Overview of the US Fusion Materials Sciences Program

Steven J. Zinkle, Oak Ridge National Lab

16th ANS Topical on Technology of Fusion Energy

Madison, Wisconsin, September 14-16, 2004

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

Performing institutions

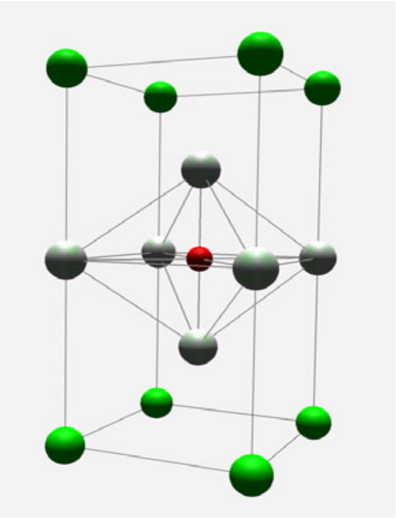
Oak Ridge National Lab
Pacific Northwest National Lab
Lawrence Livermore National Lab
UC-Berkeley
UC-Santa Barbara
UC-Los Angeles
Princeton University
Rennselaer Polytechnic Insititute
Washington State University
Merrimack College

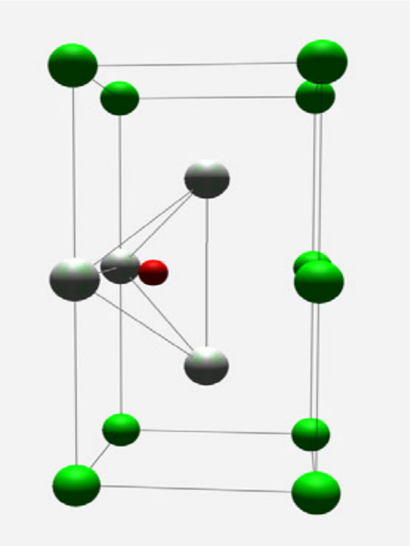
US Fusion Materials Research Portfolio

Material	FY04 effort (%)	ITER relevance (incl. TBM)	Program leverage
Crosscutting theory & modeling	25%	60%	BES, NSF, ASCI
Ferritic/martensitic/ODS steel	28%	80%	DOE-NE (Gen IV, INERI, AFCI), JAERI, NRC, BES, LDRD
SiC/SiC	21%	40%	DOE-NE (Gen IV, NERI), DOE-NR, JUPITER-II, PBMR
V alloys	15%	10%	NASA JIMO, NASA SRTP, JUPITER-II
Functional materials (MHD insulators, Cu, ductile Mo alloys, etc.)	5%	40%	DOE-NR (refractory alloys)
ITER machine R&D	4%	100%	
Neutron source	2%	0	

New interatomic potentials have been developed for vanadium and Fe-He, based on first-principles simulations

Fe-He Calculations: Unexpected stability of tetrahedral site arises from magnetic interaction



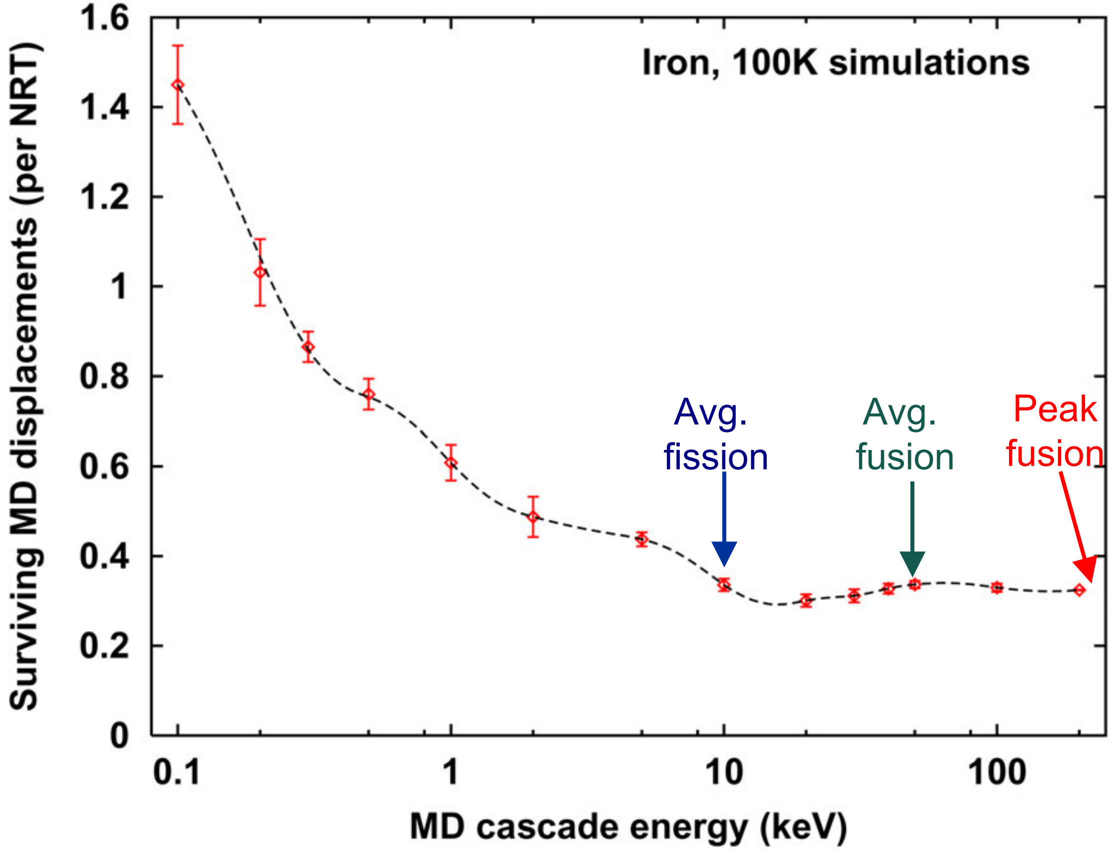


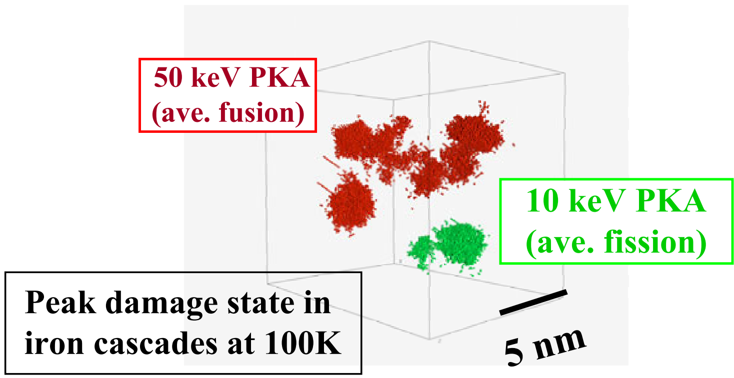
magnetic moment of He defect and surrounding Fe atoms (magnetic moment of pure *bcc* Fe=2.15 Bohr magneton)

	He	Fe, 1st neighbor	Fe, 2nd neighbor
He octa , unrelaxed	0.012	1.67	2.17
He octa, relaxed	0.015	2.01	2.24
He tetra , unrelaxed	0.007	1.99	
He tetra, relaxed	0.012	2.15	

Molecular Dynamics simulations have found the primary damage formation is similar for fission and fusion neutrons

- subcascade formation leads to asymptotic behavior at high energies





MD results have been confirmed by 14 MeV and spallation neutron experimental studies

R.E. Stoller, 2004

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

Direct formation of SFTs in Cu displacement cascades based on molecular dynamics simulations

L=1.3 nm

L=2.3 nm

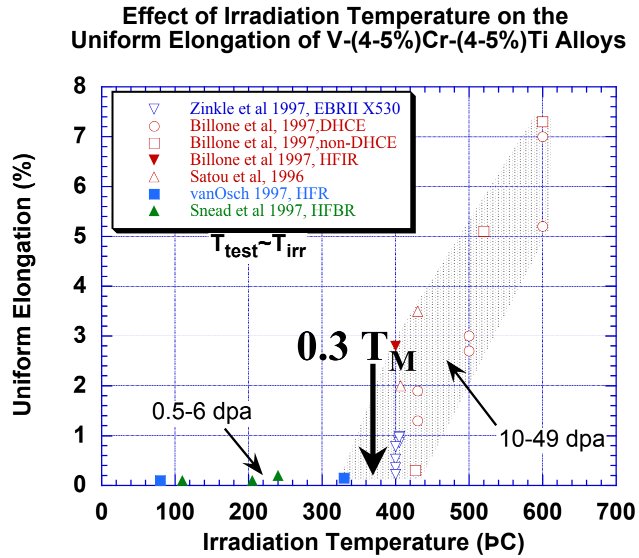
QuickTime™ and a
Planar RGB decompressor
are needed to see this picture.

