Development of High-Performance Structural Materials for Fusion

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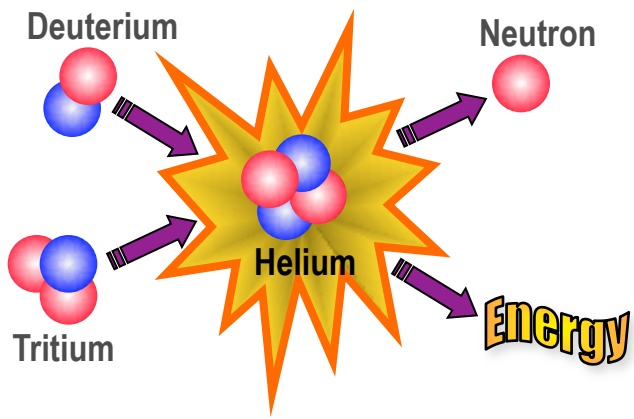
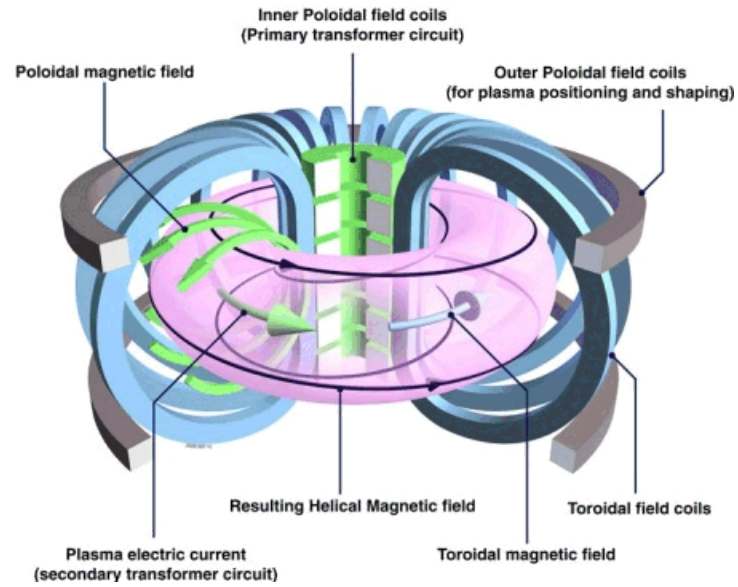
The D-T Fusion Reaction and Confinement Concepts

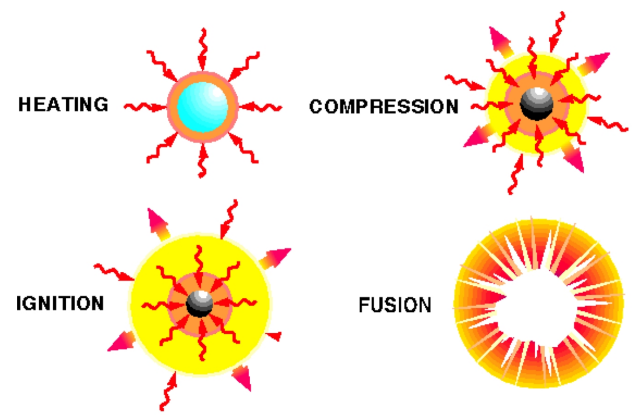
$$D + T \rightarrow {}^{4}_{2}He + {}^{1}_{0}n + 17.6MeV$$



- World fusion programs are focused on the D-T cycle (easiest to ignite)
- The fusion energy (17.6 MeV per reaction) appears as kinetic energy of neutrons (14.1 MeV) and alphas (3.5 MeV)
- Tritium does not exist in nature and must be generated inside the fusion system to have a sustainable fuel cycle
- The only possibility to adequately breed tritium is through neutron interactions with lithium



