Scientific and Technical Challenges for DEMO Materials Development

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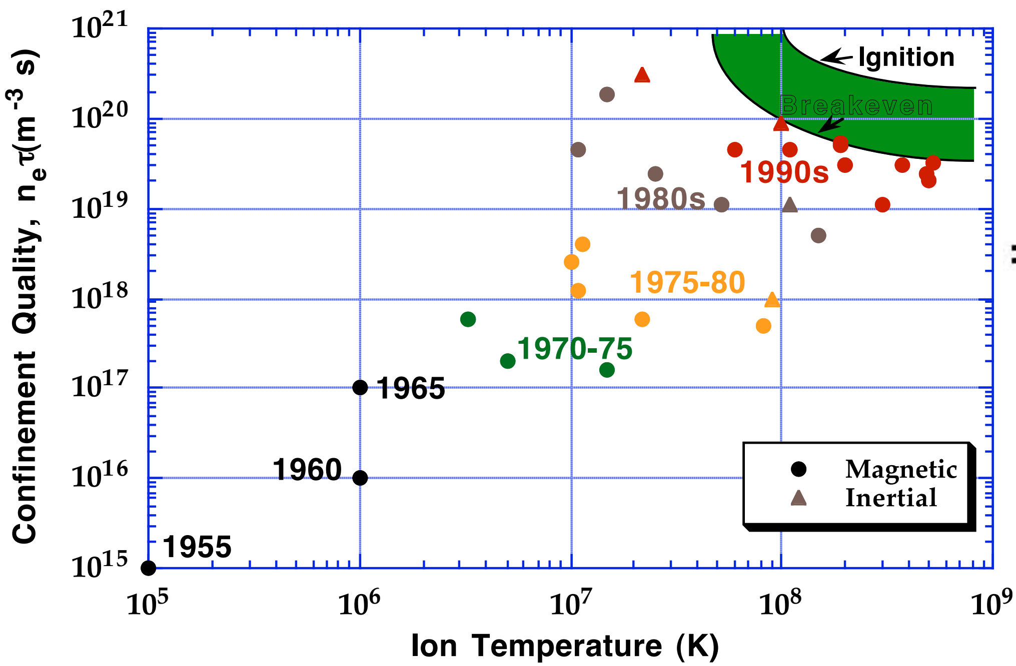
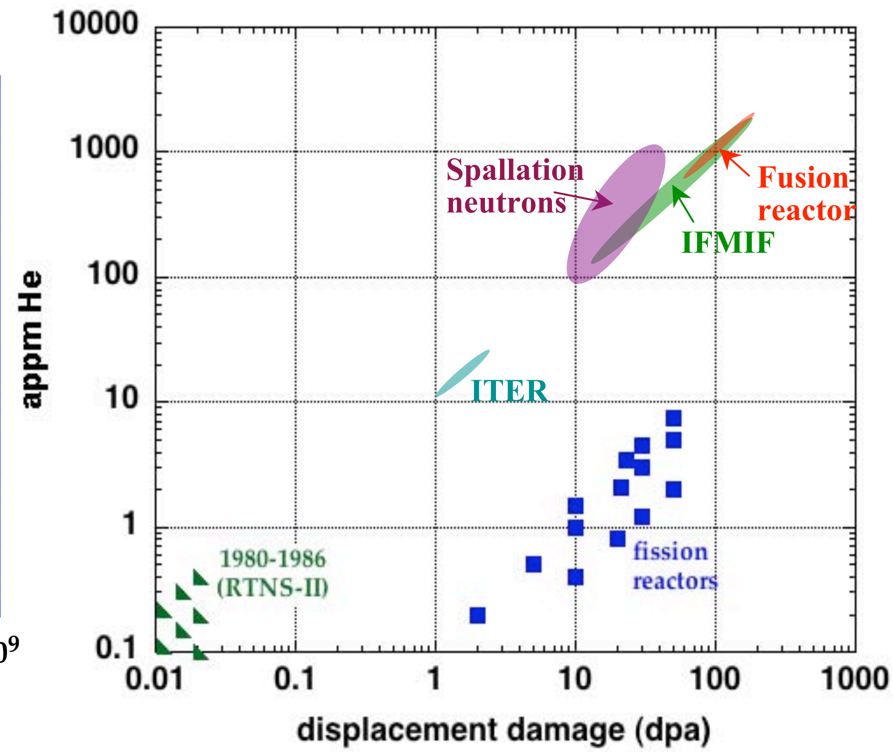
Briefing for FESAC Strategic Planning Panel
Princeton, NJ
August 7, 2007

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 a develop fundamental understanding of radiation damage.

