Overview of the Fusion Materials Science program

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Fusion Materials Sciences peer review

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University of California-Santa Barbara

Introduction/Outline (to be completed)

- intro to the Fusion materials R&D challenge (why focus on structural materials; role of low activation and safety; material/blanket candidates)
- how does the FMSP fit into the US enabling technology and overall fusion programs
- overview of recent changes in program direction (development->underlying science; studying model materials systems, in order to develop knowledge base)
- tools and techniques overview (role of modeling; examples of surrogate expts/modeling, dose/temperature/stress/chemical compatibility issues—including commonality and complementarity with fission, SSTT development, He effects, etc.)
- international connections (DOE/JAERI, US/J Jupiter I&II, US/RF, IEA)

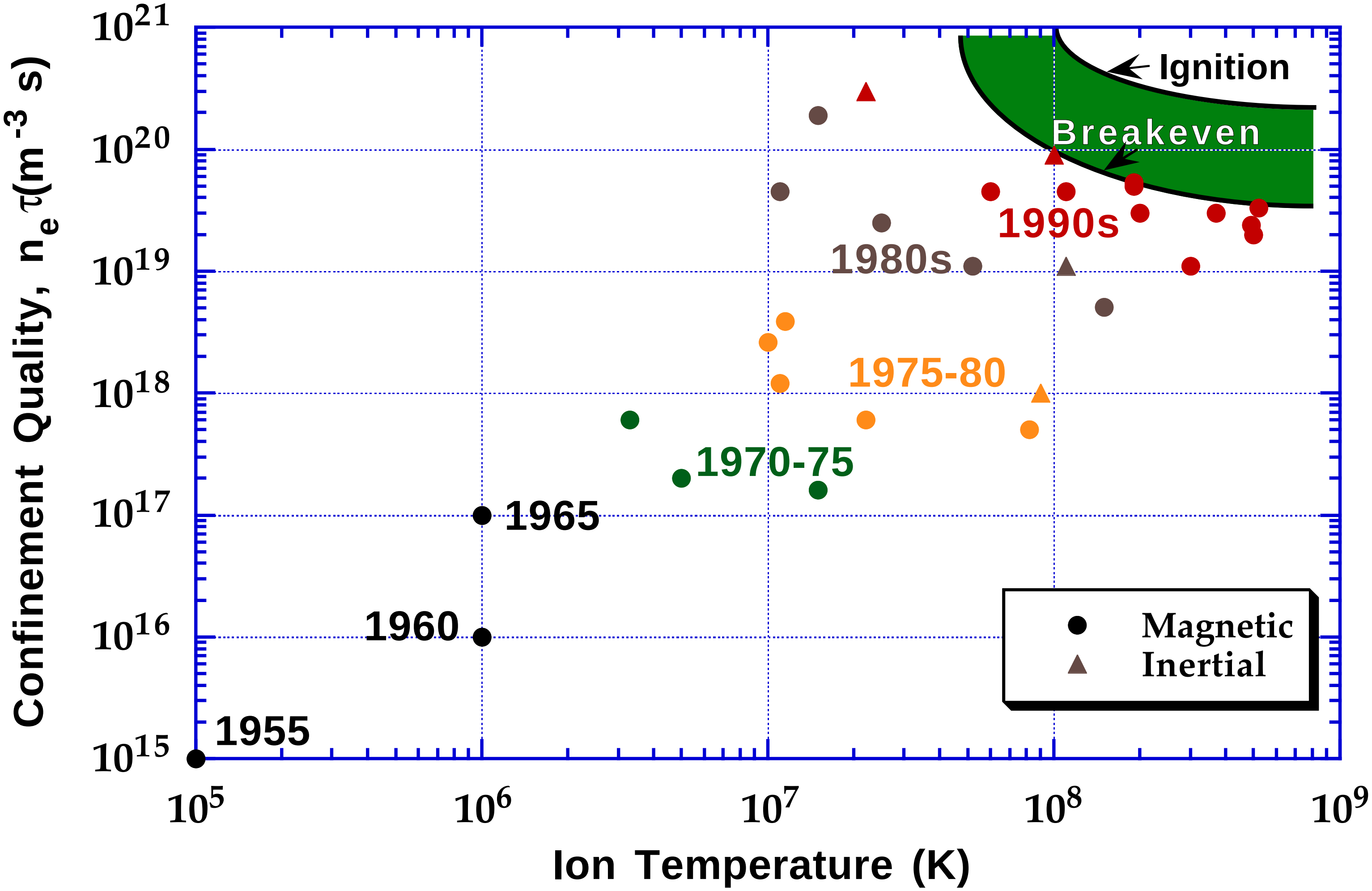
Fusion Materials Science Mission Statement

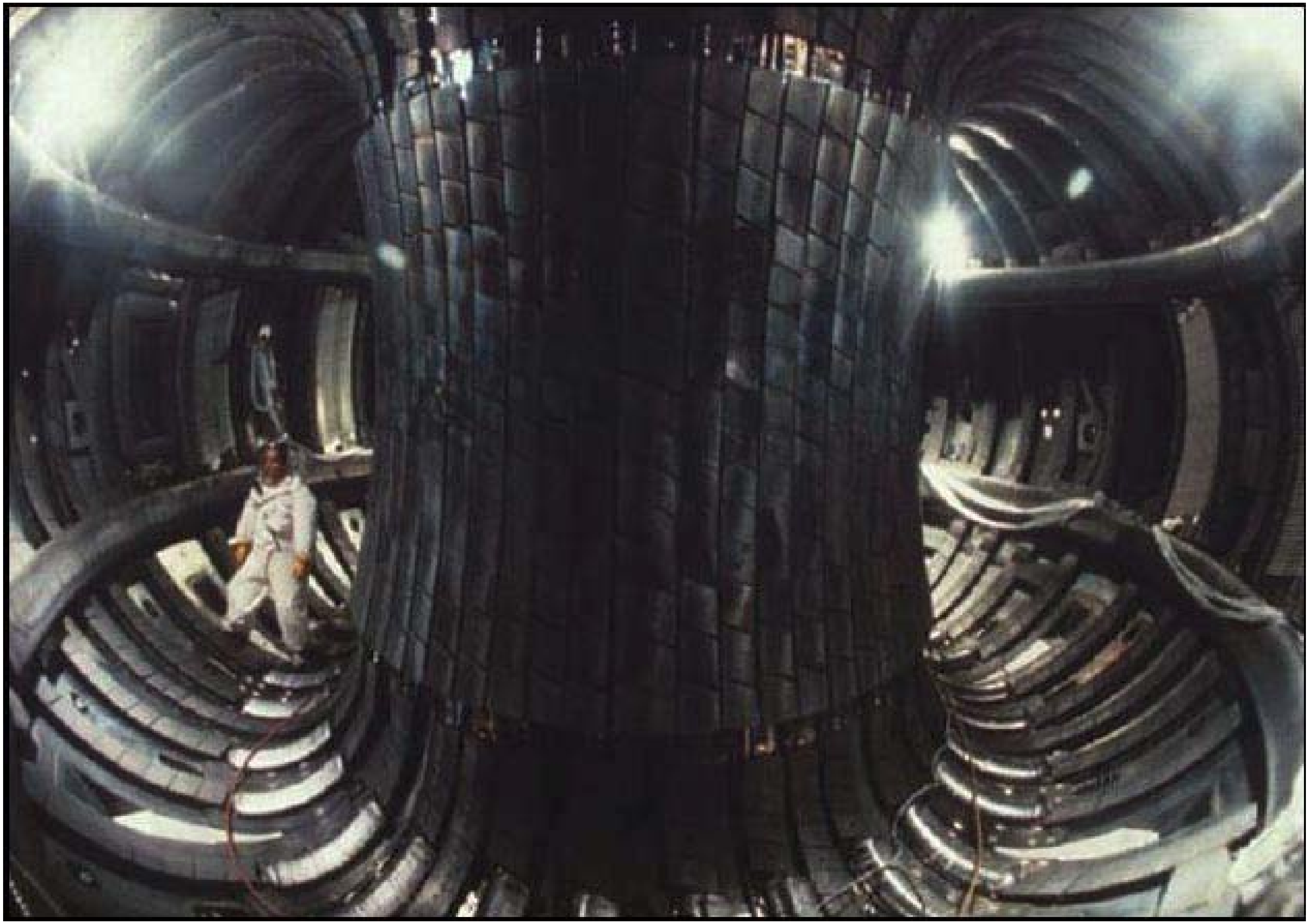
- Advance the materials science base for the development of innovative materials and fabrication methods that will establish the technological viability of fusion energy and enable improved performance, enhanced safety, and reduced overall fusion system costs so as to permit fusion to reach its full potential
- Assess facility needs for this development, including opportunities for international collaboration
- Support materials research needs for existing and near-term devices

Fusion Energy R&D is at a Crossroad

- Concept feasibility, proof of performance have been demonstrated (Tokamaks)
- Pathway for most attractive commercial power plant is uncertain
  - Magnetic vs. inertial confinement
  - Tokamak vs. spherical torus, stellarator, etc.
- **Materials technology will play a major role in determining the most viable path to commercialization**
  - "To a large extent the properties of the structural material will dictate the blanket concept which in turn determines fundamental aspects of the design of the fusion power system." *SEAB report, June, 1999*
  - "…a sustained, focused and scientifically sound materials research and development program is paramount to demonstrating the inherent feasibility of fusion power" *prologue to Fusion materials VLT white paper, January 1999*
  - No known material exists which can satisfactorily function in the hostile environment of a fusion reactor (displacement damage, H, He generation, high temperatures, thermo-mechanical stress, coolant compatibility)