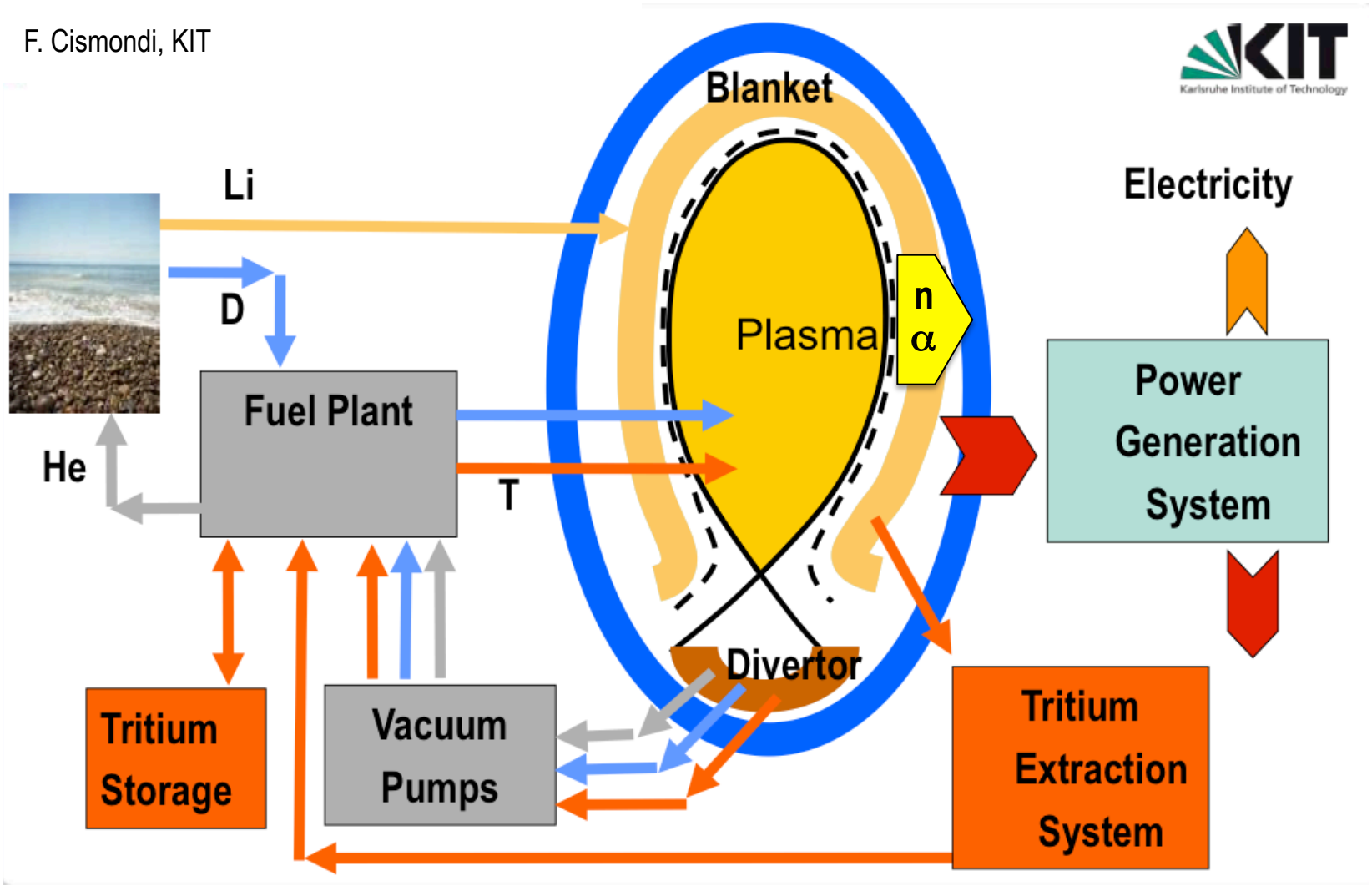
Magnetic Confinement Fusion



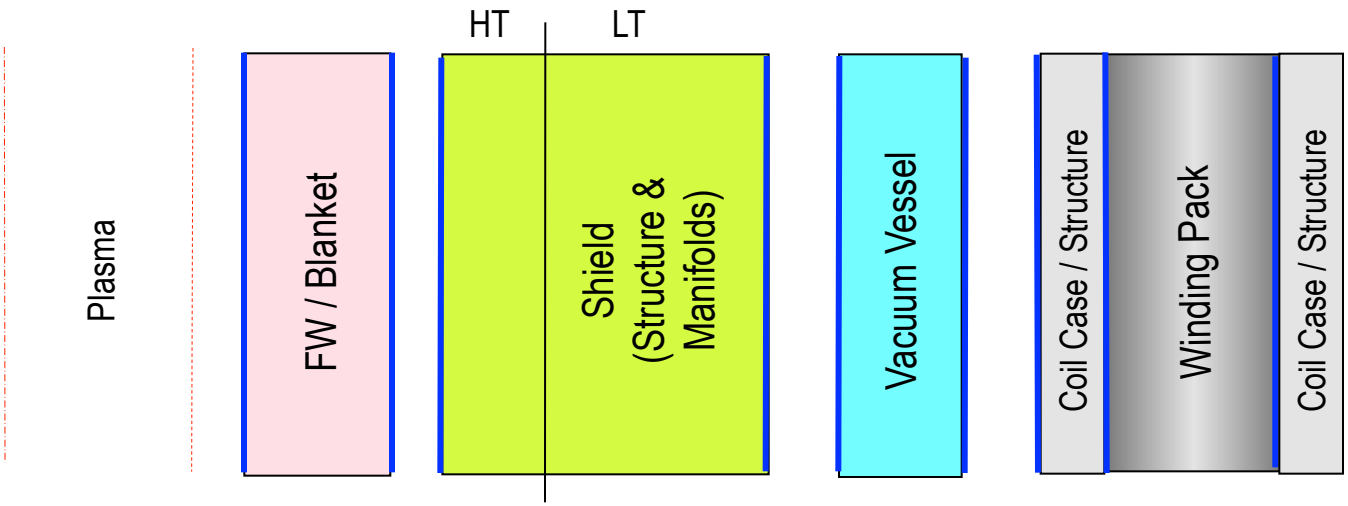
Inertial Confinement Fusion

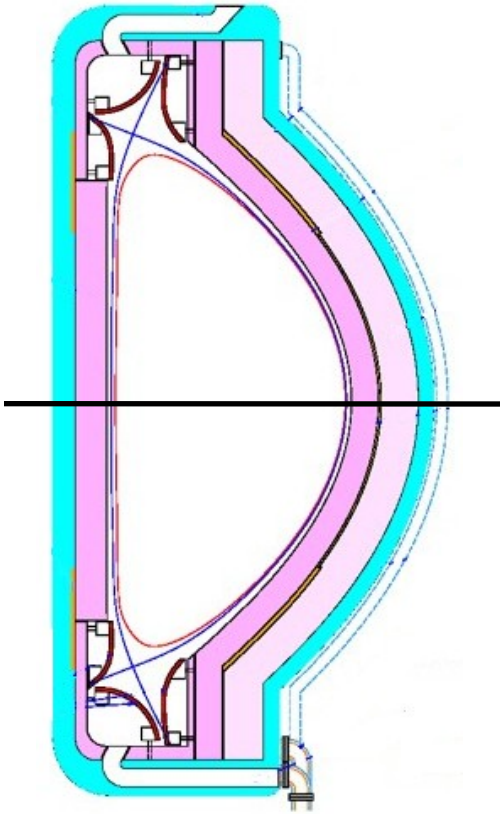
MCF Power System Schematic

F. Cismondi, KIT



Generic Elements of a Radial Build





- First-wall and blanket elements of fusion power system recover 90% of incident neutron and radiative energy and breed tritium
- All components provide shielding function:
  - Blanket protects shield
  - Blanket and shield protect vacuum vessel
  - All components protect magnets
  - All components and the building protect workers and public
- All components are permanent, except first-wall/blanket and divertor
- Inboard, outboard and vertical builds are different

M.S. Tillack, F. Najmabadi, FNS Pathway Assessment Meeting, 2010

First-wall/Blanket Functions

A. Power Extraction
- Convert kinetic energy of neutrons and secondary gamma-rays into heat
- Handle the particle and radiative power from the plasma onto the chamber wall
- Extract the heat (at high temperature, for energy conversion)

B. Tritium Breeding
- Tritium breeding, extraction, and control
- Must have lithium in some form for tritium breeding

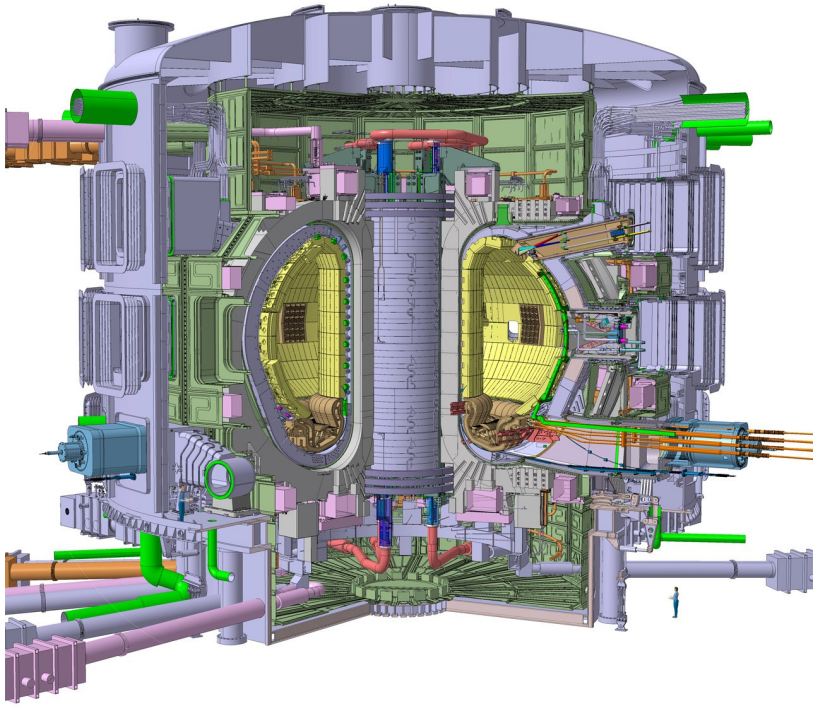
C. Physical Boundary for the Plasma
- Physical boundary surrounding the plasma, inside the vacuum vessel
- Provide access for plasma heating, fueling
- Must be compatible with plasma operation
- Innovative blanket concepts can improve plasma stability and confinement