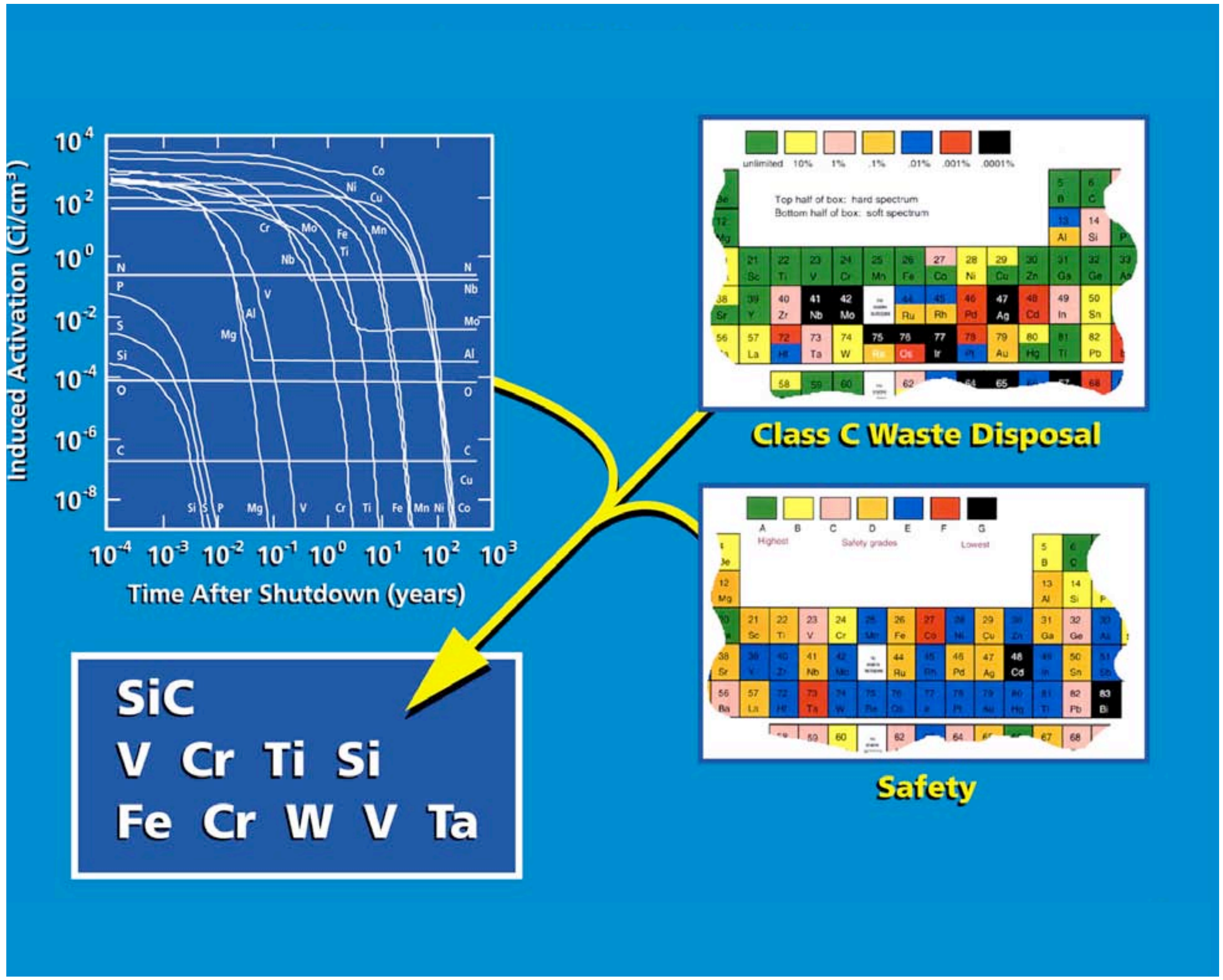


He and Displacement Damage Levels for Ferritic Steels



Low-Activation Structural Materials for Fusion

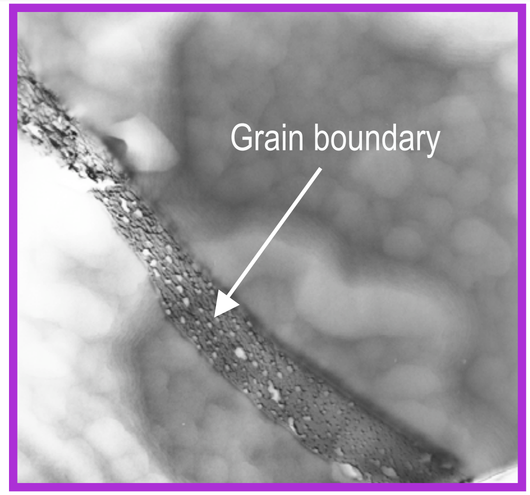
- Structural materials most strongly impact economic and environmental attractiveness of fusion power.
- Key issues: thermal stress, compatibility, safety, waste disposal, radiation damage, safe lifetime limits.
- Ti alloys, Ni base superalloys, and most refractory alloys are unacceptable for various technical reasons.
