Scientific & Technical Challenges for Development of Materials for Fusion

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Pacific Northwest
NATIONAL LABORATORY

Presentation Overview

- Overview of the **uniquely** demanding fusion environment
- Radiation damage fundamentals
- Comparisons with conventional fission
- Materials challenges for IFE and synergy with MFE
- Synergies with advanced fission and BES research portfolios
- Materials degradation in fusion and advanced fission environments
- Scientific and technical challenges for development of structural materials and plasma facing components
- Role of irradiation sources and resource needs for fusion materials research

Scientific & Technical Challenges for Fusion Materials are Significant

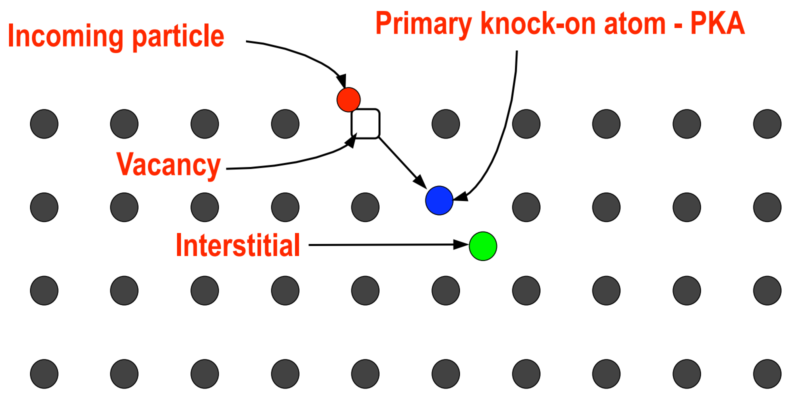
- A uniquely hostile environment that includes combinations of high temperatures, reactive chemicals, large time-dependent thermal-mechanical stresses, and intense damaging radiation.
- Developing materials that survive the **extreme** fusion environment and meet objectives for safety, environment and 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 Material Characteristics

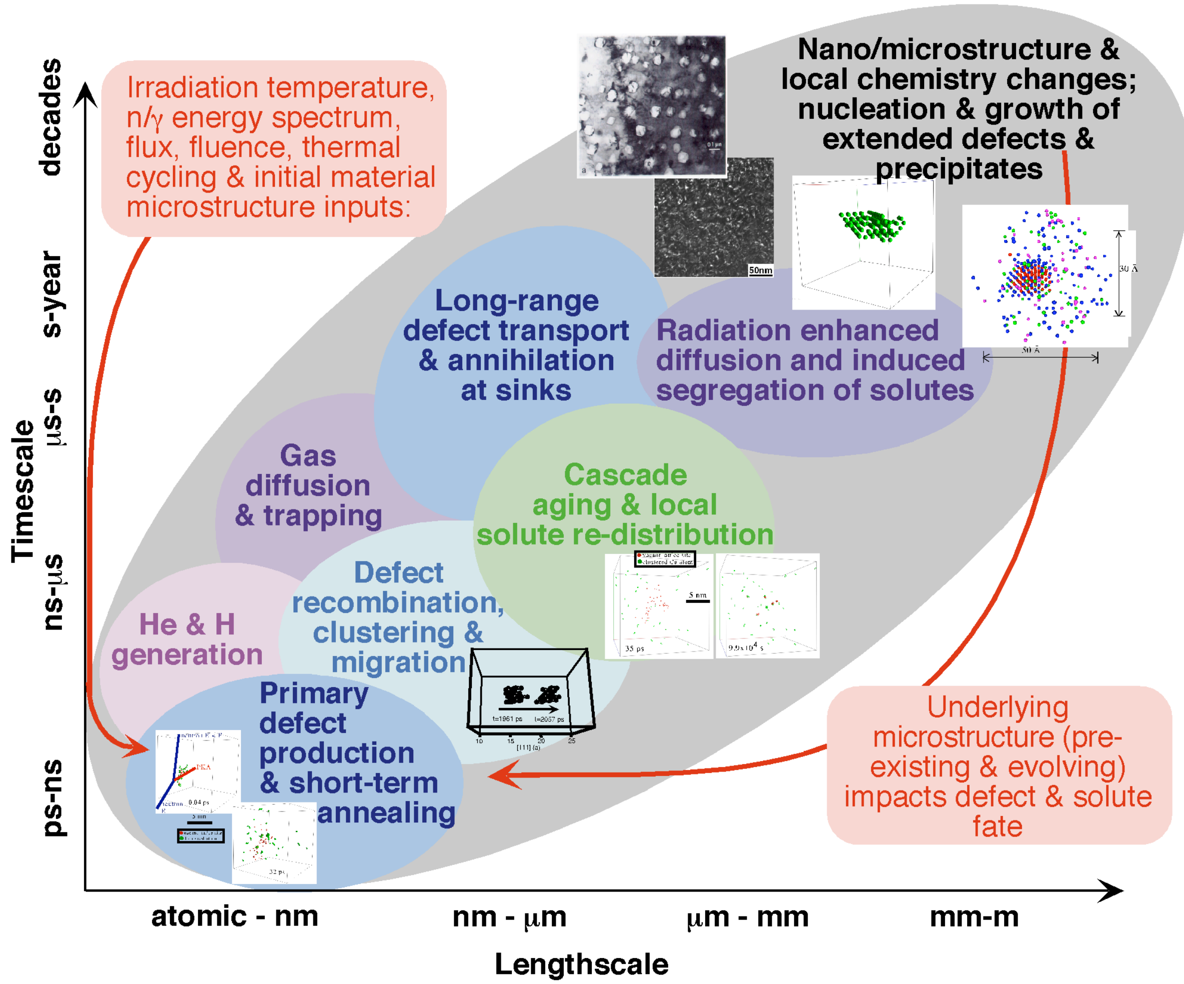
- Materials that serve in the fusion environment for acceptably long lifetimes.
- Materials that are dimensionally stable and retain a host of performance sustaining properties in the presence of radiation damage.
- Materials capable of operating at high-temperature and maintain a wide operating temperature window.
- Low-activation materials for environmental attractiveness.
- First-wall and PFC materials that are compatible with plasma requirements.
- Tritium breeding and other blanket materials that meet tritium production and power extraction needs.
- 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 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 property degradation.
- One key to achieving highly radiation resistant materials is to enhance vacancy-interstitial recombination or self-healing.

