Scientific & Technical Challenges for Development of Materials for Fusion

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Briefing for Dr. Edmund Synakowski
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U.S. Department of Energy
Germantown, MD
December 9, 2009

Pacific Northwest
NATIONAL LABORATORY

Presentation Overview

- Executive summary
- Overview of the **uniquely** demanding fusion environment.
- Radiation damage fundamentals.
- Materials challenges for IFE and synergy with MFE.
- Synergies with advanced fission and BES research portfolios.
- Scientific and technical challenges for development of fusion materials:
  - **Impact of He-Rich Environment on Neutron Irradiated Materials.**
  - **Science Based High-Temperature Design Methodology.**
  - **Plasma Facing Materials Challenges**
  - **Breaking the High Strength-Low Toughness/Ductility Paradigm.**
- Options for fusion materials irradiation experiments:
  - A fusion relevant neutron source is needed for:
    - Exploring new phenomena and acquiring an experimental understanding for development of models of materials degradation in the fusion environment.
    - An experimental database on structural materials needed to qualify and eventually license and secure funding for fusion demonstration reactor.
- Path forward for the next 10 years.

Scientific & Technical Challenges for Fusion Materials are Significant

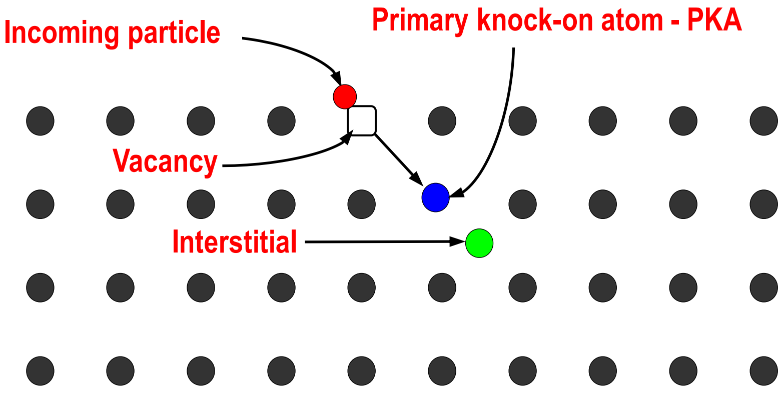
- Fusion materials must function in a uniquely hostile environment that includes combinations of high temperatures, reactive chemicals, large time-dependent thermal-mechanical stresses, and intense damaging radiation.
- The task of designing, constructing and operating a fusion energy system with materials and components that survive the **extreme** fusion environment and meet objectives for safety, environment and performance is an unprecedented challenge, even without radiation damage.
- Greenwald Tier 1 Issue: Understand the basic materials science for fusion breeding blankets, structural components, plasma diagnostics and heating components in high neutron fluence areas. *Solutions not in hand, major extrapolation from current state of knowledge, need for qualitative improvements and substantial development for both short and long term.*
- *Structural materials significantly determine fusion energy feasibility, but many other materials (e.g. breeding, insulating, superconducting, plasma facing and diagnostic) must be successfully developed for fusion to be a technologically viable power source.*
    - Current program is focused on structural materials due to feasibility considerations and resource limitations.

Top Level Requirements & Desirable Characteristics for Fusion Materials

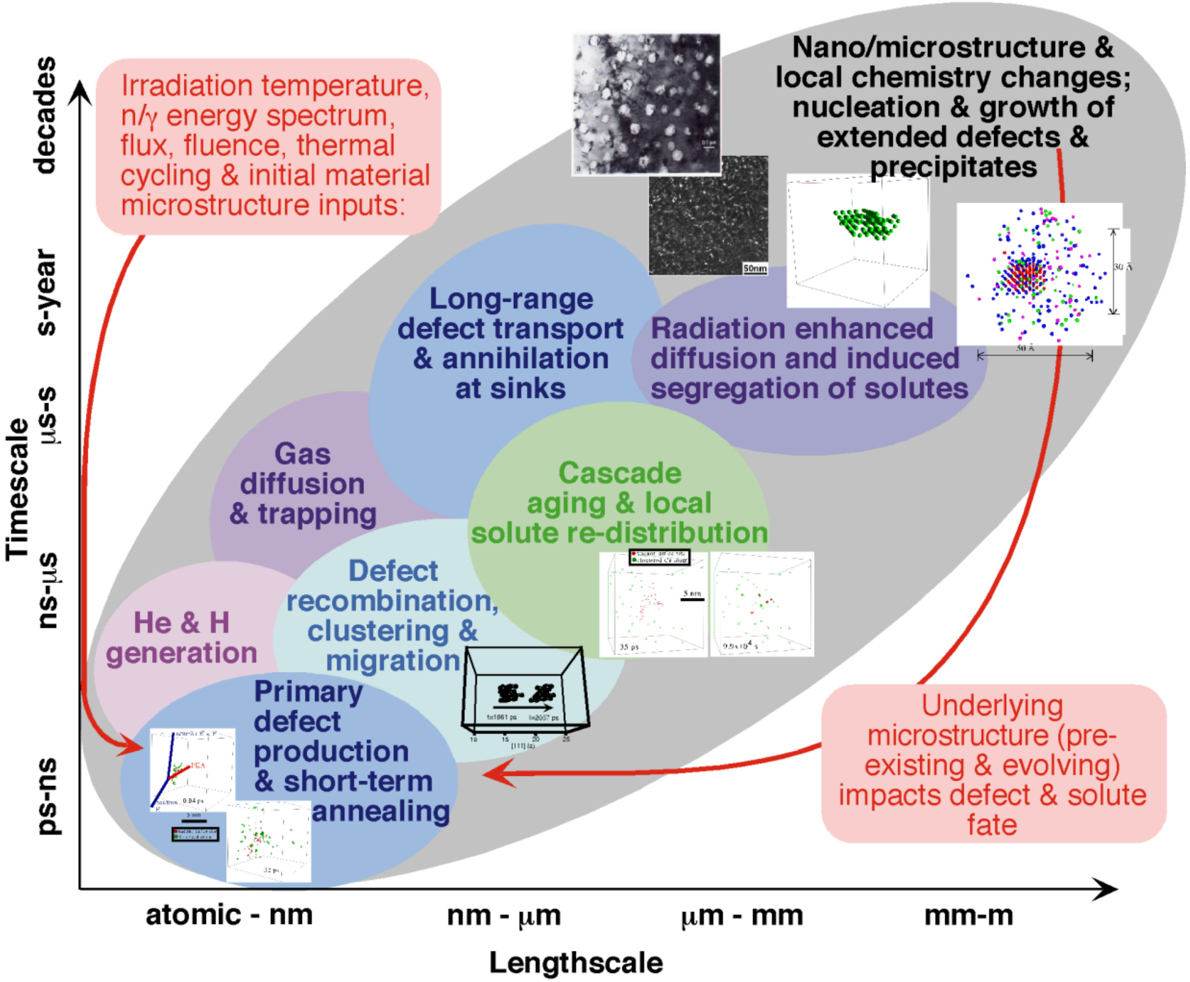
- Materials that serve in the fusion environment for acceptably long lifetimes.
- Materials that are dimensionally stable and retain a host of performance sustaining properties in the presence of radiation damage.
- Materials capable of operating at high-temperature (for high power conversion efficiency) and maintain a wide operating temperature window (minimum set by radiation-induced embrittlement).
- Low-activation materials so fusion can meet its environmental objective.
- First-wall and other PFC materials that are compatible with plasma requirements.
- Tritium breeding and other blanket materials that meet the needs for tritium production and power extraction.
- Blanket materials and coolants that are compatible and corrosion resistant.
- Integrated and validated material/component/chamber/plant systems that can meet licensing and safety requirements during design and operating phases.

