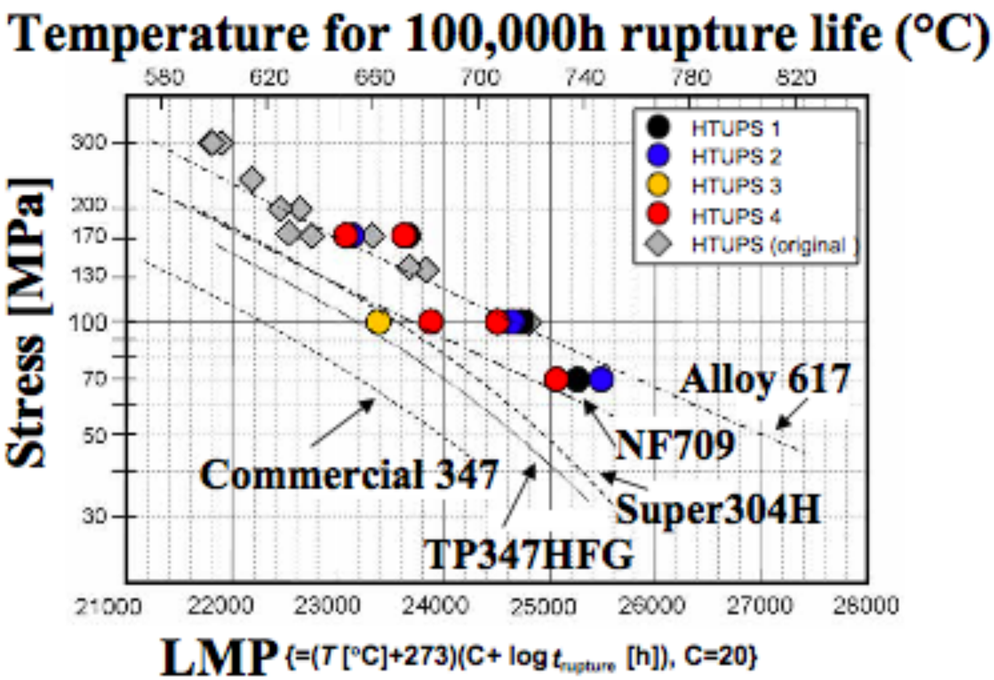
- Three experimental RAFM heats (1537, 1538, and 1539), together with a modified heat treatment of Gr.92 heat (mod-NF616), were investigated
  - The samples of the RAFM and optimized-Gr.92 heats showed tensile properties comparable to ODS steel PM2000.
  - The three RAFM heats showed similar yield strength, slightly greater than the optimized-Gr.92.