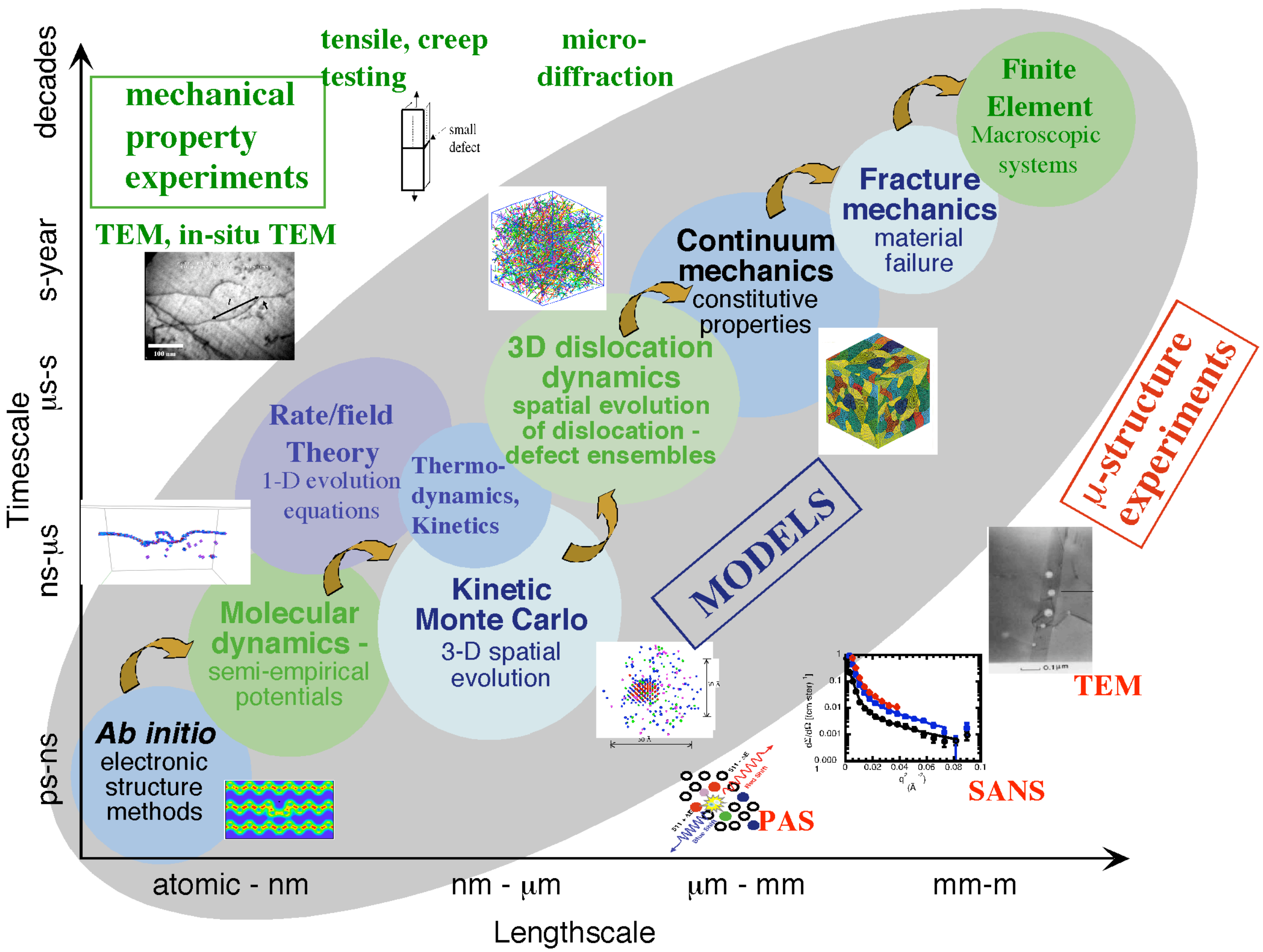


Radiation-Induced Microstructural Evolution is a Multiscale Phenomenon



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.

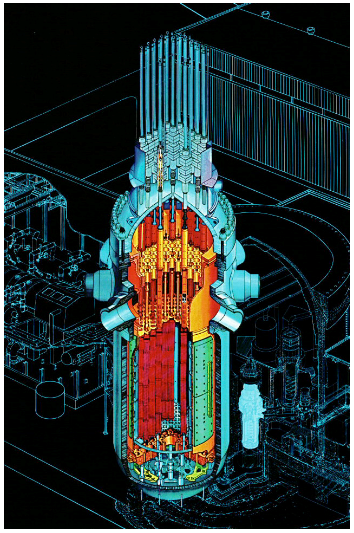
Science-Based Multiscale Modeling Approach



Apply multiple complementary modeling, experimental and theoretical techniques at appropriate scales to determine underlying mechanisms

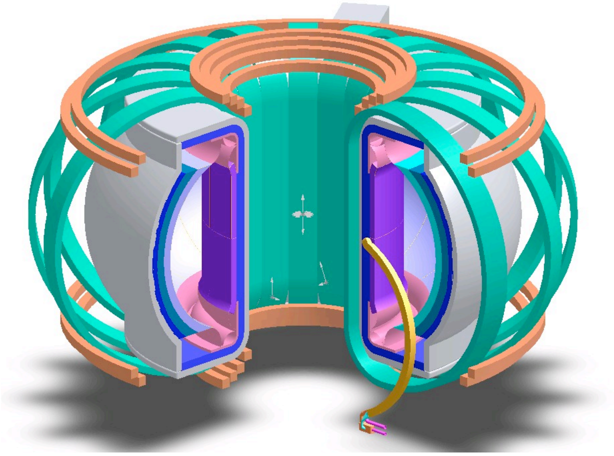
Comparison of Materials Issues Fission Versus Fusion Reactor Systems

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



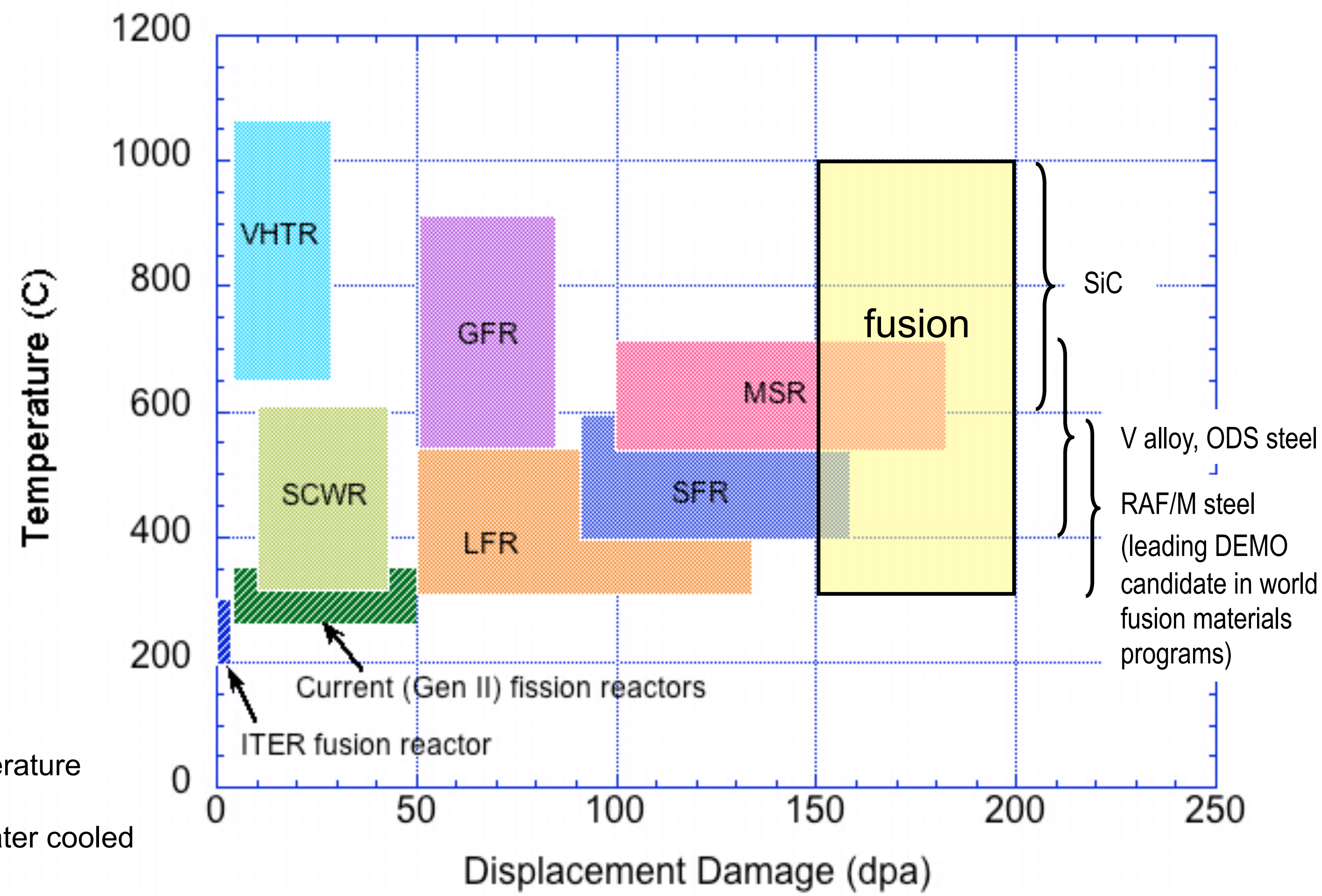
Component	Property	Dose, dpa	Temp., °C	Env.	Alloy
RPV	embrittlement	0.01	300	H_2O	Low-Alloy FS
LWR internals	irradiation creep	1-10	300	H_2O	Austenitic SS, Ni-Based Alloy
LWR internals	void swelling	10-50	350	H_2O	Austenitic SS
LWR internals	IA SCC	1-10	300	H_2O	Austenitic SS, Ni-Based Alloy
LWR internals	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.