Steady Progress in Plasma Physics has led to Achievement of Fusion Energy Breakeven Condition





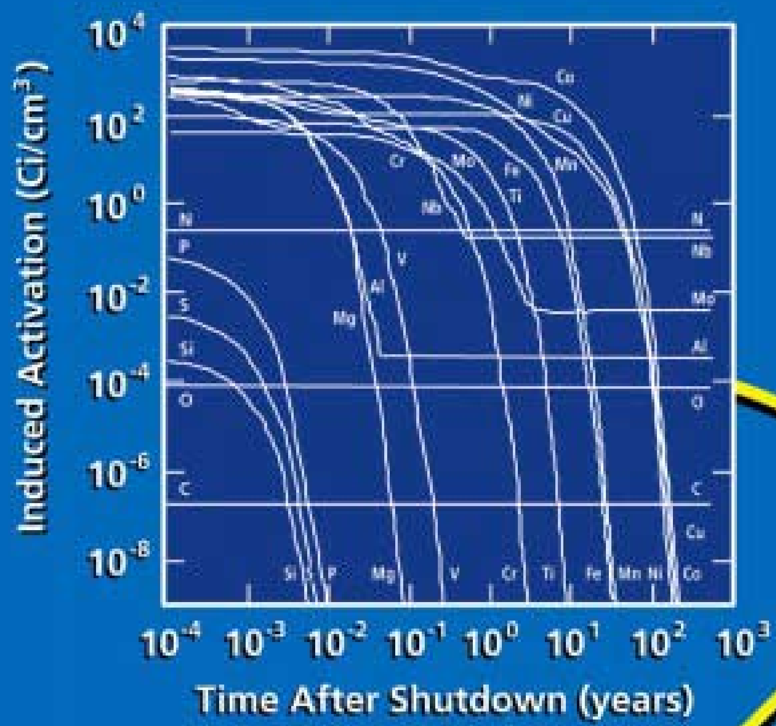
Structural Materials will Strongly Impact the Technological Viability, Safety, and Economics of Fusion Energy

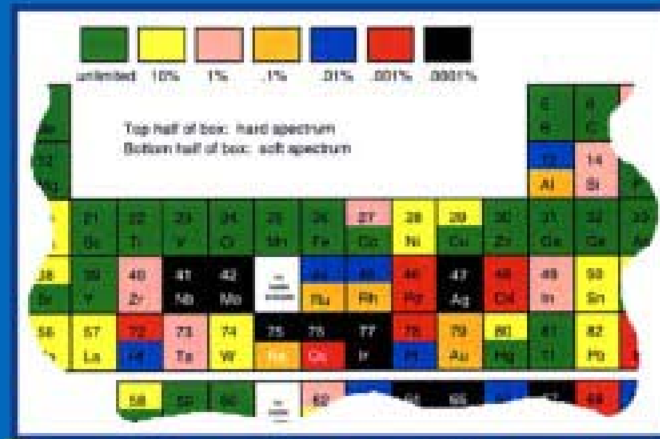
- Key issues include thermal stress capacity, coolant compatibility, safety, waste disposal, radiation damage effects, and safe lifetime limits
- The 3 leading candidates are ferritic/ martensitic steel, V alloys, and SiC/SiC (based on safety, waste disposal, and performance considerations)
  - Ti alloys have high hydrogen (tritium) solubility and permeability, and low thermal stress capacity
  - Ni base superalloys have poor radiation stability (grain boundary embrittlement)
  - Refractory alloys (Ta, Mo, W) must be operated at very high temperature (>650˚C) to avoid radiation embrittlement and have well-known fabrication and atmospheric compatibility challenges

Summary of several recent fusion energy blanket concepts

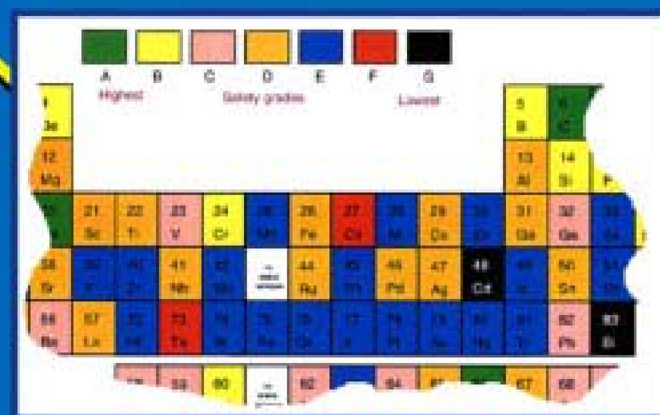
Structural Material	**Coolant/Tritium Breeding Material**					
	Li/Li	He/PbLi	H_2O/PbLi	He/Li ceramic	H_2O/Li ceramic	FLiBe/FLiBe
Ferritic steel		■	■	■	■	■
V alloy	■					
SiC/SiC		■		■		■

Structural Materials





Class C Waste Disposal



Safety

SiC

V Cr Ti Si

Fe Cr W V Ta

Fusion Materials Research Requires Multidisciplinary Effort

Fusion Materials Science Program

	Theory-Experiment Coordinating Group*				
	Microstructural Stability	Physical & Mechanical Properties	Fracture & Deformation Mechanisms	Corrosion and Compatibility Phenomena	Fabrication and Joining Science
Materials for Attractive Fusion Energy					
• **Structural Alloys*** - Vanadium Alloys - F/M and ODS Steels - High T Refractory Alloys - Exploratory Alloys					
• **Ceramic Composites*** - SiC/SiC, other CFCs					
• **Coatings**					
• **Breeder/multiplier Materials**					
• **Neutron Source Facilities**					
Materials for Near-Term Fusion Experiments					
• **PFMs (Refractory Alloys, etc.)**					
• **Copper Alloys**					
• **Ceramic Insulators**					
• **Optical Materials**					

*asterisk denotes Fusion Materials Task Group

The Fusion Materials Research Portfolio is Guided by Several Community White Papers

(http://www.ms.ornl.gov/programs/fusionmatls/planning.htm)

- **Advanced Materials Program Roadmap**
- **Integrated program of theoretical, experimental and database research for fusion materials ("crosscutting modeling white paper")**
- **US Fusion Enabling Technology program plan**

- Critical cross-cutting issues have been identified in these and other international fusion materials assessments
  - US approach: Commonality & complementarity (development of experimentally-validated models)

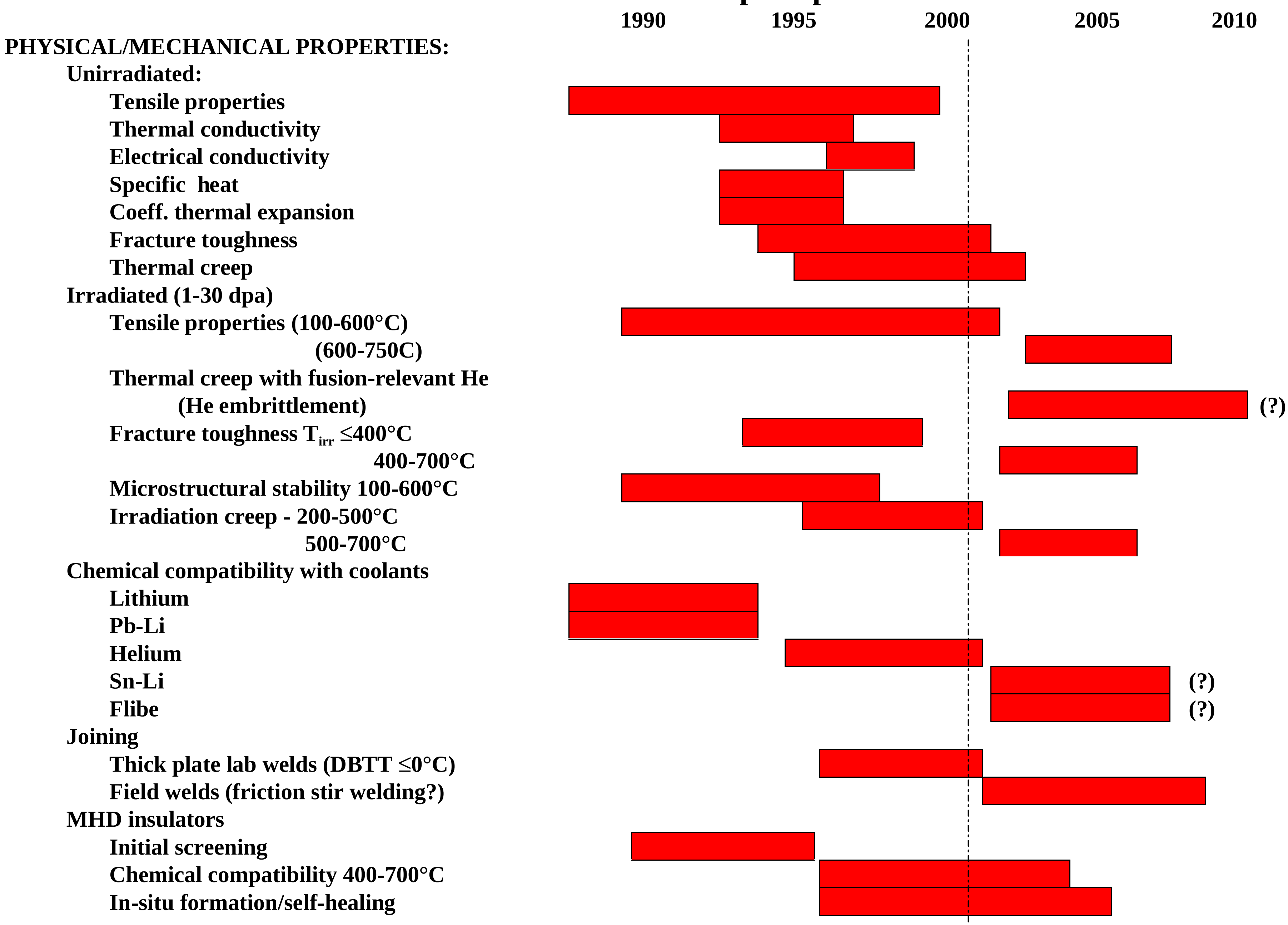
Key Cross-cutting phenomena for Fusion Structural Materials