D. Radiation Shielding of Outboard Components

Materials Development Challenges to Reach a Steady-State Fusion Energy Device

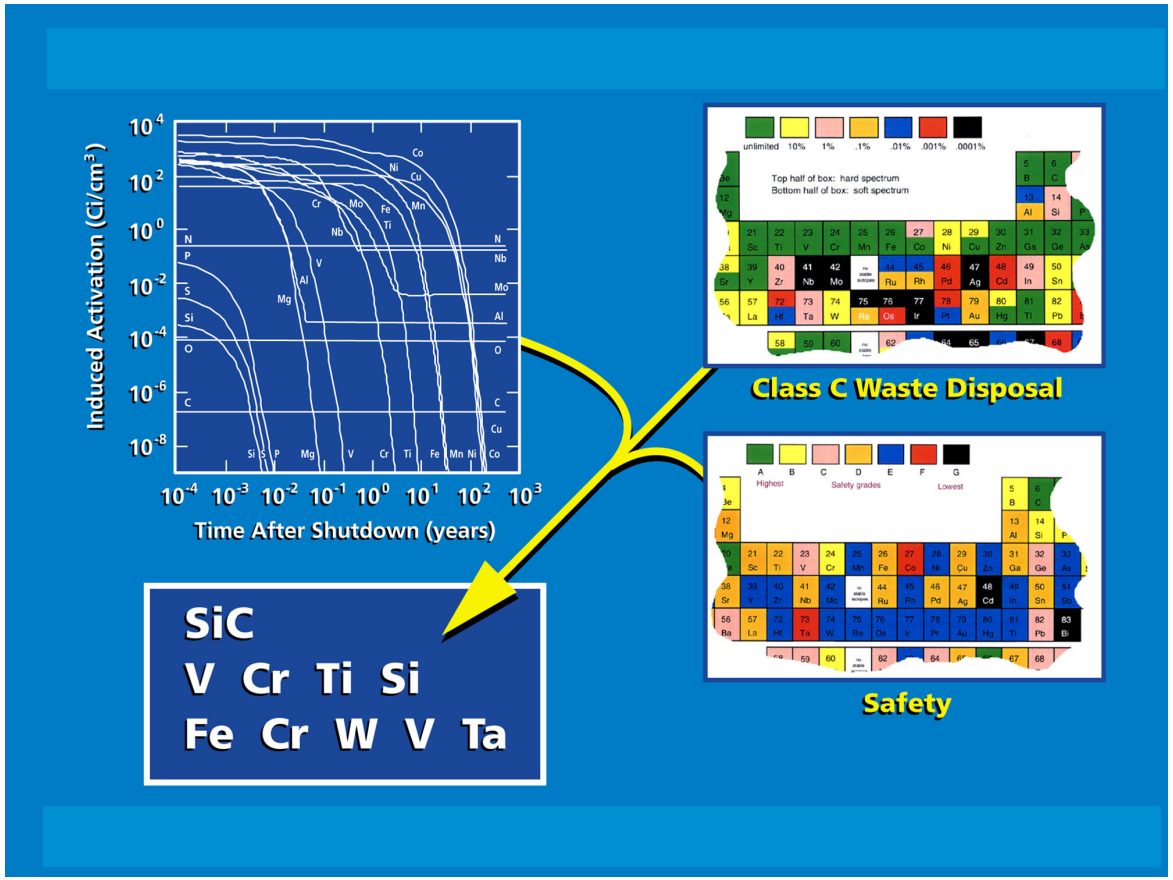
- Plasma – materials interactions
  - Sputtering, re-deposition, tritium implantation and retention
  - High heat flux
  - Time varying thermo-mechanical stresses
- Nuclear and non-nuclear degradation to materials and structures
  - Resistance to intense fusion neutron exposure (including transmutant H/He + solids)
  - Low-activation materials for safety and environmental attractiveness
  - Corrosive environments, with possible radiation enhanced corrosion
  - Large, time varying thermo-mechanical stresses and high temperatures
- Harnessing fusion energy
  - Minimize tritium inventory in blanket structures, plasma-facing components, etc.
  - Efficiently extract tritium from hot coolant
  - Thermo-hydraulic and magneto-hydrodynamic instabilities

ITER Organization, 2011



Low-Activation Structural Materials for Fusion

- 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
  - Vanadium alloys
  - SiC composites
  - Tungsten alloys



Complex, Interlinked Plasma Surface Interaction Phenomena

Wirth et al, Mater. Res. Soc. Bull. 36 (2011) 216

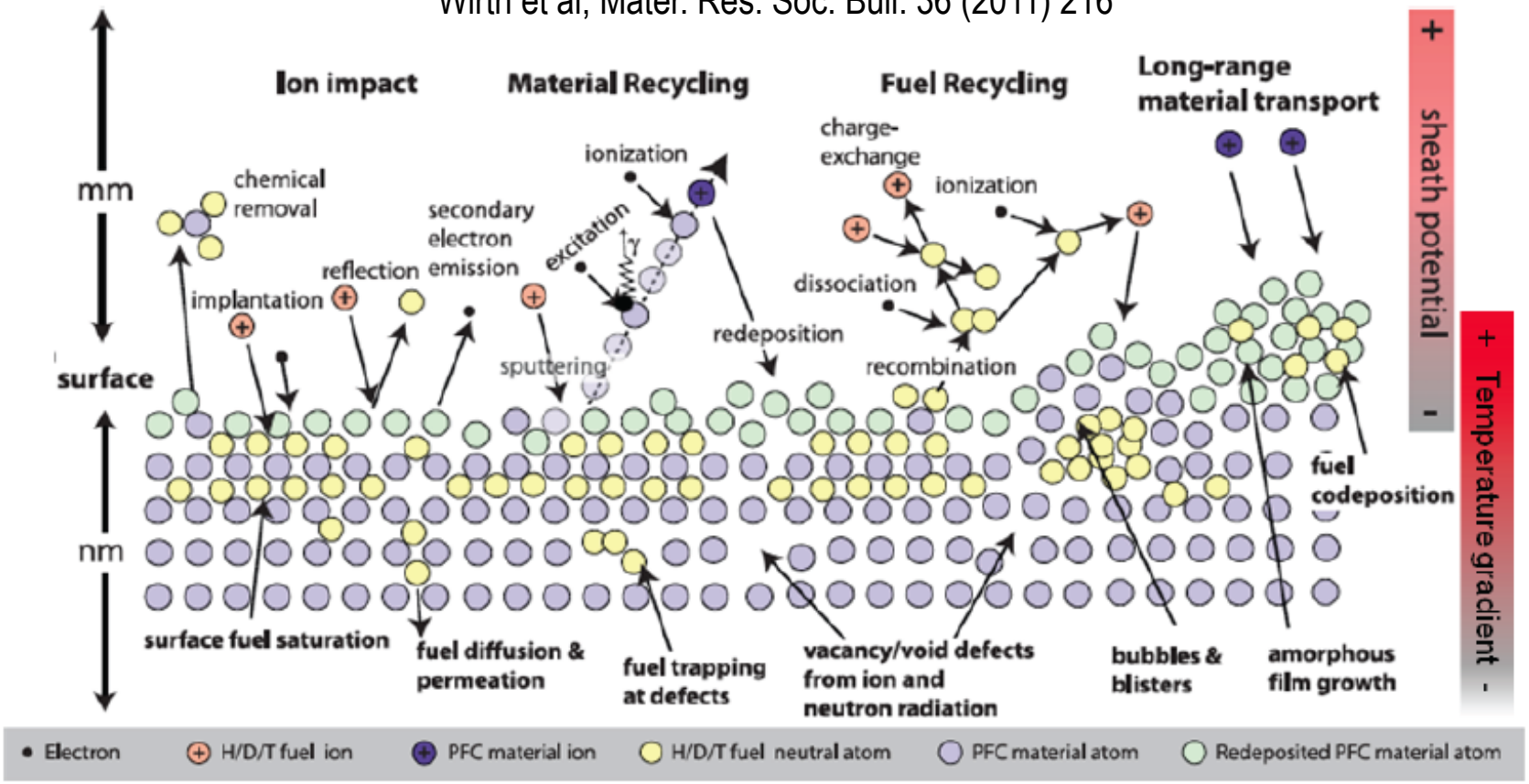


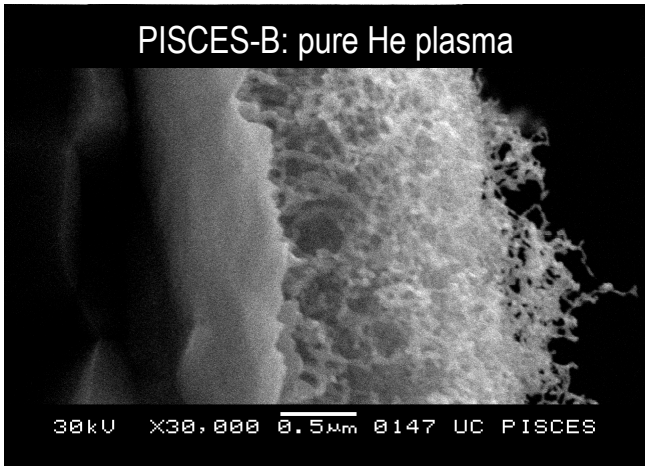
Figure of merit:

- Incident plasma ion flux near divertor strikepoint: 10^{24} $m^{-2}s^{-1}$
- Steady-state sputtering yield O (10^{-4}) on surface monolayer (10^{19} atoms/m^2) results in sputtering of every atom every 0.1 sec -> every atom sputter >10^8 times/year

