Advanced Materials for Fusion Technology

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Acknowledgements: Akira Kohyama, Rainer Lindau, Ron Klueh, Yutai Katoh, David Hoelzer, Lance Snead and Phil Maziasz

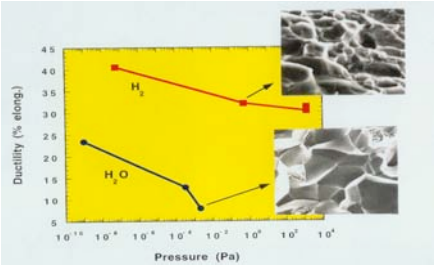
Introduction

- Development of new materials for structural applications is historically a long process
- The hostile fusion environment (thermomechanical stress, high temperatures, high fusion neutron flux) arguably makes fusion materials development the greatest challenge ever undertaken by materials scientists
  - Requirement to restrict consideration to “reduced activation” elements produces further constraint
- Nevertheless, a suite of advanced materials with impressive performance have been developed by the international fusion materials community
- This presentation will review some of the advanced materials currently under investigation, with a focus on ferritic steels

The Development And Commercialization of Ni_3Al Alloys Spans 20 Years and Includes Basic Materials Science and Materials Engineering

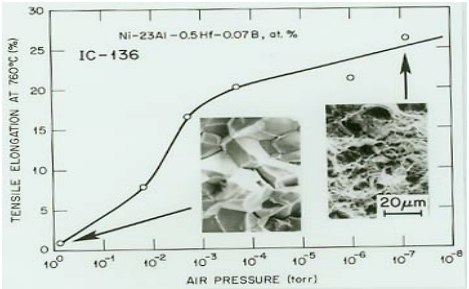
- **Ni_3Al shows brittle intergranular fracture due to moisture-induced embrittlement at RT**

1983



- **Ni_3Al shows intermediate-temperature embrittlement due to oxygen in air**

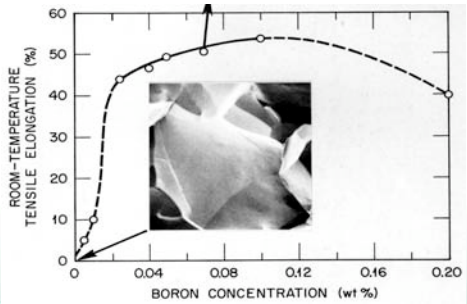
1985



Severe embrittlement in air at 750C

- **B additions dramatically improve the tensile ductility at RT**

1985



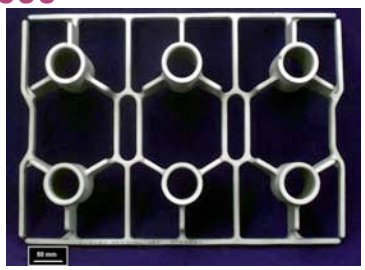
- **Cr additions substantially improve the tensile ductility at 500-800°C in air**

1988

Formation of Cr oxides at >500C reduces O_2 penetration

- New Ni_3Al alloys developed for use in carburizing & oxidizing environments

2000



furnace fixtures for heat treatment

2003

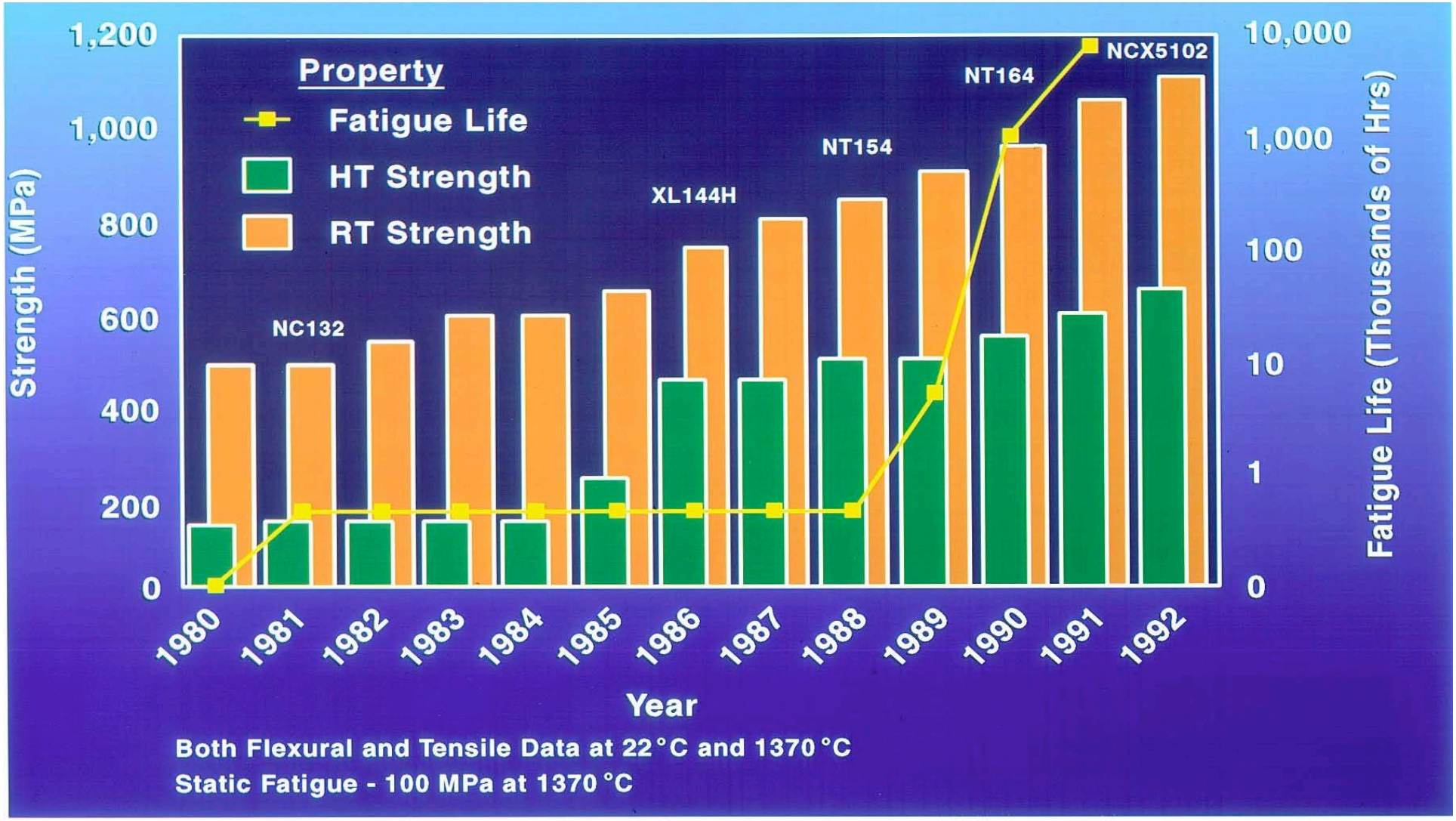
rollers used for steel fabrication

The Ceramic Technology Project

1983 – 1996, $175M

Enabled Monolithic Ceramics to Become Reliable Structural Materials

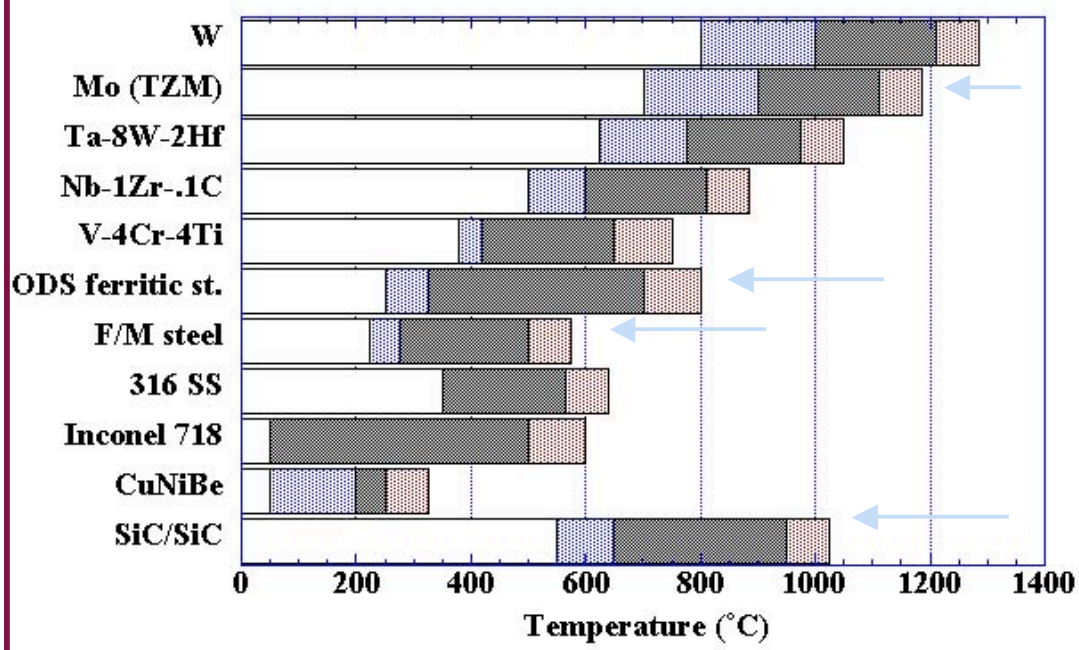
Si_3N_4



Current Alloy Systems Have Key Limitations

- 300 series austenitic stainless steels
  - thermal creep temperature limits
  - Inherently poor swelling resistance at high burnups (requires precise alloying additions and heat treatment)
- Ferritic/Martensitic Steels
  - *Excellent swelling resistance up to high burnups, but…….*
  - low temperature radiation hardening
  - thermal creep temperature limits
- Superalloys
  - *Excellent thermal creep resistance up to high temperatures, but…….*
  - radiation embrittlement at moderate doses
- Refractory Alloys
  - *adequate swelling resistance up to high burnups, but…….*
  - Fabrication, joining difficulties
  - low temperature radiation hardening
  - poor oxidation resistance