Radiation Damage Fundamentals

- Material properties such as strength, ductility, fracture toughness and dimensional stability are determined by microstructure.
  - Grain size, other internal interfaces
  - Dislocation structures
  - Size and density of second phases
- Irradiation with energetic particles leads to atomic displacements:
  - Neutron exposure can be expressed in terms of the number of atomic displacements per atom – dpa
  - Lifetime exposures range from ~0.01 to >100 dpa (0.001 – 10 MW-y/m^2).
  - Atomic displacements lead to microstructural evolution, which results in substantial mechanical and physical property degradation.
- One key to achieving highly radiation resistant materials is to enhance vacancy-interstitial recombination or self-healing.



Radiation-Induced Microstructural Evolution is a Multiscale Phenomenon



Irradiation temperature, n/γ energy spectrum, flux, fluence, thermal cycling & initial material microstructure inputs:

Nano/microstructure & local chemistry changes; nucleation & growth of extended defects & precipitates

Long-range defect transport & annihilation at sinks

Radiation enhanced diffusion and induced segregation of solutes

Gas diffusion & trapping

Cascade aging & local solute re-distribution

He & H generation

Defect recombination, clustering & migration

Primary defect production & short-term annealing

Underlying microstructure (pre-existing & evolving) impacts defect & solute fate

Timescale: ps-ns, ns-μs, μs-s, s-year, decades

Lengthscale: atomic - nm, nm - μm, μm - mm, mm-m

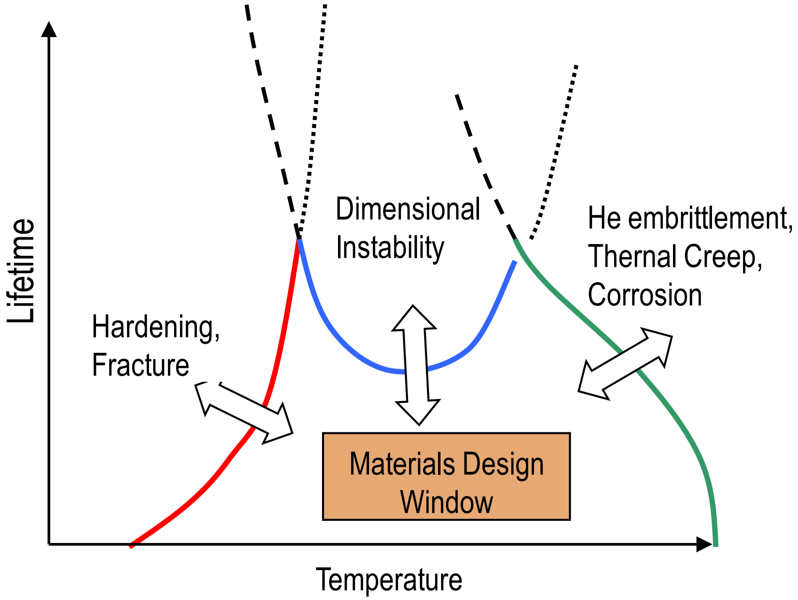
Radiation damage produces atomic defects and transmutants at the shortest time and length scales, which evolve to produce changes in microstructure and properties through multiscale - multiphysics processes that involve many variables and many degrees of freedom.

Effects of Fusion Environment on Bulk Material Properties

High dpa and He (unique to fusion) coupled with high stresses result in:

- Microstructure and property changes over long time.
  - Voids, bubbles, dislocations and phase instabilities.
  - Dimensional instabilities (swelling and irradiation-thermal creep).
  - Loss of strain hardening capability.
  - He embrittlement ay low and high temperatures.
  - Fatigue, creep-fatigue, crack growth.
  - Enhanced corrosion, oxidation and impurity embrittlement (refractories).
  - Transient and permanent changes in electrical and thermal properties.

High He may narrow or even close the window

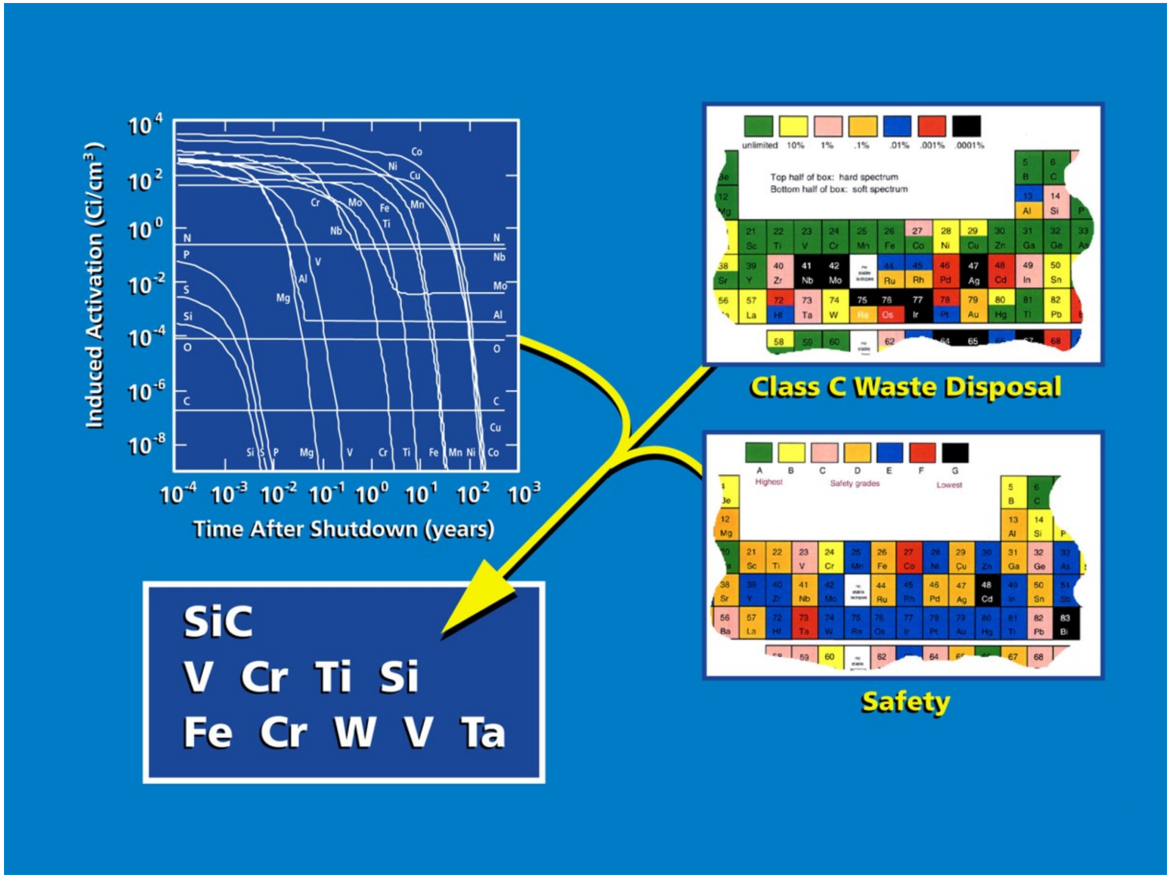


N. Ghoniem & B.D. Wirth, 2002

Low-Activation Structural Materials for Fusion

None of the current reduced or low activation fusion materials existed 15 years ago.

