Scientific & Technical Challenges for Development of Materials for Fusion

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Scientific & Technical Challenges for Fusion Materials are Significant

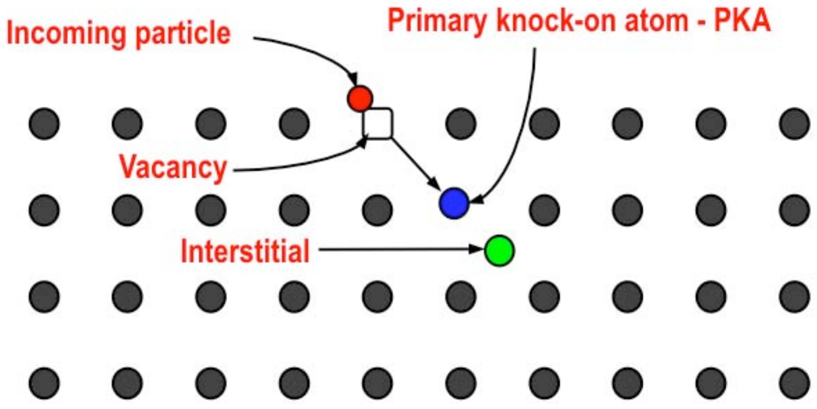
- Fusion materials must function in a uniquely hostile environment that includes combinations of high temperatures, reactive chemicals, large time-dependent thermal-mechanical stresses, and intense damaging radiation.
- The task of designing, constructing and operating a fusion energy system with materials 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.



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

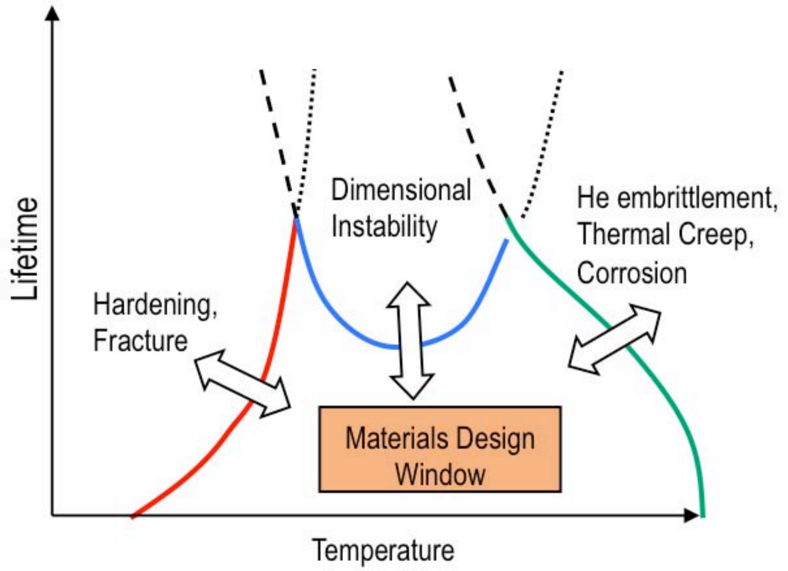
A common theme for fusion and advanced fission is the need to develop high-temperature, radiation resistant materials.

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.

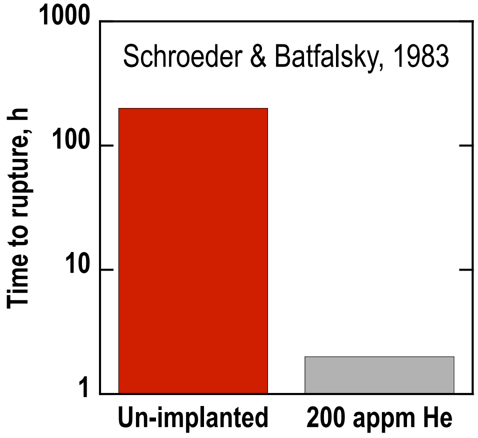
High He may narrow or even close the window

