Summary of R&D in Fusion Materials Sciences Program

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## Comparison of Advanced Fission and Fusion Structural Materials Requirements

<table>
<thead>
<tr>
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<th>Fission (Gen. IV)</th>
<th>Fusion (ITER/TBM)</th>
<th>Fusion (Demo)</th>
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</thead>
<tbody>
<tr>
<td>Structural alloy maximum</td>
<td>600 - 850°C</td>
<td>350 - 550°C</td>
<td>550 - 700°C (~1000°C for SiC)</td>
</tr>
<tr>
<td>temperature</td>
<td>(~1000°C for GFRs)</td>
<td></td>
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<tr>
<td>Max dose for core internal</td>
<td>~30-100 dpa</td>
<td>&lt;2 dpa</td>
<td>~150 dpa</td>
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<tr>
<td>structures</td>
<td></td>
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<tr>
<td>Max transmutation helium</td>
<td>~3-10 appm</td>
<td>~20 appm (~120 appm SiC)</td>
<td>~1500 appm (~10,000 appm SiC)</td>
</tr>
<tr>
<td>concentration</td>
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Microstructural evolution (property changes) due to neutron irradiation.

<table>
<thead>
<tr>
<th>Damage Phenomenon</th>
<th>Temperature Range, Fraction of Melting Point</th>
<th>Dose Level, dpa</th>
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</thead>
<tbody>
<tr>
<td>Hardening &amp; Embrittlement</td>
<td>&lt;0.3</td>
<td>≥0.1</td>
</tr>
<tr>
<td>Phase Instabilities</td>
<td>0.3 - 0.6</td>
<td>&gt;1</td>
</tr>
<tr>
<td>Irradiation Creep</td>
<td>&lt;0.45</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Volumetric Swelling</td>
<td>0.3 - 0.6</td>
<td>&gt;10</td>
</tr>
<tr>
<td>He Embrittlement</td>
<td>≥0.5</td>
<td>&gt;10</td>
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Fatigue, fatigue crack growth, thermal creep and creep-fatigue.

Effect of chemical interactions - erosion, corrosion, oxidation.
Structural materials most strongly impact economic and environmental attractiveness of fusion power.

Key issues: thermal stress, compatibility, safety, waste disposal, radiation damage, safe lifetime limits.

Ti alloys, Ni base superalloys, and most refractory alloys are unacceptable for various technical reasons.

Based on safety, waste disposal and performance considerations, the 3 leading candidates:
- Ferritic/martensitic steels
- Vanadium alloys
- SiC composites
Theoretical models provide the best available tool for understanding the critically important area of radiation effects on materials and bridging the length and time scales of phenomena important to the use of materials in the fusion environment.

**Issues**
- Understanding microstructural evolution produced by 14 MeV neutrons.
- Understanding how radiation-induced microstructural changes alter important mechanical properties: hardening, embrittlement, and flow localization.
- Effects of helium on deformation and fracture and void swelling.

**Research in Progress**
- Modeling atomic displacement cascades up to 50 keV which exceeds the average cascade energy for a fusion first wall.
- Kinetic Monte Carlo simulations of long-term cascade aging and microstructural evolution.
- Fundamental studies of radiation hardening, embrittlement and fracture mechanisms, multiscale modeling of dislocation-defect and dislocation-dislocation interactions.

**Comparison of 10 and 50 keV Atomic Displacement Cascades in Iron**
- High-energy damage events are similar to multiple, lower-energy events due to subcascade formation.
Ferritic/Martensitic Steels

**Advantages**
- Well-developed technology for nuclear and other advanced technology applications.
- Fusion materials program has developed reduced activation versions with equivalent or superior properties.
- Resistant to radiation-induced swelling.
- Compatibility with aqueous, gaseous, and liquid metal coolants permits range of design options.

**Issues**
- Upper operating temperature limited to ~550°C by loss of creep strength.
- Potential for radiation-induced embrittlement at temperatures <400°C.
- Possible design difficulties due to ferromagnetic properties.

**CURRENT APPROACH**

**Expand Low Temperature Operating Window**
- Pursue collaborative international fission reactor irradiation program (IEA activities)
  - Investigate micro-mechanics of fracture and radiation-induced reductions in fracture toughness.
  - Understand the role of helium on fracture and crack propagation.
  - Develop Master Curve approach to examine deformation modes and fracture resistance.

**Expand High Temperature Operating Window**
- Explore TiC and Nitride dispersions.
- Develop nanocomposited ferritic alloys (NFA).
  - Expand upper operating temperature.
  - Radiation-stable, tough microstructures.

3-D atom probe image; clusters of ~100 atoms of Y, Ti, and O responsible for high strength of NCF materials
Oxide dispersion strengthened (ODS) steels offer a potential route to significantly improve creep strength and trap He.

Yamamouchi et al, 1992; Shiba et al, 1997
Ukai et al, 1996; Ukai et al, 1998
Superior Creep Strength of ODS Steels is Due to the Presence of Stable Nanoclusters

Thermal creep test at 800°C and 138 MPa for 14,235h

- $R_g = 2.0$ nm
- $N_v = 1.4 \times 10^{24}/m^3$
- same as before thermal creep test

Volume = 22 x 21 x 73 nm

Nanoclusters possess long-term stability at temperatures more than 200°C higher than the upper temperature limit of advanced RAF/M steels.