- Materials strongly impact economic & environmental attractiveness of fusion power - basic feasibility.
- Many materials are not suitable for various reasons.
- Based on safety, waste disposal and performance considerations, the three leading candidates are:
  - RAF/M and NFA steels
  - SiC composites
  - Tungsten alloys



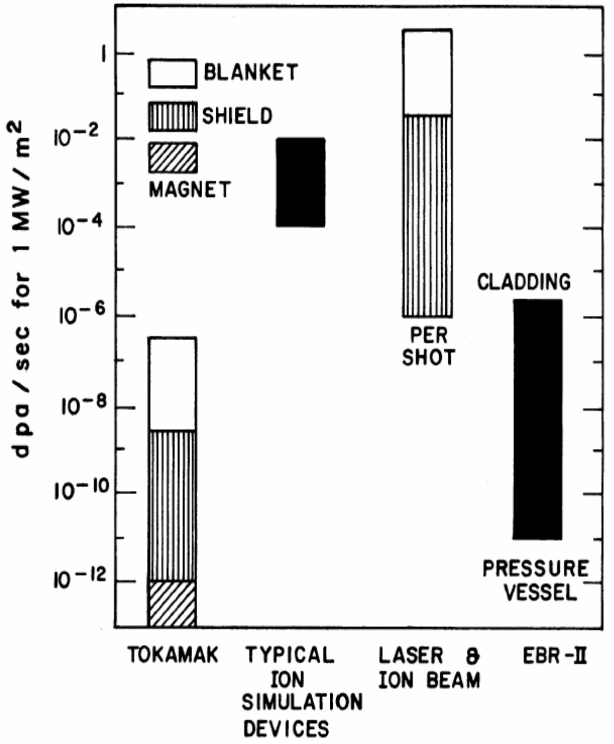
MFE and IFE Share Many Materials Science Issues and Needs

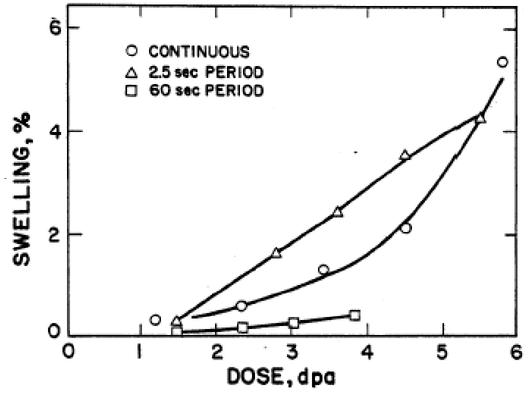
Both MFE and IFE:

- Have first-wall and blanket materials that suffer radiation damage from high-energy neutrons.
    - Displacement damage and gas production.
- Need modeling and experiments to determine acceptable limits of radiation damage.
- Seek materials that are more radiation damage resistant to give longer service life.
- Seek to develop and use low-activation structural materials.
- Desire materials capable of high-temperature operation to permit high power conversion efficiency.
- Need materials that can withstand high heat fluxes and conduct power to the coolant.
- Need materials that can resist corrosion by aggressive chemical species.
- *Fusion materials researchers participated in the HAPL program (e.g. modeling, W-armor development and thermo-mechanical fatigue, dielectric mirrors).*

IFE Faces Unique Challenges and Opportunities

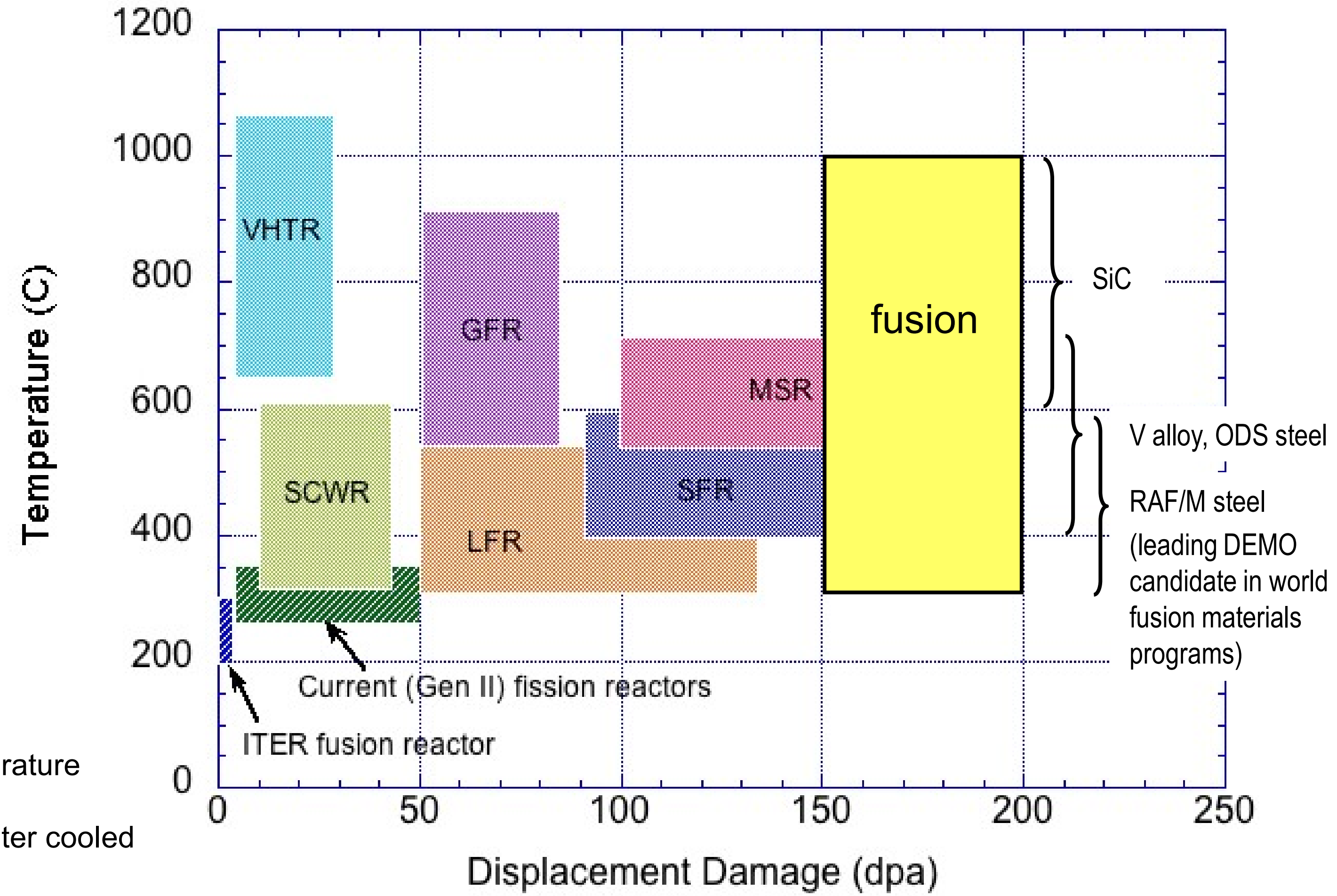
- The first-wall must tolerate intense pulses of ions and x-rays from the target.
  - Threat details depend strongly on target design.
  - Various design solutions have been explored (e.g., W-armor, gas fill, thin wetted wall).
- Instantaneous neutron damage rate is much higher in IFE.
  - Need to understand how this affects material response.
- Laser IFE must deal with neutron damage to final optics, but uses distance, design and material selection to find solutions.
- IFE wall response does not effect the plasma, but conditions for beam propagation and target injection must be re-established.
- Most IFE designs are not constrained by liquid metal MHD effects.
- In a sufficiently thick liquid wall IFE design the liquid would stop the ions and x-rays, and may significantly attenuate the neutrons. The materials challenges become comparable to present day fission systems.





Comparison of Gen IV and Fusion Structural Materials Environments

S.J. Zinkle, 2007



VHTR:	Very High temperature reactor
SCWR:	Super-critical water cooled reactor
GFR:	Gas cooled fast reactor
LFR:	Lead cooled fast reactor
SFR:	Sodium cooled fast reactor
MSR:	Molten salt cooled reactor

A common theme for fusion and advanced fission is the need to develop high-temperature, radiation resistant materials.