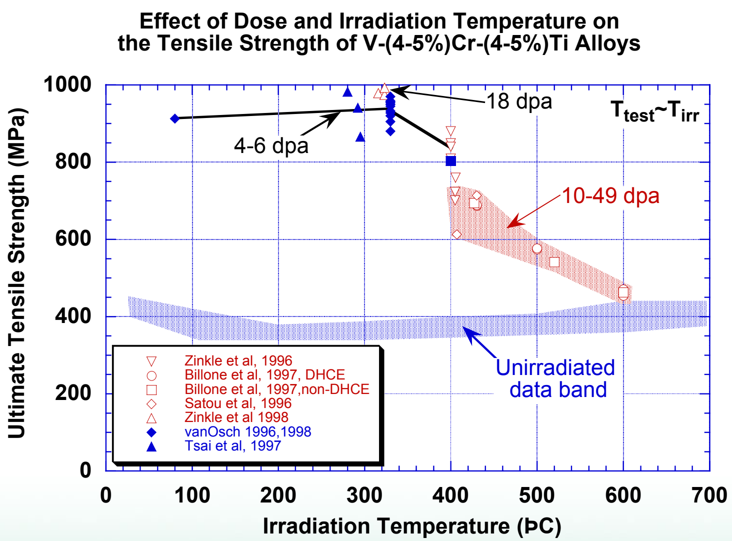
QuickTime™ and a
PNG decompressor
are needed to see this picture.

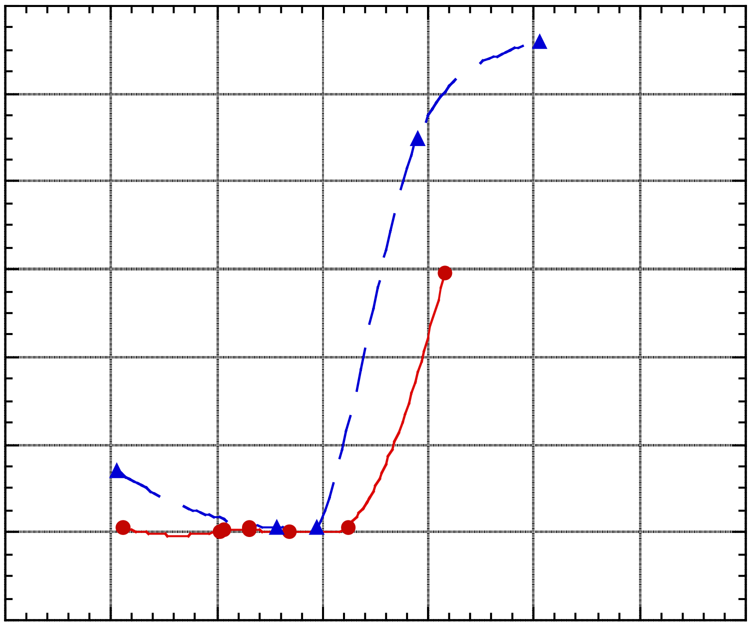
- Nearly perfect SFTs are formed in cascades within ~50 ps

Yu. N. Osetsky

Tensile Properties of Neutron-irradiated V-4Cr-4Ti

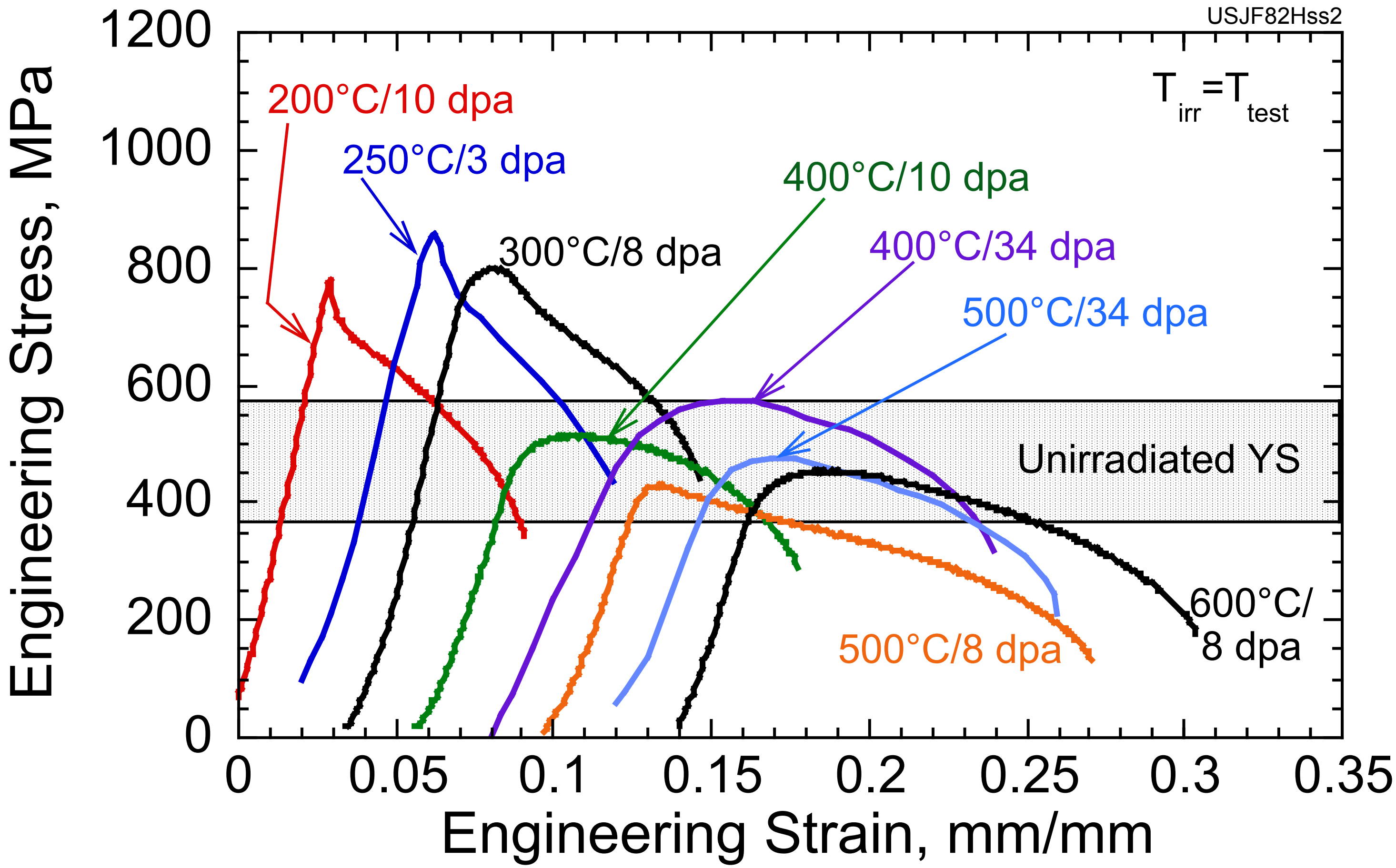






Low Temperature Radiation Hardening is Important in Ferritic/martensitic steel up to ~400˚C