- Based on safety, waste disposal and performance considerations, the 3 leading candidates:
  - **Ferritic/martensitic steels**
  - **Vanadium alloys**
  - **SiC composites**

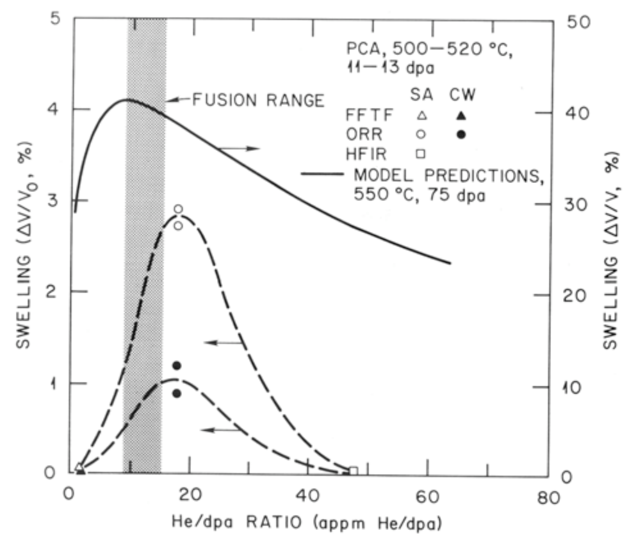


None of the current reduced activation fusion materials existed 15 years ago.

Impact of He-Rich Environment on Neutron Irradiated Materials

- 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.