Structural Material Operating Temperature Windows: 10-50 dpa

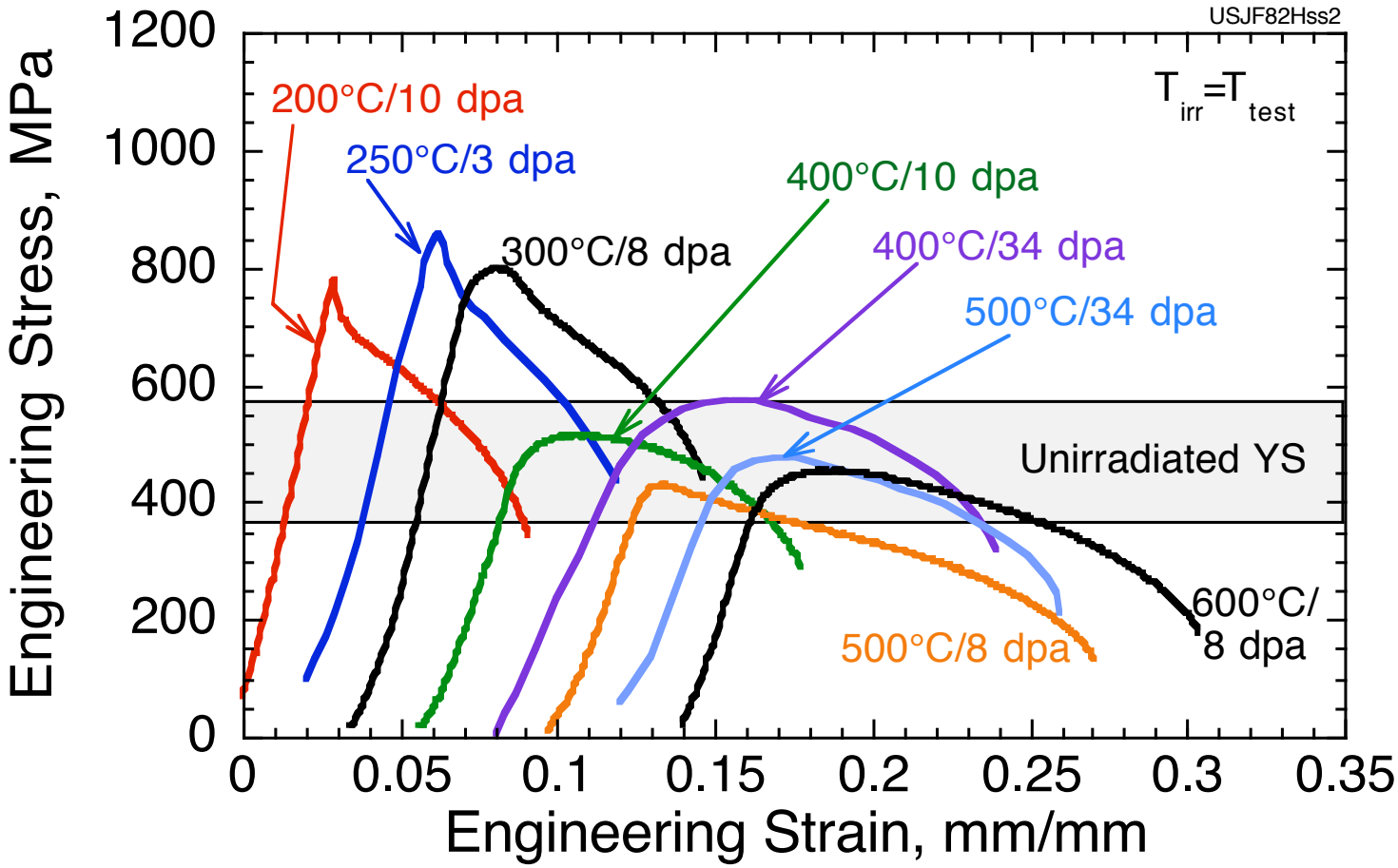


Low temperature radiation embrittlement typically occurs for damage levels ~0.1 dpa (0.01 MW-yr/m^2)

Zinkle and Ghoniem, Fusion Engr. Des. 49-50 (2000) 709

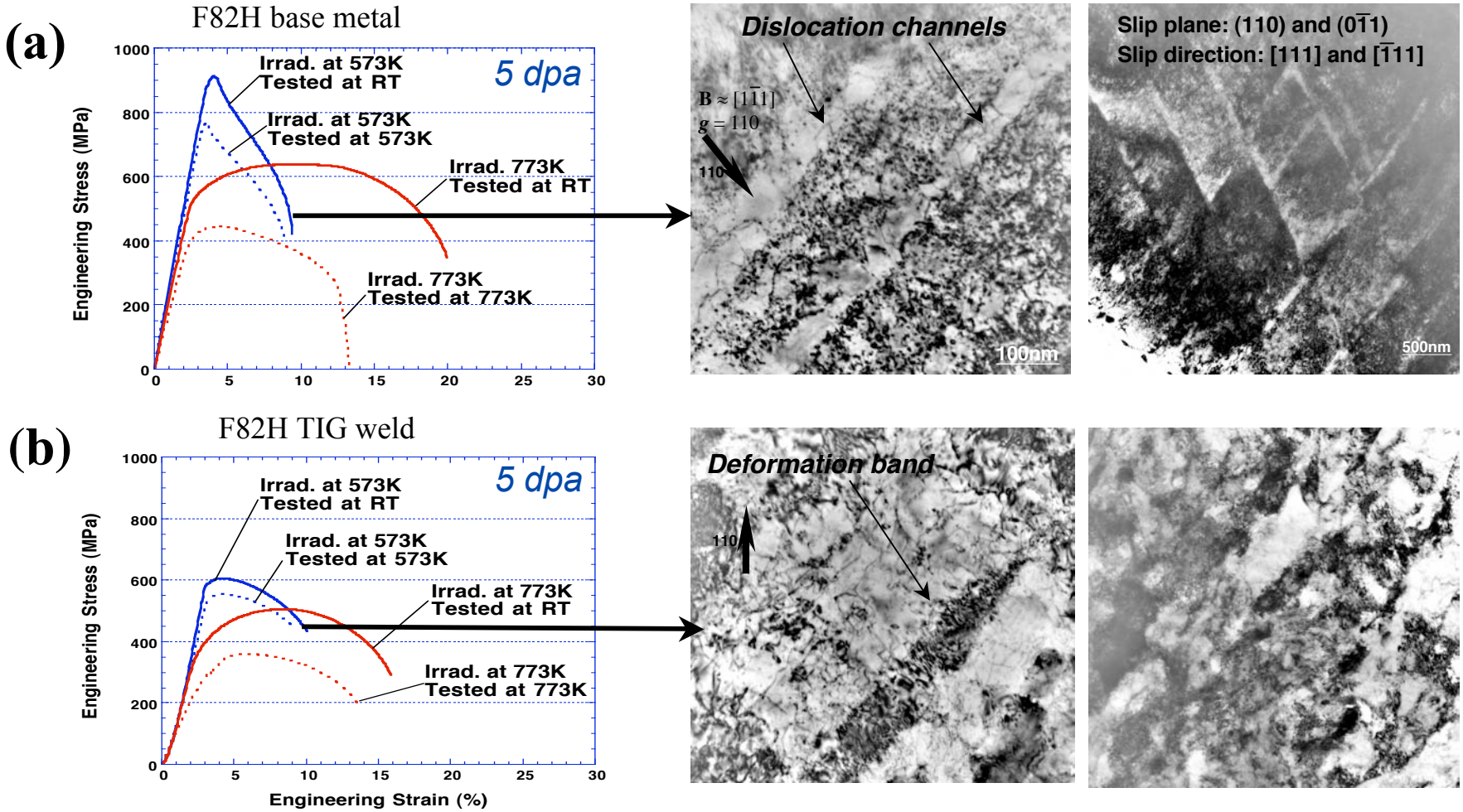
Low Temperature Radiation Hardening is Important in Ferritic/martensitic steel up to ~400°C