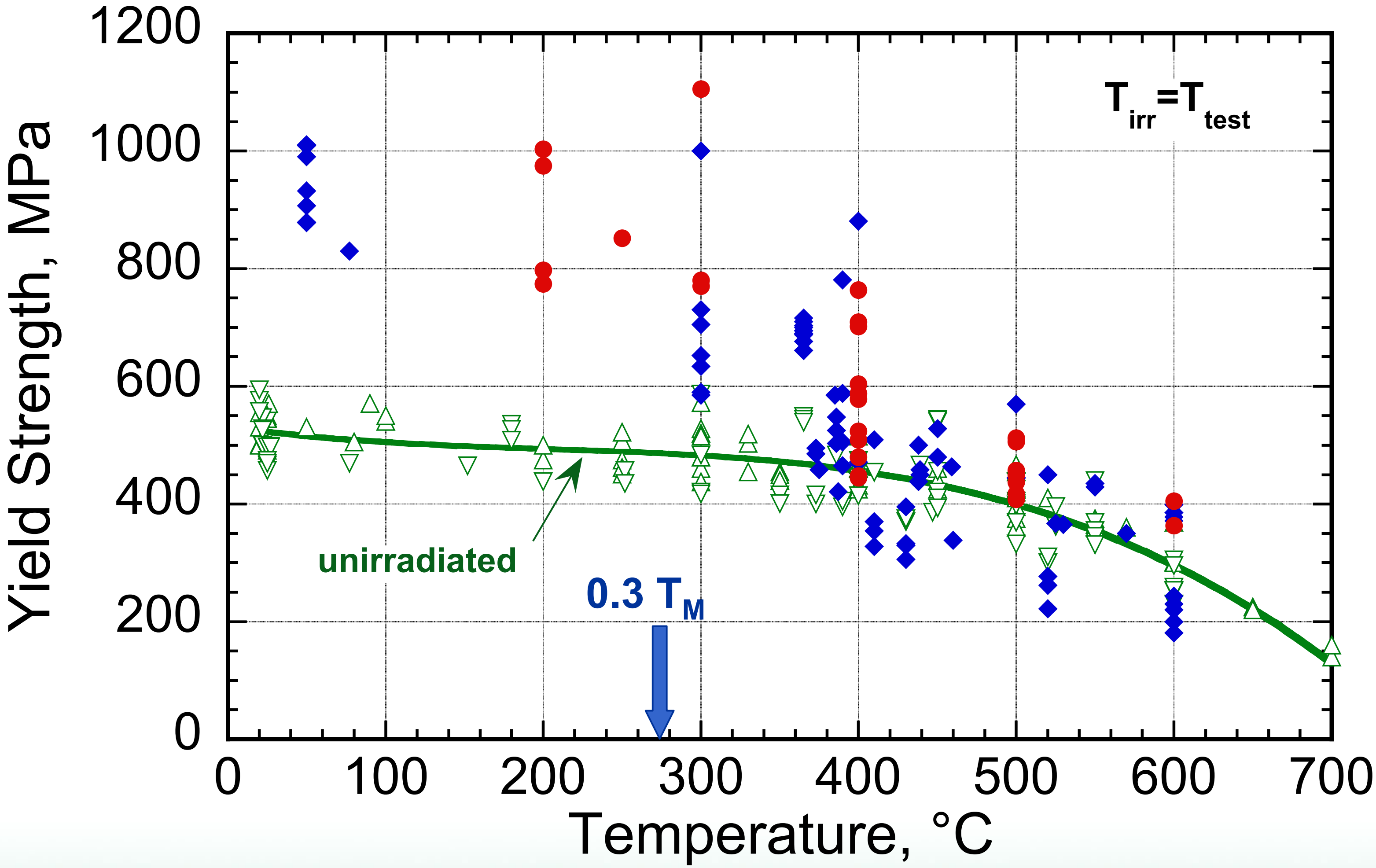
Representative USDOE/JAERI F82H Data: 200-600°C, 3-34 dpa



J.P. Robertson et al.,
(DOE/JAERI collaboration)

Radiation hardening in Fe-(8-9%Cr) steels

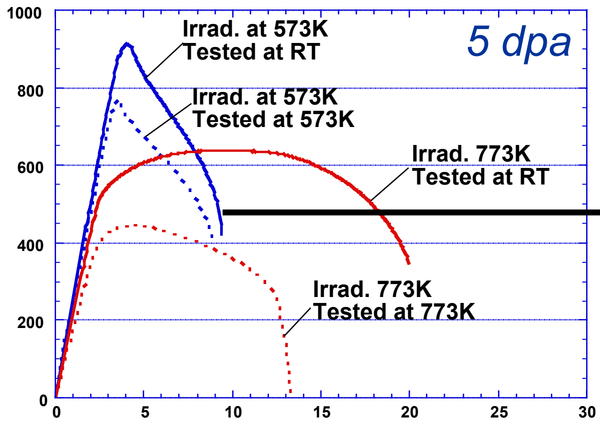
8-9Cr Steels: Yield Strength as Function of Temperature, 0.1 - 94 dpa

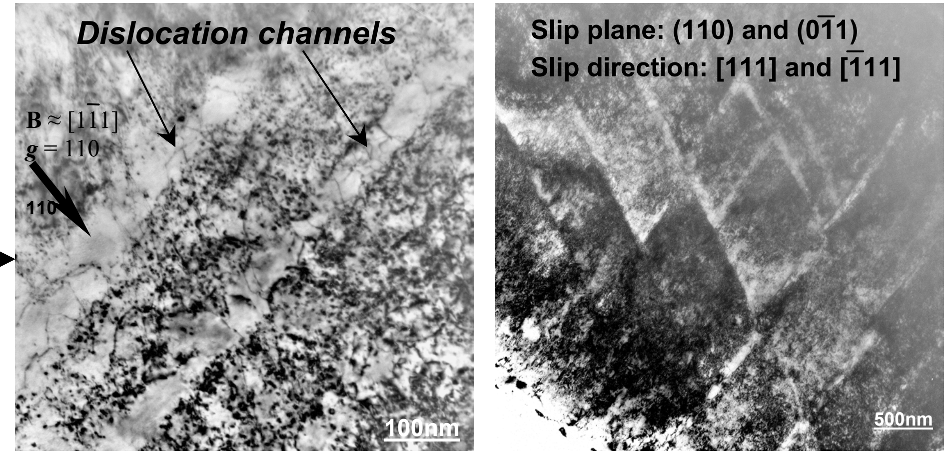


Deformation microstructures in neutron-irradiated Fe-8Cr-2WVTa ferritic/martensitic steel (F82H)

(a)

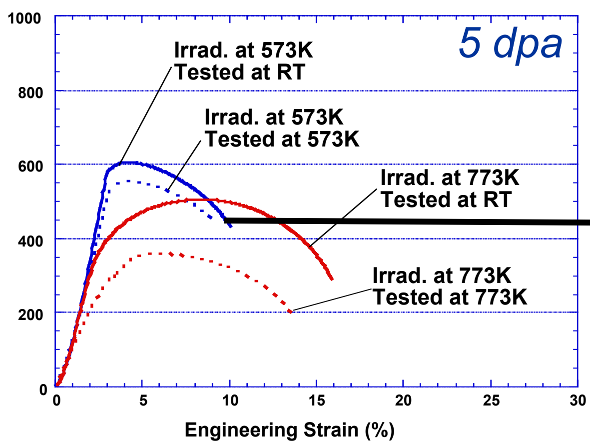
F82H base metal

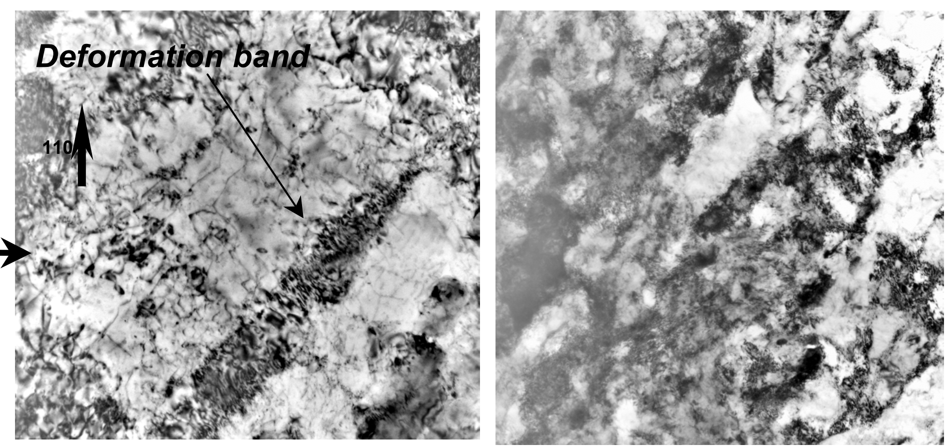




(b)