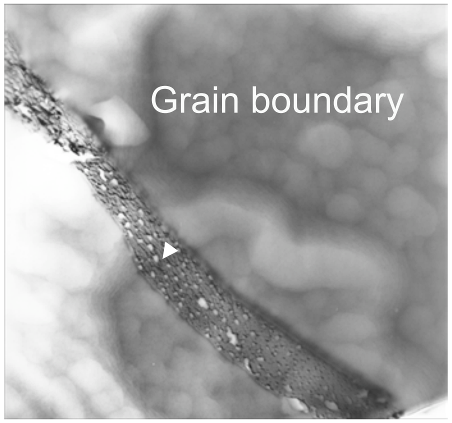


N. Ghoniem & B.D. Wirth, 2002

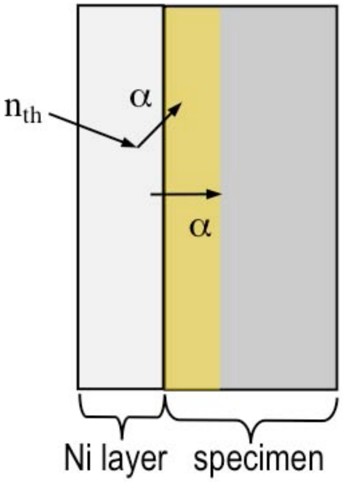
Impact of He-Rich Environment on Neutron Irradiated Materials

- 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.