Comparison of Fission and Fusion Environments

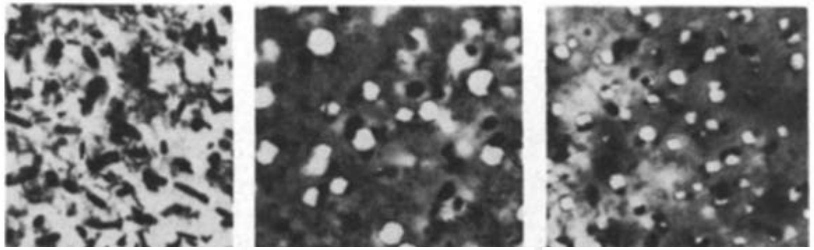
	Conventional Fission	Advanced Fission	Fusion
Max Coolant Temp., °C	<300	500 - 1000	550 – 700 (1000 for SiC)
Max He Generation, appm	~0.1	~3 - 20	~2000 (~13,000 for SiC)

Materials Degradation in the Advanced Fission & Fusion Environments

- Neutron irradiation drives microstructural evolution → property changes.
- *Key points: helium distinguishes fusion from fission and generally need doses >10 dpa to observe significant property changes. Drives need for fusion neutron source.*

Damage Phenomenon	**Temperature Range, %T_M**	**Dose Level, dpa**	**Fusion**	**Fission**
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Phase Instabilities	0.3 - 0.6	>1	Y (+He)	Y
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Volumetric Swelling	0.3 – 0.6	>10	Y (+He)	Y
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

- Ductility, fracture, fatigue, fatigue crack growth, thermal creep, and creep-fatigue.
- Effect of chemical interactions - corrosion, oxidation.



0.0 appm He/dpa
$\Delta v/v_o = 0$

0.2 appm He/dpa
$\Delta v/v_o = 3.5$

20.0 appm He/dpa
$\Delta v/v_o = 1.8$

Odette, Maziasz & Spitznagel, 1981

Relationships Between the Science and the Technology Offices in DOE

Discovery Research

- **Basic research for fundamental new understanding, the science grand challenges**
- **Development of new tools, techniques, and facilities, including those for advanced modeling and computation**

Use-inspired Basic Research

- **Basic research for new understanding specifically to overcome short-term showstoppers on real-world materials in the DOE technology programs**

Applied Research

- **Research with the goal of meeting technical targets, with emphasis on the development, performance, cost reduction, and durability of materials and components or on efficient processes**
- **Proof-of-technology concept**

Technology Maturation & Deployment

- **Codevelopment**
- **Scale-up research**
- **At-scale demonstration**
- **Cost reduction**
- **Prototyping**
- **Manufacturing R&D**
- **Deployment support**

Office of Science
BES

Goal: new knowledge/understanding
Mandate: openended
Focus: phenomena
Metric: knowledge generation

Applied Energy Offices
EERE, NE, FE, TD, EM, RW, …

Goal: practical targets
Mandate: restricted to target
Focus: performance
Metric: milestone achievement

BES FY10 Fusion Relevant Programs at National Laboratories

Inst.	PI	Title
[redacted]		
LBNL	Rob Ritchie	Hierarchical/Hybrid Structural Materials
[redacted]		
LANL	Amit Misra	Deformation Physics of Ultrafine Scale Materials
[redacted]		
LLNL	Mukul Kumar	Evolution of Grain Boundary Networks in Extreme Radiation Environments
[redacted]		
ORNL	David Singh	Materials Theory

Inst.	PI	Title
[redacted]		
ORNL	Chong-Long Fu	Self Assembly of Stable Nanoclusters in Metallic Matrices
[redacted]		
PNNL	Rick Kurtz	Exploring the Radiation Damage Resistance of Nanoscale Interfaces
[redacted]		
SNL/NM	John Sullivan	Mechanics of Small Length Scales
[redacted]		
ORNL	Malcolm Stocks	EFRC: Defect Physics in Structural Materials

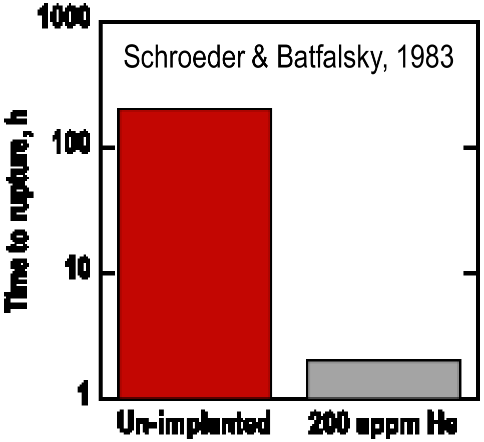
All university fusion materials program participants have highly leveraged funding from DOE NERI, NEUP, NSUF as well as other agencies.

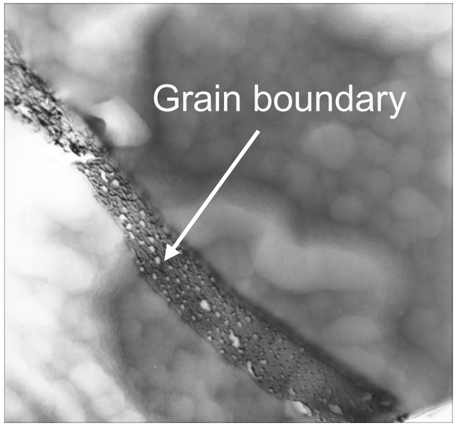
Fusion Materials Science is Connected to the Materials Science Community

- Provides mutual leveraging and forges a link between the fusion materials program and the broader materials science community.
- The average fusion materials researcher is supported <30% by OFES funding.
- All fusion materials scientists are actively involved with other research communities:
  - BES (ceramic composites, radiation effects in materials, electron microscopy, nanoscale materials, interfaces).
  - NRC (fracture mechanics, radiation effects in pressure vessel alloys, stress corrosion cracking).
  - NE (radiation effects in materials, damage-resistant alloys, high-temperature properties).
- Formal international collaborations (DOE-JAEA and MEXT) and informal (PSI, NRG Petten, …) includes cost sharing and leveraging.

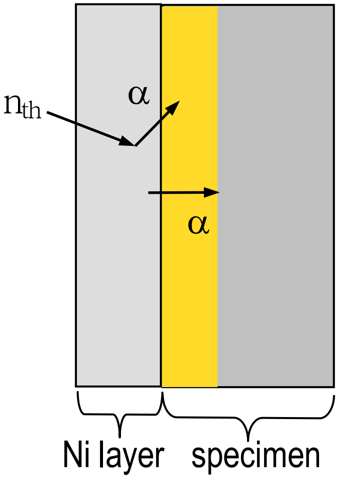
Impact of He-Rich Environment on Neutron Irradiated Materials

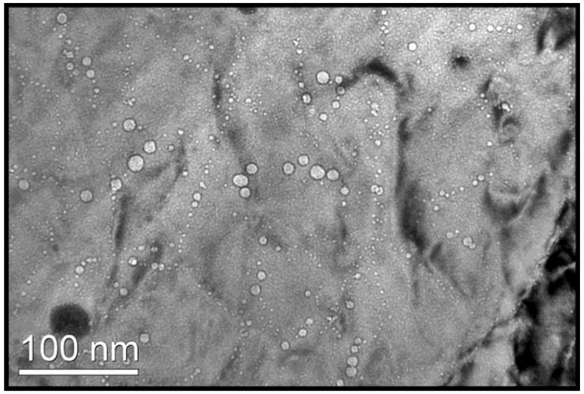
- A unique aspect of the DT fusion environment is large production of gaseous transmutant He and H.
- Accumulation of He can have major consequences for the integrity of fusion structures such as:
  - Loss of high-temperature creep strength.
  - Increased swelling and irradiation creep at intermediate temperatures.
  - Loss of ductility and fracture toughness at low temperatures.
- *In situ* He injection technique developed to inform models of He transport, fate and consequences.