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.

Materials Challenges for IFE and Synergy With MFE

IFE Faces Unique Challenges:

- The first-wall must tolerate intense pulses of ions and x-rays from the target
- Instantaneous neutron damage rate is much higher in IFE
- 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.
- Thick liquid walls would stop the ions and x-rays, and significantly attenuate the neutrons

MFE and IFE Share Many Materials Science Issues and Needs:

- Have first-wall and blanket materials that suffer radiation damage from high-energy neutrons
- Seek low-activation structural materials that are more radiation damage resistant to give longer service life
- Desire materials capable of high-temperature operation and are resistant to corrosion by aggressive chemical species
- Need materials that can withstand high heat fluxes and conduct power to the coolant

Relationships Between the Science and the Technology Offices in DOE

Discovery Research	Use-inspired Basic Research	Applied Research	Technology Maturation & Deployment
• Basic research for fundamental new understanding, the science grand challenges • Development of new tools, techniques, and facilities, including those for advanced modeling and computation	• Basic research for new understanding specifically to overcome short-term showstoppers on real-world materials in the DOE technology programs	• 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	• 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

Materials Degradation in the Fusion & Advanced Fission 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
Hardening & Embrittlement	<0.4	≥0.1	Y (+He)	Y
Phase Instabilities	0.3 - 0.6	>1	Y (+He)	Y
Irradiation Creep	<0.45	>10	Y	Y
Volumetric Swelling	0.3 – 0.6	>10	Y (+He)	Y
He Embrittlement	≥0.4	>10	Y	Y

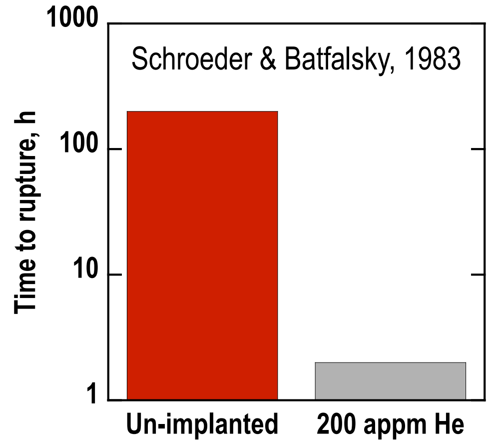
- Ductility, fracture, fatigue, fatigue crack growth, thermal creep, and creep-fatigue.
- Effect of chemical interactions - corrosion, oxidation.

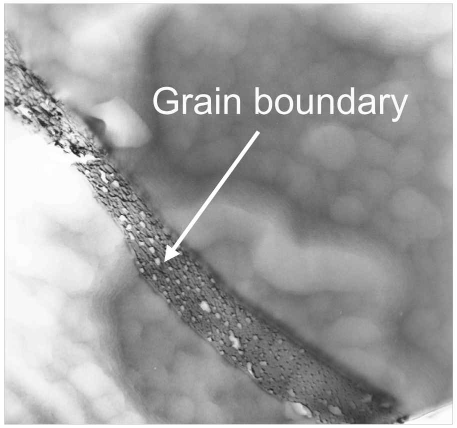
ReNeW Research Thrust Elements - I

- Improve the performance of existing and near-term materials, while also developing the next generation of high-performance materials with revolutionary properties.
  - *Understand the relationship between material strength, ductility, and resistance to cracking.*
  - *Design materials with exceptional stability, high-temperature strength and radiation damage tolerance.*
  - *Understand how interactions with the plasma affect materials selection and design.*
  - *Establish the scientific basis to control the corrosion of materials exposed to aggressive environments.*
  - *Develop the technologies for large-scale fabrication and joining.*
  - *Determine the underlying scientific principles to guide discovery of revolutionary high-performance materials while minimizing radioactive waste and maximizing recycling.*

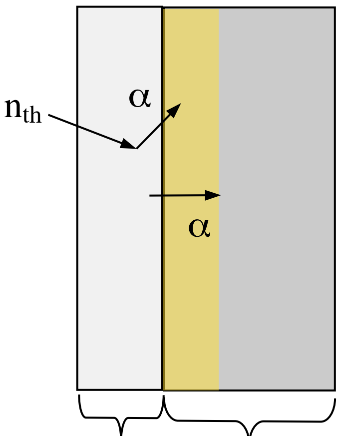
Impact of He-Rich Environment on Neutron Irradiated Materials

- 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.

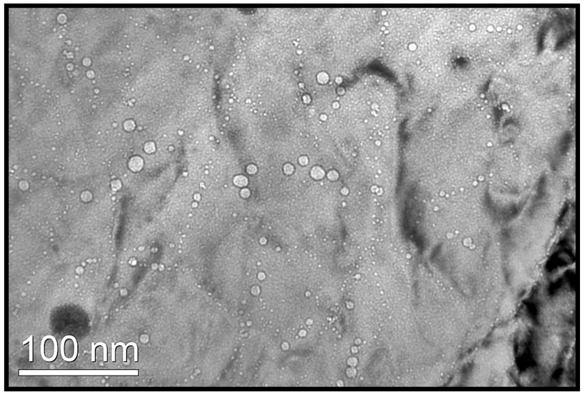




In situ He injector micro-IFMIF technique



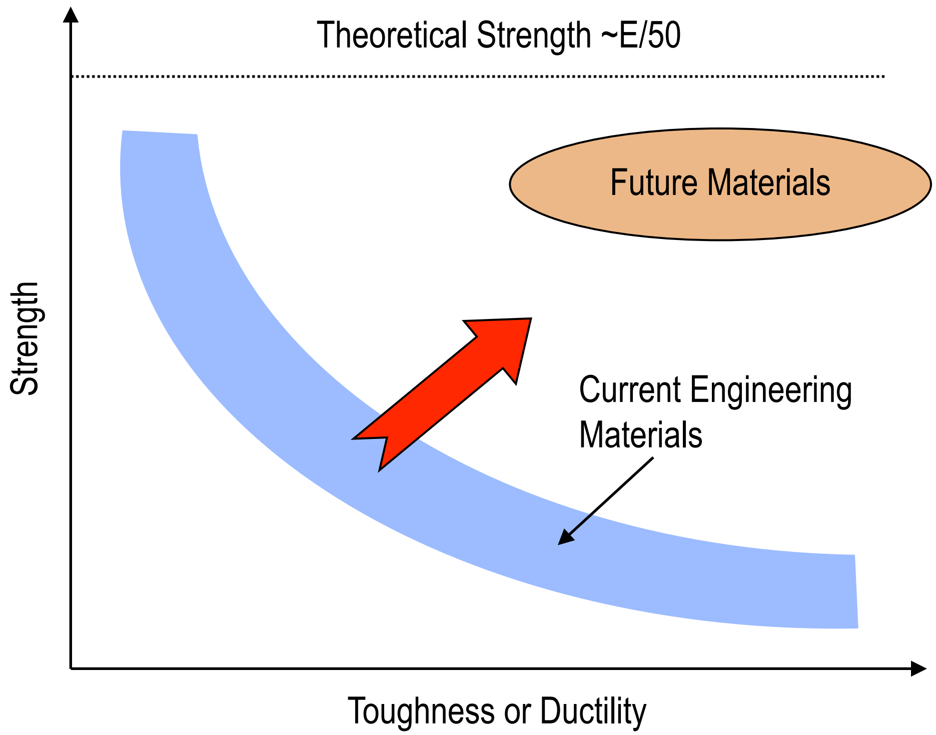
Voids & bubbles in RAF/M steel due to high He.