(from modeling whitepaper)

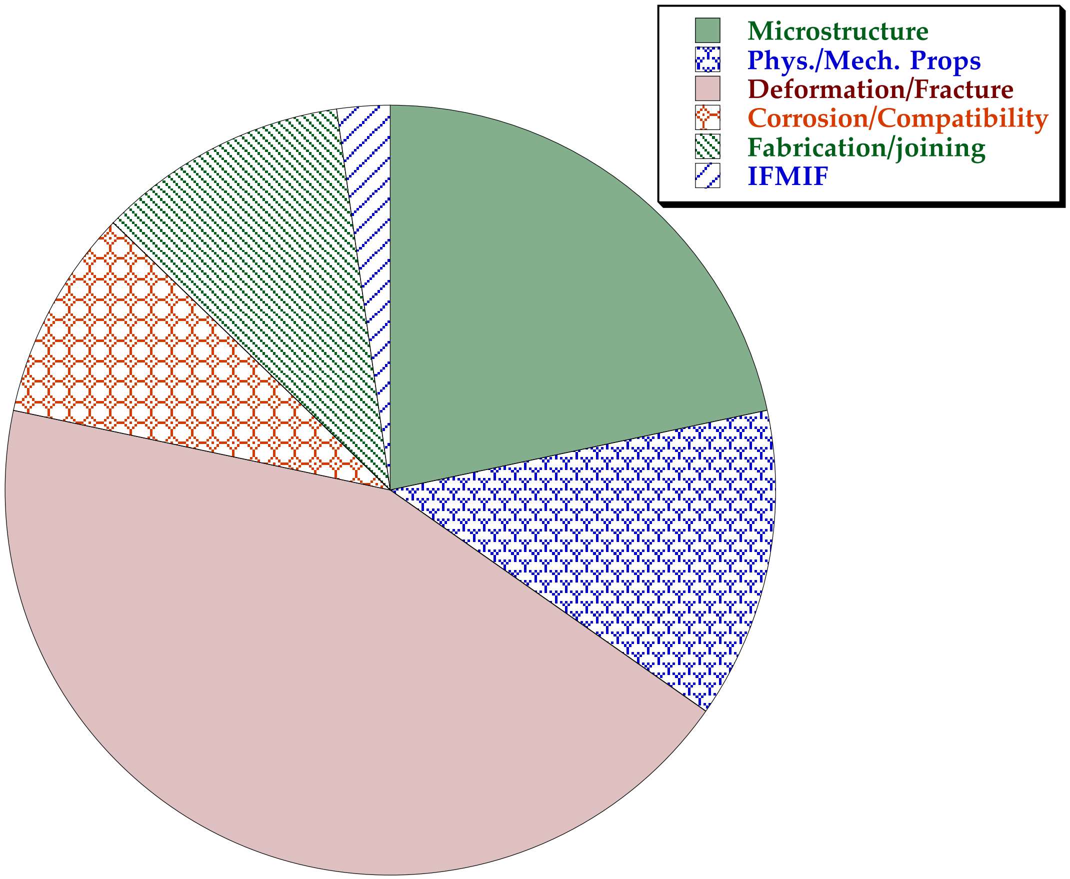
Mech. props

F/MS	V	Cu	SiC	Phenomena, Issues, Comments
***	***	***	-	hardening and nonhardening embrittlement including underlying microstructural causes and the effects of helium on fast fracture
**	**	**	-	flow localization, consequences and underlying microstructural causes
***	***	*	*	helium effects on high temperature deformation and fracture, and development of improved multiphase alloys for helium control
**	**	**	**	thermal and irradiation creep
**	**	**	**	fatigue
**	***	*	*	hydrogen and interstitial impurity effects on deformation and fracture
*	***	-	**	coatings, multilayers, functionally graded materials
**	**	**	***	swelling and general microstructural stability
**	***	**	***	welding, joining and processing issues
		*	***	physical properties, e.g. thermal conductivity
			***	permeability of gases
**	**	**	**	erosion, chemical compatibility, bulk corrosion, cracking, product transport

V-4Cr-4Ti R&D Roadmap Snapshot



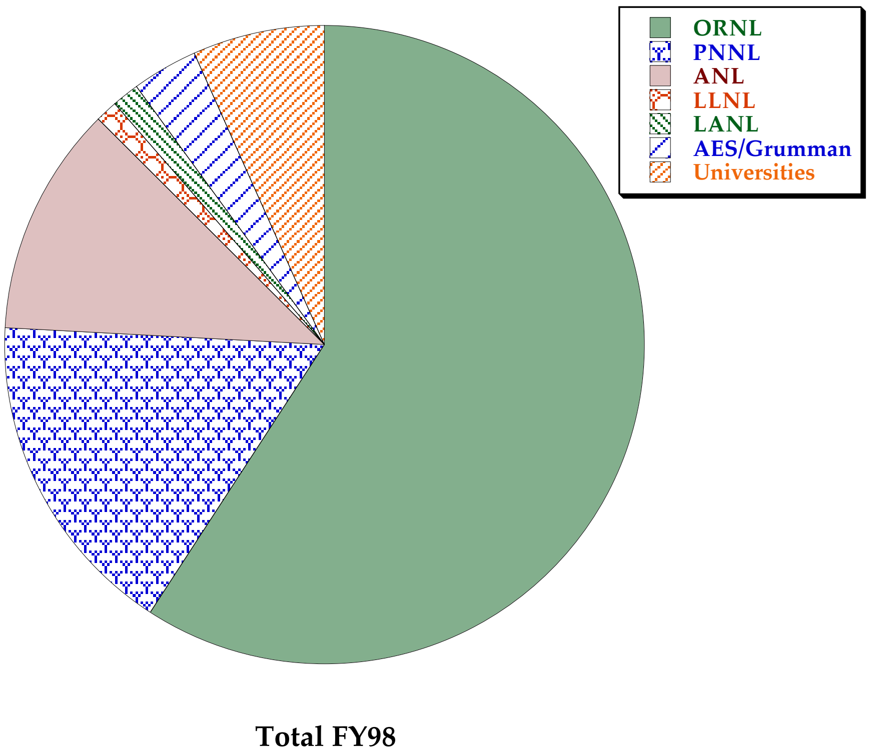
Fusion Materials Sciences R&D Portfolio

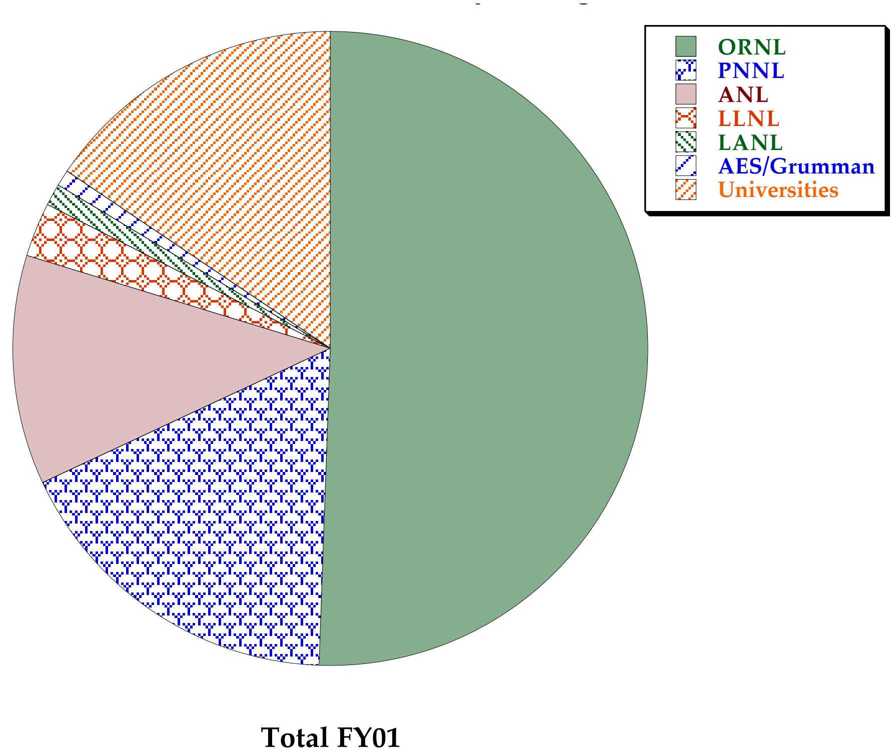


FY01 funding (7460 k$ costed funding)