F82H TIG weld



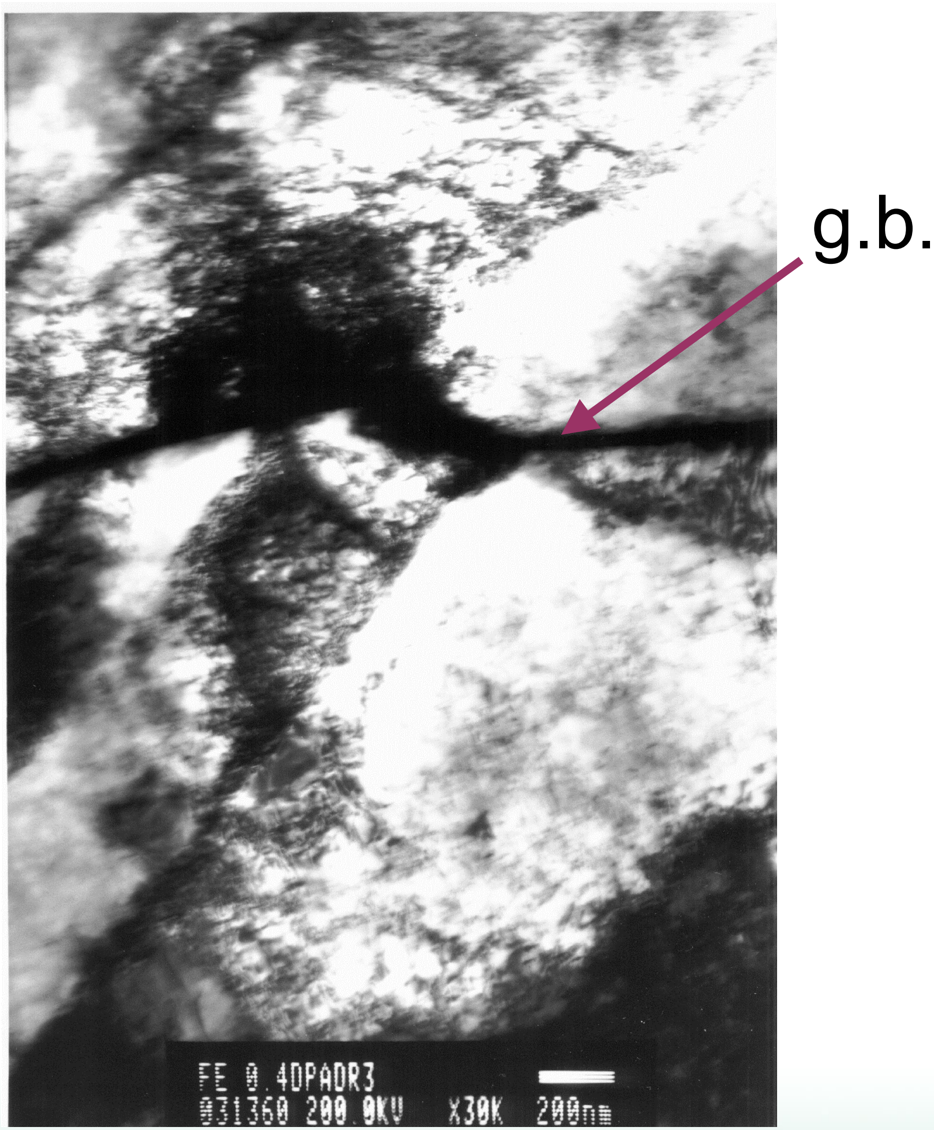


Irradiated weld metal (lower radiation hardening) did not exhibit dislocation channeling after deformation

Fig. 1 Stress-strain curves of F82H BM (a) and TIG (b) irradiated at 573K and 773K in tests at RT

N. Hashimoto et al., Fus.Sci.Tech. 44 (2003)

Dislocation channel interactions in Fe deformed following neutron irradiation at 70°C to 0.8 dpa



TEM In-situ deformation: dislocation/defect cluster interactions

SFT annihilation by a single dislocation

QuickTime™ and a Planar RGB decompressor are needed to see this picture.

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Dislocation pinning by small SFTs (no annihilation)

Understanding why annihilation sometimes does not occur is key for developing improved fusion materials

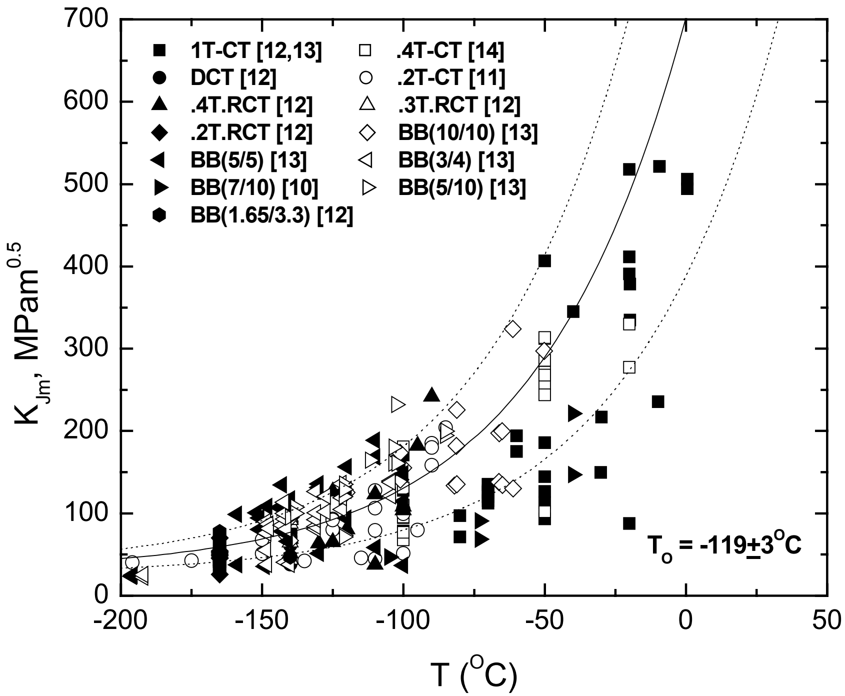
MD simulation of dislocation interaction with 8 nm SFT in Cu

QuickTime™ and a
PNG decompressor
are needed to see this picture.

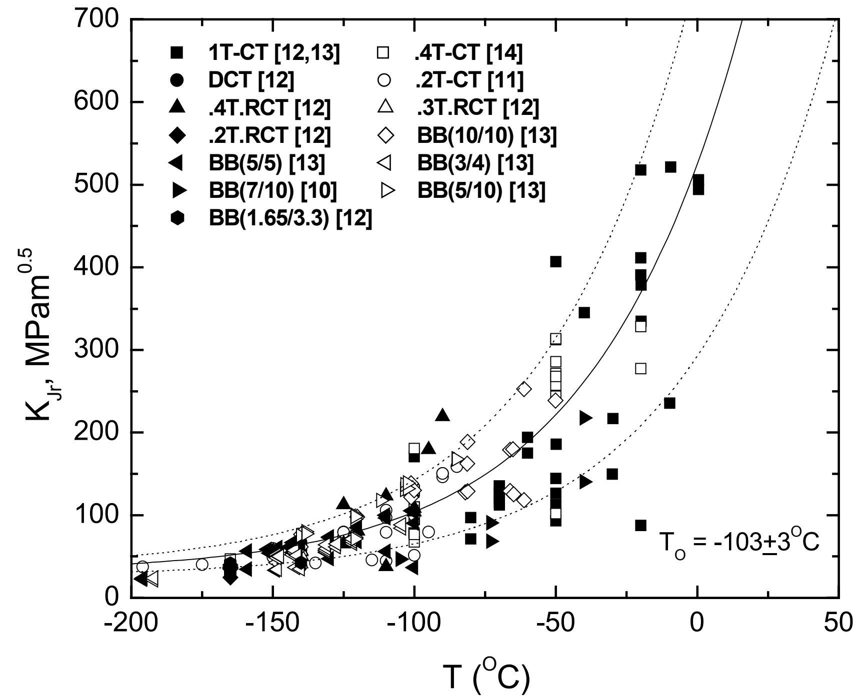
Fracture Mechanics Master Curve for F82H Ferrritic/martensitic Steel

- Constraint Loss and SSV (ASTM) adjustments produces a homogeneous self-consistent dataset with a common ASTM E1921 $T_o \approx -103°C$