In situ He injector micro-IFMIF technique



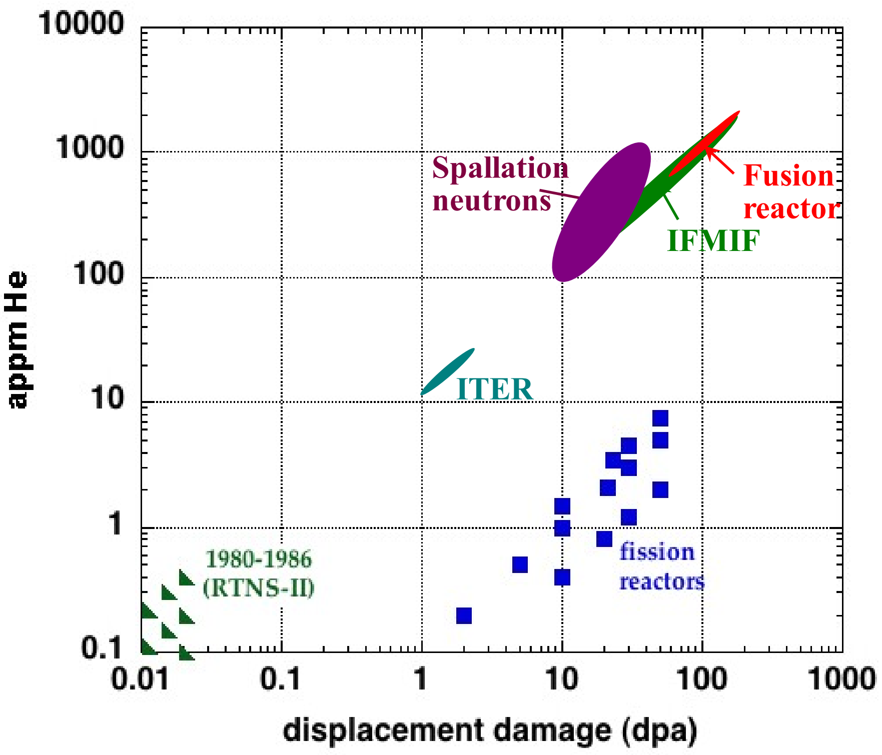


Yamamoto, et al., 2009

Fusion Materials Relies Heavily on Modeling due to Inaccessibility of Fusion Operating Regime

- Substantial extrapolation from currently available parameter space to practical fusion energy regime is required.
- Lack of fusion relevant neutron source emphasizes the need for coordinated scientific effort combining experiment, modeling & theory to develop fundamental understanding of radiation damage.

He and Displacement Damage Levels for Ferritic Steels



Role of Irradiation Sources in Fusion Materials Science

- Overcoming *neutron-induced* radiation damage degradation is a key rate-controlling step in fusion materials development.
  - Additional factors such as fabrication and joining, corrosion and compatibility, and thermophysical properties are important, but the critical data needed to evaluate feasibility can be obtained more rapidly compared to radiation effects studies.
- Evaluation of fusion radiation effects requires simultaneous displacement damage and He generation, with He concentrations above ~100 appm.
  - Low dose (<10 dpa) irradiation studies at fusion-relevant He/dpa have limited role.
- Ion irradiations – effects of dpa and gas generation can be studied to high levels, but cannot simulate neutron damage because charged particle damage rates are ~1000 times larger than for fusion conditions. In addition, ions produce damage over micron length scales thereby preventing measurement of bulk material properties.
- Evaluation of *bulk* mechanical properties of a given material at a given temperature requires a minimum volume of ~0.5 liter volume with flux gradients <20%/cm.
  - Innovative small-volume neutron sources would be useful for investigating microstructural stability of irradiated materials, but do not replace the need for a “large-volume” fusion relevant neutron source.

Displacement Damage & Gas Production in Fe for Several n Irradiation Environments

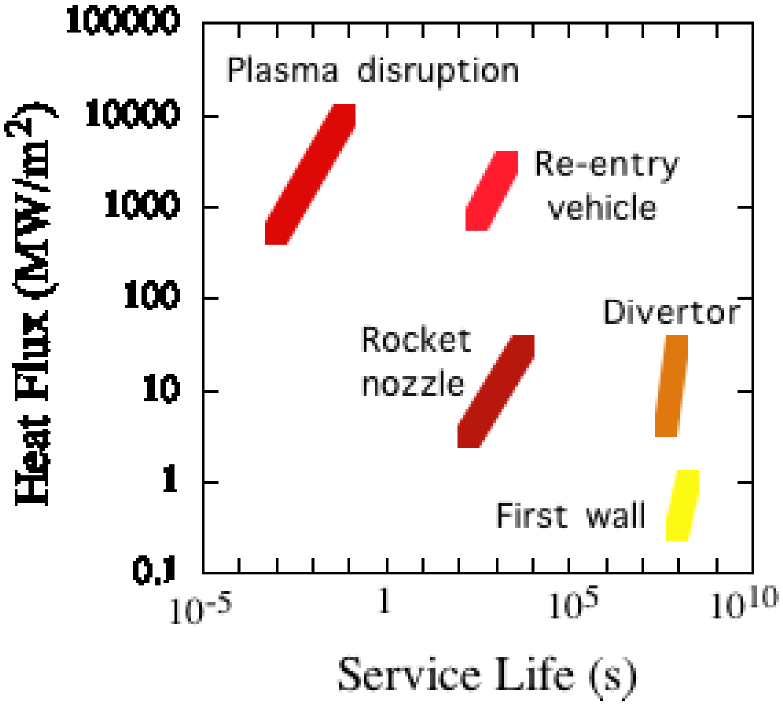
Parameter	DEMO FW	IFMIF HFTM	SNS	MTS	HFIR RB*	HFIR Target	ATR A-Hole	ATR EFT
He, appm/dpa	11	10-12	20-75	8-13	~0.3	~0.3	~0.3	~0.3
Volume, l	NA	0.5	0.025	0.3	0.23	0.1	0.24	5.4

Overview of Fission, Spallation, and D-Li Neutron Sources for Fusion Materials R&D

Neutron Source	Advantages	Disadvantages
Fission Reactors	Well characterized spectra Allows low-medium damage regimes to be investigated in bulk specimens Operating funds provided by multiple users (non-fusion)	Principal mission not fusion materials irradiations Low He/dpa ratio
Spallation (MTS, SNS)	Allows fusion relevant dpa & He/dpa irradiation conditions to be explored Operating costs may be largely provided by non-fusion agencies	Principal mission not fusion materials irradiations Temperature control, solid transmutation, pulsed irradiation
D-Li (IFMIF)	Correct He/dpa ratio Dedicated fusion materials irradiation facility	Construction and operating funds completely provided by fusion

Science-Based High-Temperature Design Criteria are Critical For Fusion

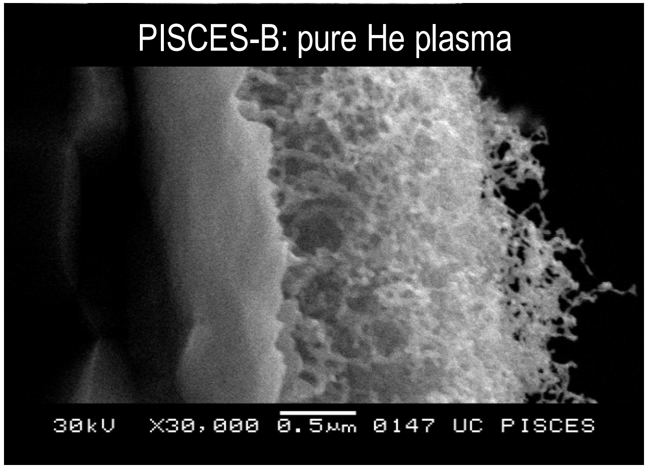
- Current high-temperature design methods are largely empirical.
- New models of high-temperature deformation and fracture are needed for:
  - Creep-fatigue interaction.
  - Elastic-plastic, time-dependent fracture mechanics.
  - Materials with low ductility, pronounced anisotropy, composites and multilayers.
- Integrated materials-component-structure development, design and testing approach needed.