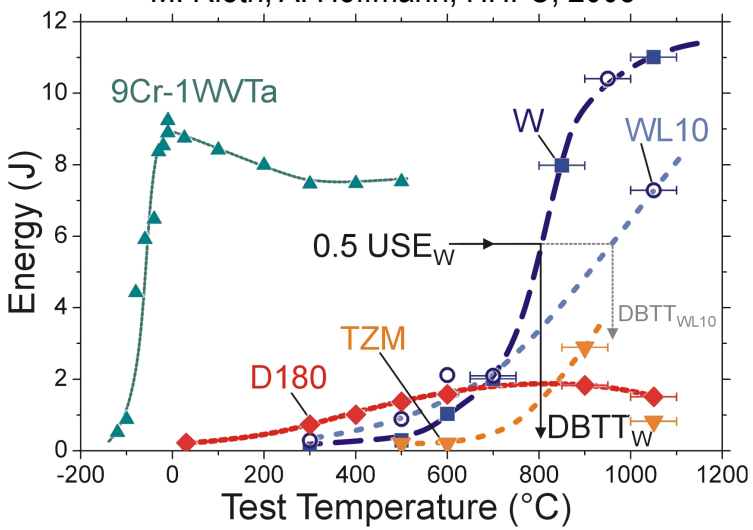
Plasma Facing Materials Must Tolerate Extreme Heat, Neutron & Particle Fluxes

- 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)
- Several new computational and experimental efforts to explore ways to predict and improve the performance of tungsten PFCs are now underway

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

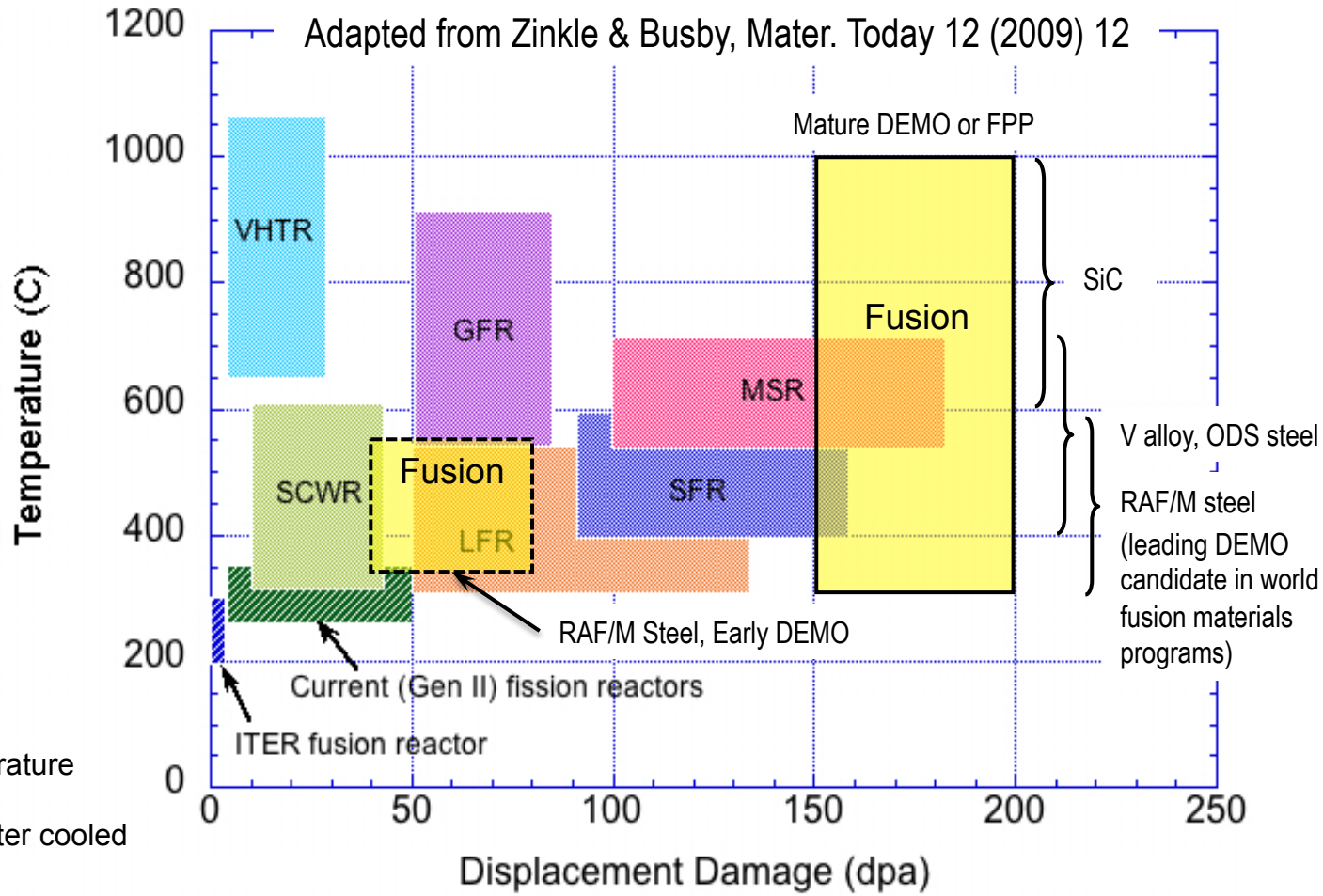


M. Rieth, A. Hoffmann, HHFC, 2008



Comparison of Gen IV and Fusion Displacement Damage Environments

The fusion nuclear environment includes additional degradation concerns such as (He/H/solid transmutants, thermo-mechanical cycling and tritium) that are > to >> than fission



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

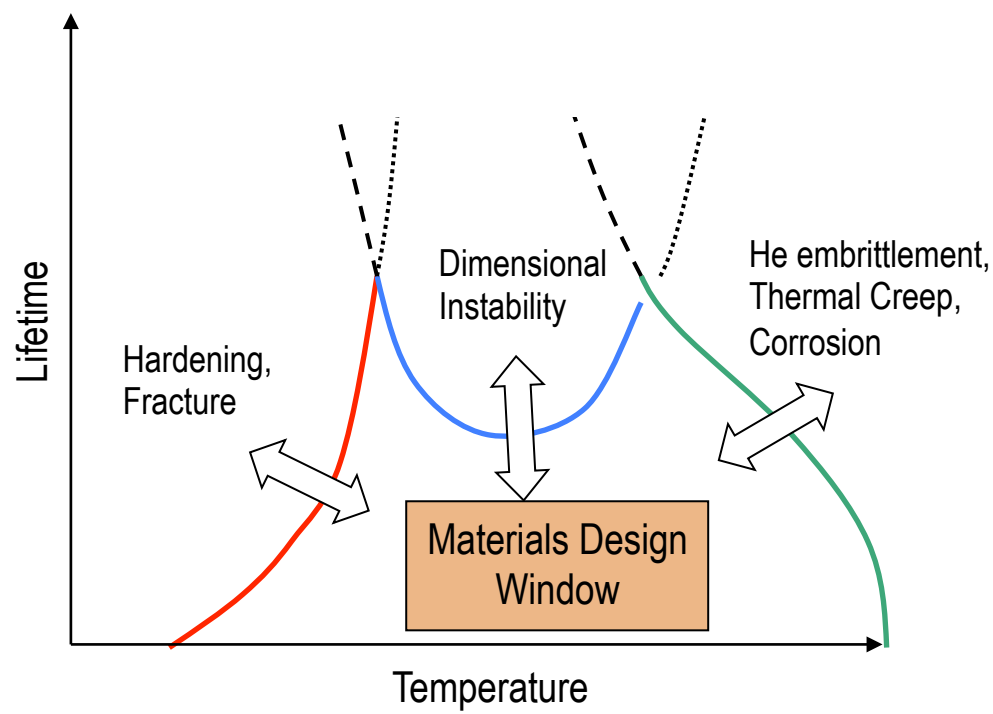
A common theme for fusion and advanced fission is the need to develop high-temperature, radiation resistant materials.