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



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

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

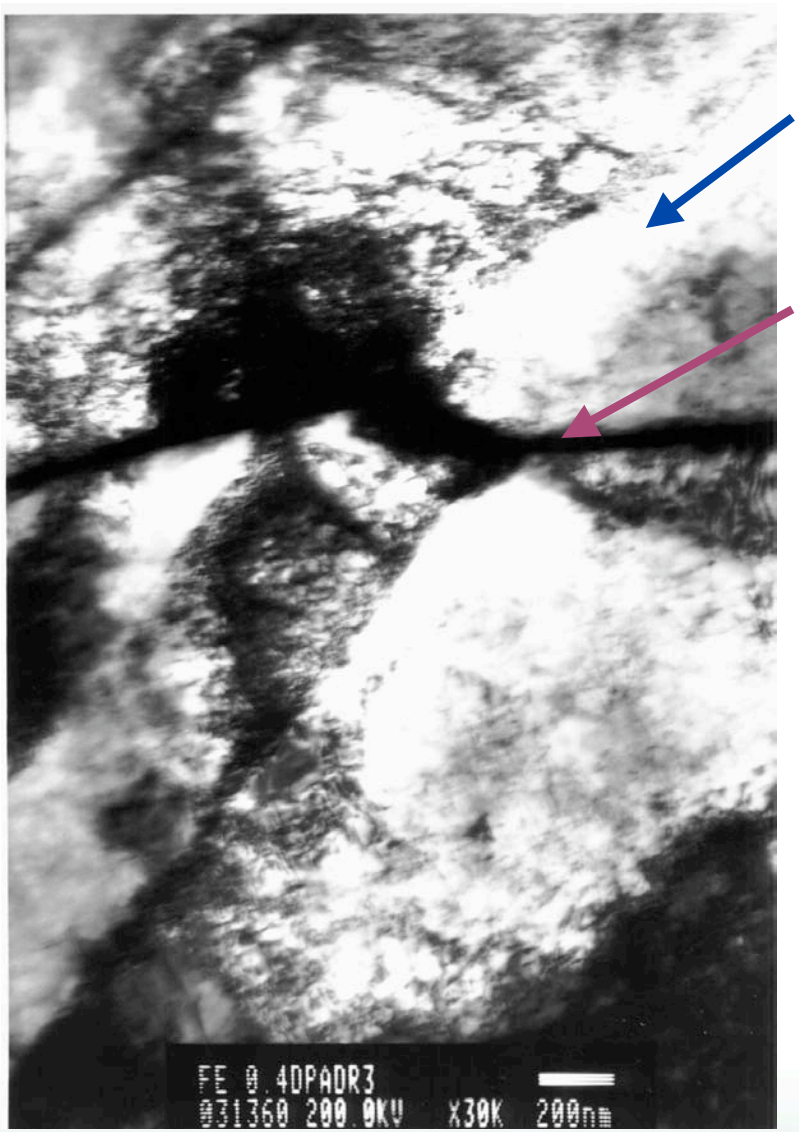


Irradiated weld metal (lower radiation hardening) did not exhibit dislocation channeling after deformation

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



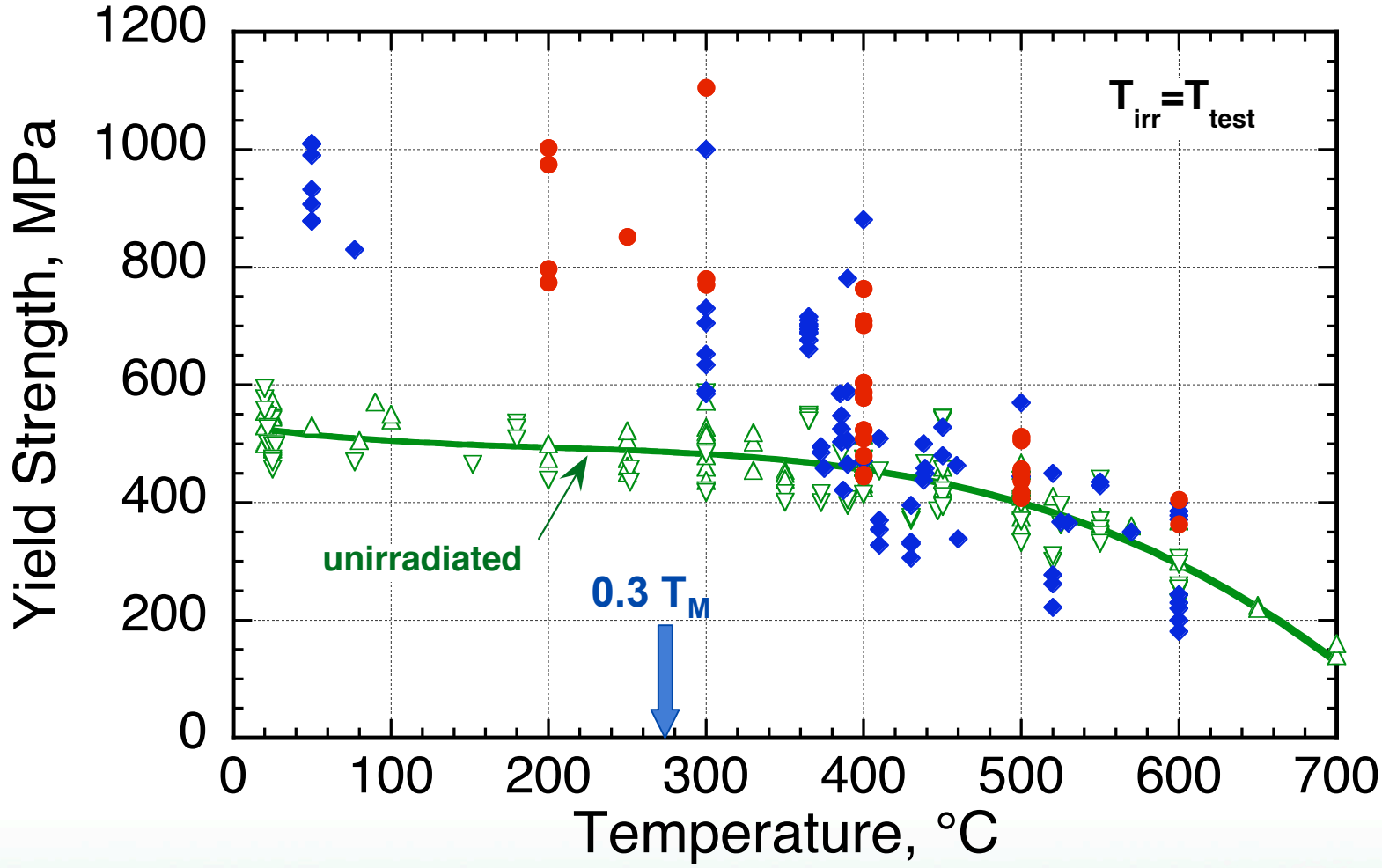
Cleared slip channel

g.b.

Need well-engineered materials to mitigate neutron radiation effects

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

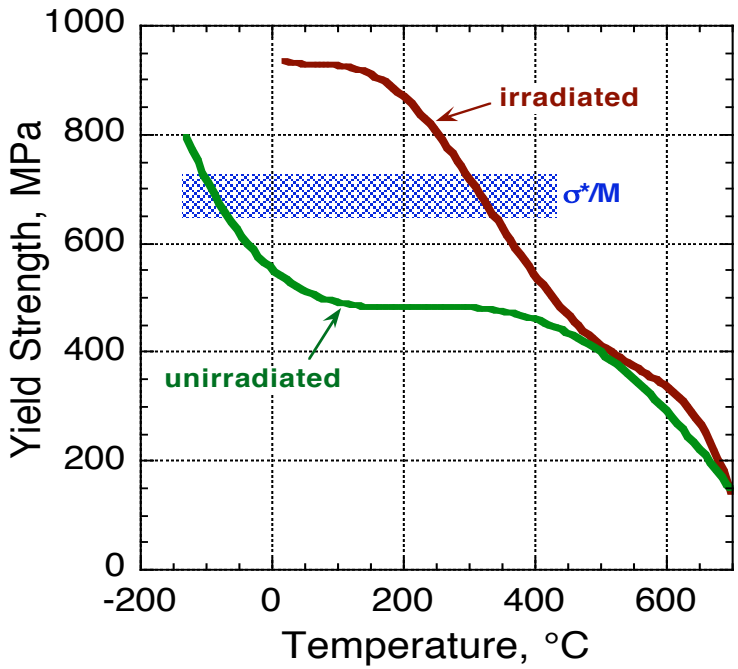
8-9Cr Steels: Yield Strength as Function of Temperature, 0.1 - 94 dpa



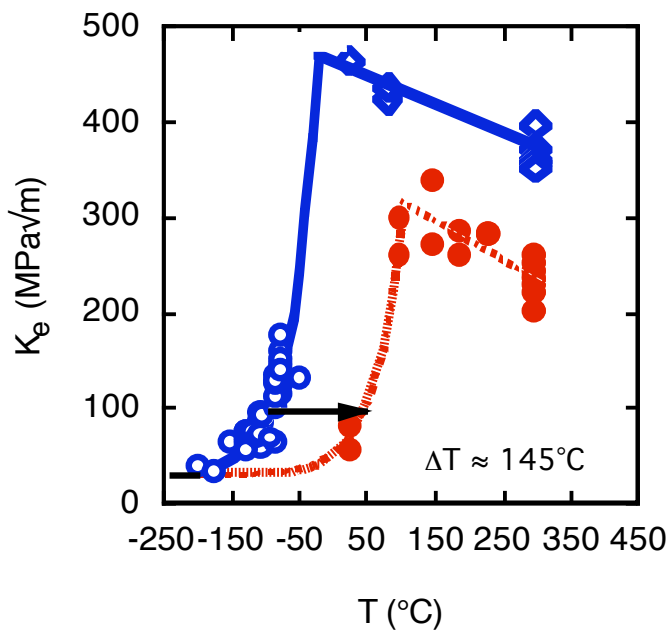
Fracture Toughness of BCC Structural Alloys

- Radiation hardening induces an increase in the ductile-brittle transition temperature (DBTT) in body-centered cubic metals