- Large emphasis on mechanical properties
- *FY01 fusion materials budget represents 3% of fusion energy budget (21% of Enabling technologies budget)*

Fusion Materials Sciences Institutional Budgets





- University funding has tripled in the past 3 years
- Significant personnel changes have occurred at institutions
  - e.g., ORNL: 18 scientists with average support of 0.4 FTE/yr; 11 staff removed and 9 new researchers added since FY98

Low Activation Ferritic Steels for First Wall/Blanket Structures

Advantages

- Well-developed technology for nuclear and other advanced technology applications
- Fusion materials program has developed low activation versions with equivalent or superior properties
- Resistant to radiation-induced swelling and helium embrittlement
- 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

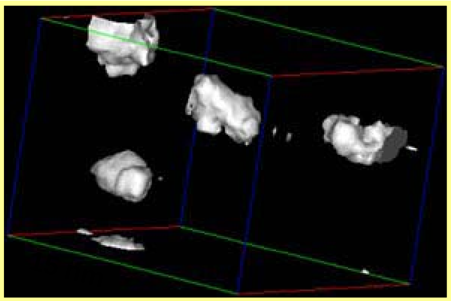
Expand Low Temperature Operating Window

- Pursue collaborative fission reactor irradiation program with EU and Japan
  - 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 potential of nanocomposited ferritic (NCF) materials to expand upper operating temperature to ~800°C
  - Develop radiation-stable, high toughness microstructures

3-D atom probe image; clusters of ~100 atoms of Y, Ti, and O responsible for high strength of NCF materials



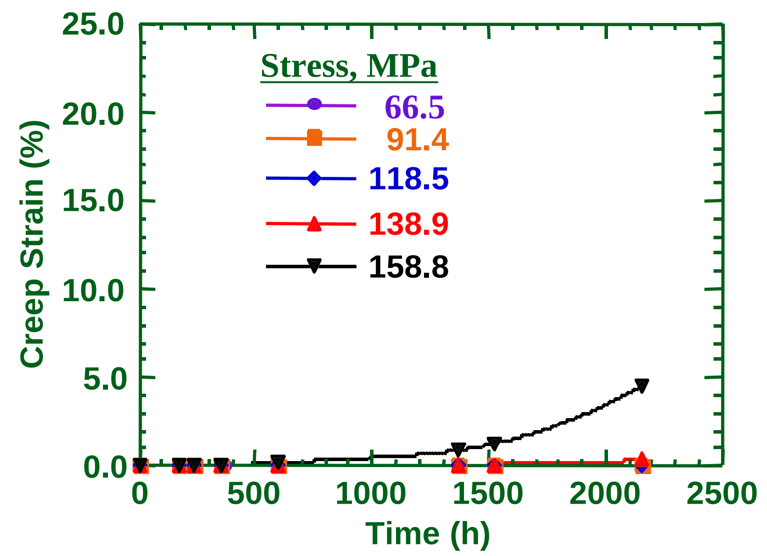
Vanadium Alloys are Most Attractive for Li-Cooled/Breeder Blanket Systems

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

- **Research Emphasis**
  - Development of V/Li MHD Insulator Systems
  - Investigation of Effects of Irradiation on Fracture Properties
  - Kinetics of Interstitial Impurity Pick-up and Effects on Properties

- **Feasibility 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

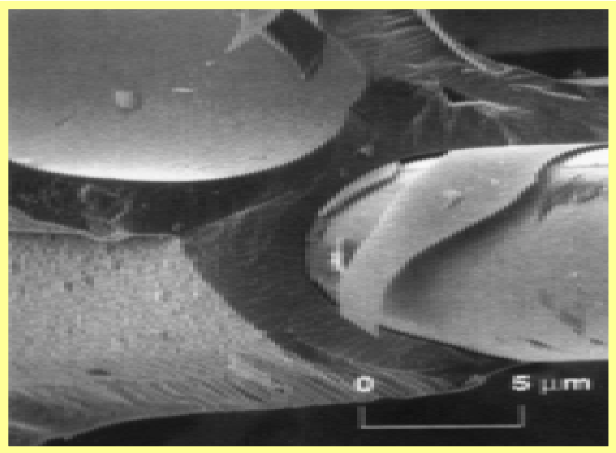
Thermal Creep of V-4% Cr-4% Ti at 700°C



Development of SiC Composites for Fusion Reactor Structural Applications: Difficult and High Risk but High Payoff

- ***SiC Composites Offer***
  - Low radioactivity and afterheat (eases waste disposal and safety concerns)
  - High operating temperatures (greater thermodynamic efficiency)
  - Ability to engineer the structure to meet design needs
- **The Feasibility Issues**
  - Thermal conductivity is reduced by irradiation
  - Unknown mechanical property response to irradiation
  - Technology base for production, joining, design of large structures, is very 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

Theory and Modeling of Materials Performance Under Fusion Conditions

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.

Critical Feasibility Issues

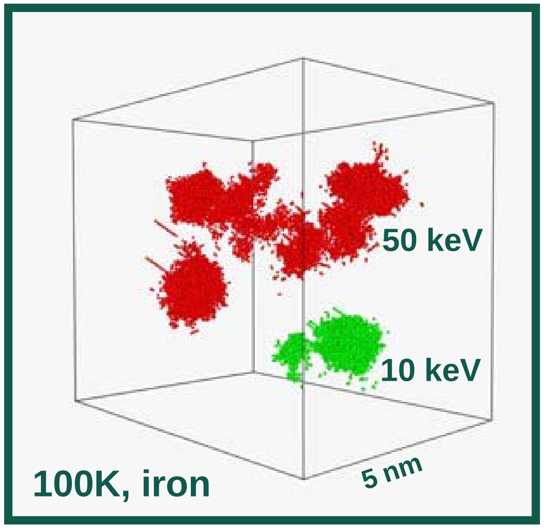
- Understanding microstructural evolution produced by 14 MeV neutrons
- How do radiation-induced microstructural changes alter hardening, embrittlement, and flow localization
- Effects of helium on deformation and fracture and void swelling

Research in Progress

- Multi-scale modeling of damage production and accumulation and dislocation-defect cluster interactions
- Deformation and fracture mechanics modeling, including effects of radiation hardening and flow localization

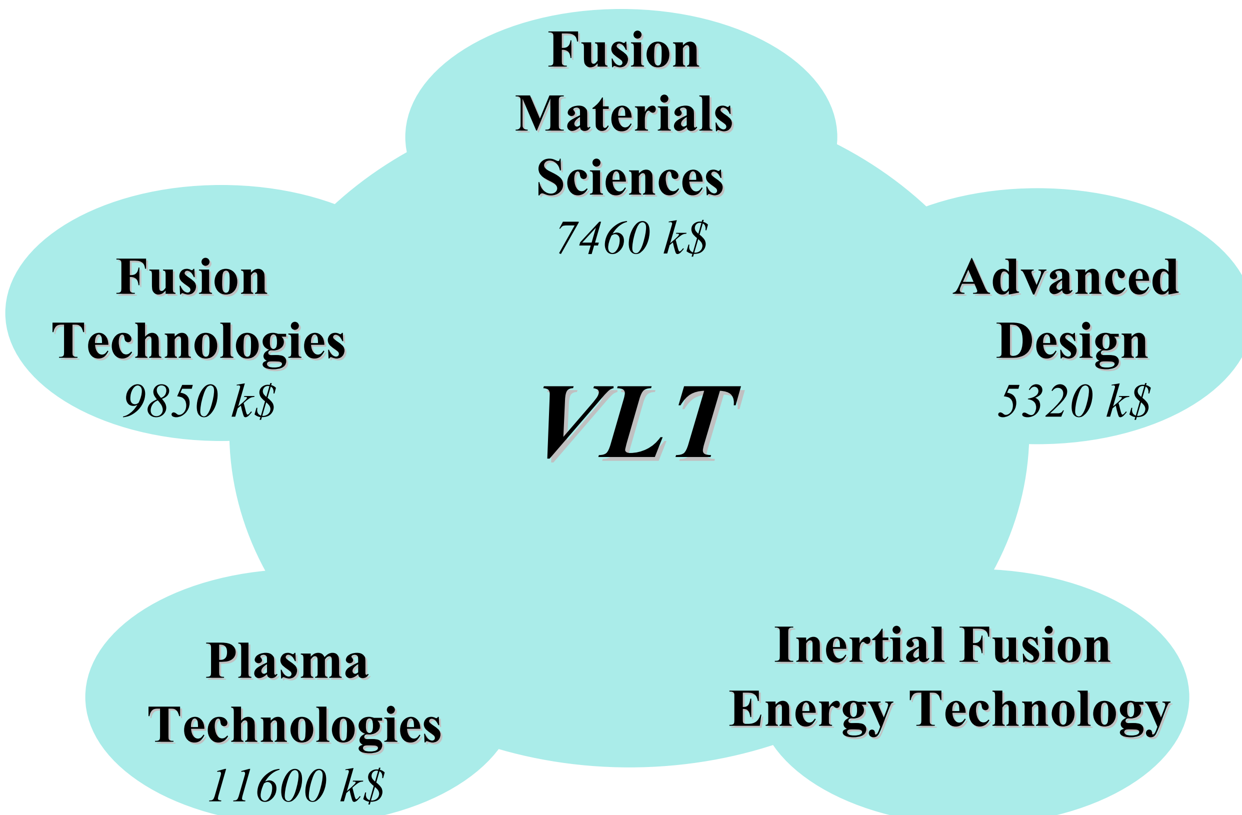
Comparison of 10 and 50 keV Atomic Displacement Cascades in Iron