ASTM only



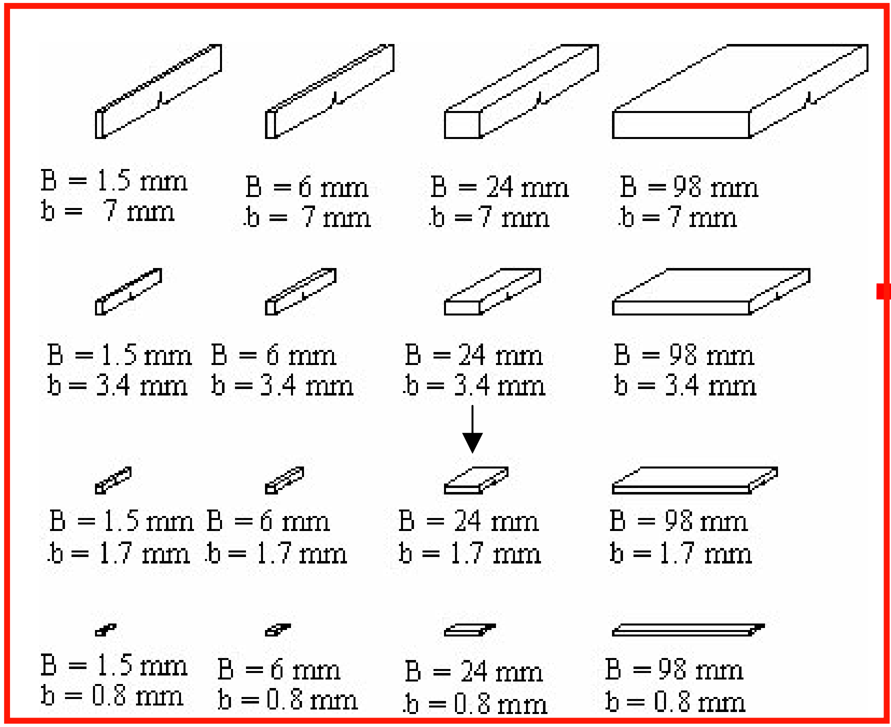
ASTM + Constraint Loss

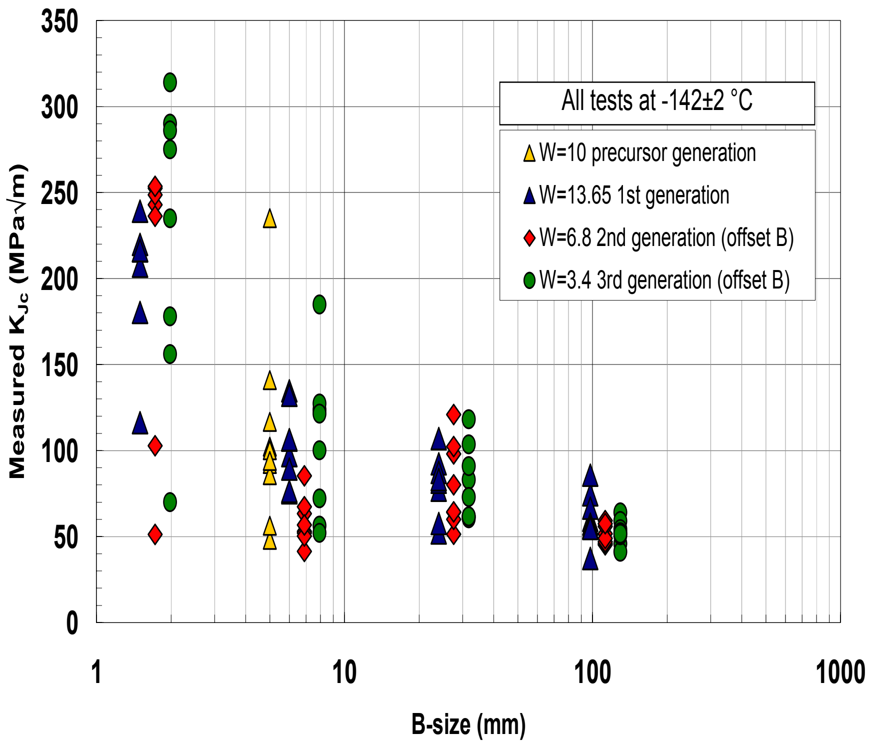


G.R. Odette, UCSB

Eurofer 97 Ferritic/martensitic steel Fracture Toughness: Size effects and Constraint Study

- UCSB collaboration with Rensman (NRG) and Yasuda (JAERI)

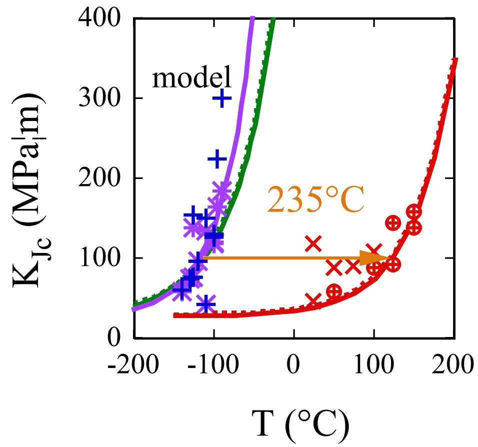


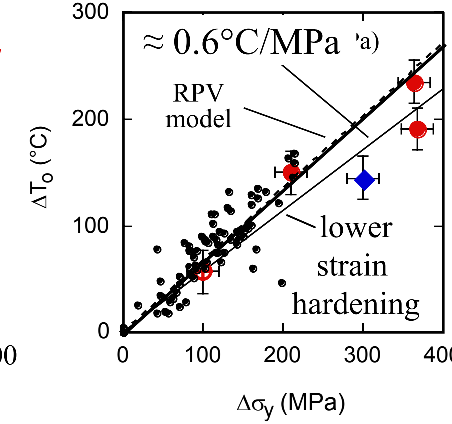


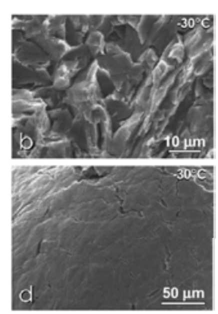
- Statistical scaling is evident
- Constraint loss is observed
- 4th (b=0.8) series, CL&SL adjustment to be completed

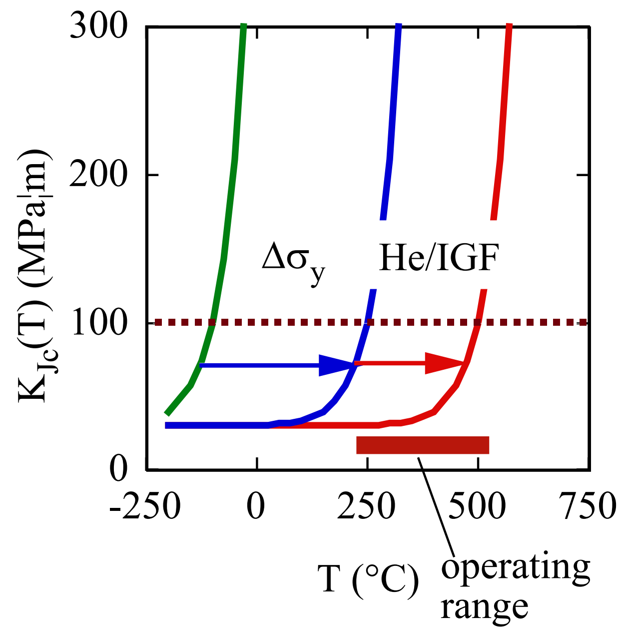
Master Curve Shifts (ΔT_o) and He Effects

- Modeled irradiation hardening ($\Delta\sigma_y$) induced $\Delta T_o \approx 0.6°C/MPa$
- Peak hardening up to ≈ 600 MPa => large ΔT_o => $T_o \geq 250°C$.
- Spallation proton data suggests at > 600-800 appm He weakens grain boundaries producing very brittle intergranular facture that interacts synergistically with $\Delta\sigma_y$.
- Estimates of combined effects suggest T_o > 500°C possible - clearly a show stopper
- High concentrations of H may also be damaging