Yamamoto, et al., 2009

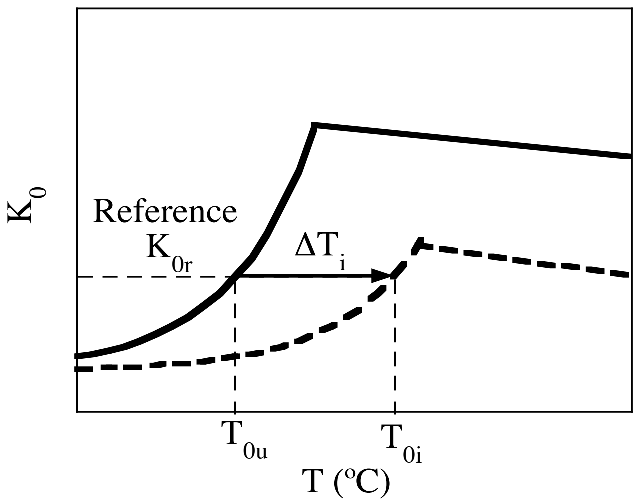
Breaking the High Strength-Low Toughness/Ductility Paradigm

- 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.

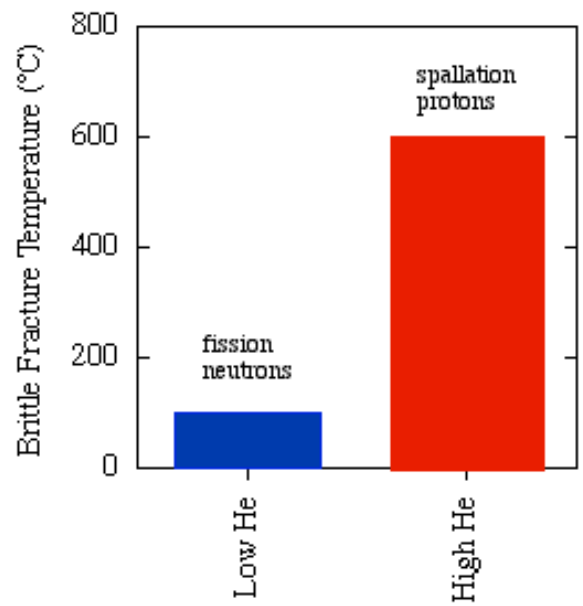


Fracture Toughness of Body-Centered Cubic Structural Alloys

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



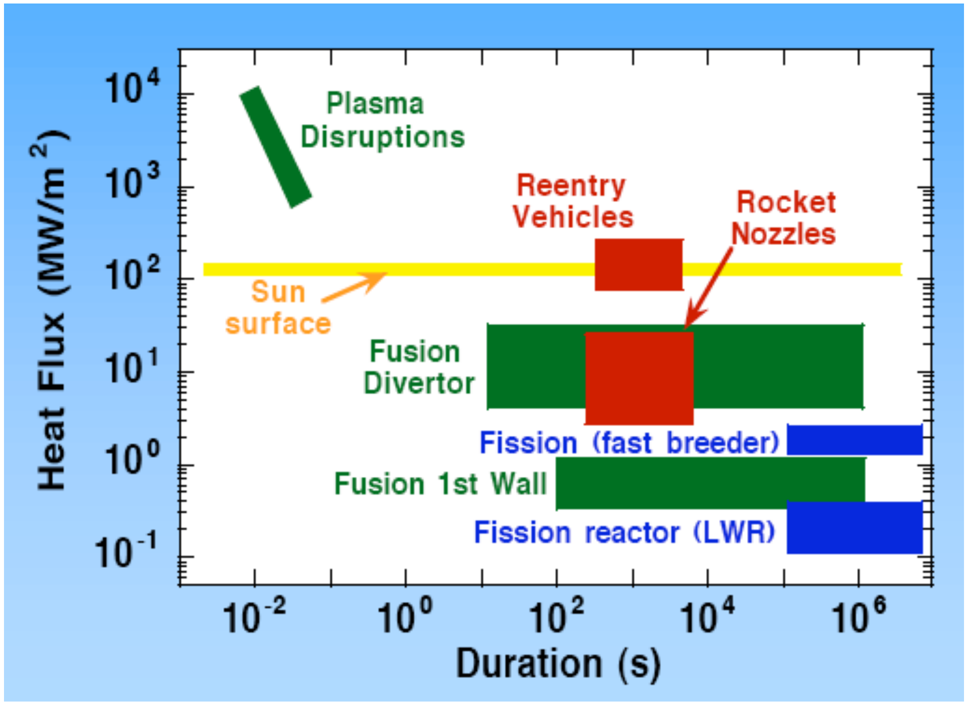
Schenectady Liberty ship, 1943



- 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.

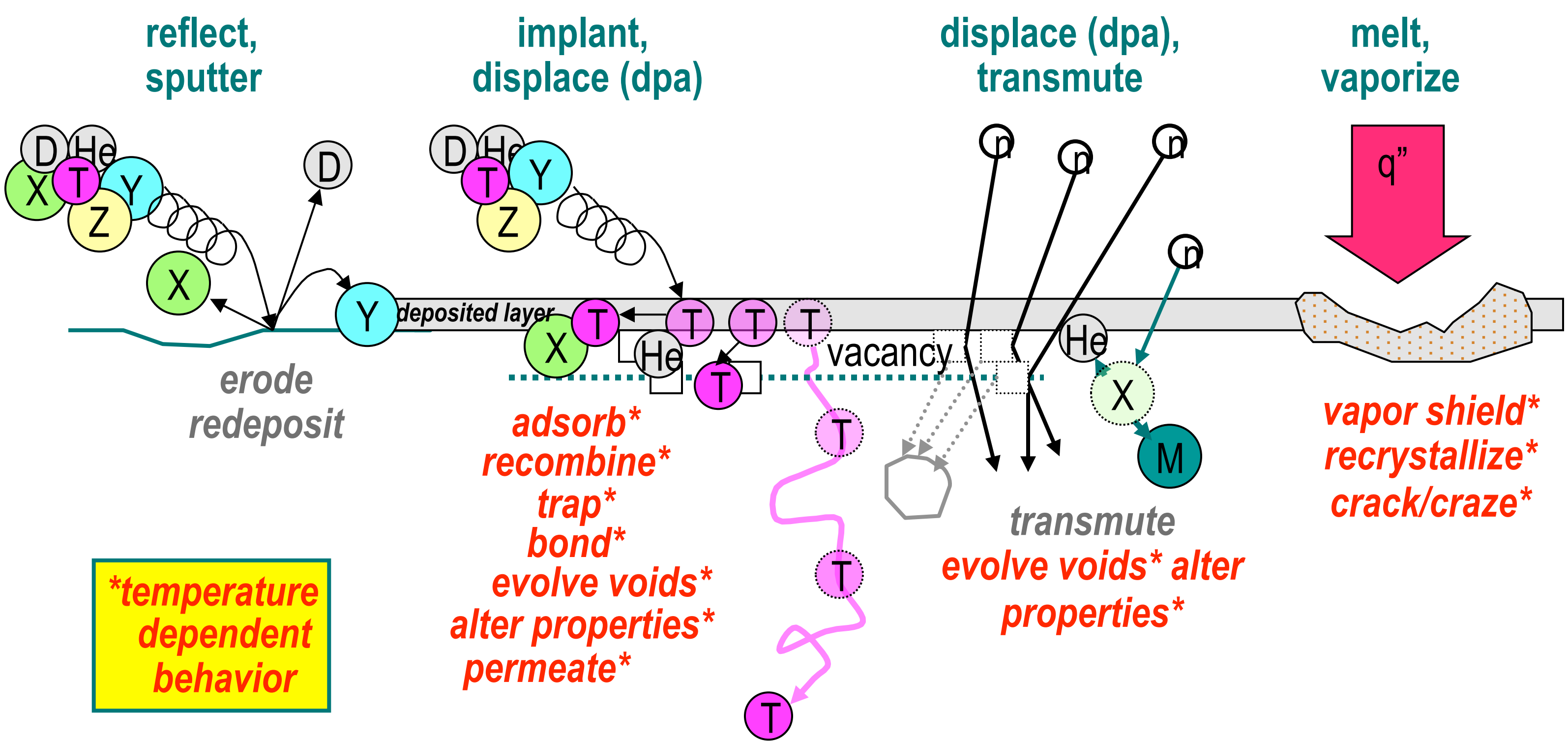
Science-Based High-Temperature Design Criteria are Critical For Fusion