Effects of the Fusion Environment on the Operating Temperature Window

Unique to fusion: displacement damage (displacements per atom or dpa) and He coupled with stress results in considerable microstructure and property changes

- Low temperatures (< 0.4 T_m, < 0.1 dpa):
  - Hardening + He embrittlement
  - Loss of ductility
  - Loss of fracture resistance
- Intermediate temperatures (0.3 < T_m < 0.6, > 10 dpa):
  - Swelling + He
  - Irradiation creep + He
- At high temperatures (> 0.4 T_m):
  - Thermal creep
  - He embrittlement (> 10 dpa)
  - Fatigue and creep-fatigue, crack growth
  - Corrosion, oxidation and impurity embrittlement

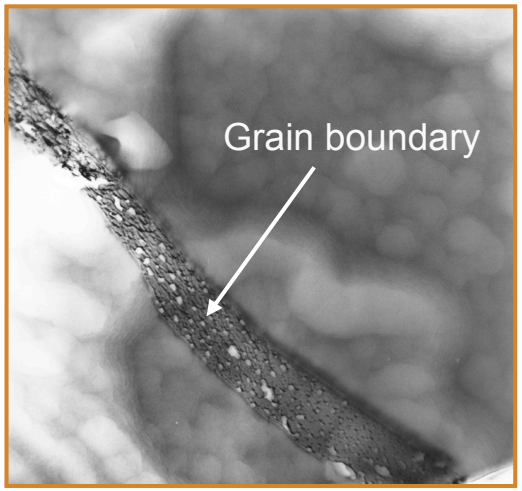
Ghoniem & Wirth, 2002



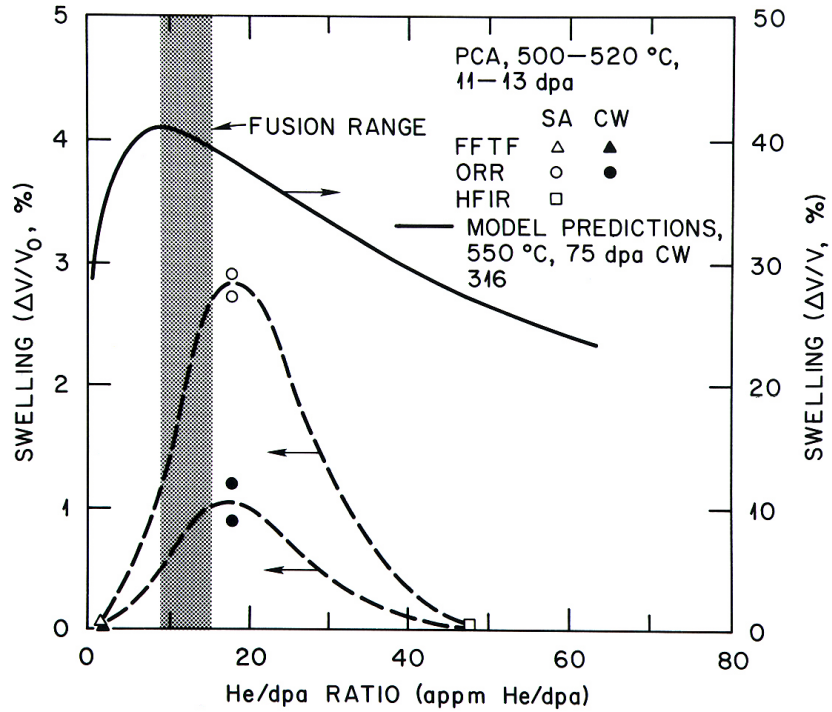
Why is He/dpa Ratio Such an Important Parameter for Materials R&D?

- He generation can alter the microstructural evolution path of irradiated materials (pronounced effects typically occur for > 100 appm)
  - Cavity formation (matrix and grain boundaries)
  - Precipitate and dislocation loop formation
- He can also increase hardening and embrittlement at low temperatures

He bubbles on grain boundaries can cause severe embrittlement at high temperatures

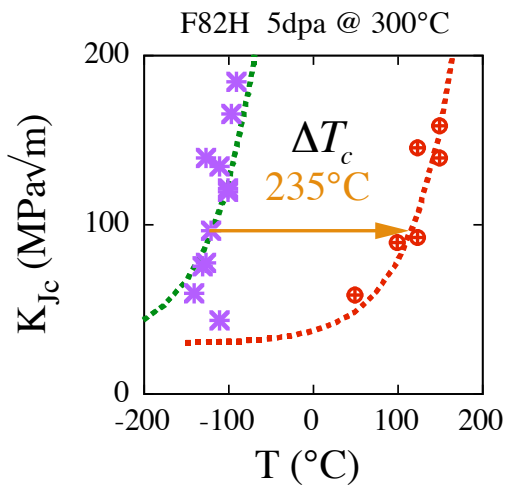


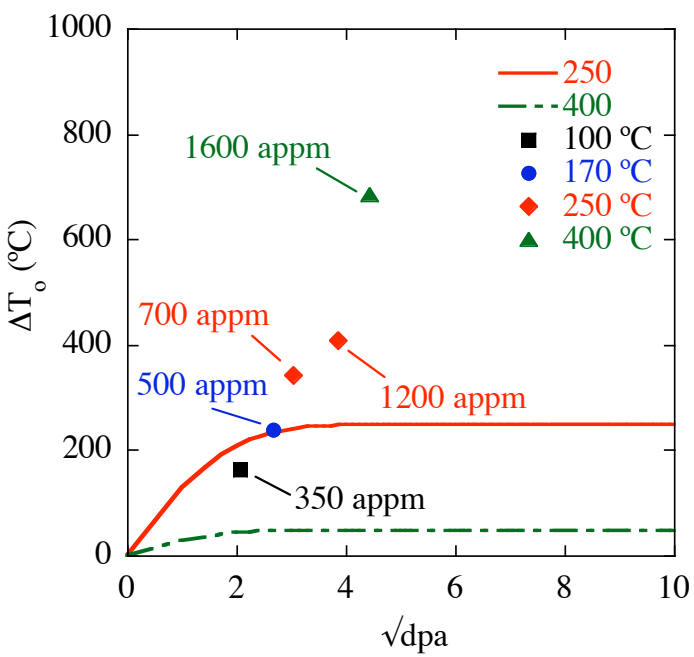
Swelling in stainless steel is maximized at fusion-relevant He/dpa values



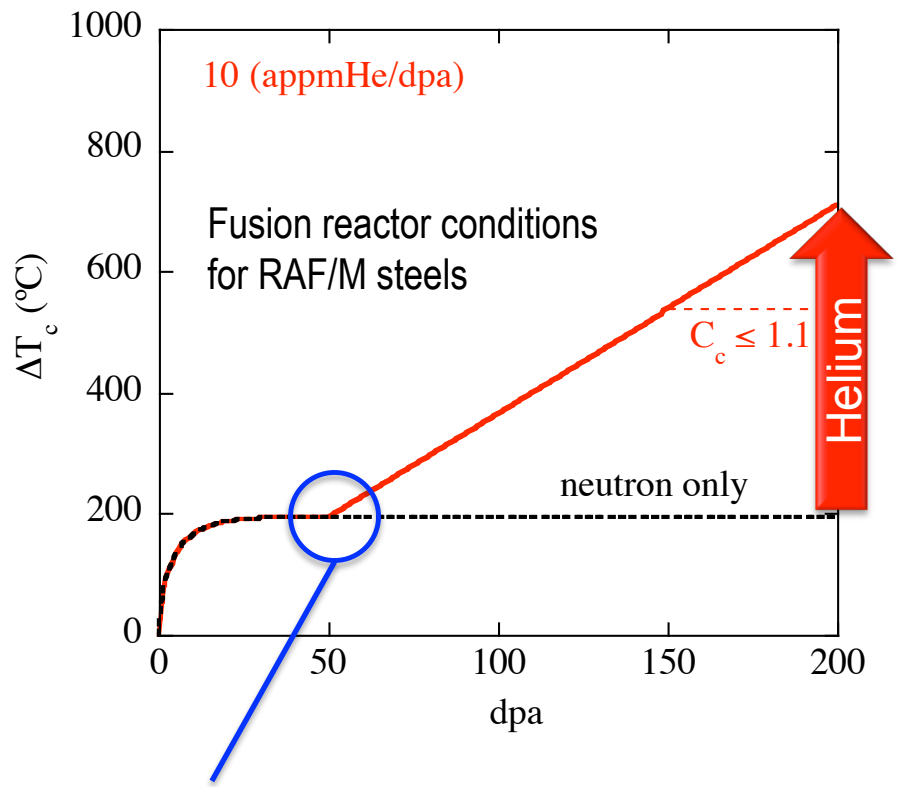
R. Stoller, J. Nuc. Mater. 174 (1990) 289