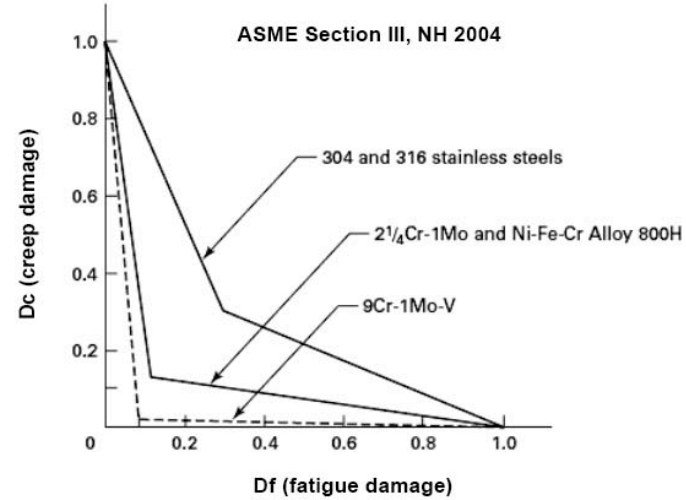




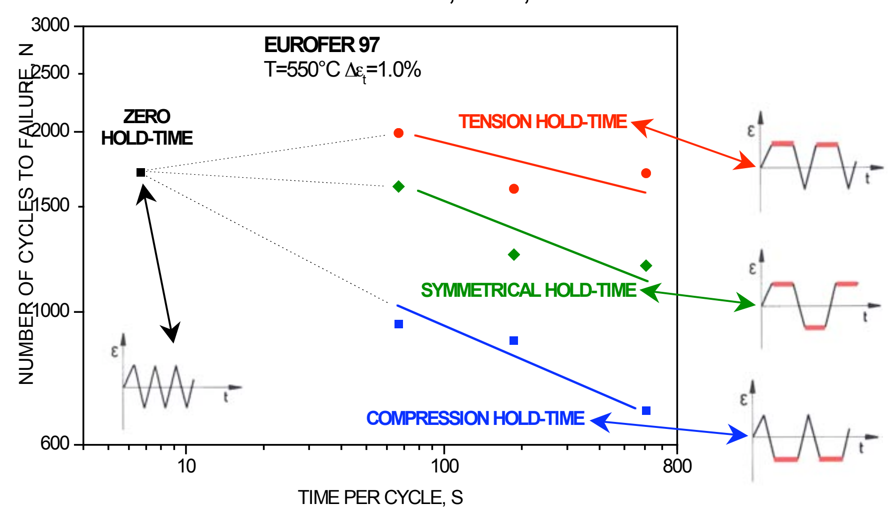
Swelling in stainless steel is maximized at fusion-relevant He/dpa values.

Science-Based High-Temperature Design Methodology

- Current high-temperature design methods are largely empirically based.
- Cyclic plastic loading is far more damaging than monotonic loading.
- New models of high-temperature deformation and fracture are needed:
  - Creep-fatigue interaction.
  - Elastic-plastic, time-dependent fracture mechanics.
  - Materials with low ductility, pronounced anisotropy, composites and multilayers.