- 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.



Temperature Dependence of Plasma Surface Interactions

The physical chemistry of PSI processes on high temperature walls will determine the strong interaction between wall and plasma in next step devices.

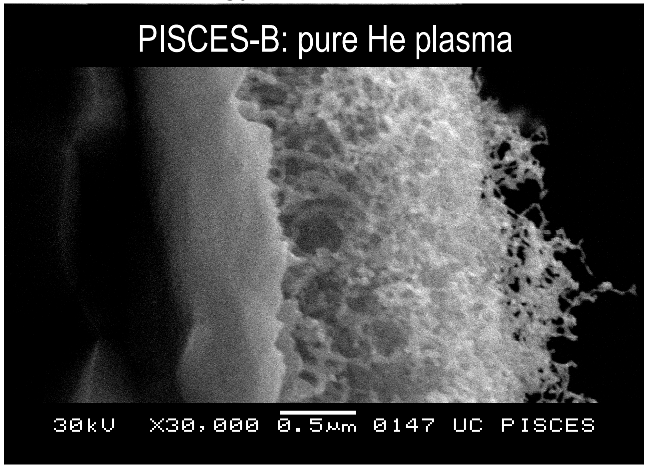


Nygren, Abdou & Sharpe, 2009

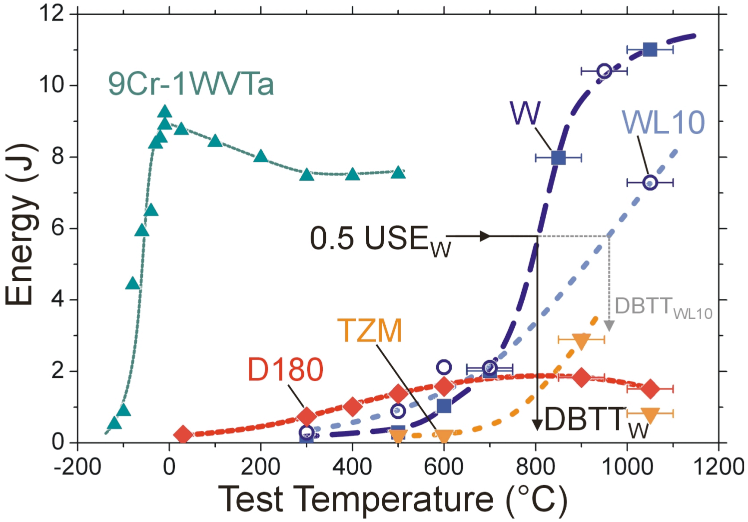
Plasma Facing Materials Must Tolerate Extreme Heat, Neutron & Particle Fluxes

- 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)
- An effort to explore ways to improve the properties of tungsten is being initiated.

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

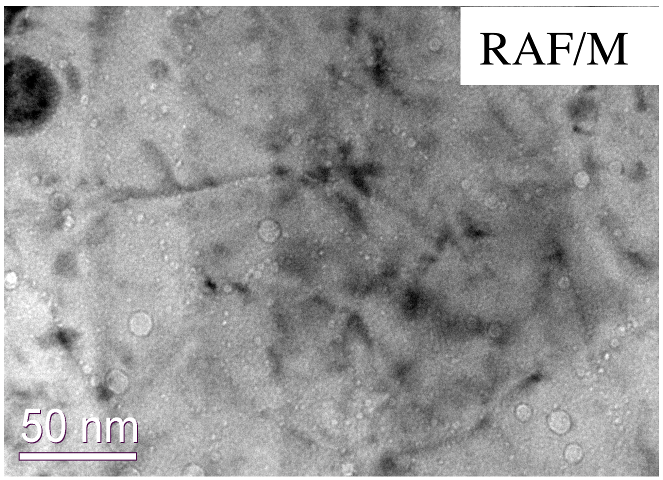


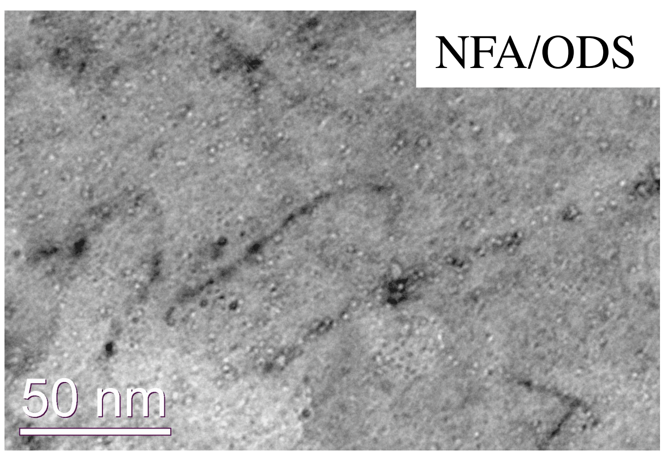
M. Rieth, A. Hoffmann, HHFC, 2008



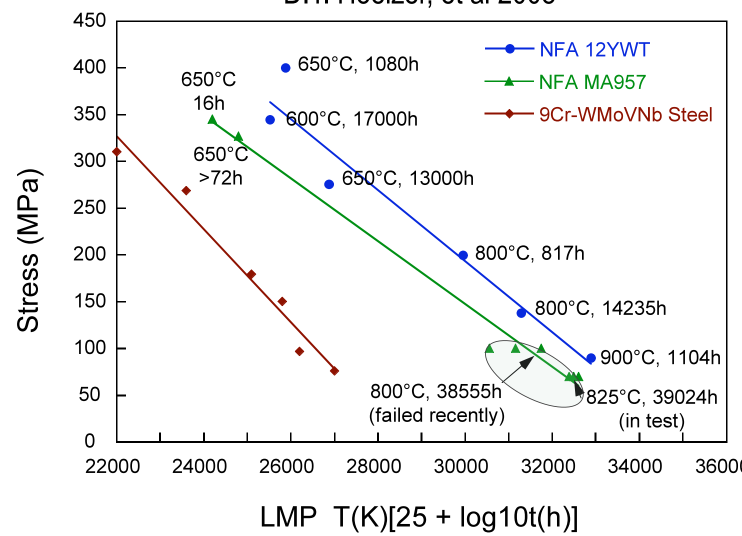
Advanced Materials Needed for Improved High-Temperature Strength & Damage Resistance

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.