Effect of Helium on Ductile-to-Brittle Transition Temperature





T. Yamamoto et al. Trans. ANS 98 (2008) 1111

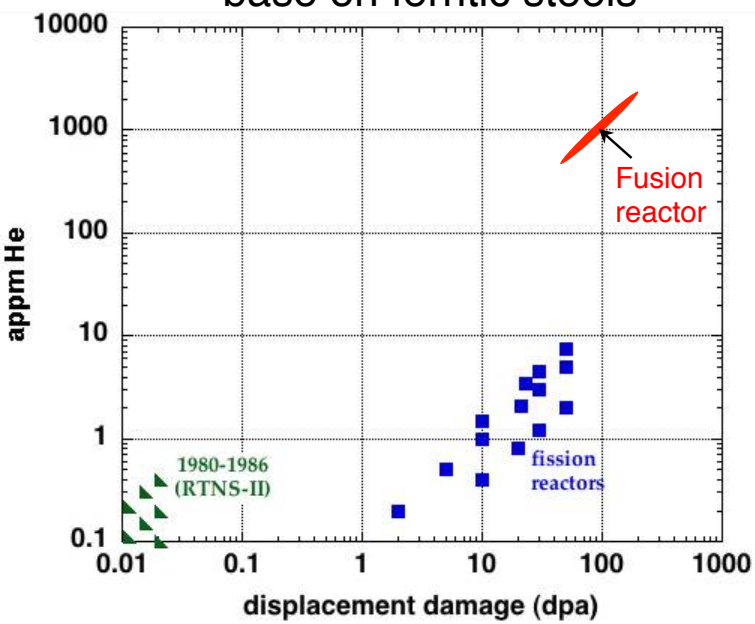


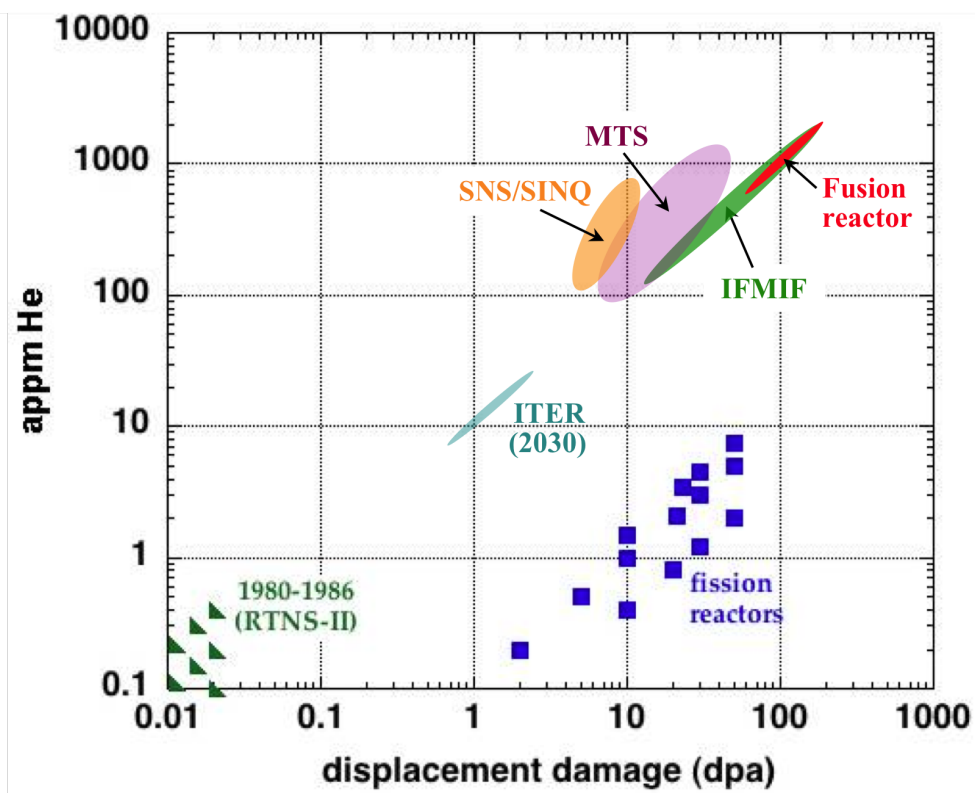
Fusion relevant behavior at 50-70 dpa or 500-700 appm He needs to be addressed

Several Options for Closing the Gap in Neutron Irradiation Effects

An intense neutron source (coupled with enhanced theory and modeling) is needed to improve understanding of neutron irradiation effects and to develop & qualify fusion structural materials

Current knowledge base on ferritic steels

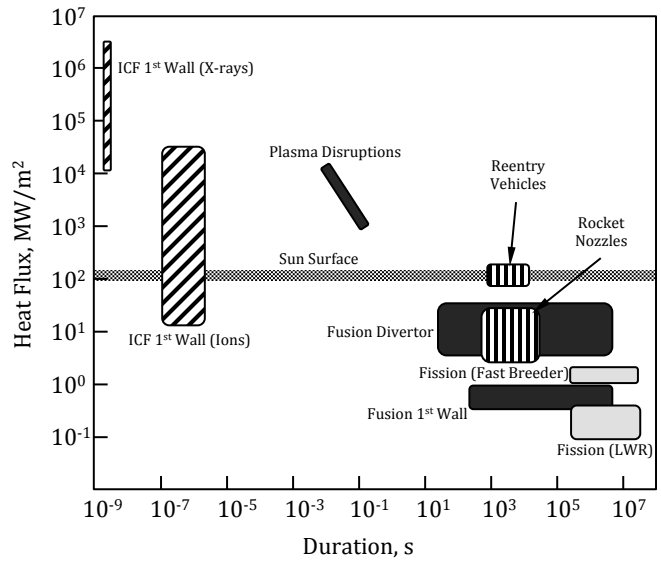




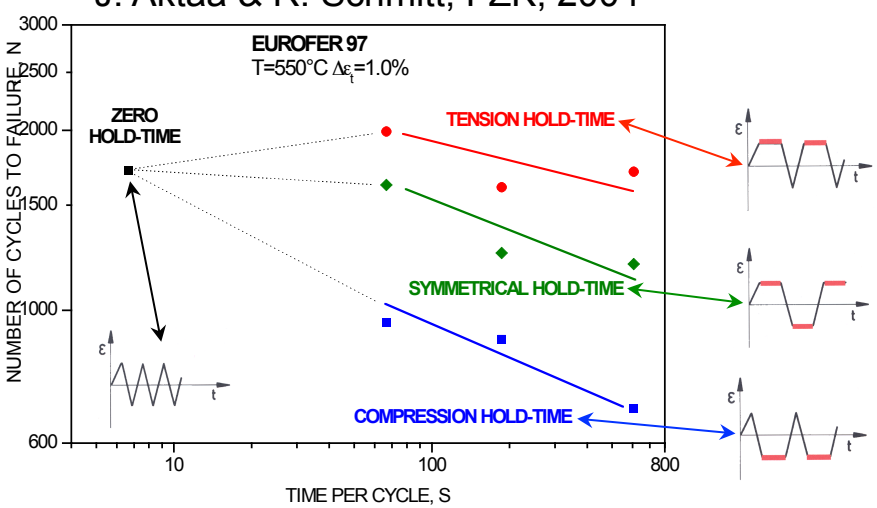
Option A: IFMIF + fission reactors +ion beams + modeling
Option B: robust spallation (e.g., MTS) + fission reactors + ion beams + modeling
Option C: modest spallation (e.g.,SNS/SINQ) + fission reactors + ion beams + modeling