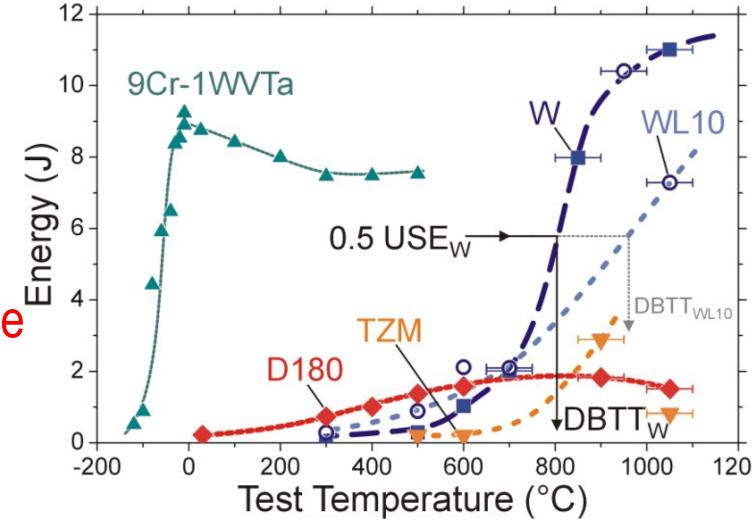
Plasma Facing Materials Must Tolerate Extreme Heat, Neutron & Particle Fluxes

- Typical materials considered for PFM include graphite, beryllium and tungsten.
- Tungsten alloys (or other refractory alloys) are the only possible structural materials for divertor applications (q''=10 MW/m^2) due to their excellent thermo-physical properties.
- However, critical issues need to be addressed:
  - Creep strength
  - Fracture toughness
  - Microstructural stability
  - Low & high cycle fatigue
  - Oxidation resistance
  - Effects of neutron irradiation (hardening & embrittlement, He)
- A modest research effort to explore ways to improve the properties of W is recommended.

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

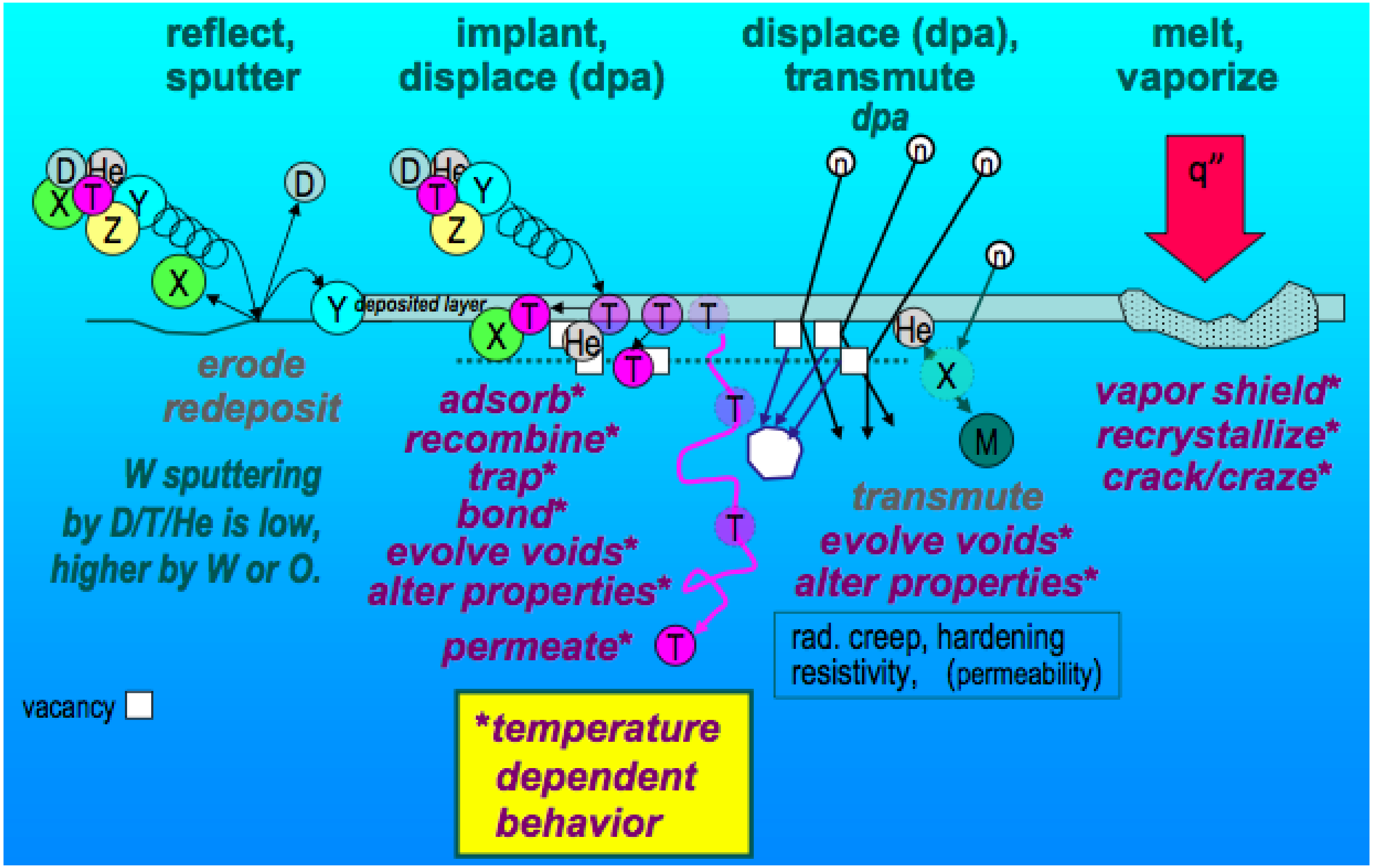


M. Rieth, A. Hoffmann, HHFC, 2008



Damage Processes in Tungsten for PSI Applications

R. Nygren et al, ICFRM-14, 2009



reflect, sputter

implant, displace (dpa)

displace (dpa), transmute

dpa

melt, vaporize

erode redeposit

W sputtering by D/T/He is low, higher by W or O.

adsorb* recombine* trap* bond* evolve voids* alter properties*

permeate*

transmute evolve voids* alter properties*

rad. creep, hardening resistivity, (permeability)

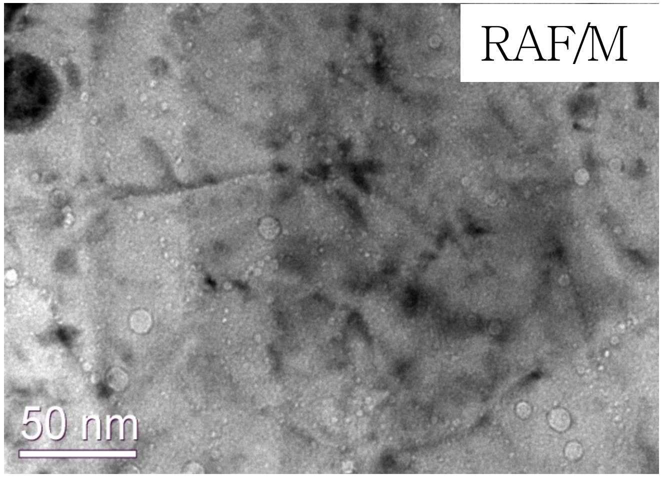
vapor shield* recrystallize* crack/craze*