- High-energy damage events are similar to multiple, lower-energy events due to subcascade formation



The Fusion Materials Sciences Program is Integrated into the OFES Enabling Technologies Program via the Virtual Laboratory for Technology (VLT)

- **The Fusion Materials Program Provides the Underlying Materials Science Knowledge Base within the VLT**



The Fusion Materials Program has Recently Shifted its Emphasis from *Development* to *Science*

Features of Restructured Fusion Materials Science Program

- Science-based materials research
- Principal product is *basic knowledge, theory, and models* needed to resolve feasibility issues of fusion materials
- Primary role of experiments is to guide and validate theory and models
- Utilize, leverage, and expand on revolutionary advances in computational and experimental methods (e.g.,nanoscience) for fusion materials design
- While focusing on long-term viability and attractiveness issues of fusion materials, apply expertise in near-term to current issues of plasma research and IFE studies

Example of Change in Approach to Materials Research V alloy (a BCC metal)

Old Approach (*Development*)	New Approach (*Science*)
• Select reference alloy (V-4Cr-4Ti)	
• Focus most research on this alloy (narrow scope)	• Focus research on fundamental understanding of BCC materials
• R&D planning based on need to develop materials to meet device construction schedule	• Research planning based on theory and modeling requirements of BCC materials
• Experiment-based R&D to build engineering data base	• Experiments used to guide and validate scientific theory and models
	• Study model BCC alloys/ surrogate materials encompassing V alloys

Interactions with International Fusion Materials Community

Science issue	Activity	US	Japan	EU	Russia	China
Deformation & fracture	V alloys	IEA working gp.			IEA working gp.	
		DOE/Monbusho				
Deformation & fracture, Nanoscience (ODS)	Ferritic steel	IEA working group				
		DOE/JAERI				
Deformation mechanisms, enhanced thermal cond.	SiC/SiC	IEA working group				
		DOE/Monbusho				
		DOE/JAERI				
Cross-cutting theory & modeling phenomena	Theory & modeling	IEA working group				
Electric, dielectric props.	Ceramic insulators	IEA working group				
		DOE/Monbusho				
Accelerator physics, liquid jet thermohydraulics, He gas cooling technology	Neutron source (IFMIF)	IEA working group				

Fusion Materials Science is Strongly Integrated with other Materials Science programs (research synergy)

-provides mutual leveraging and provides the fusion program a link to materials science

- The average fusion materials researcher is supported ~40% by OFES funding; all fusion materials scientists actively interact with other research communities
- BES (ceramic composites, radiation effects in materials, electron microscopy, deformation physics, nanoscale materials)
- NERI (deformation mechanisms in irradiated materials, damage-resistant alloys)
- EMSP program (radiation effects in nuclear waste materials, including modeling relevant for SiC and other ceramics)
- Naval programs (radiation effects in SiC/SiC, refractory alloys, cladding materials)
- NRC (fracture mechanics and radiation effects in pressure vessel alloys)
- EPRI (stress corrosion cracking in alloys)
- APT, SNS (effects of He and radiation damage on structural integrity of materials)
- Defense programs (stockpile stewardship materials issues)

PERFORMANCE GOALS FOR STRUCTURAL MATERIALS FOR BLANKET AND DIVERTOR SYSTEMS

Compatibility with operating environment (liquid metal, water, helium coolants, tritium breeders, hydrogen plasma)

Adequate performance design window (temperature and stress limits)

– neutron fluxes >3 MW/m^2
– high heat fluxes 1-20 MW/m^2
– sustain high primary and secondary mechanical loads, load cycling
– maintain structural integrity and dimensional stability for lifetimes of ~15 MW a/m^2 (150 dpa)

Reliable production, component fabrication, welding, and joining technologies

ENERGETIC NEUTRON INTERACTIONS WITH STRUCTURAL MATERIALS

- Combination of radiation damage and transmutations produce major changes in physical properties (dimensional stability, conductivity) and in mechanical behavior (strength, ductility, fracture toughness) of structural materials

  – 14 MeV fusion neutron nuclear transmutations produce changes in composition and generate hydrogen and helium which often cannot be simulated in fission reactors

- Induced radioactivity of structural materials impacts safety (decay heat, isotope inventory) and waste disposal (decay characteristics, biological health potential, specific activity).

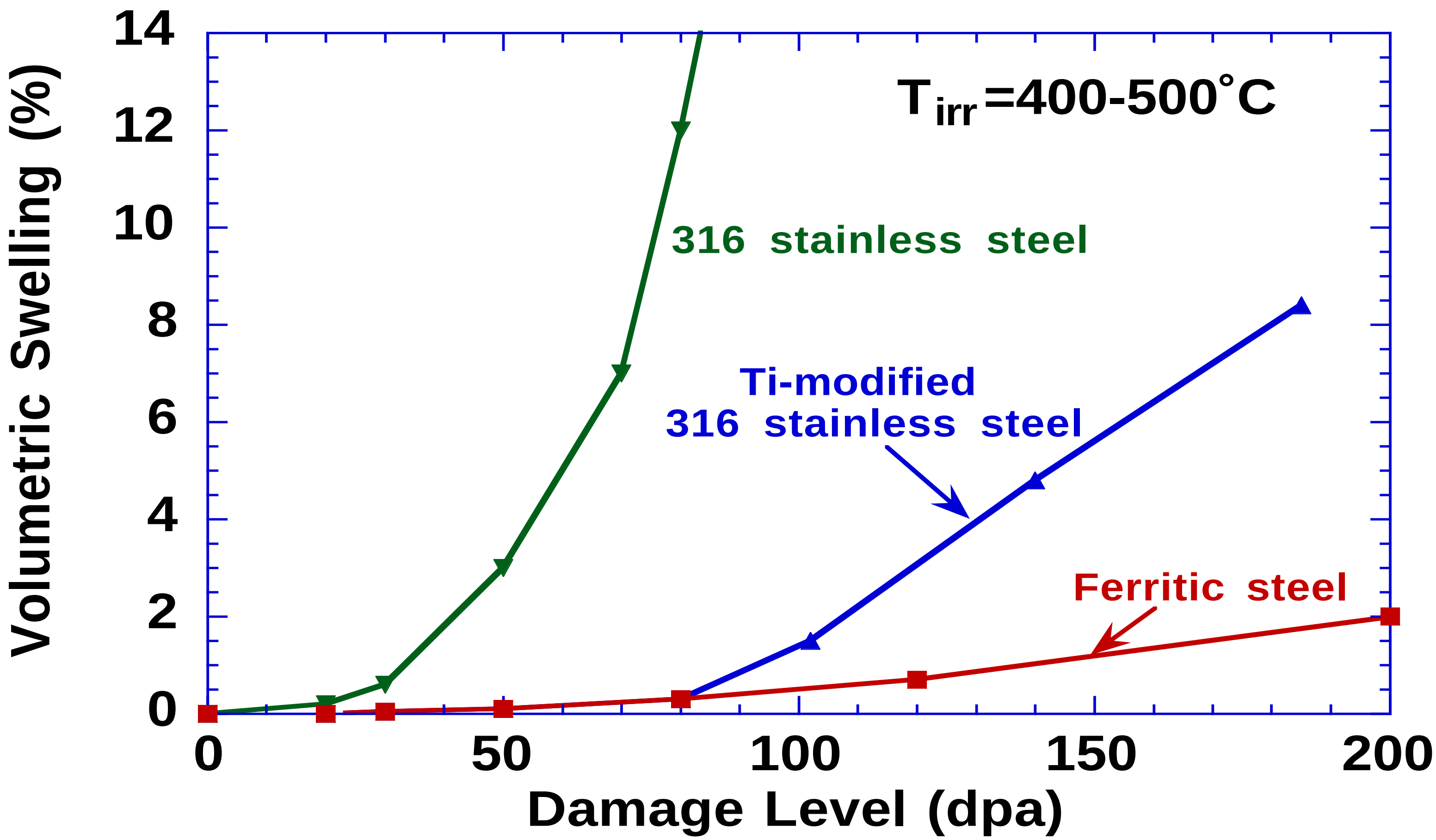
Radiation Damage can Produce Large Changes in Structural Materials

- Radiation hardening and embrittlement (<0.4 T_M)
- Irradiation creep (<0.45 T_M)
- Volumetric swelling from void formation (0.3-0.6 T_M)
- High temperature He embrittlement (>0.5 T_M)