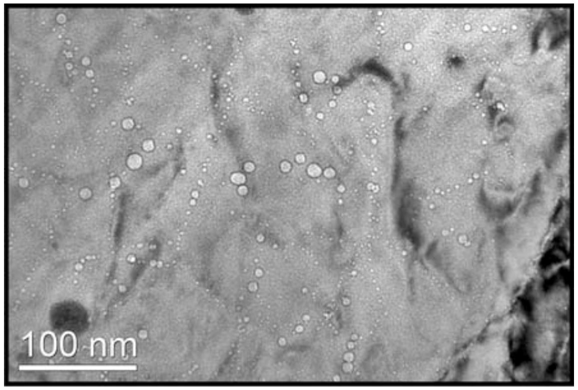




In situ He injector micro-IFMIF technique



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



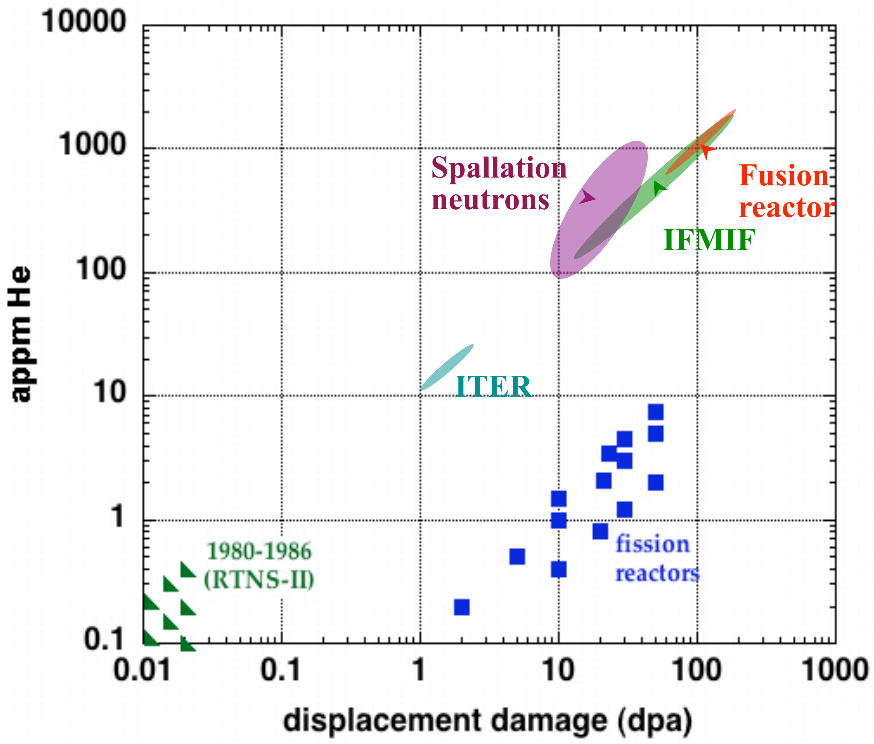
Yamamoto, et al., 2009

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

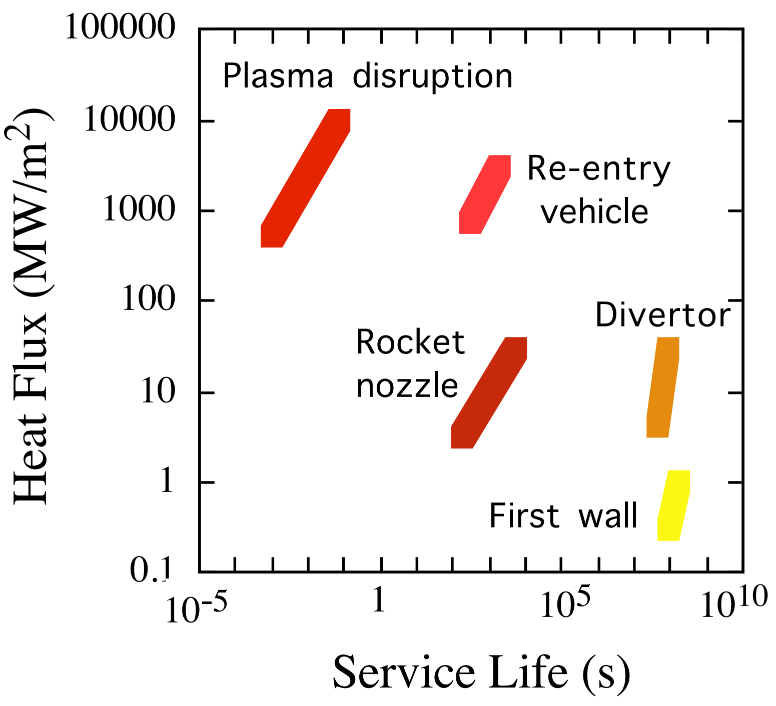


Role of Irradiation Sources in Fusion Materials Science

- 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.

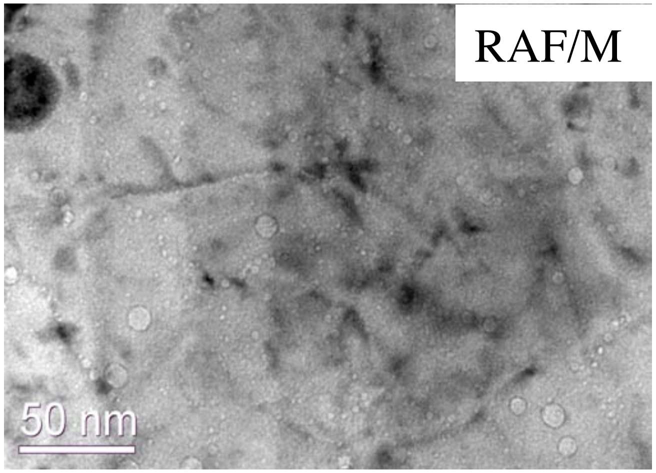
Science-Based High-Temperature Design Criteria are Critical For Fusion

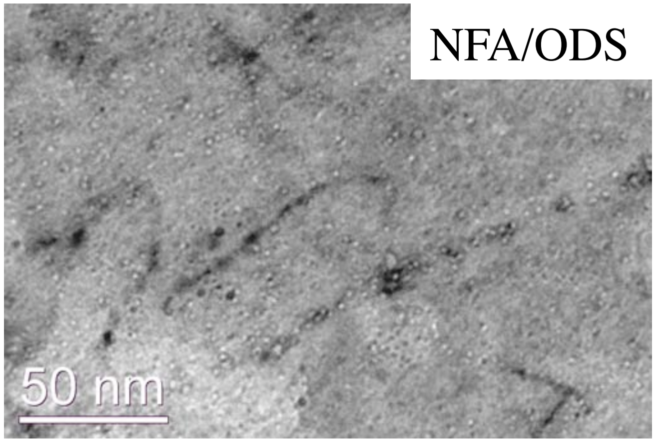
- Current high-temperature design methods are largely empirical.
- New models of high-temperature deformation and fracture are needed for:
  - Creep-fatigue interaction.
  - Elastic-plastic, time-dependent fracture mechanics.
  - Materials with low ductility, pronounced anisotropy, composites and multilayers.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