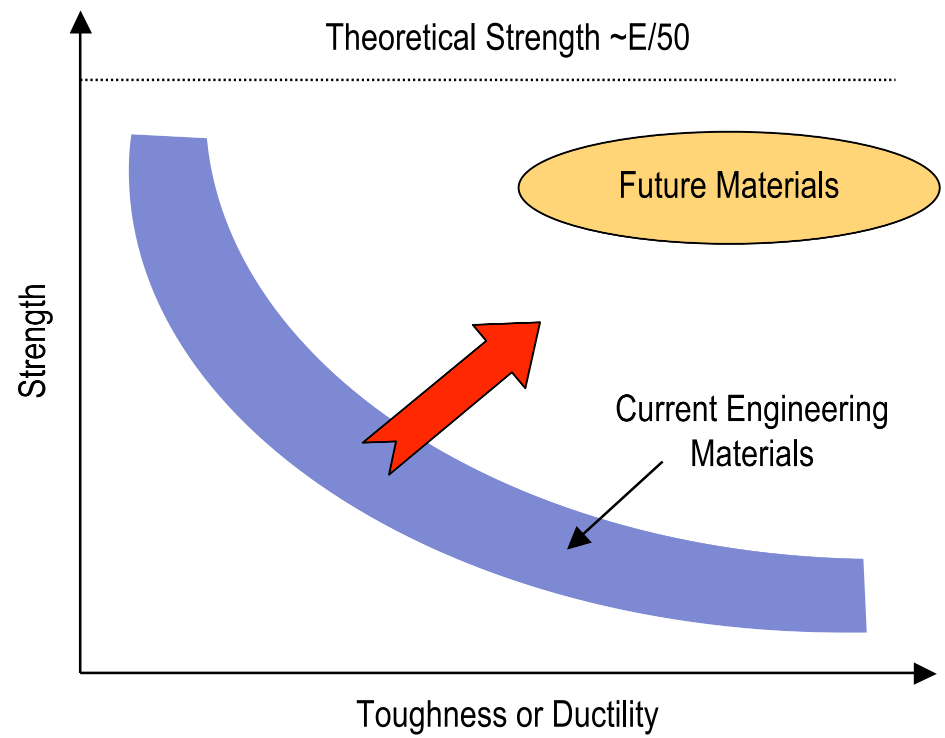


J. Aktaa & R. Schmitt, FZK, 2004



Breaking the High Strength-Low Toughness/Ductility Paradigm

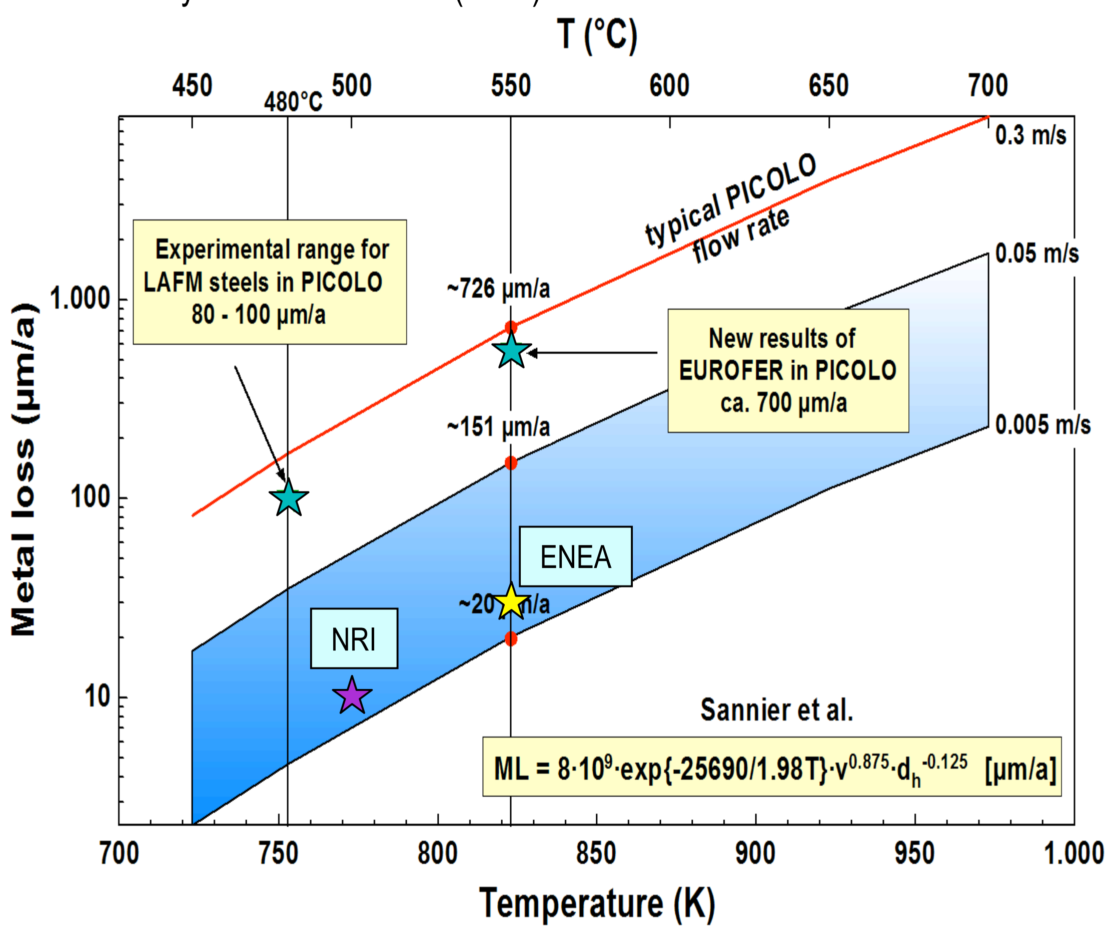
- A general feature of engineering materials is increased strength tends to be offset by losses of toughness (resistance to crack growth) and ductility.
- Strength increases may result from alloying, material processing, or radiation damage.
- Loss of toughness and ductility is a loss of margin against 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.).