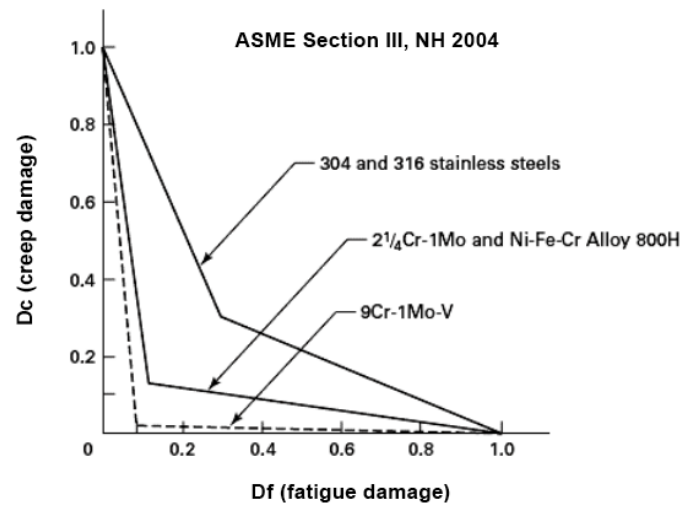
Science-Based High-Temperature Design Criteria are Critical For Fusion

- 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



J. Aktaa & R. Schmitt, FZK, 2004

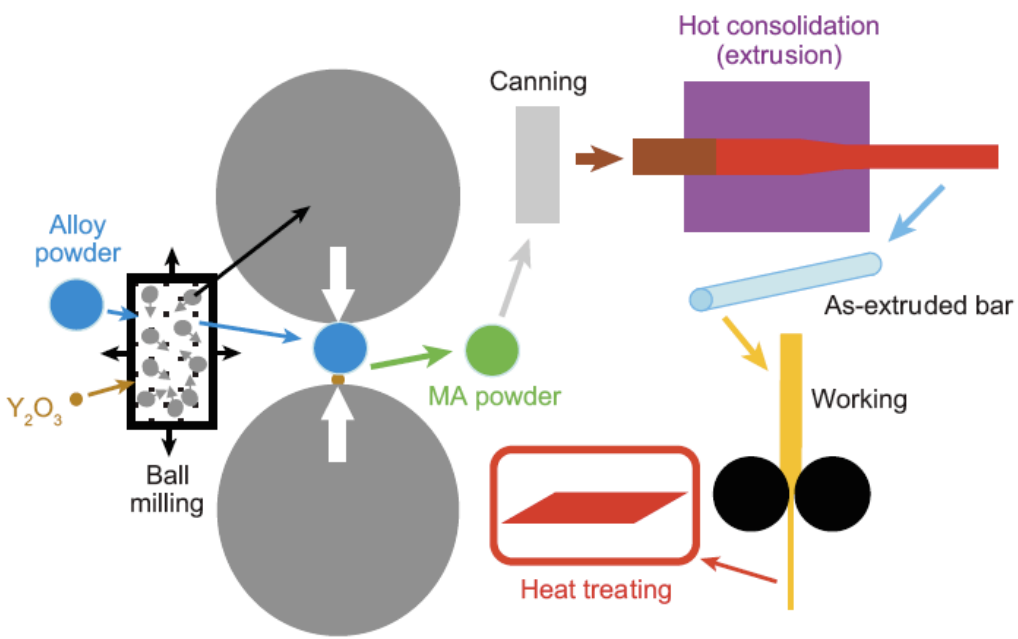


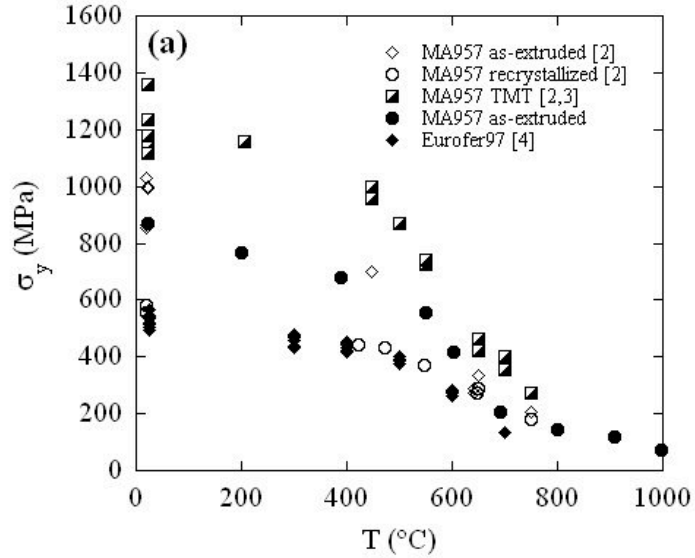


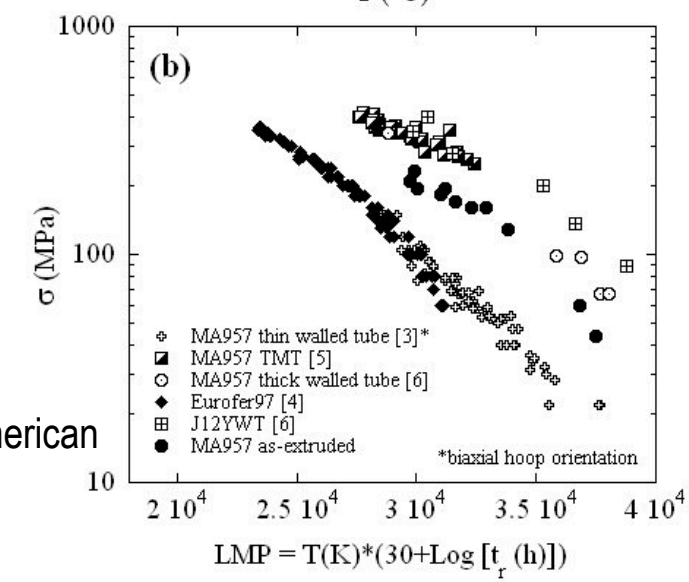
Advanced Materials are Needed for Improved High-Temperature Strength

Fe – (12-14)Cr – Ti – Y_2O_3

G.R. Odette, et al, Annu. Rev. Mater. Res. 2008. 38:471.