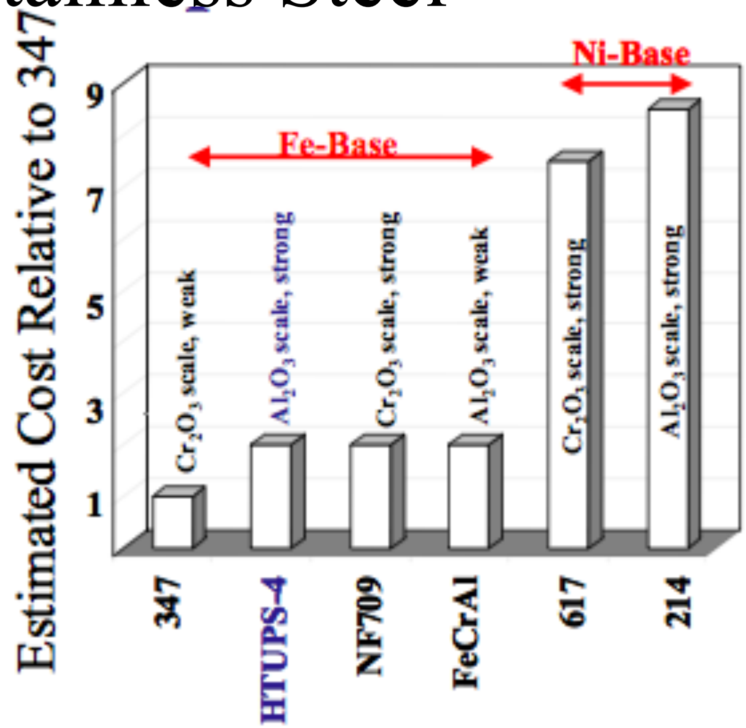


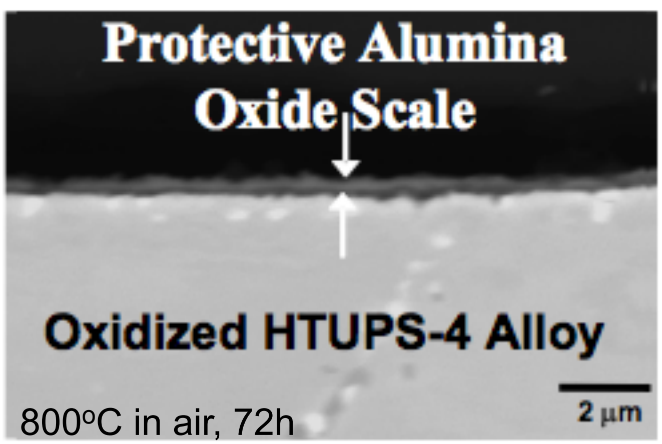


L. Tan & Y. Yamamoto, ORNL

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





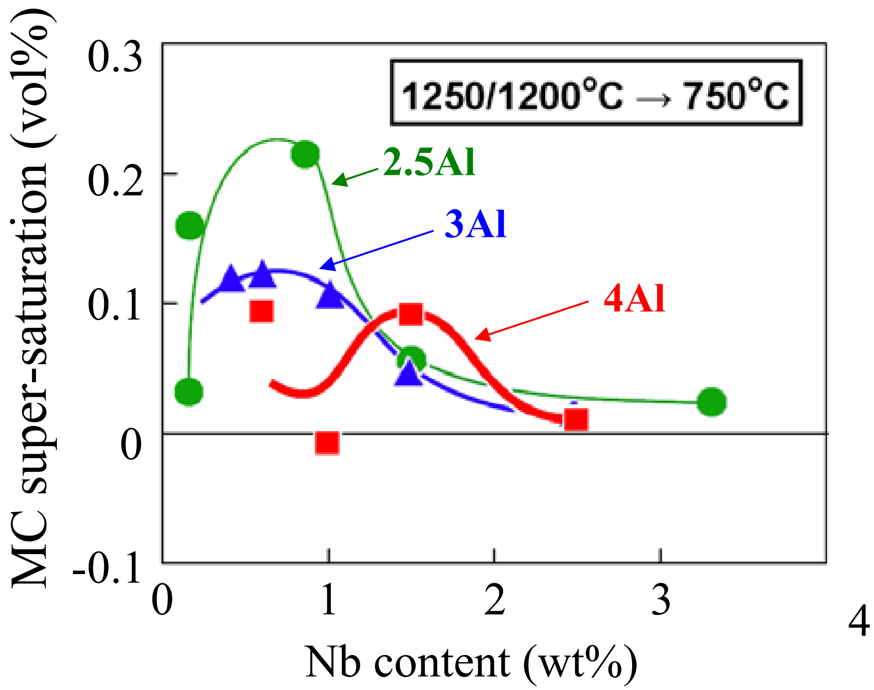


- Designed for 600-800°C structural use under aggressive oxidizing conditions
  - -superior oxidation resistance to conventional chromia-forming alloys
- Comparable cost to current heat-resistant austenitic stainless steels