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



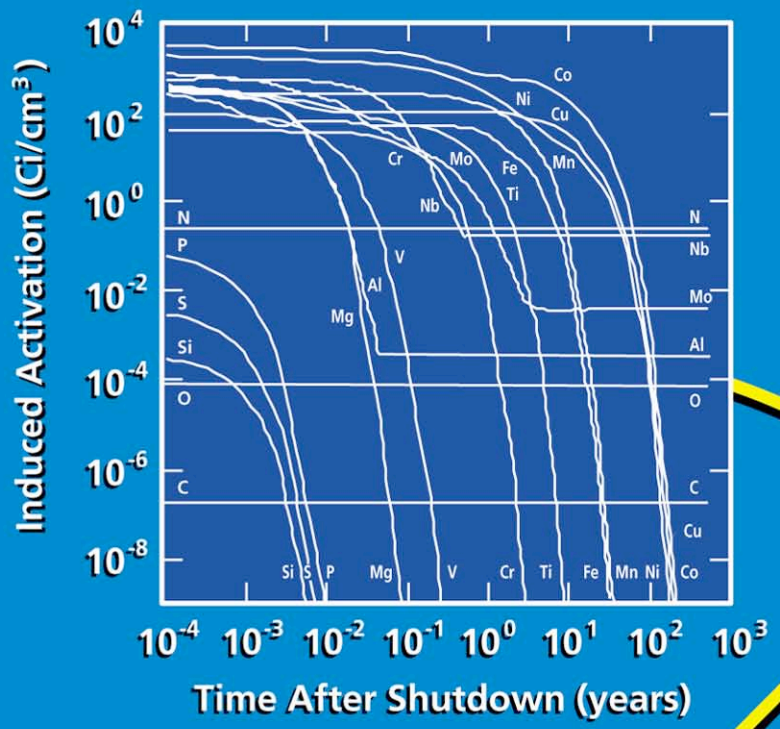
- Important parameters such as constraint and strain rate are included in recent advanced approaches (Master curve)

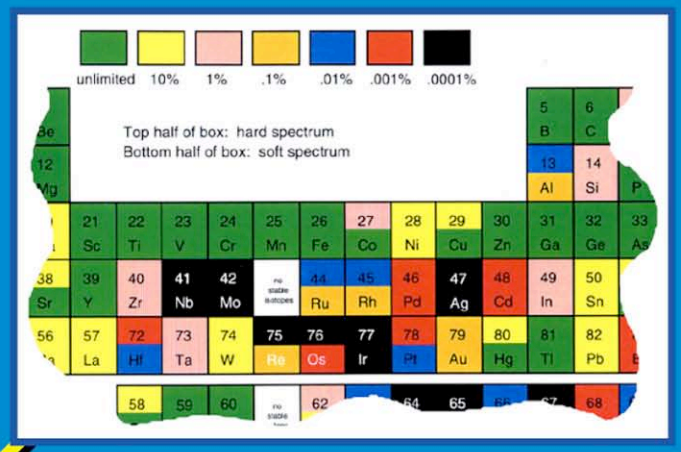


Need well-engineered materials to mitigate neutron radiation effects

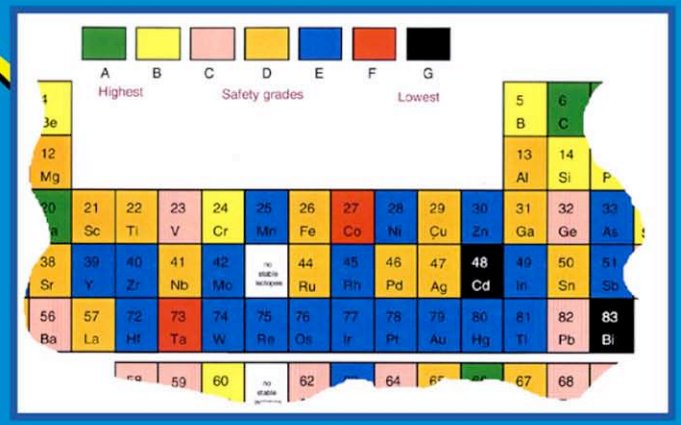
UCSB

Structural Materials





Class C Waste Disposal



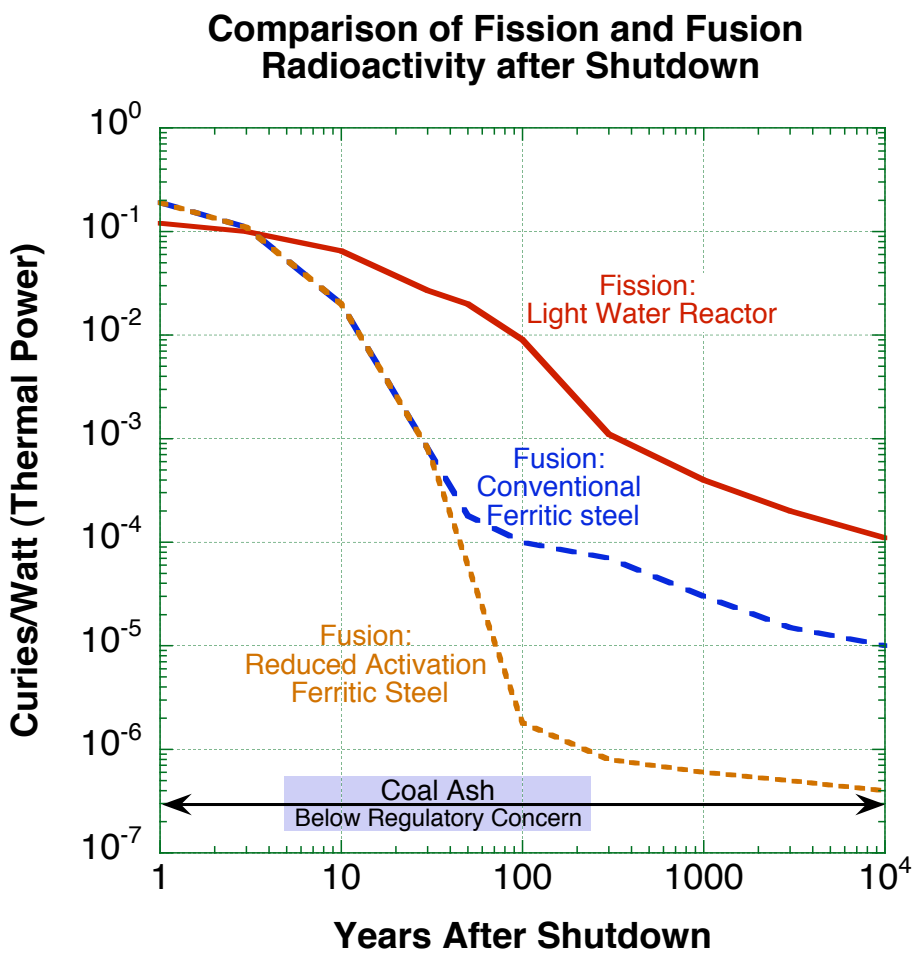
Safety

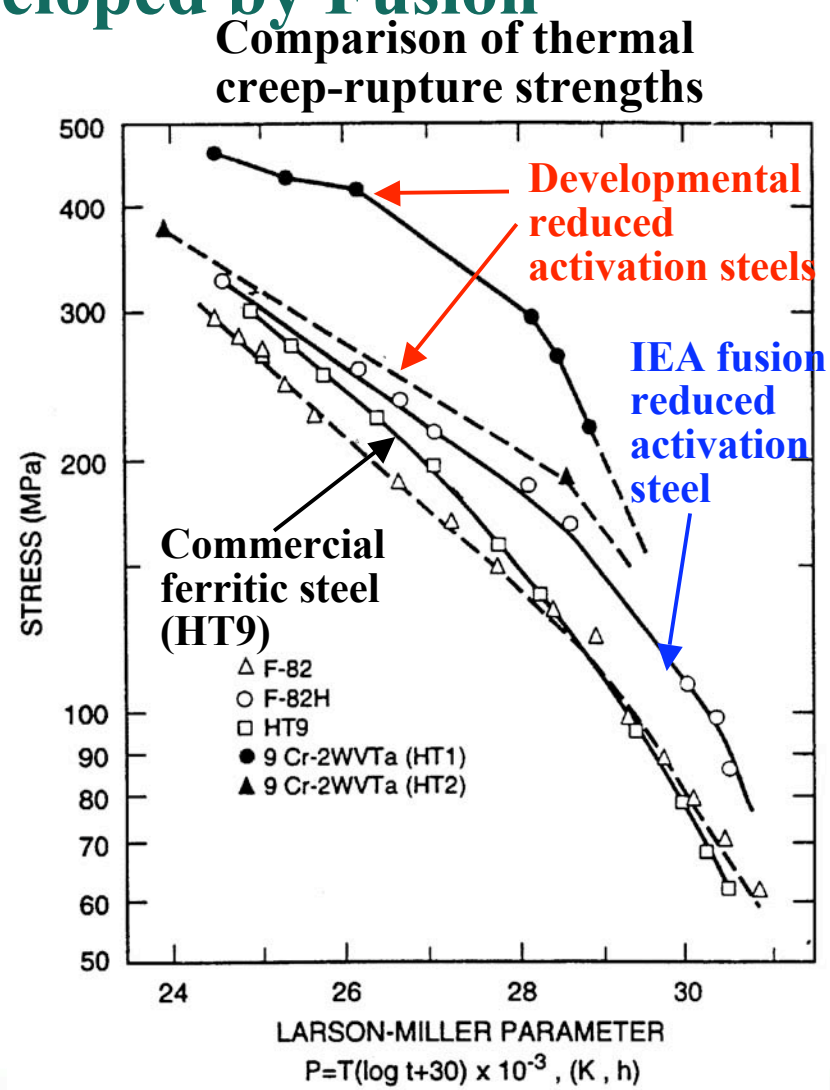
SiC

V Cr Ti Si

Fe Cr W V Ta

Ferritic/martensitic Steels with Reduced Radioactivity and Superior Properties Compared to Commercial Steels have been Developed by Fusion