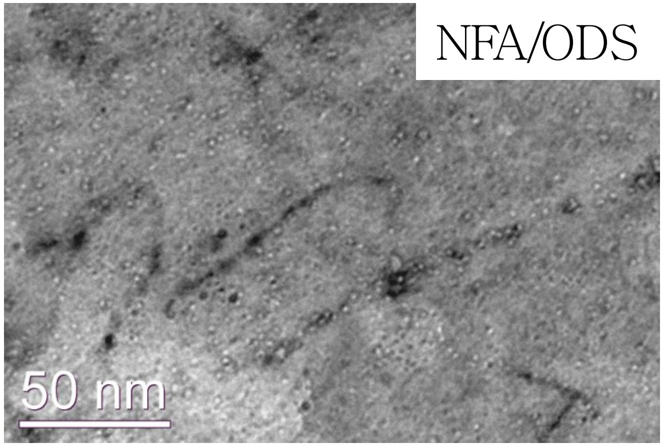
vacancy ☐

****temperature dependent behavior***

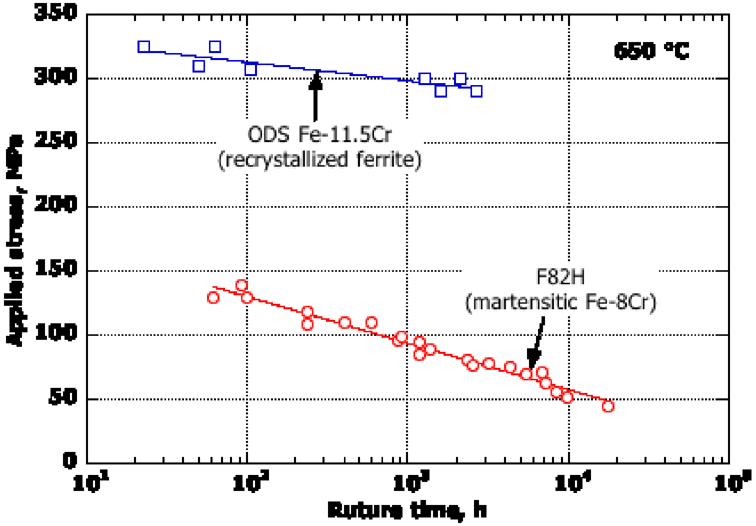
Advanced Materials Needed for Improved High-Temperature Strength & Damage Resistance

Fe-14Cr-Y-Ti-O nanostructured ferritic alloys (advanced ODS steels) offer remarkable creep strength and unique radiation damage tolerance by promoting recombination & trapping of He.

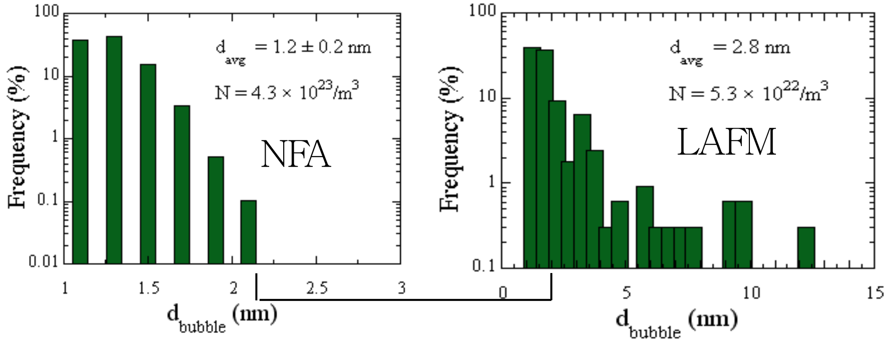




Yamamouchi et al, 1992; Shiba et al, 1997; Ukai et al, 1996; Ukai et al, 1998

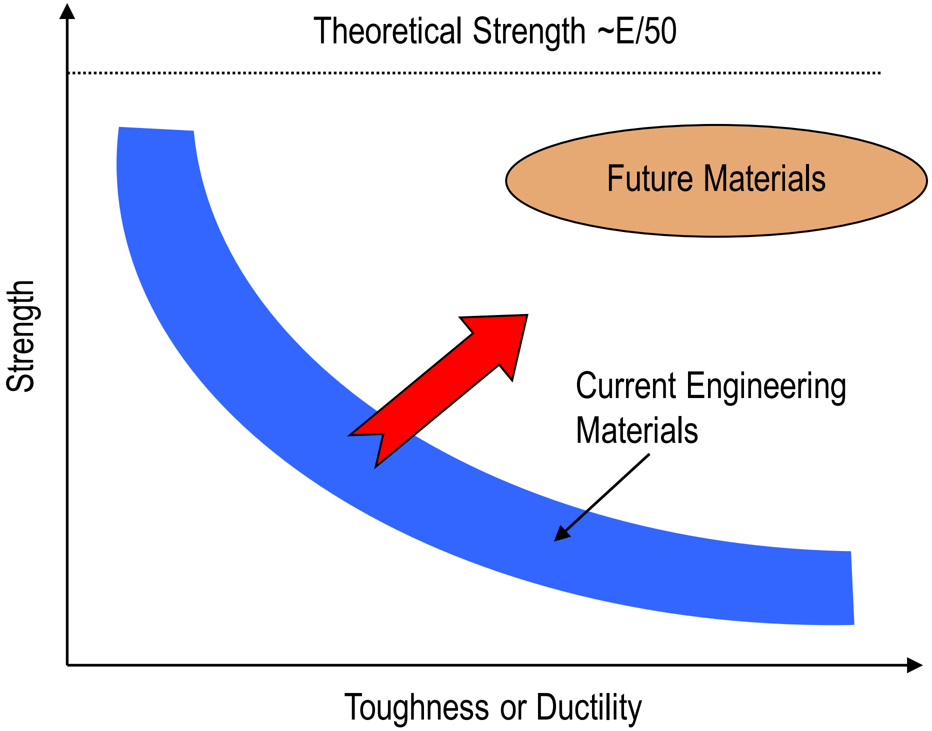


G.R. Odette, et al, 2008. 2009



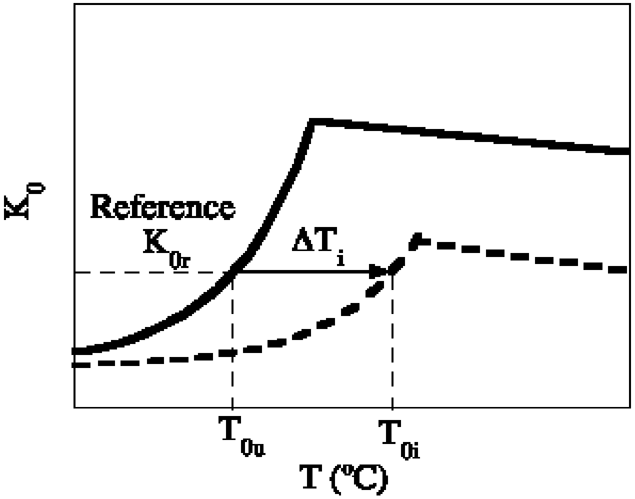
Breaking the High Strength-Low Toughness/Ductility Paradigm

- Increased strength is generally accompanied by reduced toughness (cracking resistance) and ductility.
- Strength is increased by alloying, processing and radiation damage.
- Low toughness and ductility reduce failure margins.
- The benefits of simultaneously achieving high-strength and high ductility and fracture toughness would be enormous.

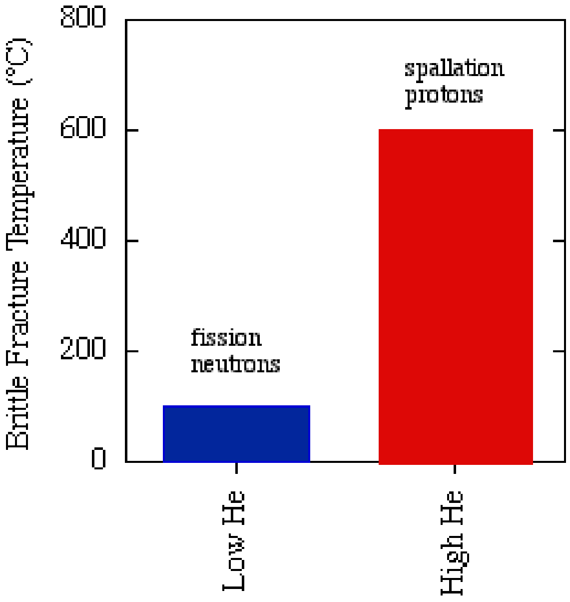


Fracture Toughness of Body-Centered Cubic Structural Alloys

Radiation hardening induces an increase in the ductile-brittle transition temperature (DBTT) for structural alloys with body-centered cubic crystal structure.