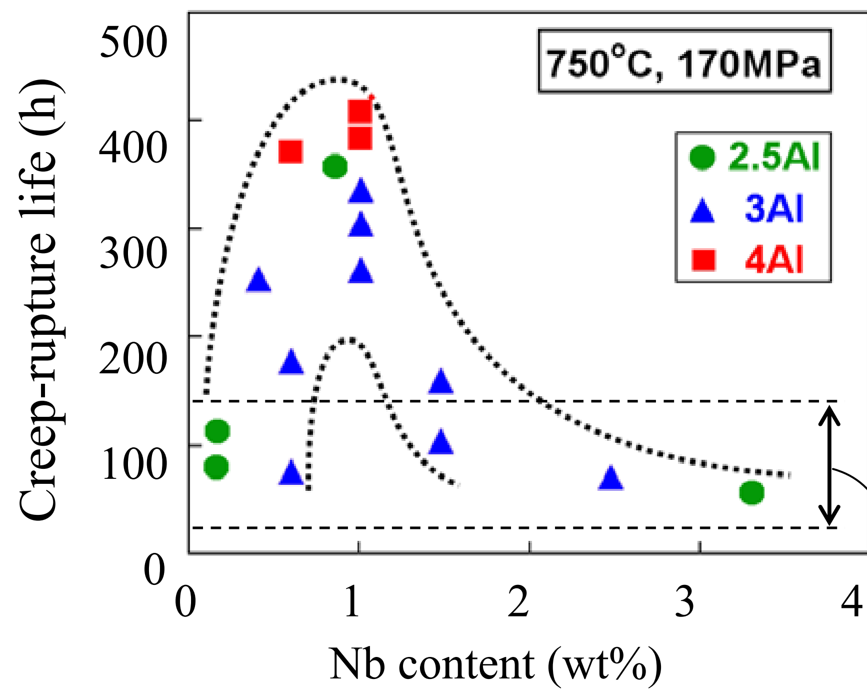
Y. Yamamoto, M.P. Brady et al., Science 316 (2007) 433

Computational Thermodynamics Guide Optimal NbC Nanocarbide Precipitate Strengthening

Calculated Volume fraction of super-saturated nanocarbide



Creep-rupture lives of AFA alloys
(Fe-20Ni-14Cr+Nb,C base)