In addition…

- The irradiation environment associated with a D-T fusion reactor is more severe than in fission reactors
  - Higher lifetime dose requirements for structure
  - Higher He generation rates (promotes He embrittlement of grain boundaries, void swelling)

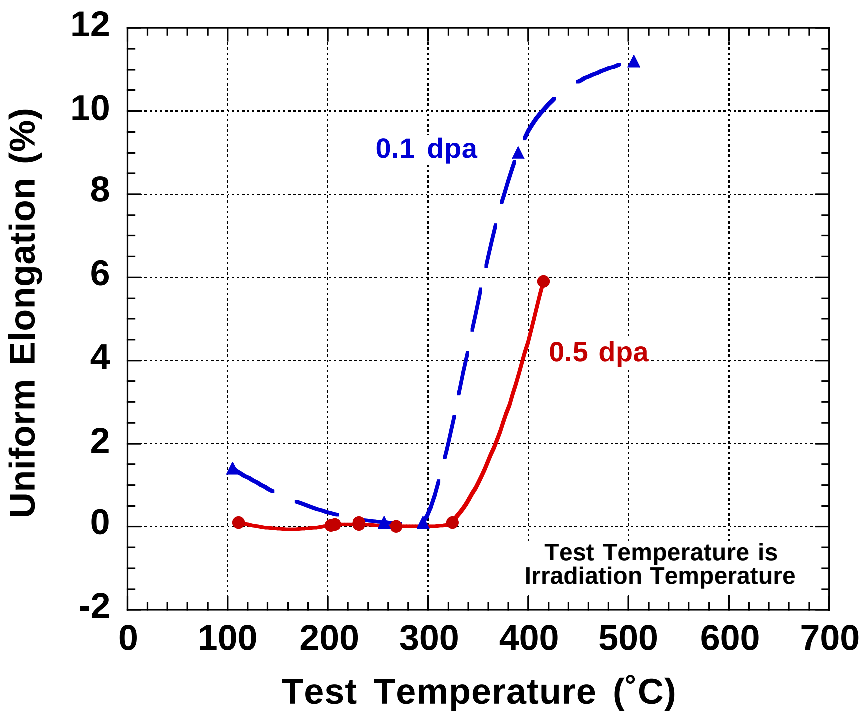
Swelling resistant alloys have been developed via international collaborations



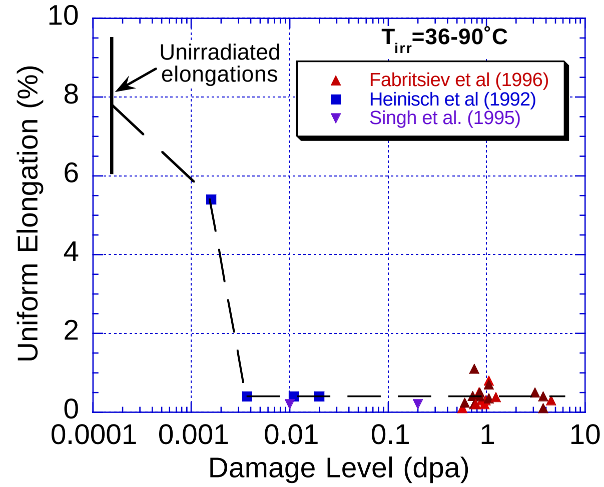
- Lowest swelling is observed in body-centered cubic alloys (V alloys, ferritic steel)
- A key issue regarding BCC alloys is radiation embrittlement

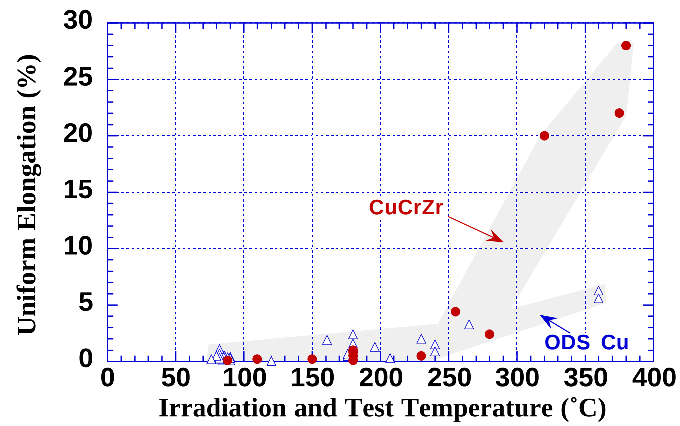
Low uniform elongations occur in many FCC and BCC metals after low-dose irradiation at low temperature

Uniform elongation of neutron-irradiated V-4Cr-4Ti

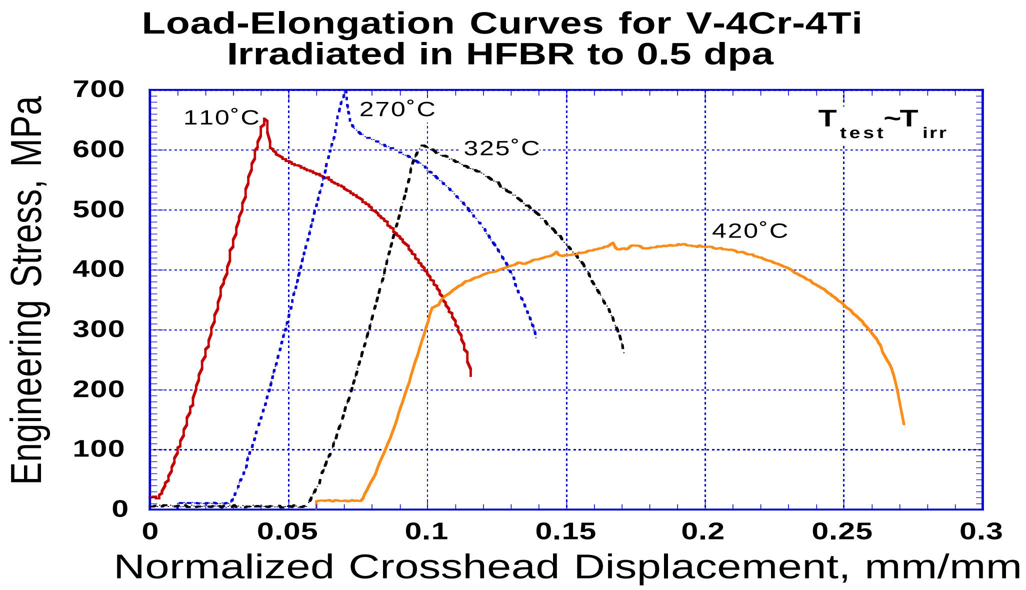


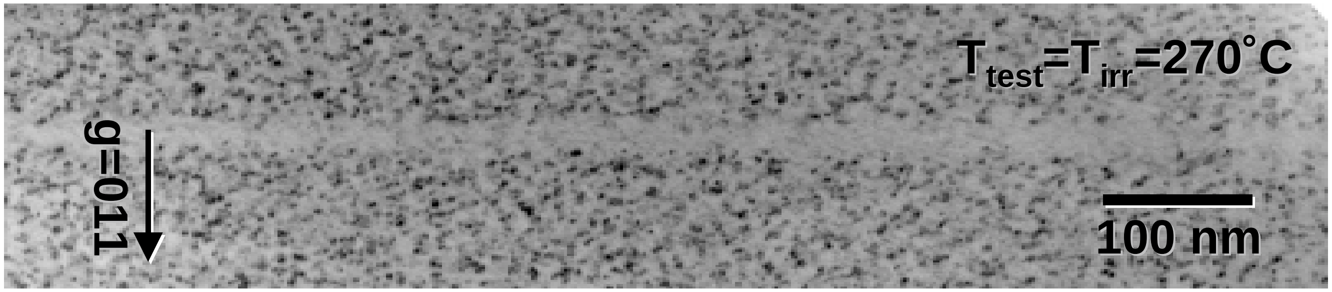
Uniform elongation of neutron-irradiated GlidCop Al25 and CuCrZr





Irradiated Materials Suffer Plastic Instability due to Dislocation Channeling





FUSION MATERIALS SCIENCES PROGRAM

Organization:

- National program involving **ORNL** , **PNNL**, **ANL**, **LLNL, UCSB**, **UCLA, RPI**
  - WSU, Princeton, Merrimack College recently added to materials program

- The Fusion Materials Sciences Program is involved in strong, well-established international collaborative programs:

  – **DOE/JAERI** (irradiation experiments in HFIR)
  – **DOE/MEXT Jupiter-II** (irradiation experiments in HFIR and complementary nonirradiation tests using unique US facilities)
  – **RF** (irradiation experiments in BOR-60, SM-2)
  – **EU** (PSI, Risø, irradiation experiments in HFR-Petten)

- International fusion materials programs are coordinated through **IEA Implementing Agreements** involving U.S. RF, EU, PRC, Canada, and Switzerland.