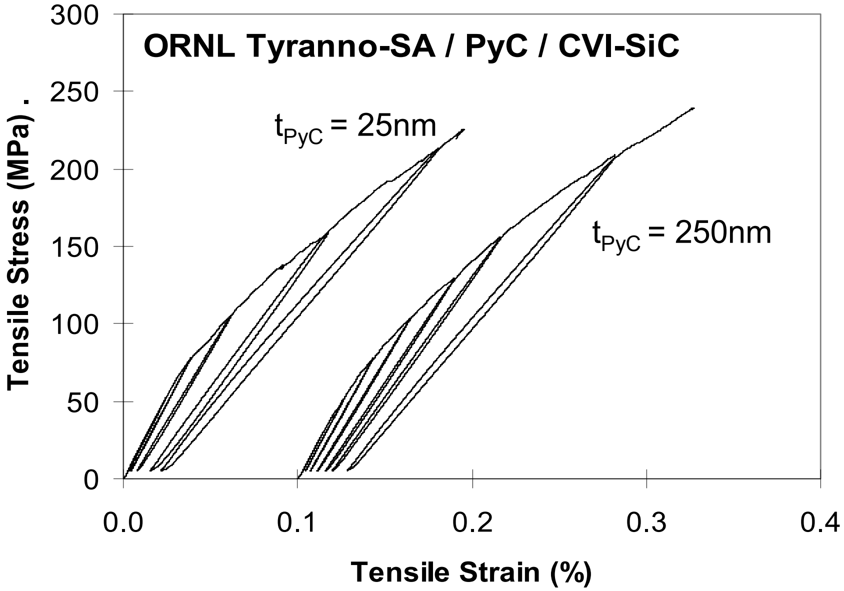


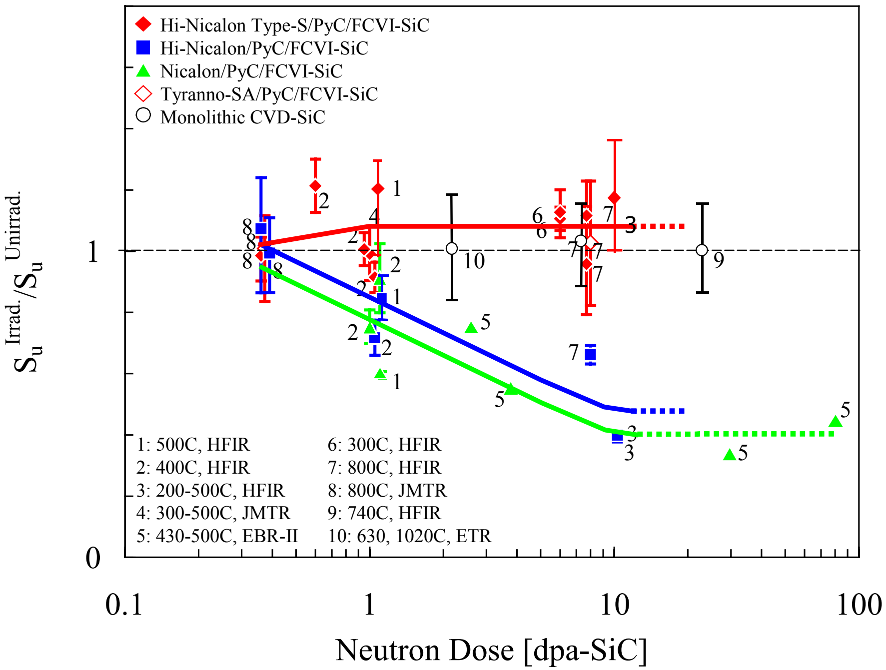


SiC/SiC Composites Development

Reference Chemical Vapor Infiltrated (CVI) Composites for Irradiation Studies

- Hi-Nicalon™ Type-S or Tyranno™-SA3 / PyC(50–150nm^t) / CVI-SiC composites have been selected as the reference materials
- Materials are under fabrication in US/Japan collaboration
- Extensive data generation for irradiated properties (including statistical strength) is planned.

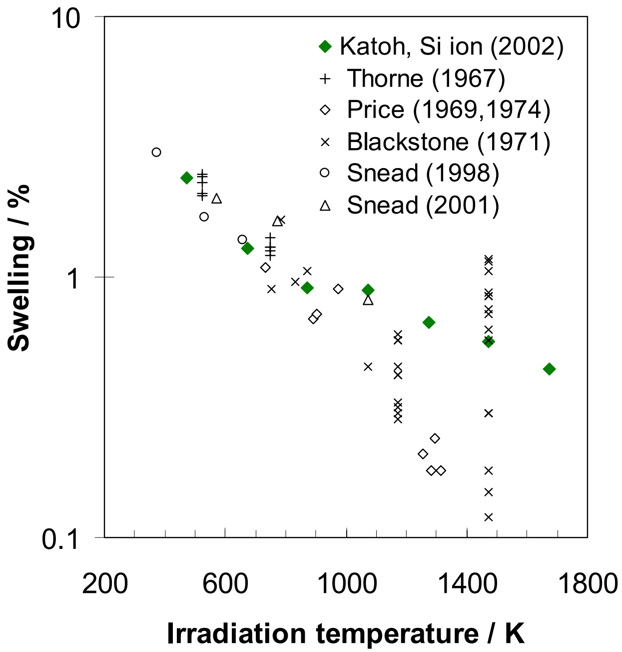




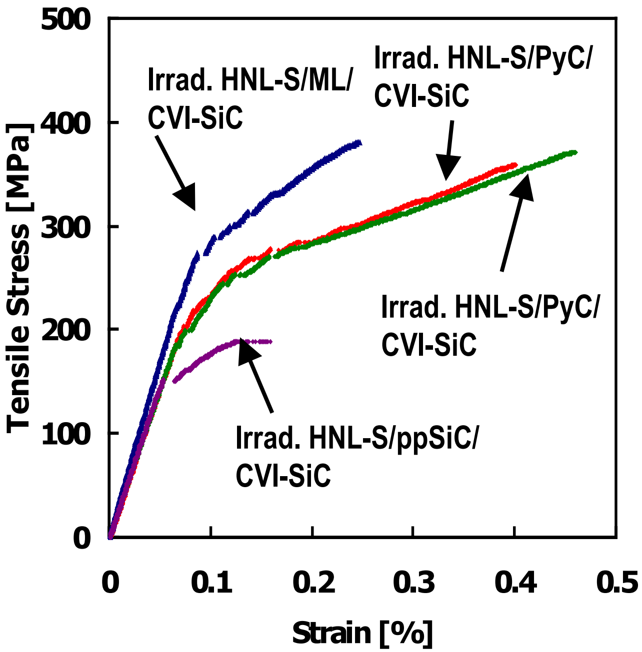
Irradiation Effect Studies in SiC/SiC

Composite Properties

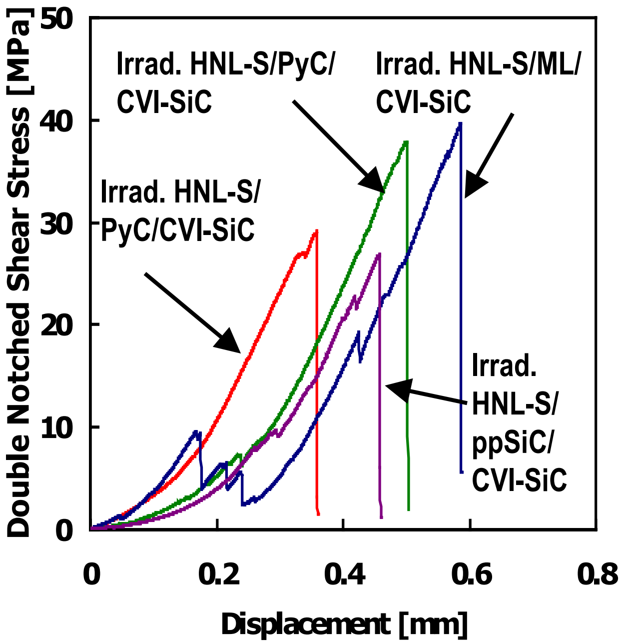
- Various mechanical and thermo-physical properties of irradiated SiC/SiC composites are being evaluated.
- Swelling, thermal conductivity, elastic modulus, tensile strength, shear strength, etc.