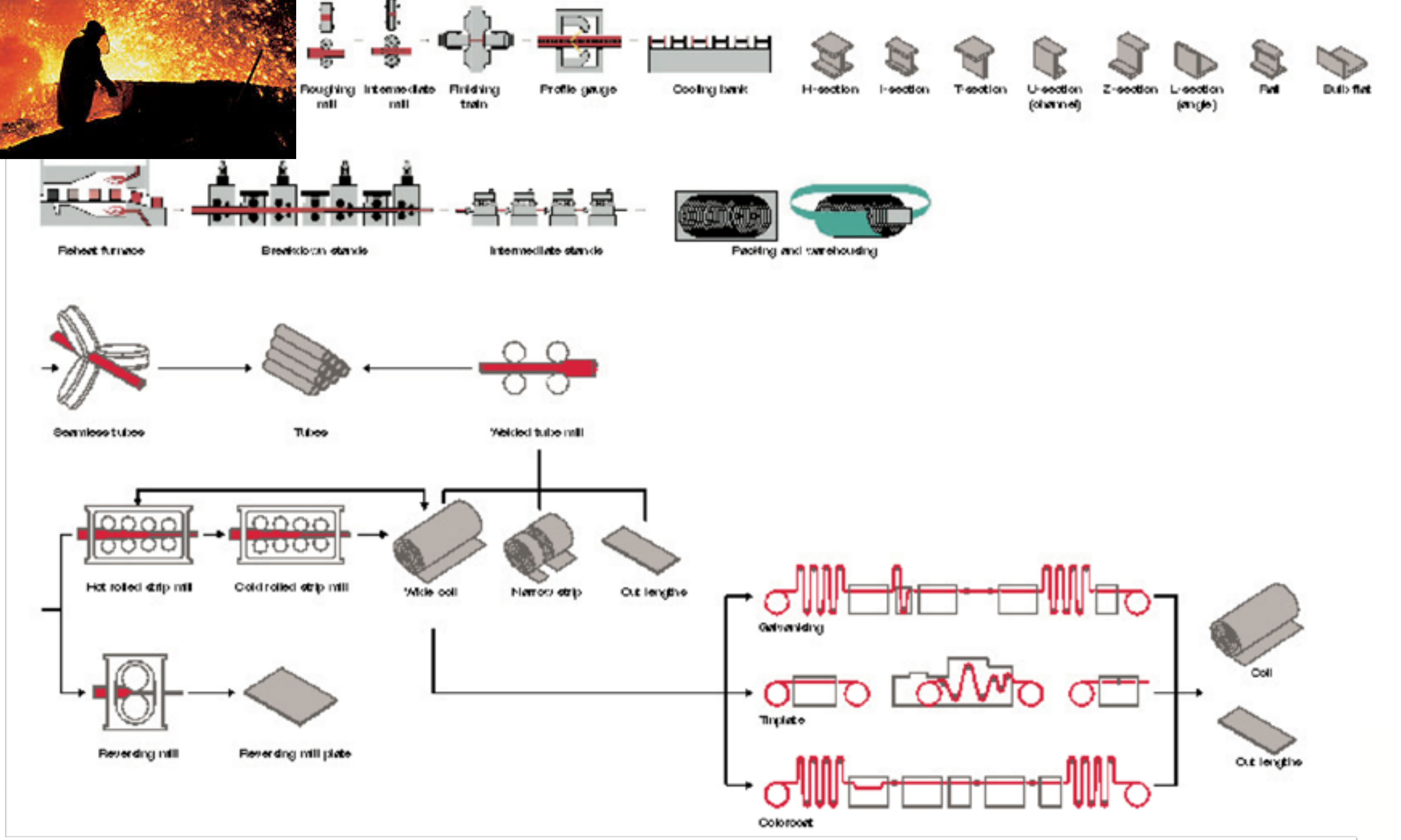


(Conventional Heat-Resistant Stainless Steels

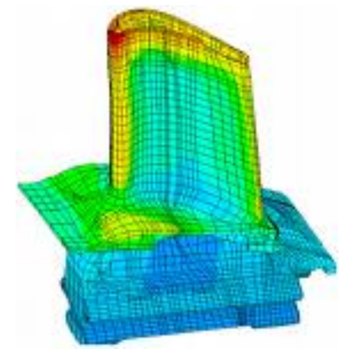
- Computational design sped development of alumina-forming austenitic (AFA) stainless steels combining superior creep and corrosion resistance

M.P. Brady, Y. Yamamoto et al.

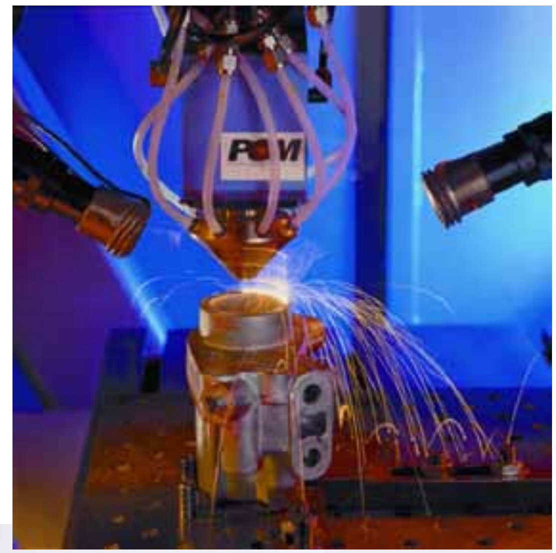
Conventional steelmaking involves numerous steps



Direct Manufacturing of Complex Components



- **Revolutionary manufacturing technologies in which feed material is added at specific locations to build net-shaped components from computer models**
  - **Electron Beam Melting**
  - **Direct Metal Deposition**
  - **Ultrasonic Additive Manufacturing**