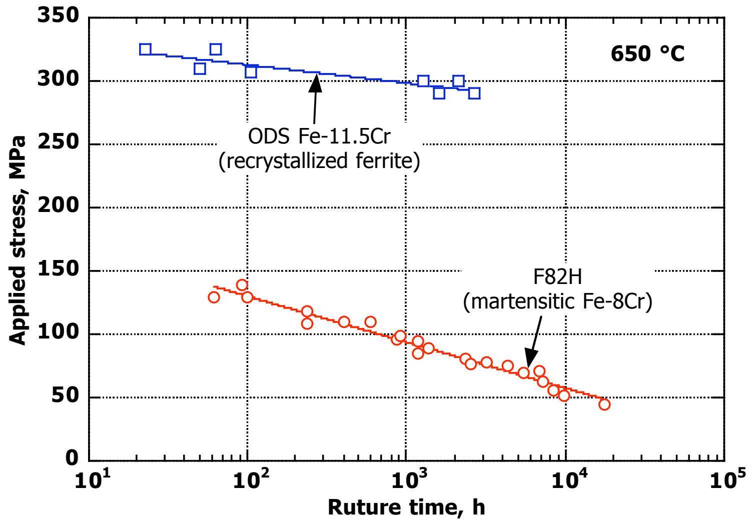
Advanced Materials Needed for Improved High-Temperature Strength & Damage Resistance

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.

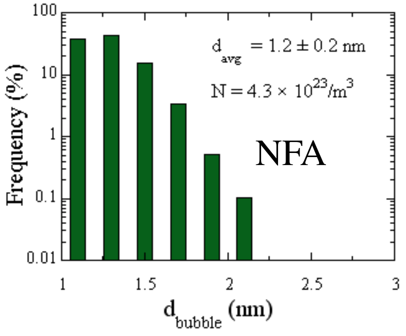


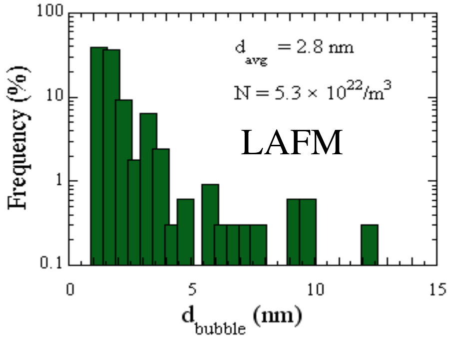


Yamamouchi et al, 1992; Shiba et al, 1997; Ukai et al, 1996; Ukai et al, 1998



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

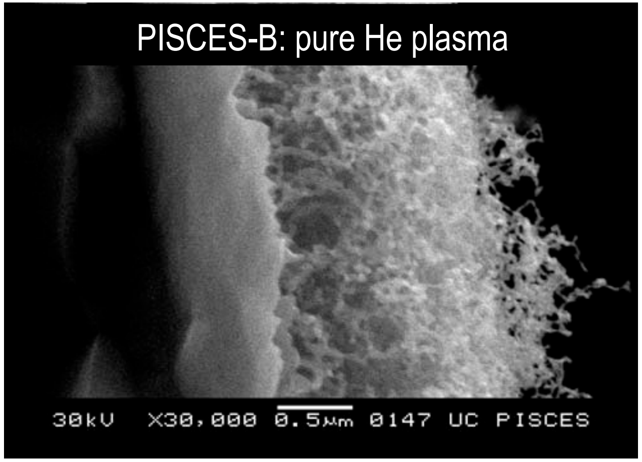




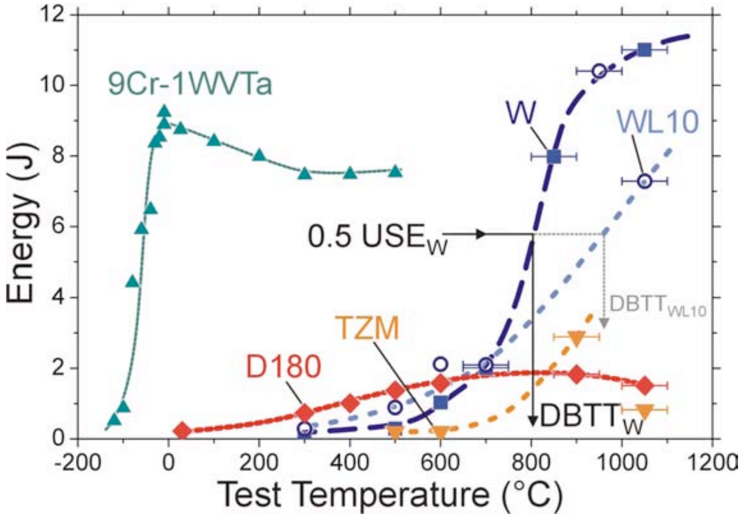
Plasma Facing Materials Must Tolerate Extreme Heat, Neutron & Particle Fluxes

- 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 planned.

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


PISCES-B: pure He plasma

M. Rieth, A. Hoffmann, HHFC, 2008



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.