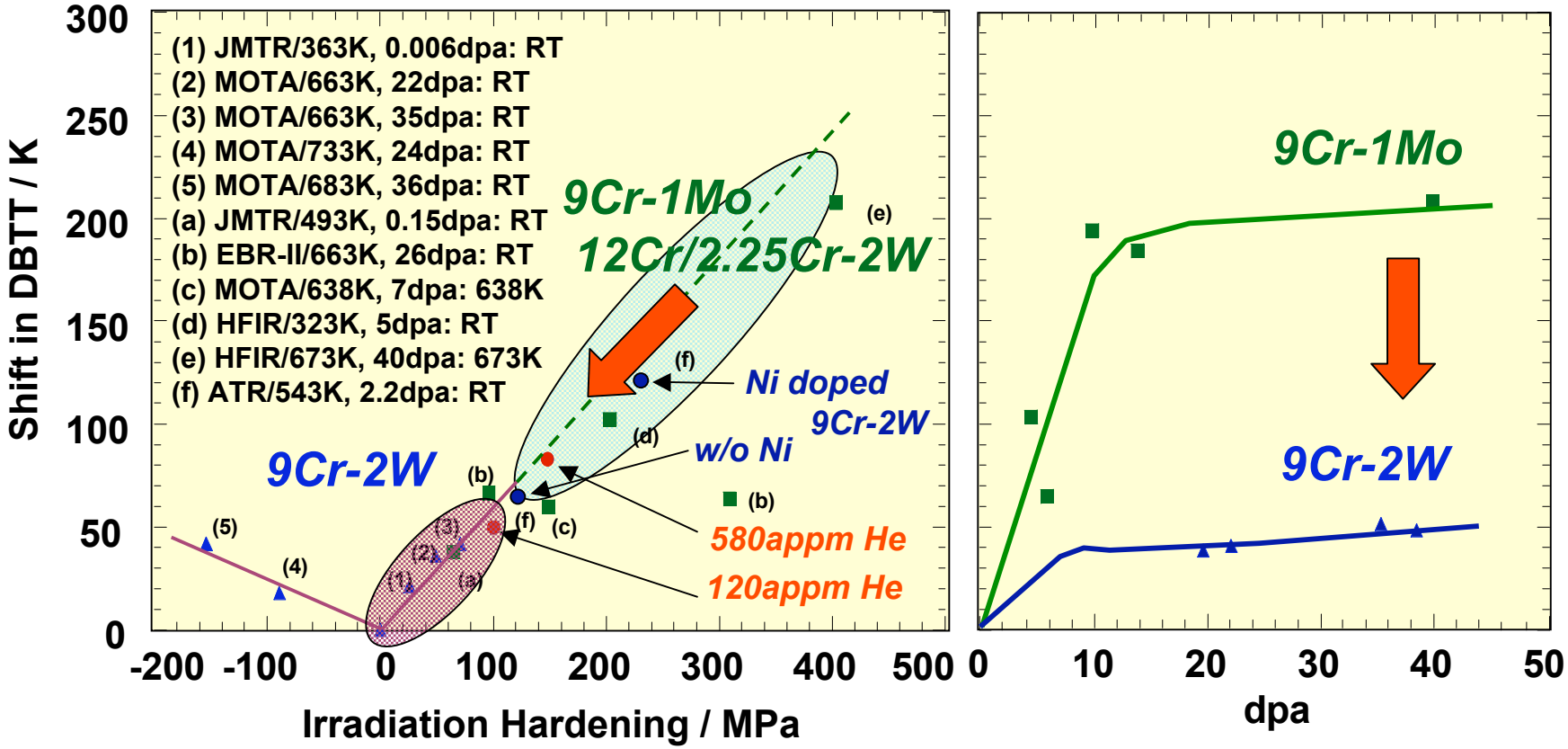




Fusion-developed steels also have superior tensile strength, irradiated fracture toughness, and thermal conductivity

Fusion Reduced Activation Ferritic/martensitic Steels Exhibit Superior Irradiation Performance Compared to Conventional 9Cr-1Mo and 12Cr Steels

- Suppression of irradiation embrittlement

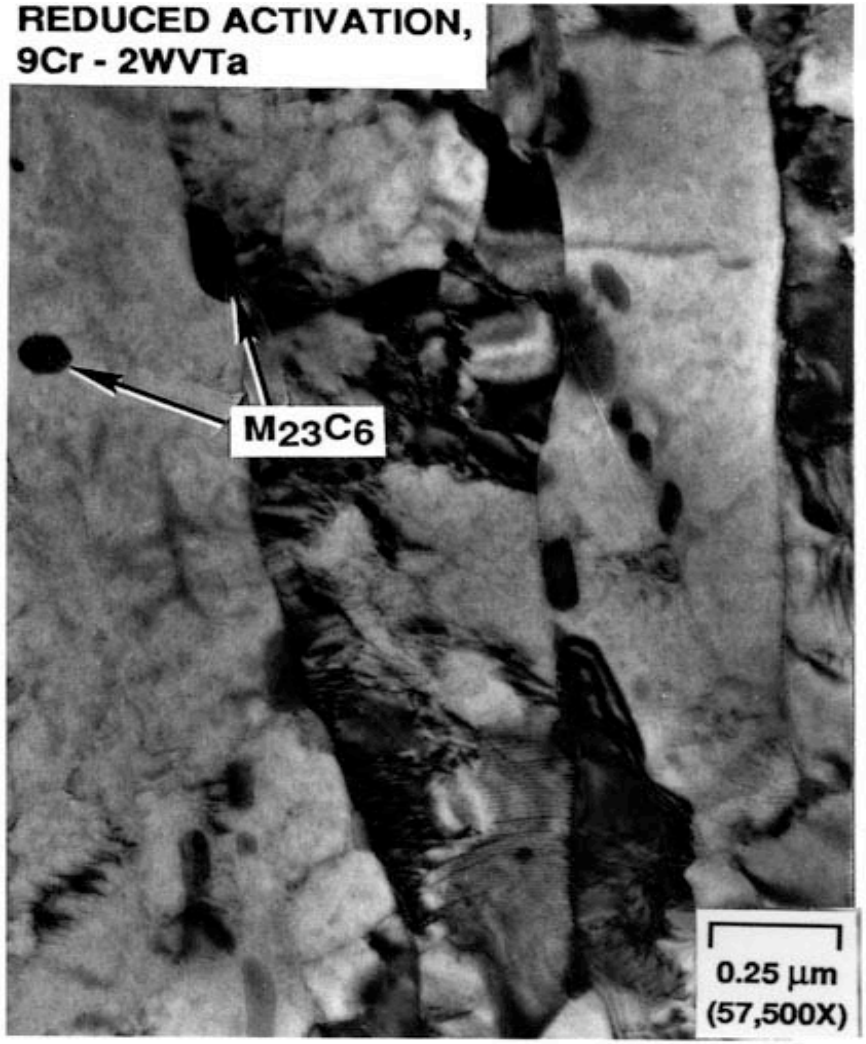


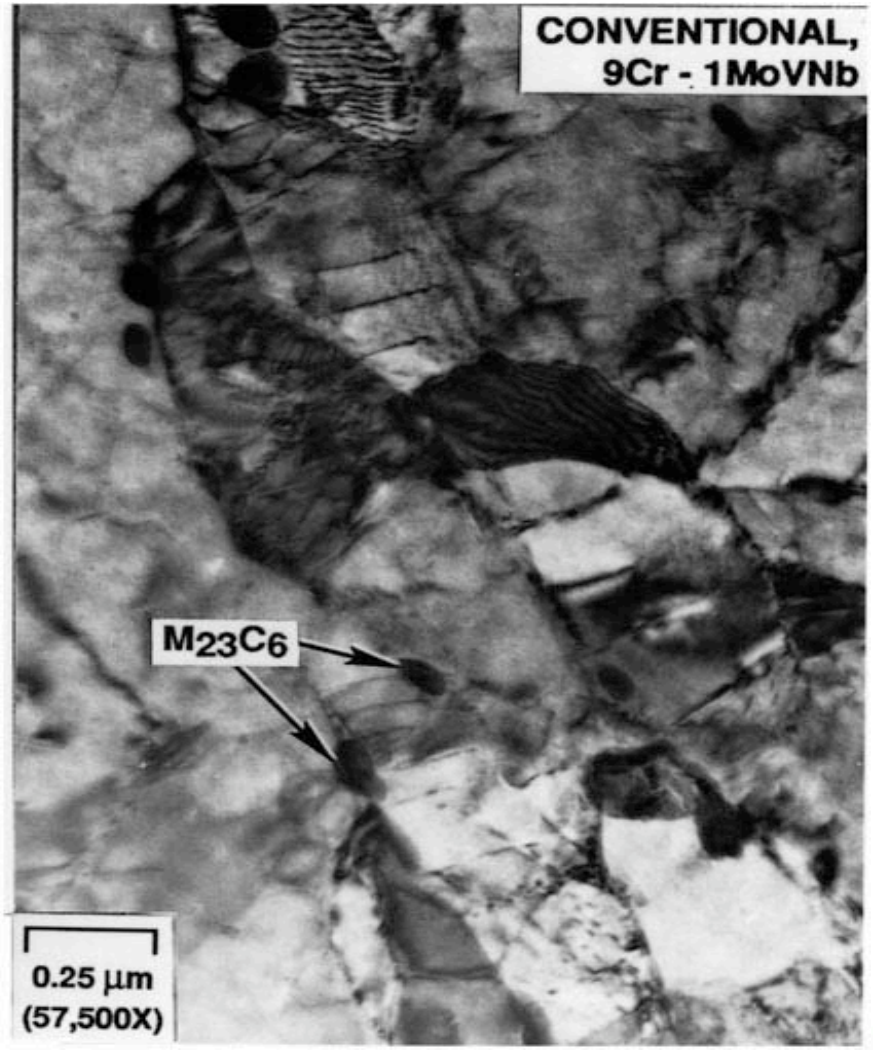
A. Kohyama, ANS TOFE (Madison, WI, 2004)