Fundamentals of Material-Coolant Chemical Compatibility in the Fusion Environment

- The traditional approach to study corrosion has been largely empirical.
- Empirical correlations do not capture the fundamental physics involved and provide limited predictive capability.
- Opportunities:
  - Controlled experiments combined with physical models utilizing advanced thermodynamics & kinetics codes.
  - Integrated experiments enhanced by use of 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)

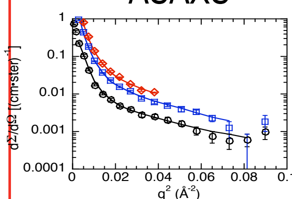


Coupling of Modeling and Experiment to Determine He Transport and Fate

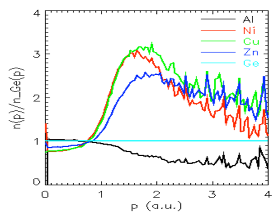
Experimental characterization

feature
'signals'

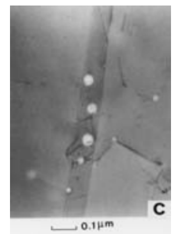
SANS/
ASAXS



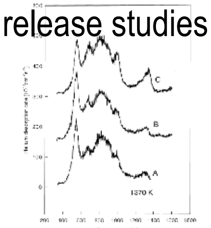
PAS



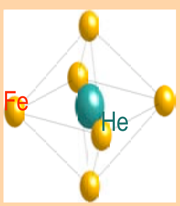
TEM

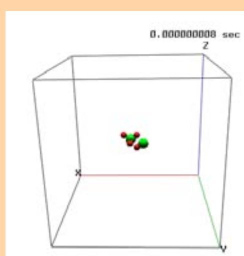


He desorption
& release studies



Multiscale modeling



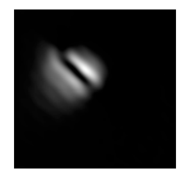


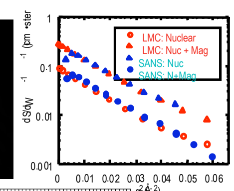
self-consistent
'understanding'
of He effects

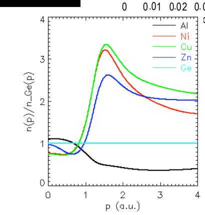
predict
features

simulate
observables

TEM, SANS, Positron theory







GR Odette, UCSB & BD Wirth, UCB

Critical Facility Needs - I

■ Fission Reactor Irradiations

- The capability to perform irradiation experiments in fission reactors is essential for identifying the most promising materials and specimen geometries for irradiation in an intense neutron source.

■ Intense Neutron Source

- Overcoming radiation damage degradation is the rate-controlling step in fusion materials development.
- Evaluation of fusion radiation effects requires simultaneous displacement damage and He generation, with He concentrations above ~100 appm.
- International assessments have concluded that an intense neutron source with ≥ 0.5 liter volume with ≥ 2 MW/m^2 equivalent 14 MeV neutron flux to enable testing up to a least 10 MW-y/m^2, availability > 70%, and flux gradients ≤ 20%/cm is essential to develop and qualify radiation resistant structural materials for DEMO.

Critical Facility Needs - II

- **Component Test Facility**
  - A facility for testing of various components such as blanket modules is also needed to explore the potential for synergistic effects that are not revealed in simpler single-variable experiments or limited multiple-variable studies.
  - Deployment of an intense neutron source should precede this facility (strong interactions between users of facility are essential).
- **Non-Nuclear Facilities**
  - Computational resources will be needed at phases of fusion materials development to support model development but, in particular, large-scale structural damage mechanics computational capability will be needed to guide and interpret data obtained from the component test facility.
  - Flow loops for chemical compatibility studies.
  - Hot cells and associated materials characterization equipment for conducting post-irradiation examinations.

Conclusions

- Recent fusion materials R&D efforts have led to the development of high-performance reduced-activation materials with good radiation resistance for doses > ~10 dpa/ ~100 appm He.
- The overarching scientific challenge facing structural materials for DEMO is microstructural evolution and property changes that may occur for neutron doses > ~10 dpa along with concomitant high levels of transmutant He.
- Better mechanistic physical models of thermal creep and creep-fatigue interactions are needed for development of advanced materials and science-based high-temperature design criteria.
- Current understanding of strength-ductility/toughness relationships is inadequate to simultaneously achieve high-strength and high-ductility and toughness.
- A robust theory and modeling activity is vital for understanding the complex physical phenomena associated with development of radiation-resistant fusion materials.
- The most critical facility need is an intense neutron source. Irradiations in other sources (fission reactors, spallation sources, etc.) combined with theory and modeling will not be able to fully address needs for DEMO (Workshop on Advanced Computational Materials Science, 2004).