Average Composition of Nano-Particles (at.%)

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<tr>
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<th>O</th>
<th>Ti</th>
<th>Y</th>
<th>Balance</th>
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</thead>
<tbody>
<tr>
<td>Avg</td>
<td>28.1</td>
<td>24.6</td>
<td>7.9</td>
<td>Fe ~5.6Cr</td>
</tr>
<tr>
<td>Std</td>
<td>+/- 9.8</td>
<td>+/- 8.5</td>
<td>+/- 4.9</td>
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A unique aspect of the DT fusion environment is substantial production of gaseous transmutants such as 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.
- Potential for loss of ductility and fracture toughness at low temperatures.

Trapping at a high-density of tailored interfaces is a key strategy for management of He.

Swelling in stainless steel is maximized at fusion-relevant He/dpa values.
He Embrittlement: Unresolved Questions

- What is the sequence of events after He generation that controls its fate?
  - How does He diffuse?
  - How and where is He trapped?
  - What is the effect of grain boundary type on He bubble density and size?
  - How does He behave at trapping sites to form bubbles?

- Can nano features in advanced ferritic alloys stably trap He and render it innocuous in very fine bubbles?
Atomistic model of grain boundary in Fe used to determine the dependence of He binding energy on GB excess volume.

Computational models and novel experimental techniques are providing important mechanistic insight on He behavior, but model validation at fusion relevant He levels and determination of bulk properties requires an intense neutron source.
A general feature of engineering materials is increased strength tends to be offset by losses of toughness (resistance to crack growth) and ductility.

Strength increases may result from alloying, material processing, or radiation damage.

Loss of toughness and ductility is a loss of margin against structural failure.

Simultaneous achievement of high-strength and high toughness/ductility would provide enormous benefits for fusion, but also many other areas (e.g., transportation, magnets, robotics, etc.).
Radiation hardening induces an increase in the ductile-brittle transition temperature. Operation in the low-toughness brittle regime should be avoided.

Ludwig-Davidenkov relation provides a rough estimation of embrittlement due to radiation hardening.

Two approaches: reduce hardening or increase $\sigma^*$

- Significant reductions in low temperature radiation hardening can be achieved by selective alloying (e.g., reduced Cu in reactor pressure vessel steels).
- Recent nanocomposited ODS steel developed by US fusion materials scientists exhibits $\sigma^*$ 2x higher than conventional steels.
What is the physical basis for the Master Curve-Shifts method for characterizing fracture toughness?

Does the Master Curve have a universal shape?

What are the effects of specimen geometry and shallow cracks?

What are the effects of high He levels on fracture toughness?
Loss of Ductility: Unresolved Questions

- What controls the complete loss of uniform strain capacity?
- What controls the initiation and propagation of dislocation channels?
- What controls the channel width and spacing?
- Why is the plastic instability stress appear to be a material constant, independent of initial cold-work or radiation-induced defect clusters?
- Why are the work hardening rates near instability similar to that of the unirradiated material?
- What is the significance of heterogeneous deformation (channeling)?
SiC Composites

Advantages

- Very low radioactivity and afterheat eases waste disposal and safety concerns.
- High operating temperatures for greater thermodynamic efficiency.
- Ability to engineer the structure to meet design needs.

Issues

- Thermal conductivity is reduced by irradiation.
- Joining, hermeticity, compatibility with coolants.
- Technology base for production, joining, design of large structures, is limited.

Research Approach

- Understand the magnitude and cause of radiation effects on key properties such as thermal conductivity and strength.
- With knowledge of underlying mechanisms, design composite structures (fiber, fiber-matrix interphase and matrix) with improved performance
- Through SBIRs work to develop the required technology base

Silicon carbide composites offer engineerability for extreme environments through tailoring of the fiber, matrix, and interphase structures
Inclined fiber bridging model captures observed toughness decrease with increasing fiber inclination angle (PNNL Model using Brian Cox Equations). There is a need for a study as a function of fiber inclination angle.
**Vanadium Alloys**

**Advantages**
- High Wall Load/Power Density.
- High Operating Temperature and Thermodynamic Efficiency.
- Low Activation/Potential Recycle.

**Issues**
- Establish operating temperature window
  - Effects of He and displacement damage on properties.
  - High temperature creep behavior.
- Insulator coatings to mitigate MHD effects in Li/V system.
- Impurity Interactions from environment, e.g. oxidation.

**Research Approach**
- Development of MHD Insulator System.
- Investigation of Effects of Irradiation on Fracture Properties.
- Kinetics of Interstitial Impurity Pick-up and Effects on Properties.

Thermal Creep of V-4Cr-Ti
Overcoming radiation damage degradation is the rate-controlling step in fusion materials development.

- Additional factors such as joining and thermophysical properties are important, but 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.

Evaluation of mechanical properties of a given material at a given temperature requires a minimum volume of ~10 cm$^3$ 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 moderate-volume intense neutron source.