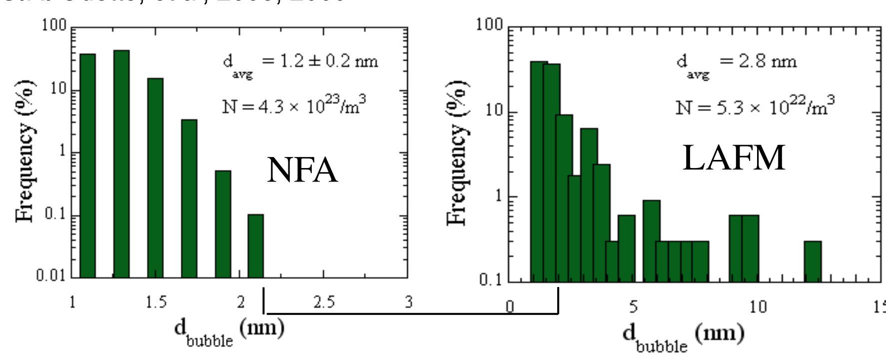




D.T. Hoelzer, et al 2008



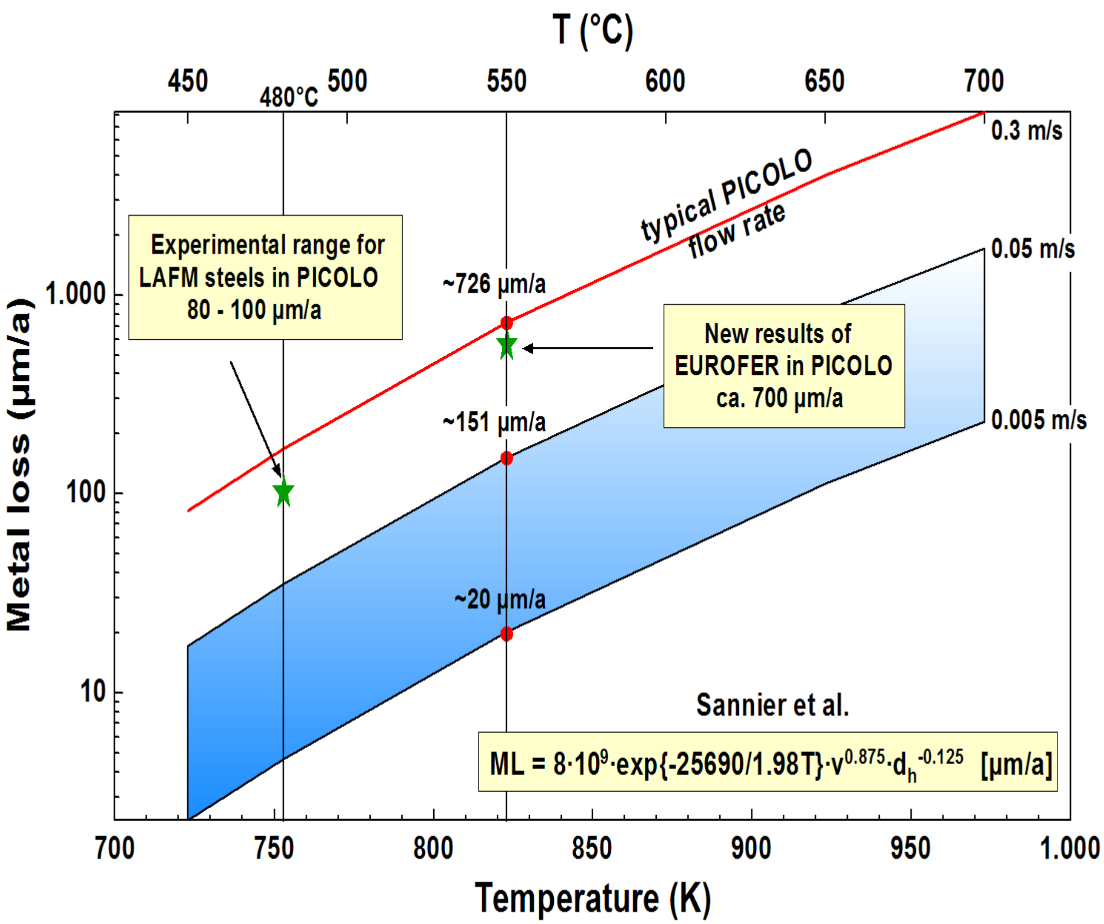
G.R. Odette, et al, 2008, 2009



Material-Coolant Chemical Compatibility in the Fusion Environment

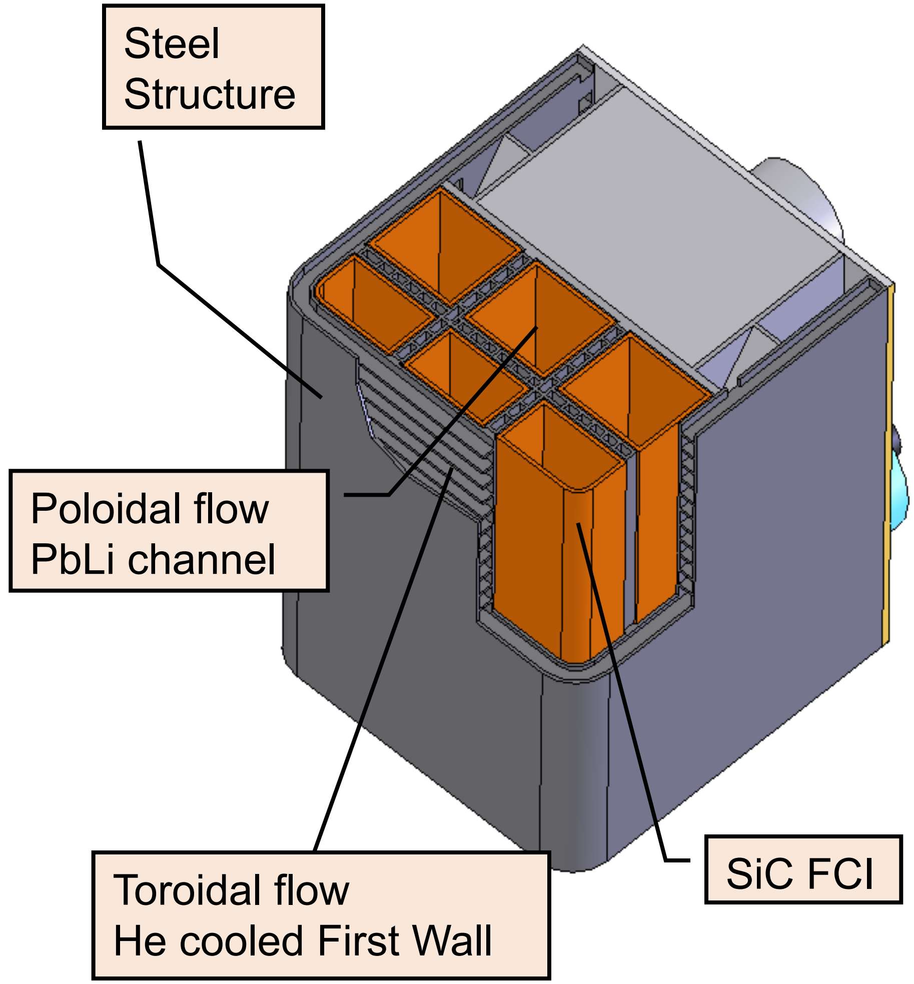
- The traditional approach to corrosion is empirical.
- Correlations do not capture basic physics and have limited predictive capability.
- Opportunities:
  - Controlled experiments combined with physical models utilizing advanced thermodynamics & kinetics codes.
  - Integrated experiments using sophisticated *in situ* diagnostic and sensor technologies.