Overview of Improved Steels

- Steels can exhibit a wide range of properties depending on detailed composition and thermomechanical treatment
- Four generations of ferritic steels based on materials science principles have been commercialized (R. Viswanathan, Adv. Mater. & Processes 162, No. 8 (2004) 73)
  - 1st generation 1960-1970; 2nd generation 1970-1985; 3rd generation 1985-1995; 4th generation currently emerging
- Fusion 9Cr ferritic/martensitic steels are based on "2nd Generation" steels developed around 1985; fusion steels are comparable to 3rd generation commercial steels
  - Fusion substitution of W for Mo (reduced activation) was also pursued for "3rd generation" commercial steels
- Future steel development options will likely be based on evolutionary (ingot metallurgy/ classical precipitation) and revolutionary (nanoscale oxide dispersion strengthening) approaches

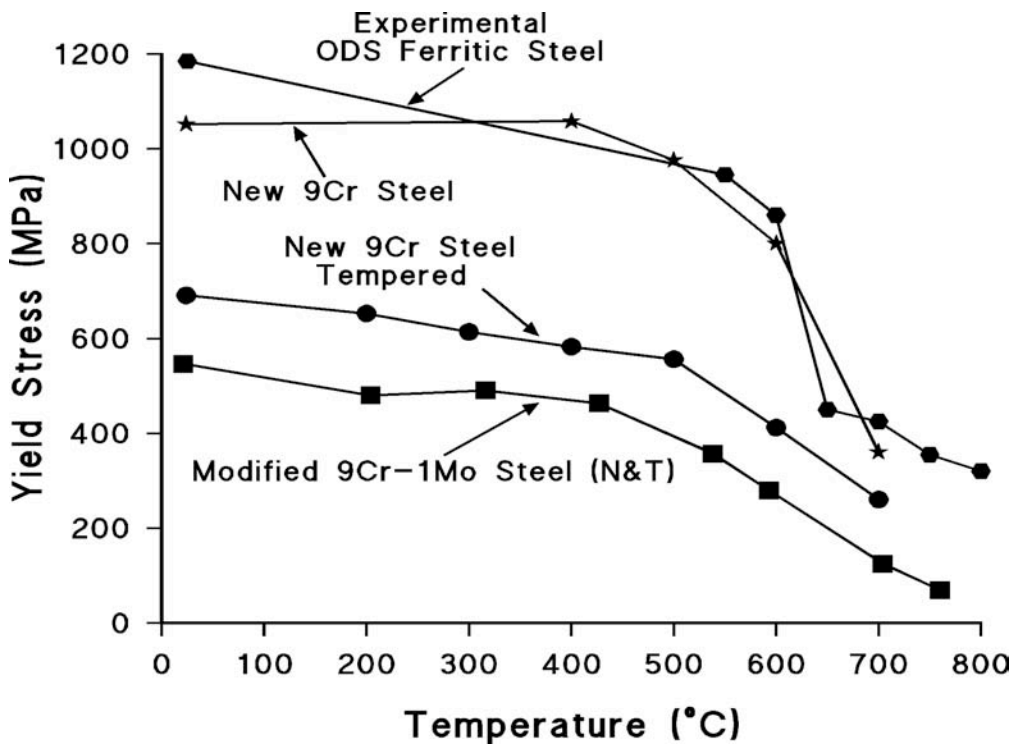
Microstructure of 9Cr-2WVTa Steel is Similar to Modified 9Cr-1Mo





Modified Thermomechanical Treatment Procedure for New 9Cr Ferritic/Martensitic Steel Produced High Strength

- Strength and ductility in tensile test are comparable to high-strength experimental ODS steel



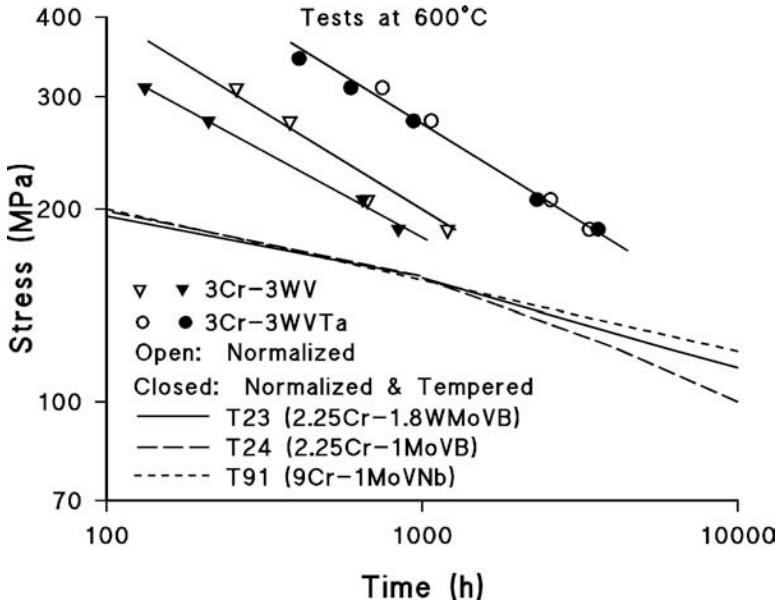
R.L. Klueh, to be published

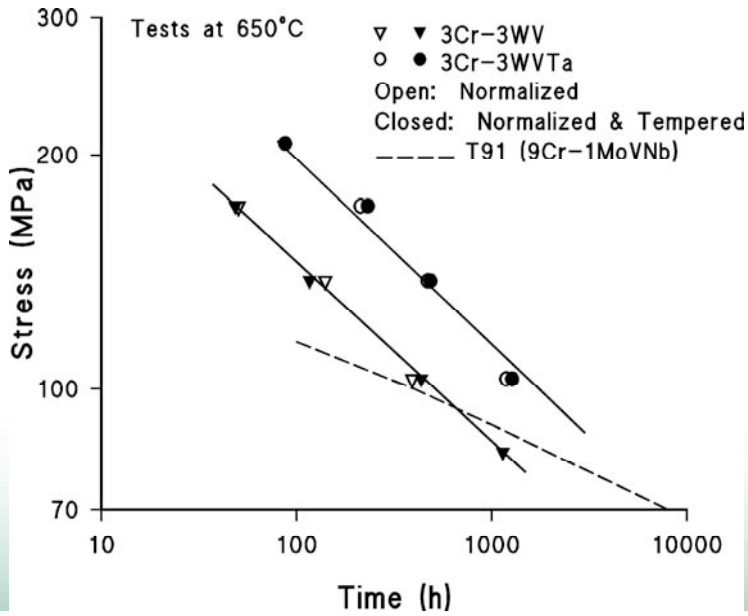
Low-Cr Bainitic Steels Originally Developed as Replacement for 2 1/4 Cr-1Mo Steel

- Low-chromium steels have advantages
  - Better weldabiltiy for easier plant fabrication—an important consideration
    - May not require post-weld heat treatment
  - Cheaper because of less chromium
- Previous studies at ORNL discovered effect of heat treatment on type of bainite formed
- Mechanical properties determined by type of bainite formed
- Discovery was used to develop 3Cr steels

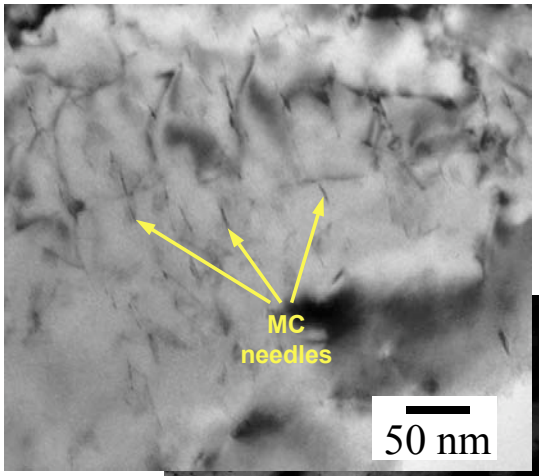
Creep Properties of 3 Cr Steels have Advantages Over 2 1/4Cr and 12Cr Steels