- **Numerous benefits over conventional processing techniques**
  - **Significantly reduced waste material**
    - **Cost savings for complex fabricated components**
  - **Component Design Optimization**
  - **Geometrically Impossible Designs**

Advanced Manufacturing Techniques offer the potential to enable rapid fabrication of complex geometries

Examples of additive manufacturing technologies

Electron beam melting	Ultrasonic additive manufacturing	Laser metal deposition	Fused deposition modeling
• Precision melting of powder materials • Processing of complex geometries not possible through machining	• Simultaneous additive and subtractive process for manufacturing complex geometries • Solid-state process allows embedding of optical fibers and sensors	• Site-specific material addition • Application of advanced coating materials for corrosion and wear resistance • Repair of dies, punches, turbines, etc.	• Precision deposition of thermoplastic materials • Development of high-strength composite materials for industrial applications • Transformation of rapid prototyping to rapid manufacturing

Consideration of function of as-fabricated component highlights the potential tradeoffs between conventional and advanced manufacturing processes

	Strength	Radiation resistance	Heat flux capacity	Fabrication complexity and cost
Conventional manufacturing	+	+	-	-
Additive manufacturing	-	-	+	+

Numerous Scientific Grand Challenges Still Need to be Resolved

Examples for Harness Fusion Energy

- **Develop a predictive capability for the highly non-linear thermo-fluid physics and the transport of tritium and corrosion products in tritium breeding and power extraction systems.**
  - **Can tritium be extracted from hot PbLi with the required high efficiency to limit tritium permeation below an acceptable level?**
  - **Can we simulate the 3-D MHD effects in flowing liquid breeders to the degree necessary to fully predict the temperature, temperature gradients and stress states of blanket components and materials?**

FESAC Report DOE/SC-0149, Feb. 2012

Numerous Scientific Grand Challenges Still Need to be Resolved

Examples for Conquering Degradation to Materials and Structures

- **Understand and devise mitigation strategies for deleterious microstructural evolution and property changes that occurs to materials exposed to high fusion-neutron fluence (dpa and H, He transmutations)**
- **Comprehend and control tritium permeation, trapping, and retention in neutron radiation-damaged materials**
  - **Are materials development strategies for fusion neutron radiation resistance incompatible with minimizing tritium trapping?**
- **Understand the fundamental mechanisms controlling chemical compatibility of materials exposed to coolants and/or breeders in strong temperature and electro-magnetic fields.**
  - **How do MHD and ionization effects impact corrosion**

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Numerous Scientific Grand Challenges Still Need to be Resolved

Examples for Taming the Plasma-Materials Interface

- **Understand and mitigate synergistic damage from intense fusion neutron and plasma exposure.**
  - **How does the coupling of intense heat flux, high temperature, and associated thermal gradients provide failure modes for plasma facing components?**
- **Understand, predict and manage the material erosion and migration that will occur in the month-to-year-long plasma durations required in FNSF/DEMO devices, due to plasma-material interactions and scrape-off layer plasma processes.**
  - **Can the boundary plasma and plasma-material interface be sufficiently manipulated to ensure that year-long erosion does not exceed the material thickness ~5-10 mm anywhere in the device?**

FESAC Report DOE/SC-0149, Feb. 2012

Conclusions

- Experience gained from development of fission energy provides useful insight for fusion (lessons learned/ best practices)
- Next steps for addressing three overarching challenges to materials for fusion technology might involve utilization of new/refurbished medium-scale facilities
  - Fundamental processes and length scales in plasma-materials interactions
  - Several fundamental materials degradation phenomena are not yet well understood (e.g., void swelling at fusion-relevant He/dpa and dose rate; tritium binding energy to cavities and nanoscale clusters; stress-enhanced defect accumulation…)
  - A rational focusing of breeding blanket and T_2 transport/recovery options would be helpful to accelerate the development of fusion energy
- Utilization of a systems approach is important for prioritizing scope and schedule of materials R&D activities
  - Reduced activation mandate encompasses both waste disposal/recycling and off-normal transient operations; Impact of coolant/breeding material, etc.