Specialized Facilities utilized for Fusion Materials R&D

- **Structural characterization of radioactive materials from the meso to the atomic scale**
  - scanning electron microscopy
  - analytical electron microscopy
  - small angle neutron scattering
  - x-ray synchrotron source, microdiffraction and microfluorescence

- **Mechanical properties equipment**
  - confocal microscopy/fracture reconstruction
  - small-scale fracture mechanics
  - large-scale deformation mapping

- **High Flux Isotope Reactor**
  - irradiation testing of materials
  - controlled temperatures and neutron spectra

- **Remotely operated shielded facilities**
  - disassembly of irradiation experiments
  - shipment and disposal of radioactive materials
  - mechanical and physical property measurements of irradiated structural materials and nuclear fuels

RELATED MATERIALS SCIENCE AND TECHNOLOGY

Materials Technologies with Applications to Fusion Structural Materials

- Melting, casting, and rolling technologies, including high-temperature extrusion of refractory alloys and production of uniform metal powders

- Chemical vapor infiltration and chemical vapor deposition for production of high performance ceramic-matrix composites

- Liquid metal, molten salt and oxidation corrosion equipment

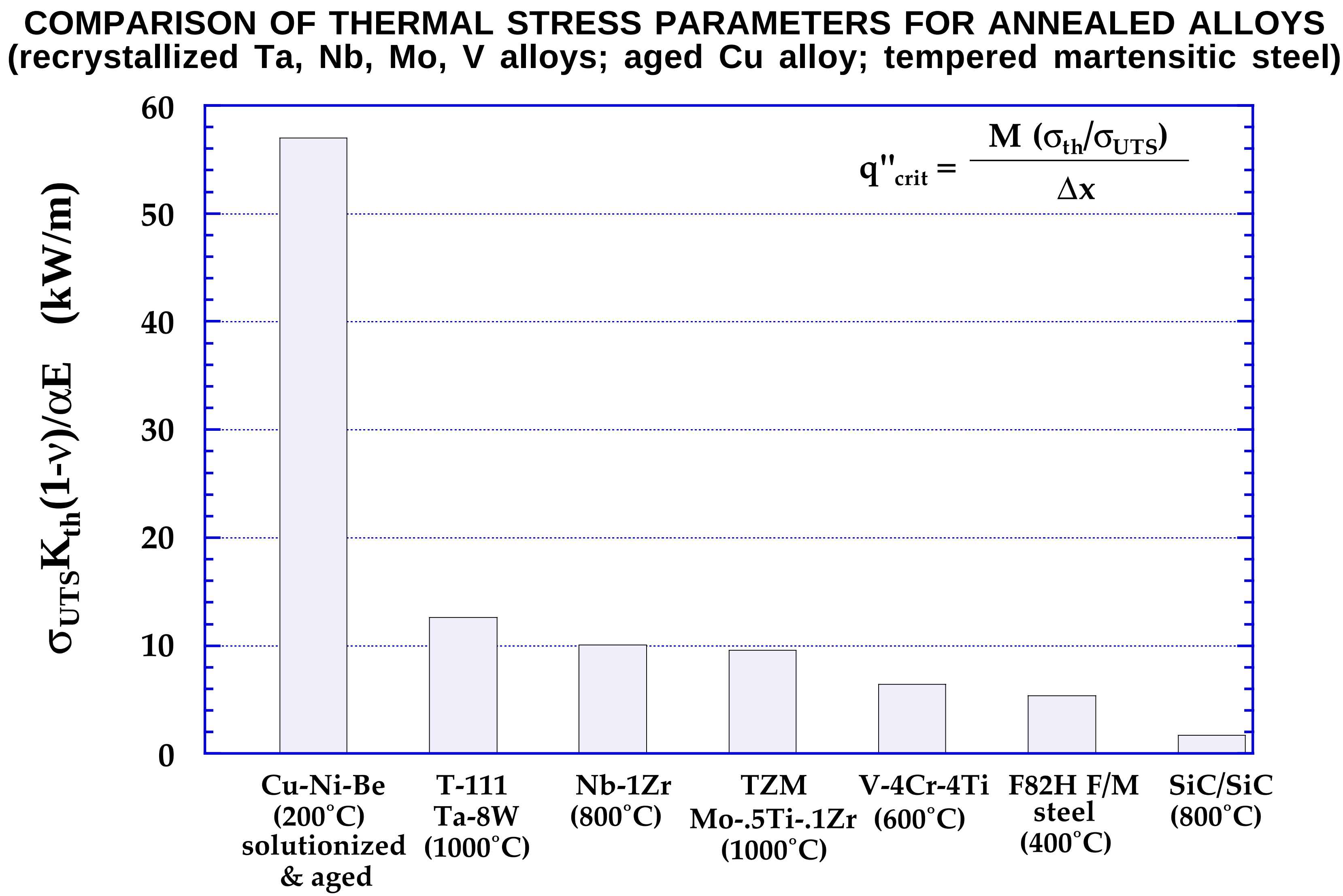
- Unparalleled materials characterization facilities (electron microscopes, X-ray and neutron scattering, thermomechanical properties, etc.)

- Brazing and advanced welding technologies

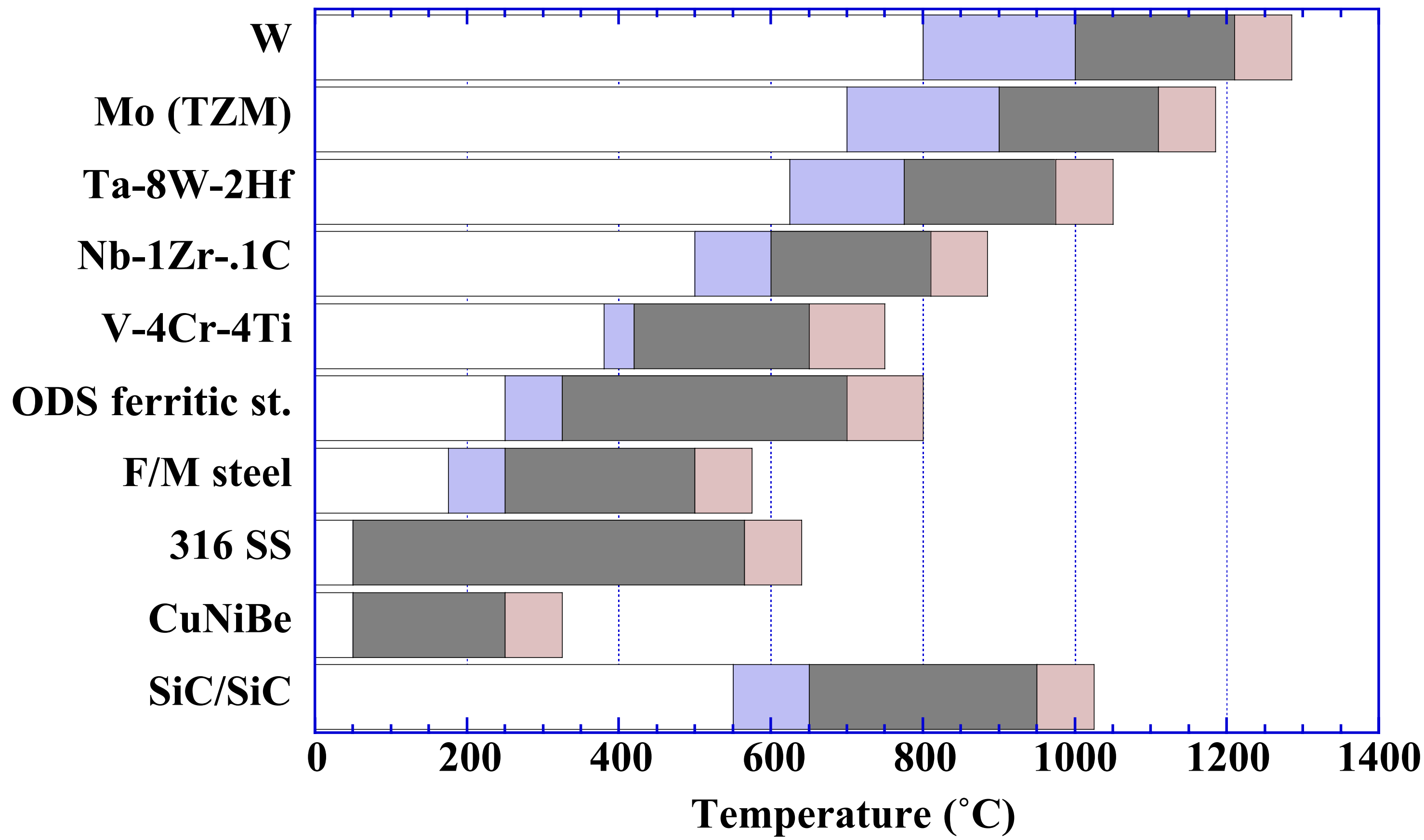
- Massively Parallel Computational Modeling Capabilities (weld solidification, simulation of deformation at the microstructural scale, etc.)

Conclusions

Comparison of Thermal Stress Figure of Merit



Operating Temperature Windows for Structural Alloys in Fusion Reactors



• Lower temperature limit of alloys based on radiation hardening/ fracture toughness embrittlement (K_{1C}< ~30 MPa-$m^{1/2}$)—large uncertainty for W,Mo due to lack of data
• Upper temperature limit based on 150 MPa creep strength (1% in 1000 h); chemical compatibility considerations may cause further decreases in the max operating temp.

S.J. Zinkle and N.M. Ghoniem
Fus. Eng. Des. 51-52 (2000) 55.