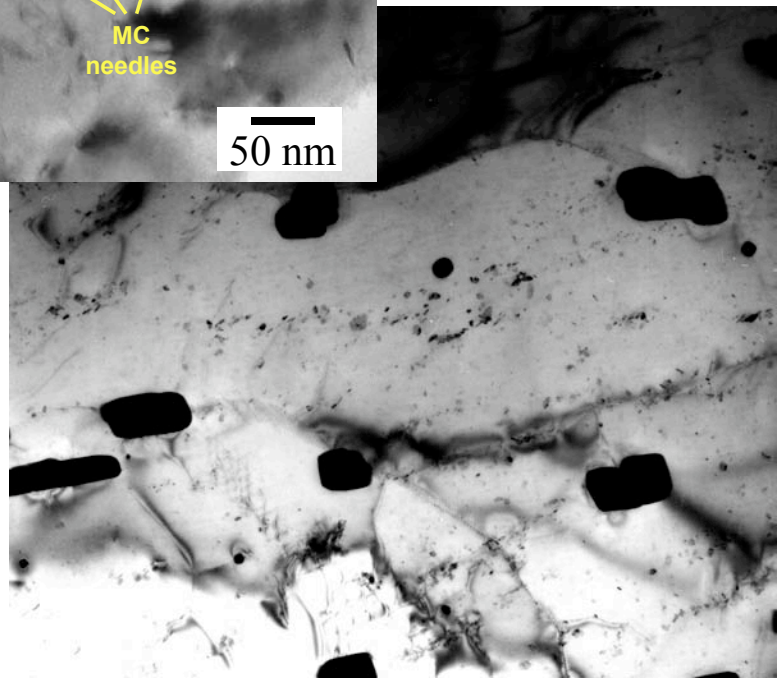
- Creep resistance improved over Japanese 2.25Cr (T23,T24) steels
- Properties better than for HT9 and as good or better than for modified 9Cr-1Mo steel
- Long-term creep behavior (>5000 h) still needs to be determined
- Two 50 ton heats have been fabricated to initiate ASME code approval





Better Creep Resistance of 3Cr-3WVTa is due to Fine MC Precipitate in Matrix





500 nm

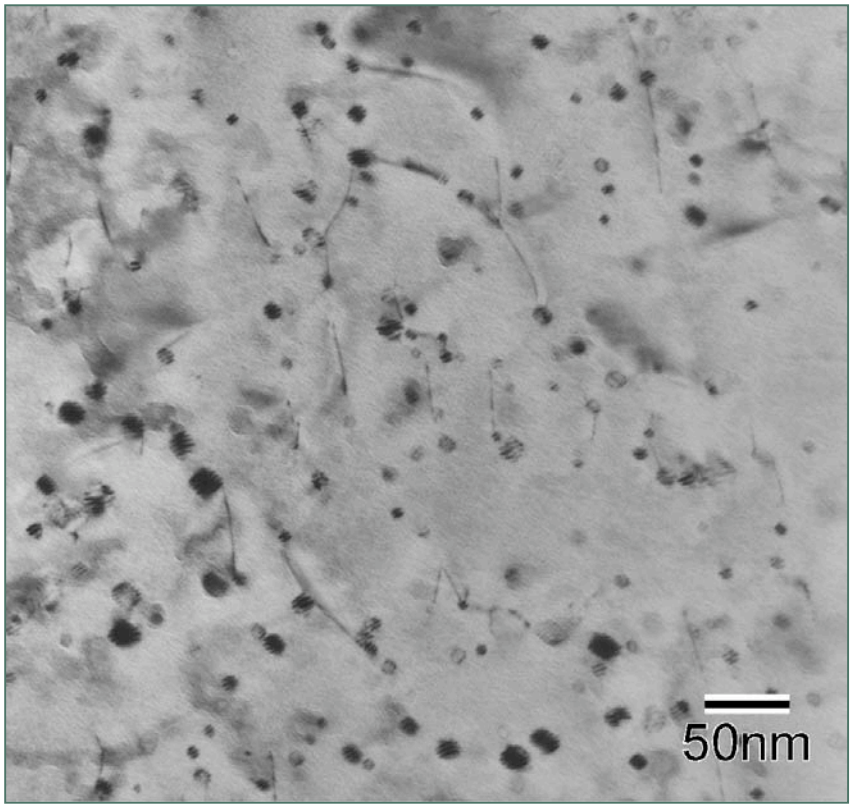
3Cr-3WVTa (N+T)
83 MPa/650°C/ t_r = 3086h

3Cr-3WV (N+T)
83 MPa/650°C/t_r = 1141h

•**Ultra-Fine V-Rich MC needles are present after nomalizing at 1100ºC**

Potential New Ferritic/Martensitic Alloy

- Dispersion-Strengthened Fe-9.5Cr-3Co-1Ni-0.6Mo-0.3Ti-0.07C steel
  - High number density of nano-size TiC precipitates
- Superior elevated-temperature strength and impact properties compared to conventional 9-12Cr steels
- Advantage over ODS steels: produced by conventional steel processing techniques
- Present composition not for optimized for nuclear applications (Co); reduced-activation compositions can be made using same processing technique



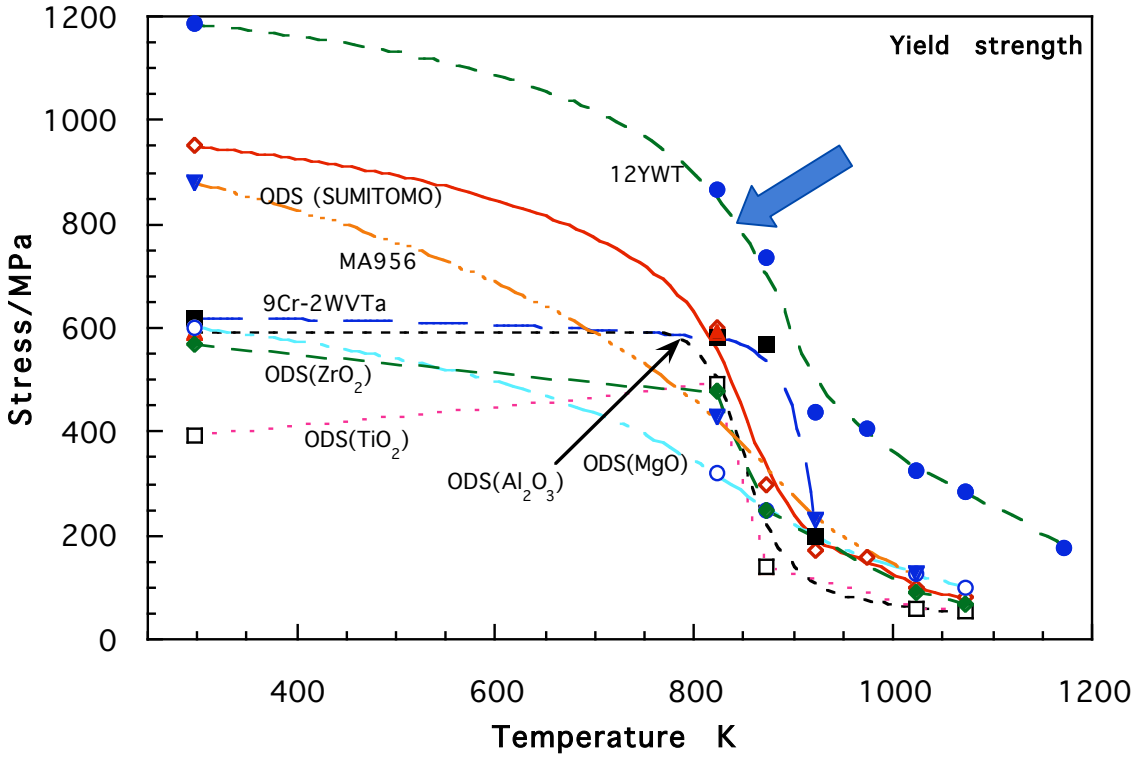
Klueh and Buck, J. Nucl. Mater. 283-287 (2000)

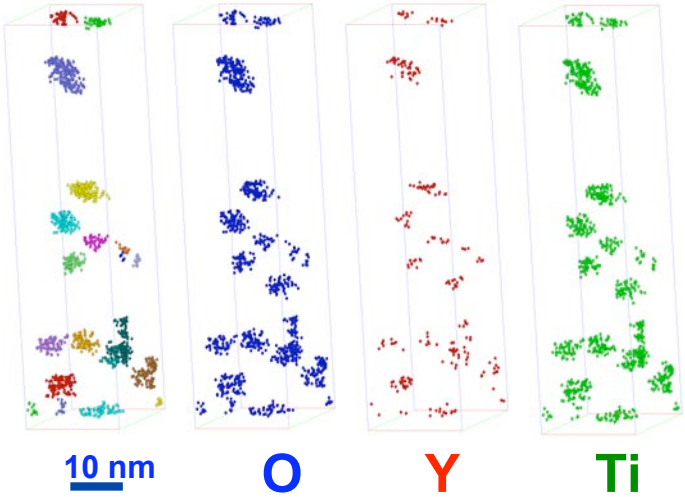
Oxide dispersion strengthened Steels

- There are two main options for ODS steels, based on pioneering work by Ukai and coworkers
  - Ferritic ODS steel (typically 12-16%Cr)
  - Ferritic/martensitic ODS steel (typically ~9%Cr)

Steel	Advantages	Disadvantages
12-16% ODS ferritic steel	Higher temperature capability Better oxidation resistance	Anisotropic mechanical properties Lower fracture toughness
9% ODS ferritic/martensitic steel	Nearly isotropic properties after heat treatment Better fracture toughness	Limited to temperature below ~700 C Marginal oxidation resistance at high temperatures