Swelling



Irradiated tensile properties (800C, 1dpa)

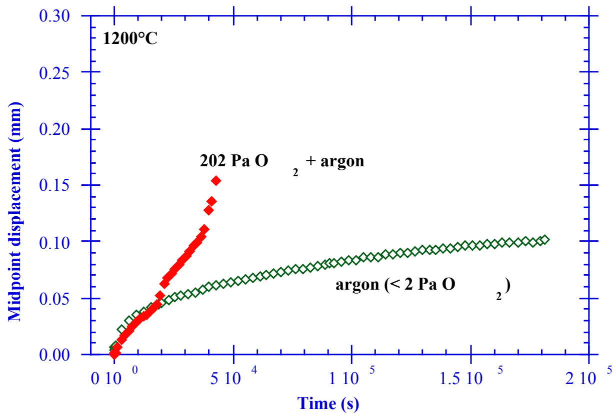


Irradiated inter-laminar shear properties (800C, 1dpa)

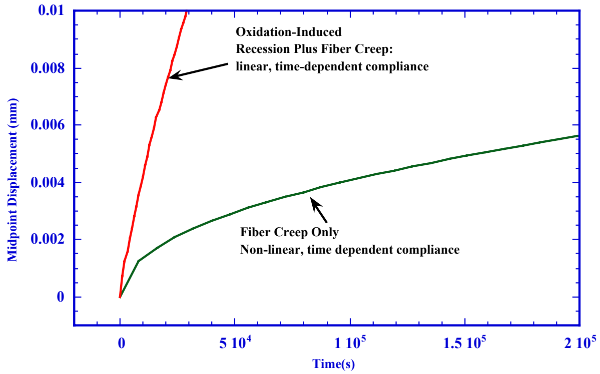
Micromechanical Modeling Allows Prediction of Component Lifetime of Ceramic Composites

Model verification

experiment



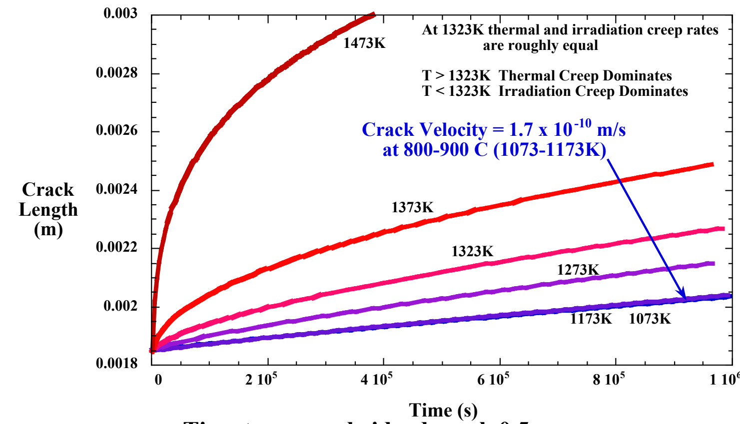
model



Oxygen atmosphere investigated in conjunction with DOE office of Basic Energy Science Program

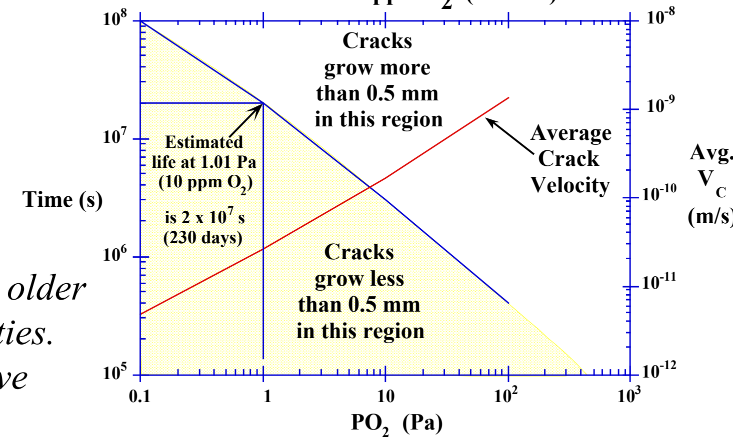
Predictive capabilities

Irradiation-enhanced creep of fibers controls crack growth below ≈ 1073 K



Model predicts crack velocity and crack length

Time to grow a bridged crack 0.5 mm at 800ÞC in 10 ppm O_2 (1.01 Pa)



NOTE: Lifetime predicted for older generation material properties. More recent materials have enhanced lifetimes.

Battelle

U.S. Department of Energy
Pacific Northwest National Laboratory

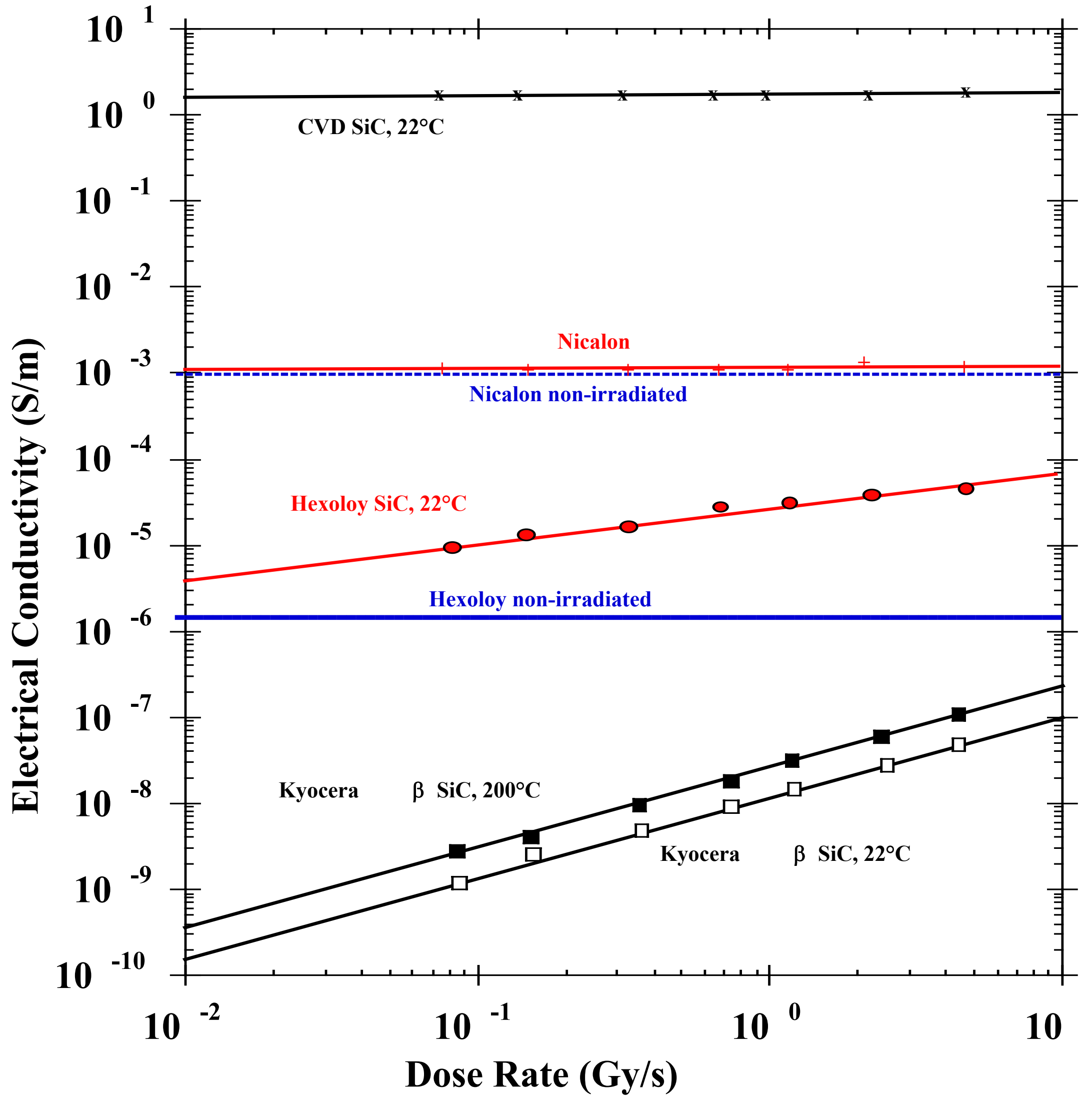
Radiation Induced Conductivity for different grades of SiC: Electrical Conductivity varies by 8 orders of magnitude!