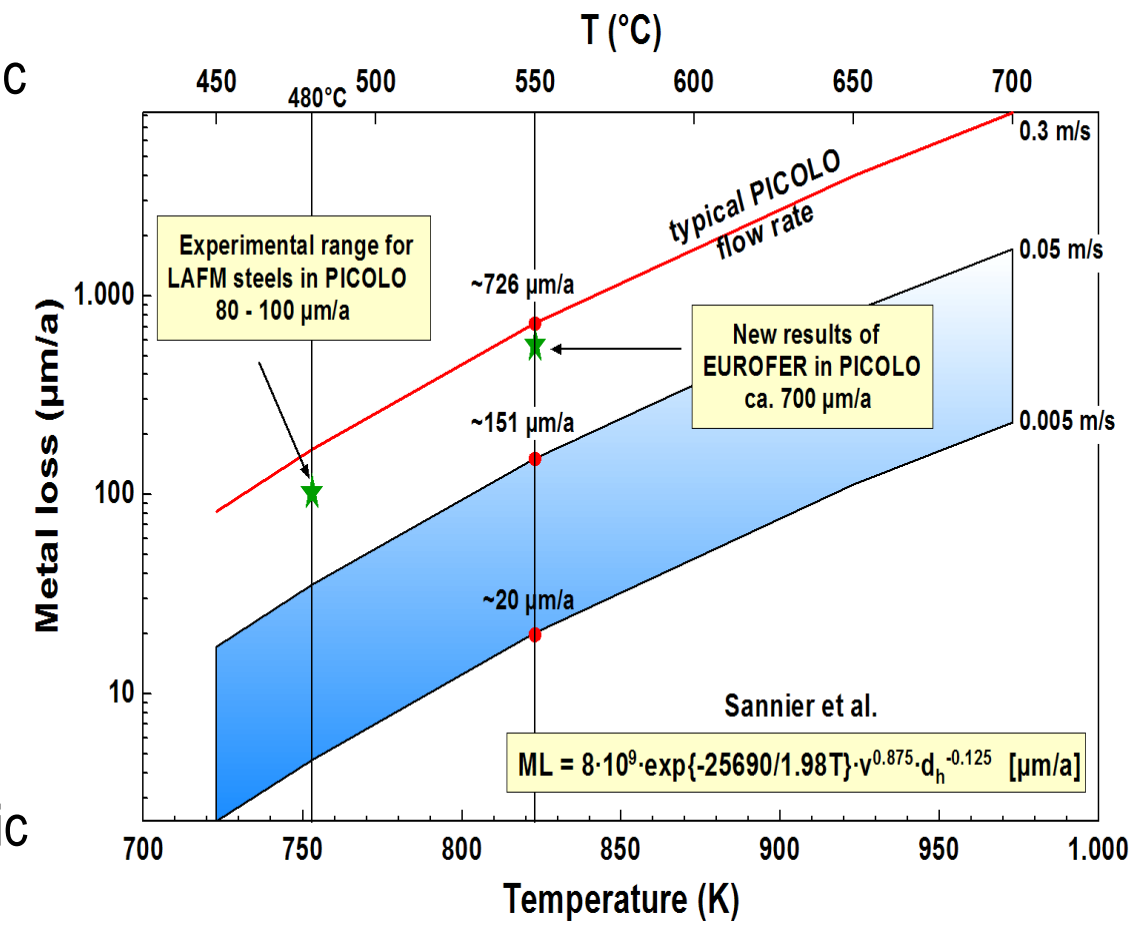


M.C. Salston, G.R. Odette, Trans. American Nuclear Society 98 (2008) 1146.

Material-Coolant Chemical Compatibility in the Fusion Environment

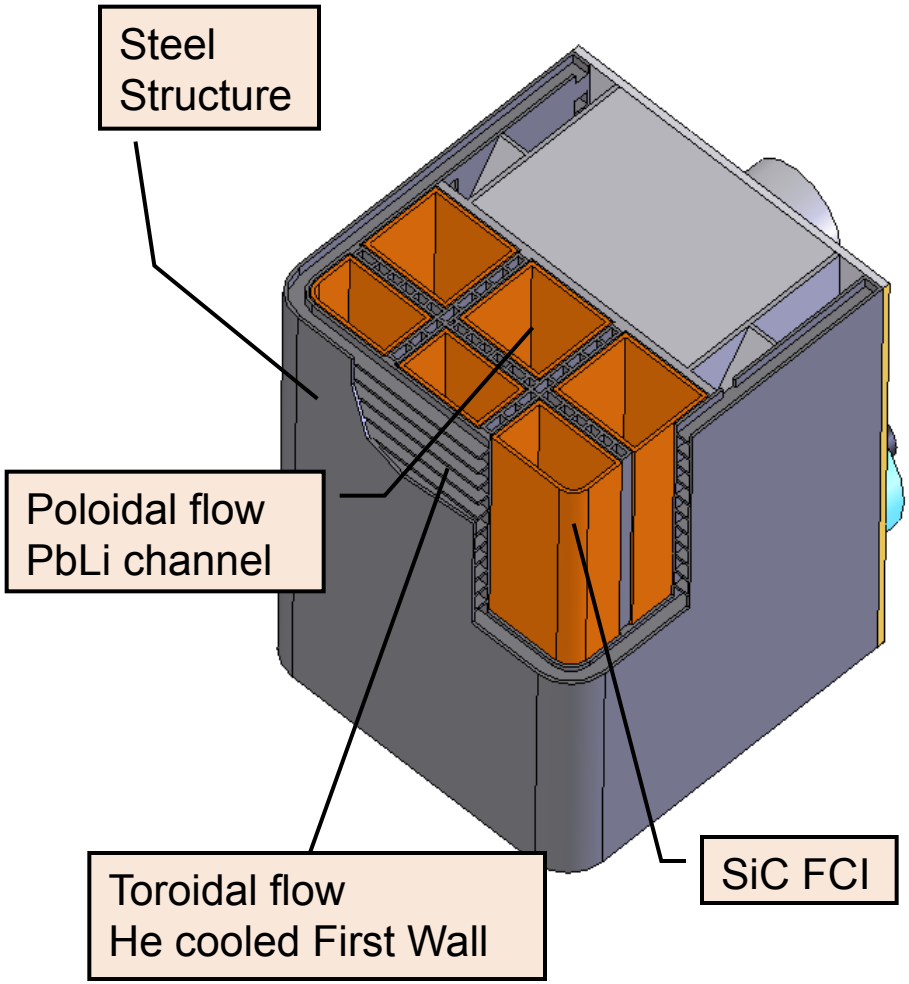
- The traditional approach to corrosion is empirical
- Correlations do not capture basic physics and have limited predictive capability
- Opportunities:
  - Controlled experiments combined with physical models utilizing advanced thermodynamics & kinetics codes
  - Integrated experiments using sophisticated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

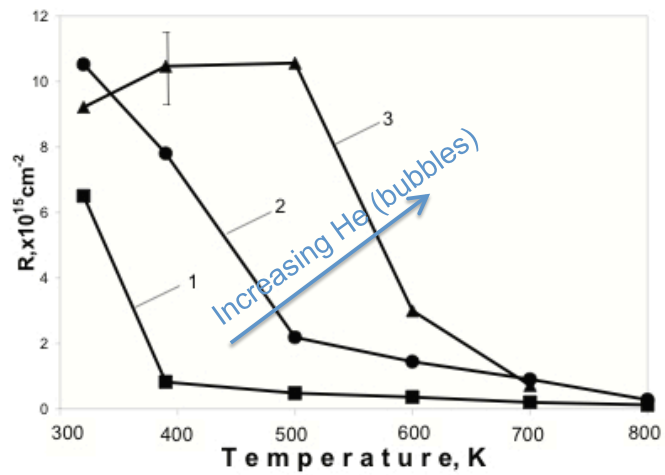
- Dual coolant PbLi blanket concept
- Reduced activation ferritic/martensitic steel structure cooled by He
- Breeding zone is self-cooled PbLi
  - Operates at much higher temperature than He and steel
- Structure and breeding zone separated by SiC flow channel inserts that:
  - Thermally insolate hot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



Tritium Retention & Release Issues Require Additional Research

- Identification of a robust, efficient and economic method for extraction of tritium from high temperature coolants
  - Large number of potential tritium blanket systems is both advantageous and a hindrance
- Current materials science strategies to develop radiation-resistant materials may (or may not) lead to dramatically enhanced tritium retention in the fusion blanket
  - Fission power reactors {typical annual T_2 discharges of 100 - 800 Ci/GW_e (~10% of production)} are drawing increasing scrutiny
  - A 1 GW_e fusion plant will produce ~10^9 Ci/yr; typical assumed releases are ~0.3 to $1x10^5$ Ci/yr (<0.01% of production)
  - Nanoscale cavity formation may lead to significant trapping of hydrogen isotopes in the blanket structure
  - Trapping of tritium by precipitates and nanoscale solute clusters is poorly understood from a fundamental perspective

G.D. Tolstolutskaya et al., 12th Int. Conf. on Env. Deg. Mater. Nucl. Power System (TMS, 2005)



Deuterium retention in 18Cr10NiTi steel implanted to $1x10^{16}$ cm^{-2} without He (1) and with He to $5x10^{15}$ cm^{-2} (2) and $5x10^{16}$ cm^{-2} (3)

Critical 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 and He (+H) generation 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

Critical Resource Needs for Fusion Materials Development - II

- Fusion Nuclear Science Facility (ITER – FNSF - DEMO)
  - 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

Summary

- The fusion neutron environment represents an enormous materials development challenge (high T, dpa, H and He)
- The U.S. Fusion Materials Program is engaged in a science-based effort to develop basic understanding of the damage mechanisms controlling performance-limiting phenomena
- Research is focused on reduced or low-activation materials (RAF/M steels, NFAs (ODS), SiC composites, and W-alloys) for safety and environmental attractiveness
- Considerable progress has been made determining the effects of neutron damage and He on properties of RAF/M steels and NFAs using novel experimental techniques coupled with physics-based computational models
- Several fundamental phenomena are not well understood or adequately characterized (e.g., effects of He on void swelling, irradiation creep and creep-rupture; tritium binding energy to cavities and nanoscale clusters; creep-fatigue interaction; effects of particle impingement on surface evolution of W)
- The most critical facility need is a fusion relevant neutron source to resolve the scientific challenges (He/dpa) and qualify materials for next-step fusion devices