M. Zmitko / US-EU Material and Breeding Blanket Experts Meeting (2005)
J. Konys et al./ ICFRM-12 (2005)



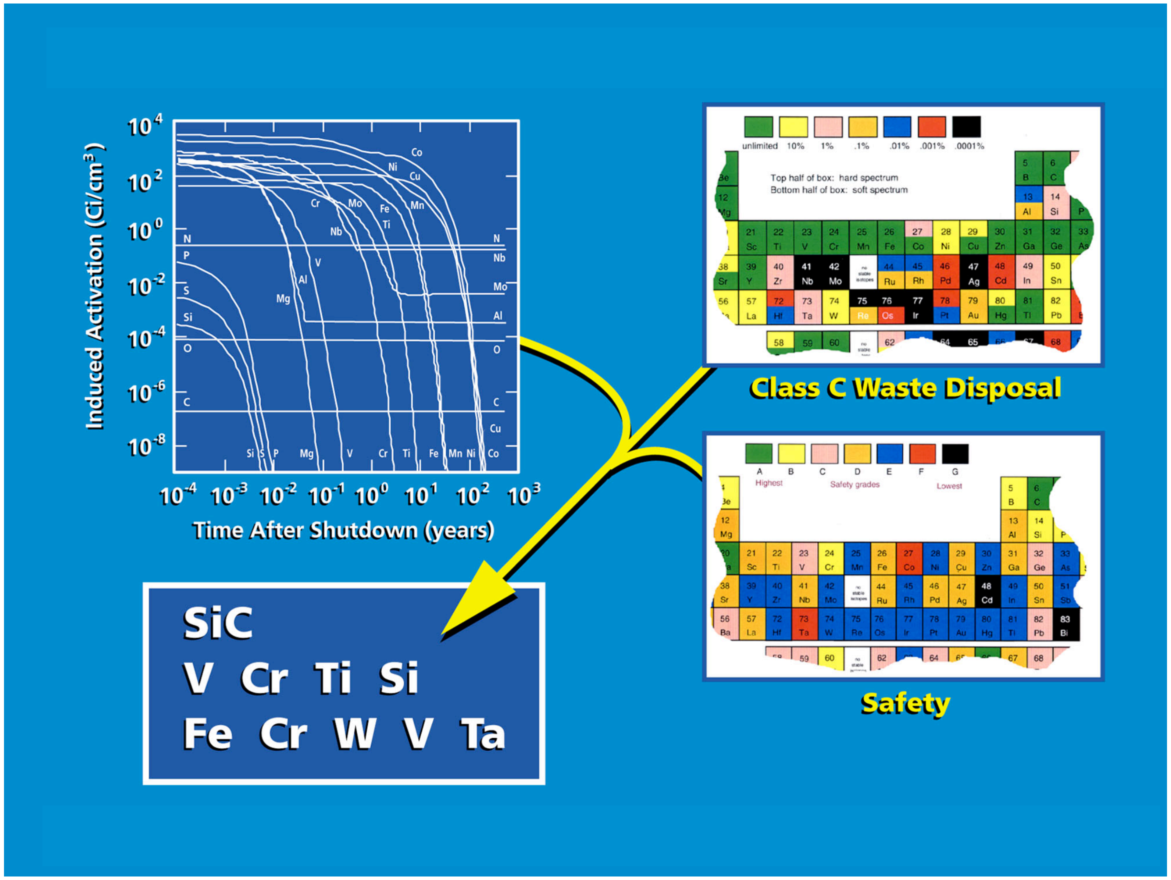
Advanced Fabrication & Joining Technologies Needed for Fusion Blankets

- Dual coolant PbLi blanket concept.
- Reduced activation ferritic steel structure cooled by He.
- Breeding zone is self-cooled PbLi.
  - Operates at much higher temperature than He and steel.
- Structure and breeding zone separated by SiC flow channel inserts that:
  - Thermally insolate hot PbLi from steel structure.
  - Electrical insulation to reduce MHD pressure drop in the flowing liquid metal.



Low-Activation Structural Materials for Fusion

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



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

ReNeW Research Thrust Elements - II

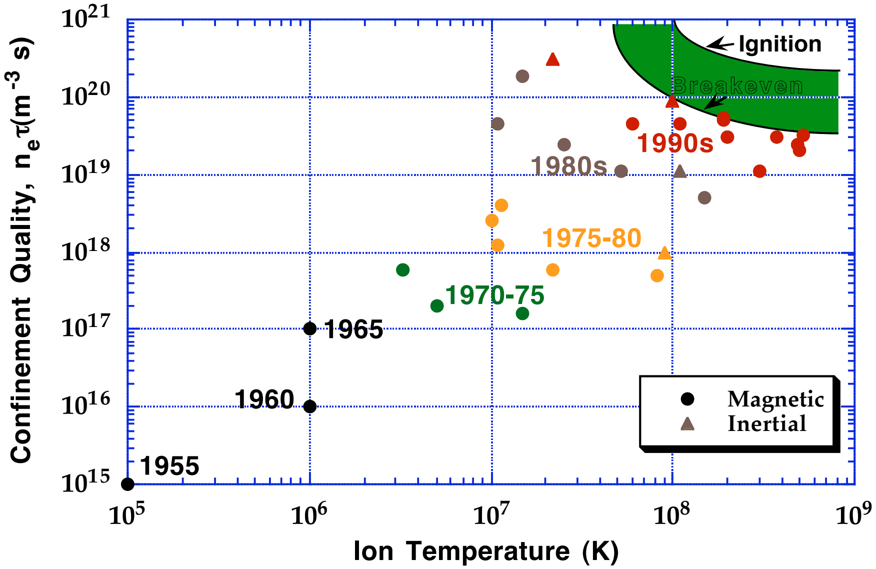
- Develop and experimentally validate predictive models describing the behavior and lifetimes of materials in the fusion environment.
- Establish a fusion-relevant neutron source to enable accelerated evaluations of the effects of radiation-induced damage to materials.
- Implement an integrated design and testing approach for developing materials, components and structures for fusion power plants.
- Use a combination of existing and new non-nuclear and nuclear test facilities to validate predictive models and determine the performance limits of materials, components and structures.

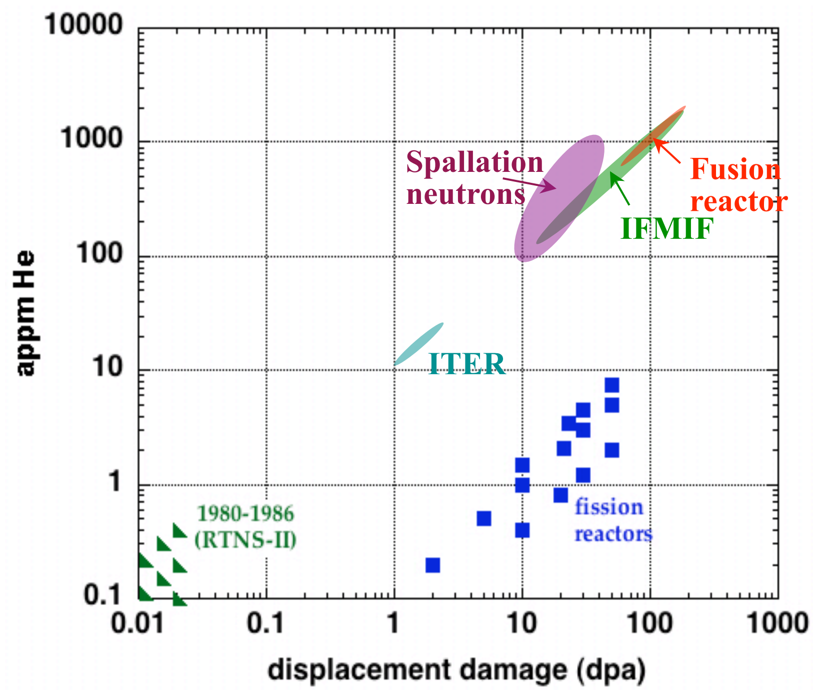
Role of Irradiation Sources in Fusion Materials Science

- 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 10 dpa/100 appm He.
- Ion irradiations – effects of dpa and gas generation can be studied to high levels, but cannot simulate neutron damage because damage rates are ~1000 times larger than for fusion. Also, 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.