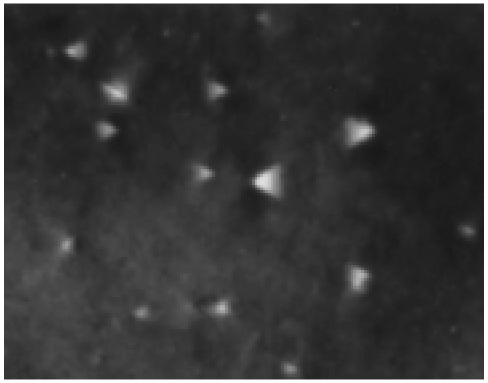
The Materials Science Program Provides the Underlying Materials Science Knowledge Base within the VLT

Technology Program Element	Types of Materials Addressed	Key Materials Issues
• Materials Science	**• Structures • Coatings • Insulating ceramics • Optical materials**	**•deformation,fracture mechanisms • thermodynamic, kinetic stability • electric, dielectric degradation • F center formation, stability**
• Plasma Technology	• Plasma facing/high heat flux components • Magnet components • ICH/ECH launcher/ antennas	• plasma interactions, heat transport • critical current, insulator perform. • low-loss coatings and feedthroughs
• Fusion Technology	• Fuels (tritium) • Breeder systems	• tritium permeation • thermal, neutronics, hydrodynamics
• IFE	• Chamber wall • Final optics	• durability, tritium retention • surface crazing, bulk defects
• Safety	• Structure, coolant, breeder	• volatization, decay heat
• Advanced Design	• Overall integration	• compatibility, performance limits

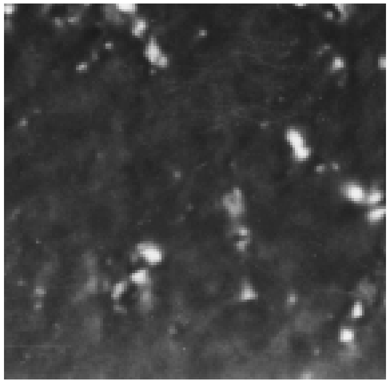
One of the Most Important Scientific Results From the US/Japan Collaborations on Fusion Materials has been the Demonstration of Equivalency of Displacement Damage Produced by Fission and Fusion Neutrons

Similar defect clusters produced by fission and fusion neutrons as observed by TEM

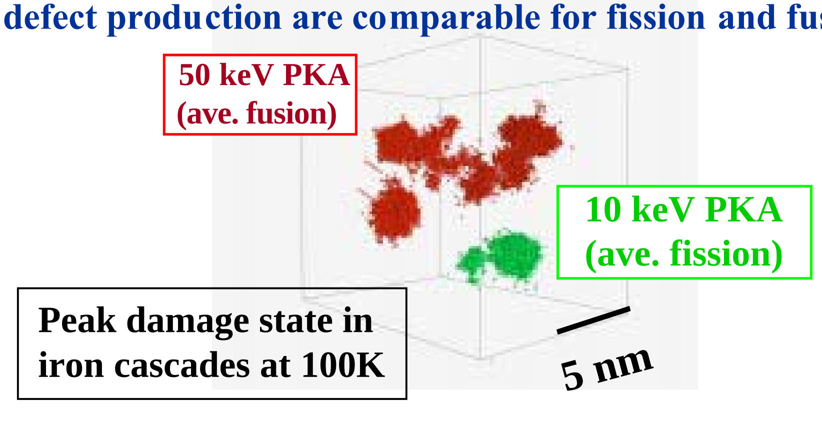
Fission (0.1 - 3 MeV)



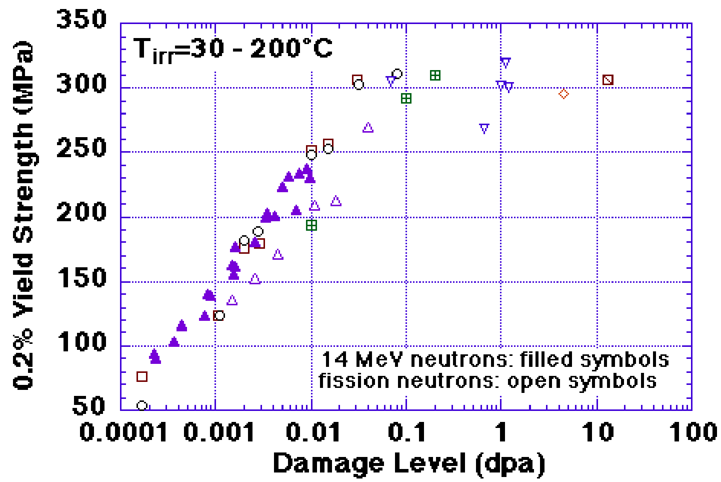
Fusion (14 MeV)



MD computer simulations show that subcascades and defect production are comparable for fission and fusion

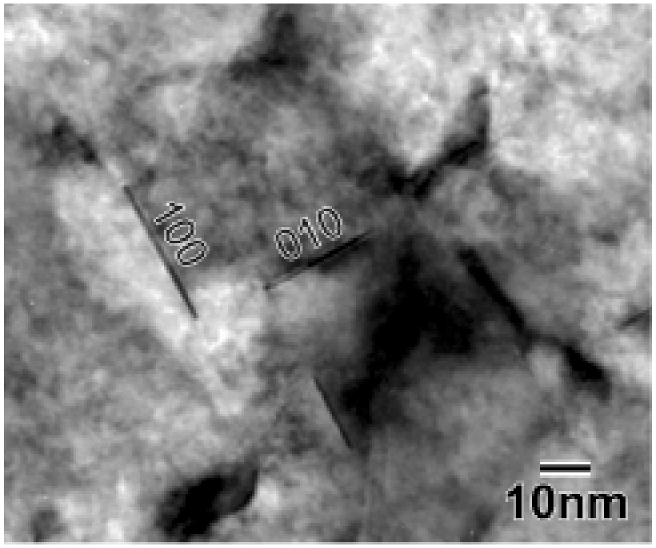


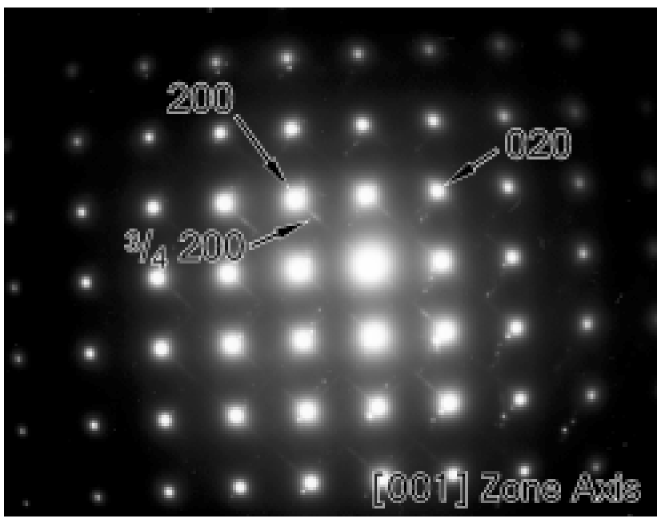
Similar hardening behavior confirms the equivalency



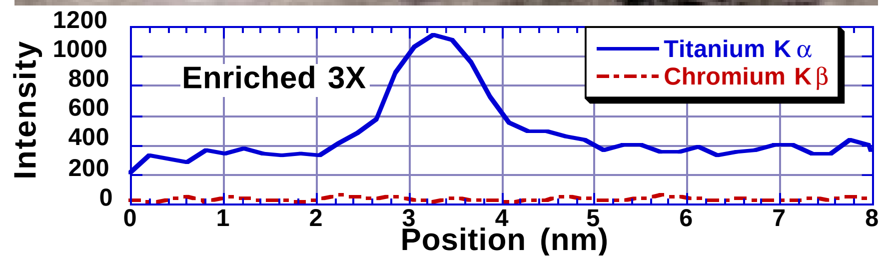
A critical unanswered question is the effect of higher transmutant H and He production in the fusion spectrum

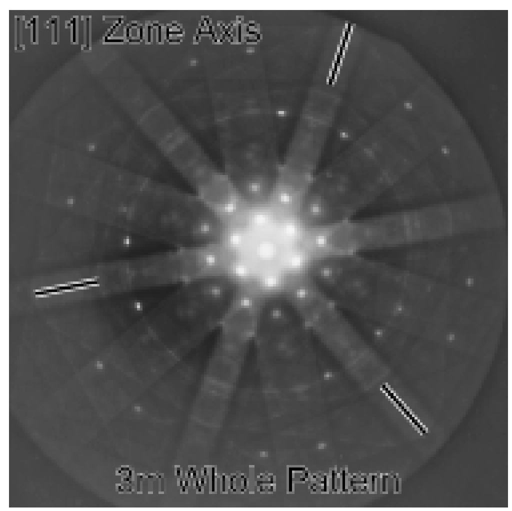
Advanced Analytical Electron Microscopy Techniques are being used to Examine Precipitates in V alloys





Solute Segregation Was Detected in V-4Cr-4Ti Following Neutron Irradiation to 0.5 dpa at Elevated Temperatures





Analytical microscopy reveals Ti-rich precipitates with Fm3m space group
(Baker-Nutting precipitate-matrix orientation)