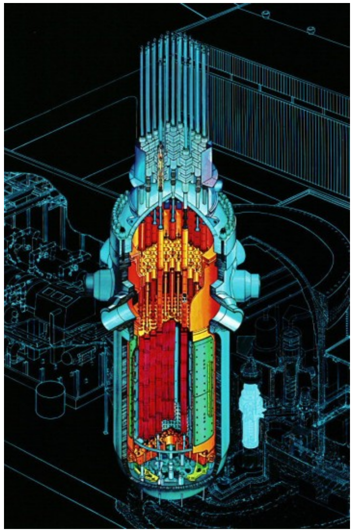
Schenectady Liberty ship, 1943



- Reduced activation F/M steels and W-alloys.
- The DBTT increases with irradiation damage.
- The ‘ductile’ tearing resistance on the upper shelf decreases.
- Significant effects are observed in fraction of a dpa at low-temperatures.
- Changes in DBTT can be magnified by high helium.

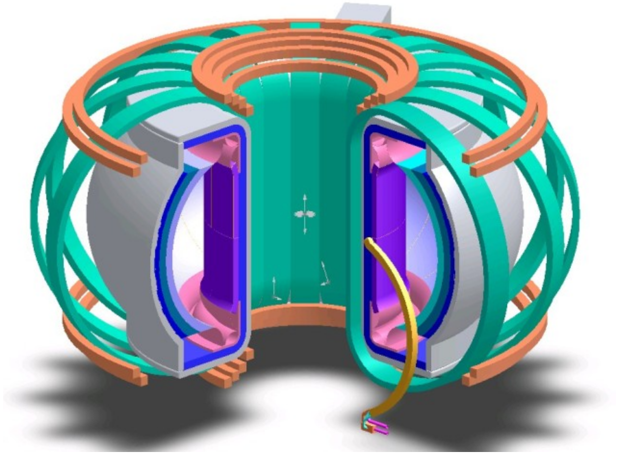
Comparison of Materials Issues Fission Versus Fusion Reactor Systems

- Big pot and pipes
- dpa < 0.15, He ≈ 0
- T ≈ 300°C
- Heat flux: ≈ 0
- Coolant: Pure H_2O
- Issue: embrittlement limits on start-up thermal shock events.



Component	Property	Dose, dpa	Temp., °C	Env.	Alloy
RPV	embrittlement	0.01	300	H_2O	Low-Alloy FS
LWR internals	irradiation creep	1-10	300	H_2O	Austenitic SS, Ni-Based Alloy
LWR internals	void swelling	10-50	350	H_2O	Austenitic SS
LWR internals	IA SCC	1-10	300	H_2O	Austenitic SS, Ni-Based Alloy
LWR internals	embrittlement	1-20	300	H_2O	Austenitic SS, Ni-Based Alloy
PWR HEX	SCC	0	300	H_2O	Ni-Based Alloy
LWR comp	fatigue	0	300	H_2O	Low-Alloy FS, Austenitic SS
LWR piping	embrittlement	0	300	H_2O	Ferritic SS
LWR pipe/pen	corrosion	0		H_2O	Low-Alloy FS, Ferritic SS, Ni-Based Alloy
LMFBR piping	creep/fatigue	0	550	Na	Austenitic SS

- Intricate, large-scale, interconnected multifunctional structure with gradients, startup/shutdown and other transients, dimensional instabilities, continuous time-dependent stress redistributions.
- dpa ≈ 200, He ≈ 2000 appm (steels)
- T ≈ 400 – 700 °C
- Heat flux: ≈ 1 – 15 MW/m^2
- Coolants: He, PbLi, Li, …..
- Issues: possibly too many to count or even know.



Significance of Fusion Materials Sciences

- Fusion materials is recognized as one of two critical path issues to be resolved for DEMO (2003 FESAC Development Path Panel).
- Structural materials development is a long-term endeavor.
  - Historical precedent is 10 - 20 years with 150-200 M$ budgets.
- Technical challenges for conventional structural materials systems pale in comparison with fusion materials.
- The materials challenge is as difficult and important for fusion energy generation as achieving a burning plasma!
- The fusion materials program is highly leveraged and very productive having achieved a long list of important accomplishments, but
  - The current budget constrains progress and it is increasingly difficult to retain technical expertise.
  - Even modest new investments would yield significant benefits.

Resource Needs for DEMO Materials Development - I

- **Non-Nuclear Structural Integrity Benchmarking Facilities**
  - Facilities for testing components are needed to investigate the potential for synergistic effects that are not revealed in simpler single-variable experiments or limited multiple-variable studies.
  - Data is needed to develop and validate computational models and codes at the component level for test blanket modules, next step nuclear devices and DEMO.
  - Provides a test bed for evaluation of operational procedures, transient event mitigation, nondestructive inspection techniques, and repair procedures.
- **Irradiation Facilities**
  - "Large" Volume, Fusion Relevant Neutron Source
    - ➢ The capability to perform accelerated evaluations of the effects of simultaneous displacement damage (~200 dpa) and He (+H) generation (~2000 appm) is essential.
  - Surrogate Irradiation Facilities
    - ➢ The capability to perform irradiation experiments under a variety of conditions (fission reactors, ion beams, spallation sources, etc.) is essential for identifying the most promising materials and specimen geometries for irradiation in a fusion relevant neutron source and developing robust models of materials behavior.

Resource Needs for DEMO Materials Development - II

- **Fusion Nuclear Science Facility (FNSF)**
  - Needed to explore for synergistic degradation modes in a fully integrated fusion neutron environment. *Data and models generated from non-nuclear test facilities, other irradiation studies and a fusion relevant neutron source will be needed to design this facility.*
- **Other Facilities and Capabilities**
  - Computational capability to support model development, but also large-scale structural damage mechanics to interpret data from the FNSF.
  - Materials evaluation equipment – TEM, SEM, FIB, Auger, APT, etc.
  - High-temperature materials testing – creep, fatigue, fracture, thermal-shock.
  - Compatibility testing – flow loops for corrosion testing, oxidation.
  - Physical property measurements – thermal, electrical, optical, etc.
  - Material fabrication and joining of small to large-scale components.
  - Hot cells for handling and testing of activated materials.

A Path Forward for the Next 10 Years - I

- Recent R&D efforts have led to the development of reduced-activation structural materials with reasonably good radiation resistance to doses of ~30 dpa, but the synergistic effects of concomitant levels of He and H has not been resolved, especially at high temperatures.
- The most efficient approach to materials development and characterization is the current science-based effort that closely couples development of physics-based, predictive models of materials behavior with key experiments to validate the models and leverages the efforts in relevant areas of materials science and technology.
- Due to resource limitations the current program is principally focused on structural materials development, which is the highest priority, long-lead time activity. Program scope will need to be greatly expanded to address the many materials issues (e.g. breeding, insulating, superconducting, plasma facing and diagnostic) of next step fusion devices such as FNSF and DEMO.
- A fusion-relevant, “large-volume” neutron source will be needed to enable accelerated evaluations of the effects of radiation-induced damage to materials. A working group could be formed to conduct a careful evaluation and selection from the most promising options.

A Path Forward for the Next 10 Years - II

- A development program is needed to qualify nearer-term materials, fabrication and joining technologies, NDE techniques and structural design methods and benchmarks for ITER test blanket modules and next-step fusion devices (e.g. FNSF).
- There is a critical need to accelerate the development of the next generation of high-performance materials with revolutionary properties (e.g., NFA, advanced W alloys, composites, and ceramics).
- Multiscale modeling and mechanism experiments are vital for the development of radiation-resistant materials and high-performance fusion power systems. We can build on and expand current activities to develop and validate predictive models of materials behavior and extend to component lifetime prediction in the fusion environment.