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

- Extrapolation from currently available parameter space to fusion regime is much larger for fusion materials than for plasma physics program.
- Lack of intense 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

Materials Research and the Path to Fusion Power

Plasma Physics Confinement

Fusion Reactor Concept Definition

- Materials research to identify candidate materials
  - Radiation damage
  - Activation
  - Mechanical & physical properties
  - Compatibility with coolants and tritium breeders
  - Large-scale fabrication & joining issues

Ion Accelerators

RTNS

Fission Reactors

ITER

- Identify and demonstrate approaches to improve material performance
- Identify concept specific issues and demonstrate proof-of-principle solutions, e.g.
  - Design with ferromagnetic material
  - Methods for design of large, thermo-mechanically loaded structures

Neutron Source

DEMO Conceptual Designs

DEMO Final Design & Construction

- Development of materials with acceptable performance and demonstrate to goal life (dpa, He)
- Demonstrate solutions to concept specific issues on actual structural materials and prototypic components
- Develop design data base, constitutive equations, and models to describe all aspects of material behavior required for design and licensing

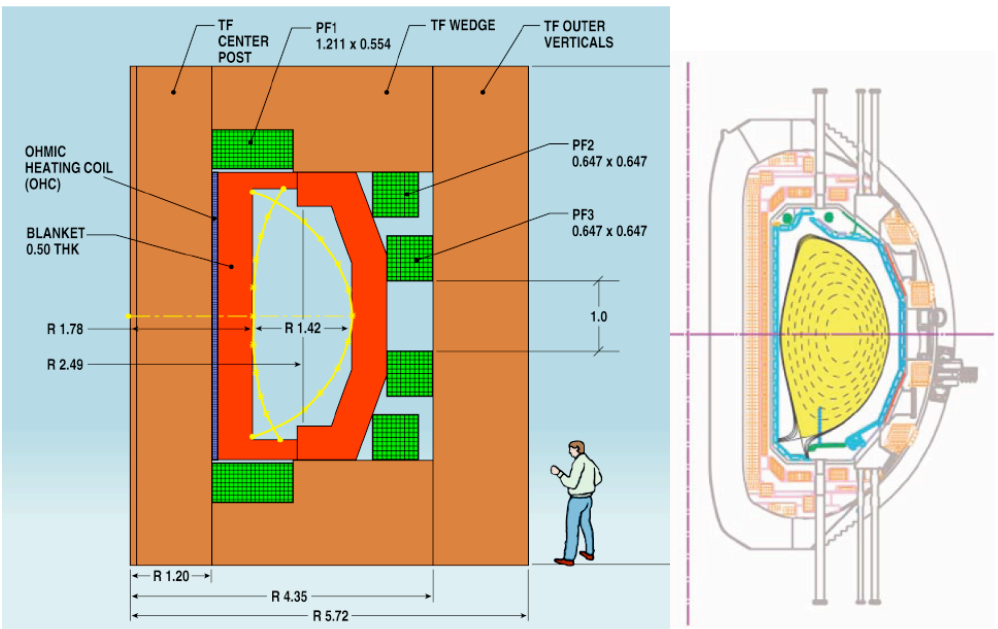
Component Test Facilities

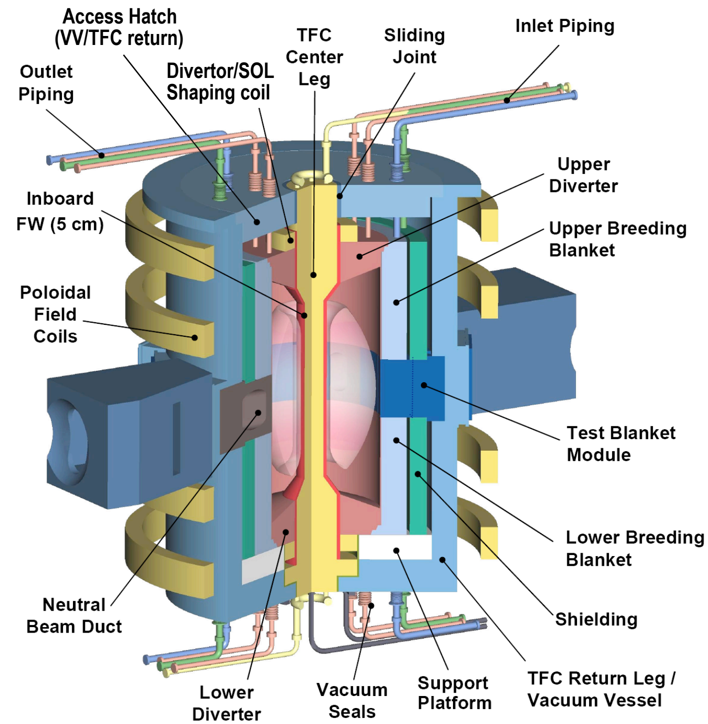
Actual Fusion Environment Test Results

Key need is close integration of materials science with the structural analysis-design process.

Proposed Fusion Nuclear Science Facilities

Nygren, Abdou & Sharpe, 2009





FNSF/FDF GA Design

P_{fusion} 125 MW at P_{NW} of 1 MW/m^2

FNSF/ST ORNL Design

P_{fusion} 76MW at P_{NW} of 1 MW/m^2

FNSF Strategy/Design for Breeding Blankets & Structural Materials

Nygren, Abdou & Sharpe, 2009

Day 1 Design

- Vacuum vessel – low dose environment, proven materials and technology
- Inside the VV – all is "experimental." Understanding failure modes, rates, effects and component maintainability is a crucial FNSF mission
- Structural material - reduced activation ferritic steel
- Base breeding blankets - conservative operating parameters, ferritic steel, 10 dpa design life
- Testing ports - well instrumented, high performance blanket experiments

Upgrade Blanket Design, Bootstrap Approach

- Extrapolate a factor of 2 (standard in fission, other development), 20 dpa, 200 appm He, then extrapolate next stage of 40 dpa…
- Conclusive results (real environment) for testing structural materials,
  - no uncertainty in spectrum or other environmental effects
  - prototypical response, e.g., gradients, materials interactions, joints, …

Materials Development Challenges for FNSF

- **Low-dose environment (≤10 dpa, Phase 1 FNSF)**
  - Radiation effects not primary concern
  - Fabrication and joining technologies
  - Thermal loading – PFC (tungsten), fatigue, creep-fatigue
  - Compatibility with coolants
  - High-temperature design criteria and structural codes
  - Non-destructive inspection techniques and procedures, maintenance
- **Intermediate-dose environment (>10 – 60 dpa, later phases FNSF)**
  - Materials degradation phenomena such as He embrittlement, irradiation creep, volumetric swelling, and phase instabilities manifested at >10 dpa
  - Data from a fusion-relevant neutron source and non-nuclear testing facilities needed to understand single-effects and multiple-effects phenomena
  - Without such data it will be difficult to deconvolve synergistic effects observed in FNSF
  - Also likely increases the capital, mission and regulatory risk of building and operating an FNSF

Resource Needs for Fusion 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**
  - 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 Fusion 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 support this facility and generate the data for DEMO.
- **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.