- Ionizing radiation excites electrons into the conduction band enhancing conductivity.

$$\sigma=\sigma_o+KR^\delta$$

Dose rate

- If unirradiated conductivity is high, RIC is insignificant

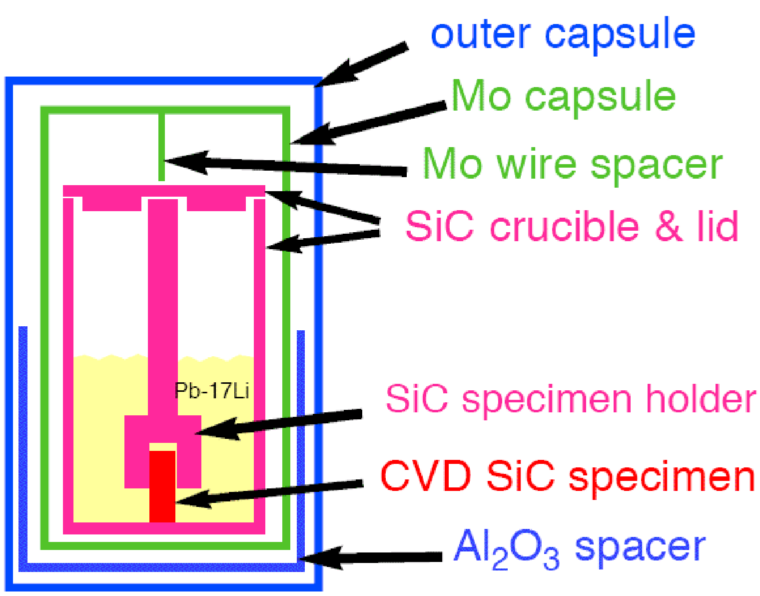


L.L. Snead, J. Nucl. Mater.329-333 (2004) 524

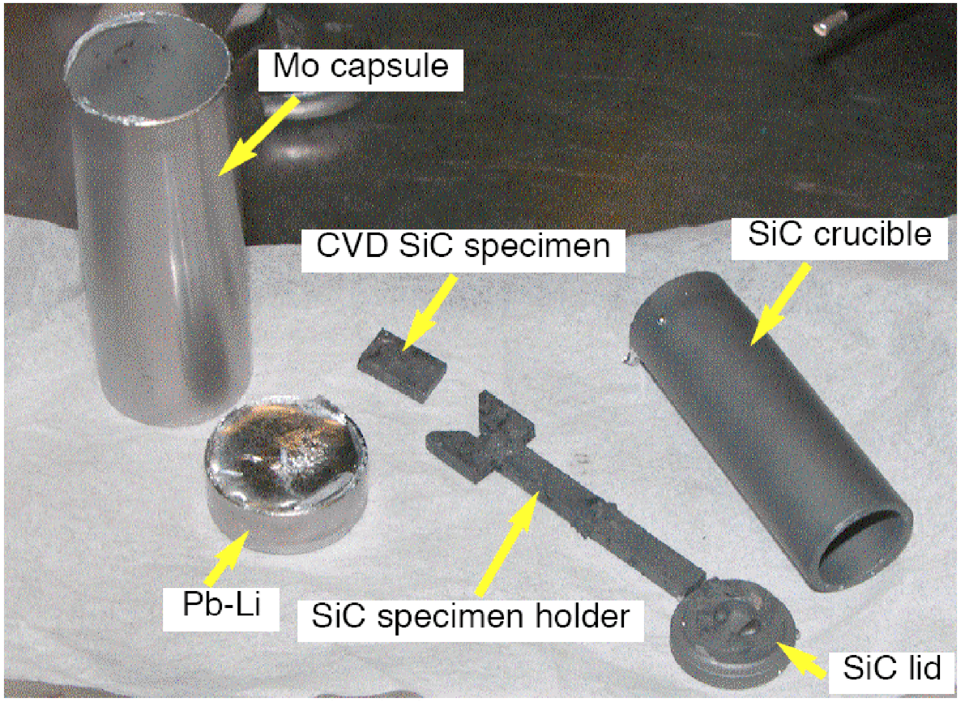
Compatibility Study

SiC / Pb-Li Static Compatibility

- Good compatibility was observed between monolithic SiC and Pb-17Li at 800° and 1100°C in a static capsule test up to 1000h.
- Planned work includes chemical composition measurement of the Pb-Li after the capsule test and characterization of SiC specimens.



800°C: No wetting, no mass change



Irradiation / Collaboration Programs

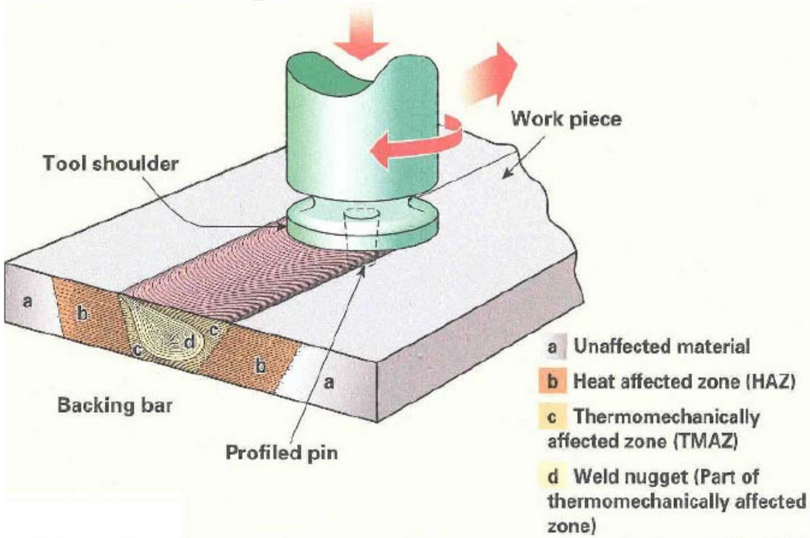
Coverage of Irradiation Condition by Recently completed, On-going, and Planned Programs

- Planned irradiation programs cover most of the conditions of interest for near-term ITER Test Blanket.
- Data to be obtained will focus on fundamental and scientifically valuable properties.

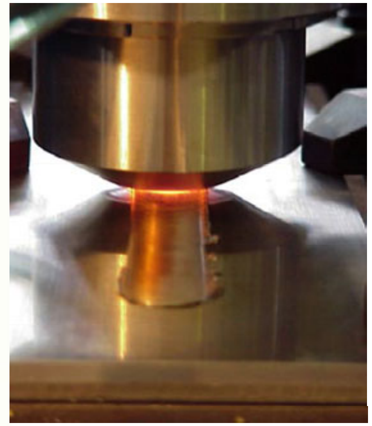
Overview of Radiation Effects Experiments

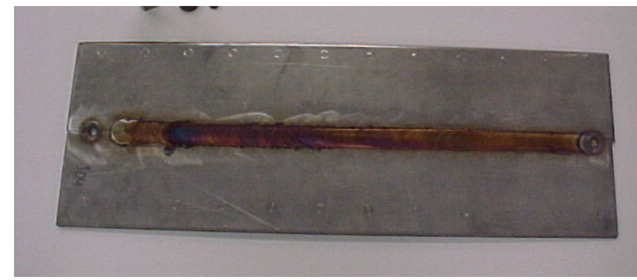
Program	Irrad. Capsule	Materials	Irrad. conditions	Irrad. start	Irrad. finish
JAERI	JP26 (HFIR target)	Ferritic steel	9 dpa 300, 400, 500˚C	Dec. 03	Sep. 04
"	JP27 (HFIR target)	Ferritic steel	23 dpa 300, 400, 500˚C	Apr. 04	June 06
"	JP28 (HFIR target)	Ferritic steel	50 dpa 300, 400, 500˚C	Oct. 04	Mar. 09
"	JP29 (HFIR target)	Ferritic steel	50 dpa 300, 400, 500˚C	Oct. 04	Mar. 09
"	RB15J (Eu shield)	Ferritic steel	6 dpa 300, 400, 500˚C	Sep. 05	Apr. 07
"	RB16J	Ferritic steel	6 dpa 300, 400, 500˚C	June 05	Nov. 06
Jupiter-II	RB17J (Eu shield)	V alloys & MHD insul.	6 dpa 425, 600, 700˚C	Apr. 04	Aug. 05
"	RB18J	SiC and SiC/SiC	8 dpa 600, 900, 1100˚C	Apr. 05	June 06

Friction Stir Welding may enable joining of numerous advanced materials (ODS steels, He-containing metals, etc.)



Sketch provided by TWI





SS304 stainless steel

- FSW uses a rotating tool that is translated along the joint to create solid-state bonding by thermo-mechanically working the material.
- Currently, FSW is used to weld low-melting temperature materials such as Al alloys using tool steel for tool material.
- The challenge is to develop tool materials that can weld high-temperature alloys such as steels, Ti alloys, Ni-based superalloys. Recent developmental studies at ORNL have created several tool materials that successfully welded stainless steel

Conclusions

- The US fusion materials program is increasing activities related to ITER (machine and test blanket modules)
- Underlying deformation and fracture mechanisms at low temperatures are currently of high interest (due to ITER environment)
- High temperature deformation and fracture (He embrittlement) is also of major concern, but is not a major activity due to funding limitations
- SiC/SiC composite R&D has progressed from initial qualitative screening studies to measurement of engineering-relevant mechanical properties (unirradiated and irradiated)