New 12YWT Nanocomposited Ferritic Steel has Superior Strength compared to conventional ODS steels



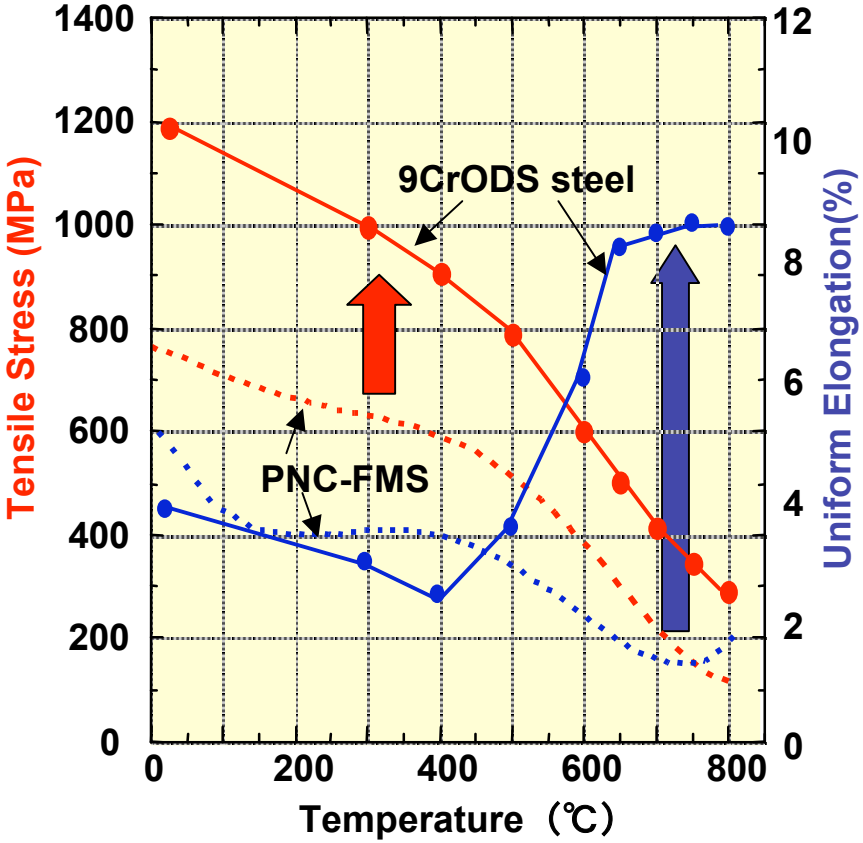


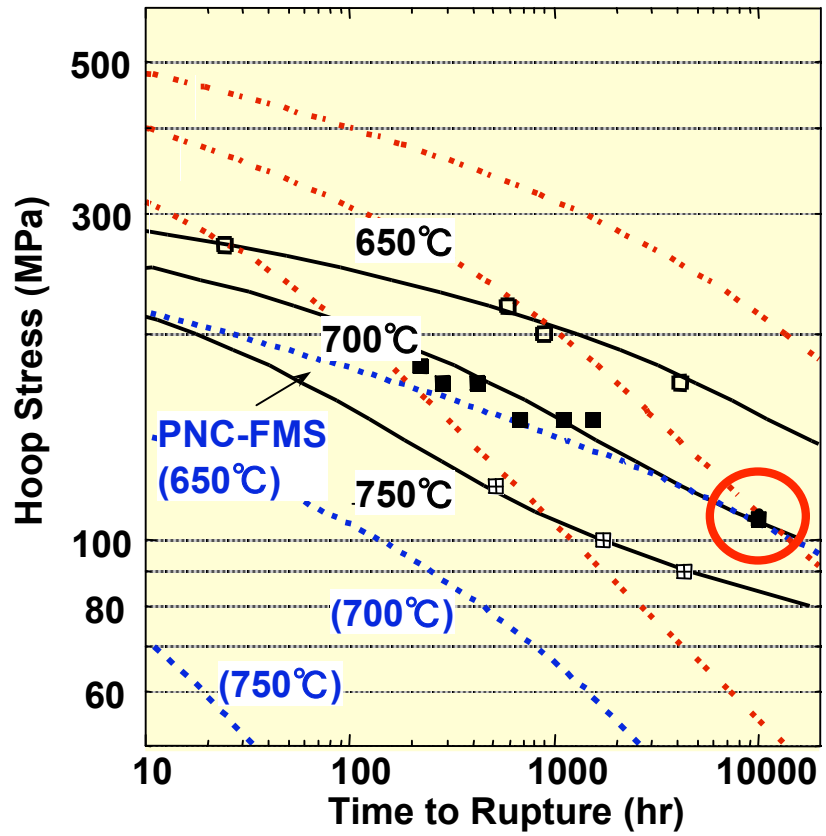
- Thermal creep time to failure is increased by several orders of magnitude at 800°C compared to ferritic/martensitic steels
- Potential for increasing the upper operating temperature of iron based alloys by ~200°C
- Acceptable fracture toughness near room temperature

- Atom Probe reveals nanoscale clusters to be source of superior strength
  - Enriched in O(24 at%), Ti(20%), Y (9%)
  - Size : $r_g = 2.0 \pm 0.8$ nm
  - Number Density : $n_v = 1.4 \times 10^{24}/m^3$
- Original Y_2O_3 particles convert to thermally stable nanoscale (Ti,Y,Cr,O) particles during processing
- Nanoclusters not present in ODS Fe-13Cr + 0.25Y_2O_3 alloy

Japan ODS Reduced Activation Ferritic Steel R & D for Fusion

● Big improvement of high temp. properties

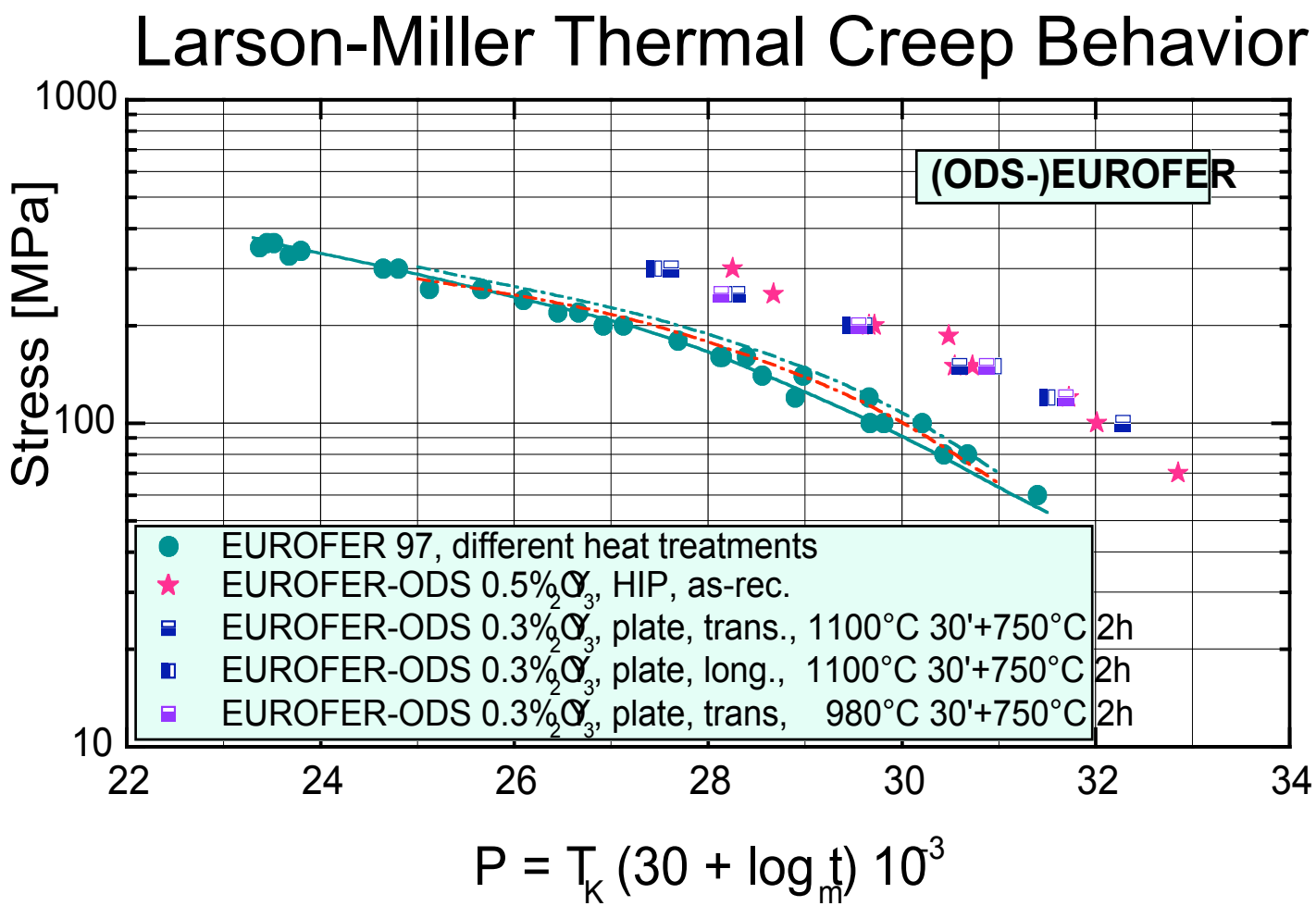




Time to rupture: 100 times longer than RAFS

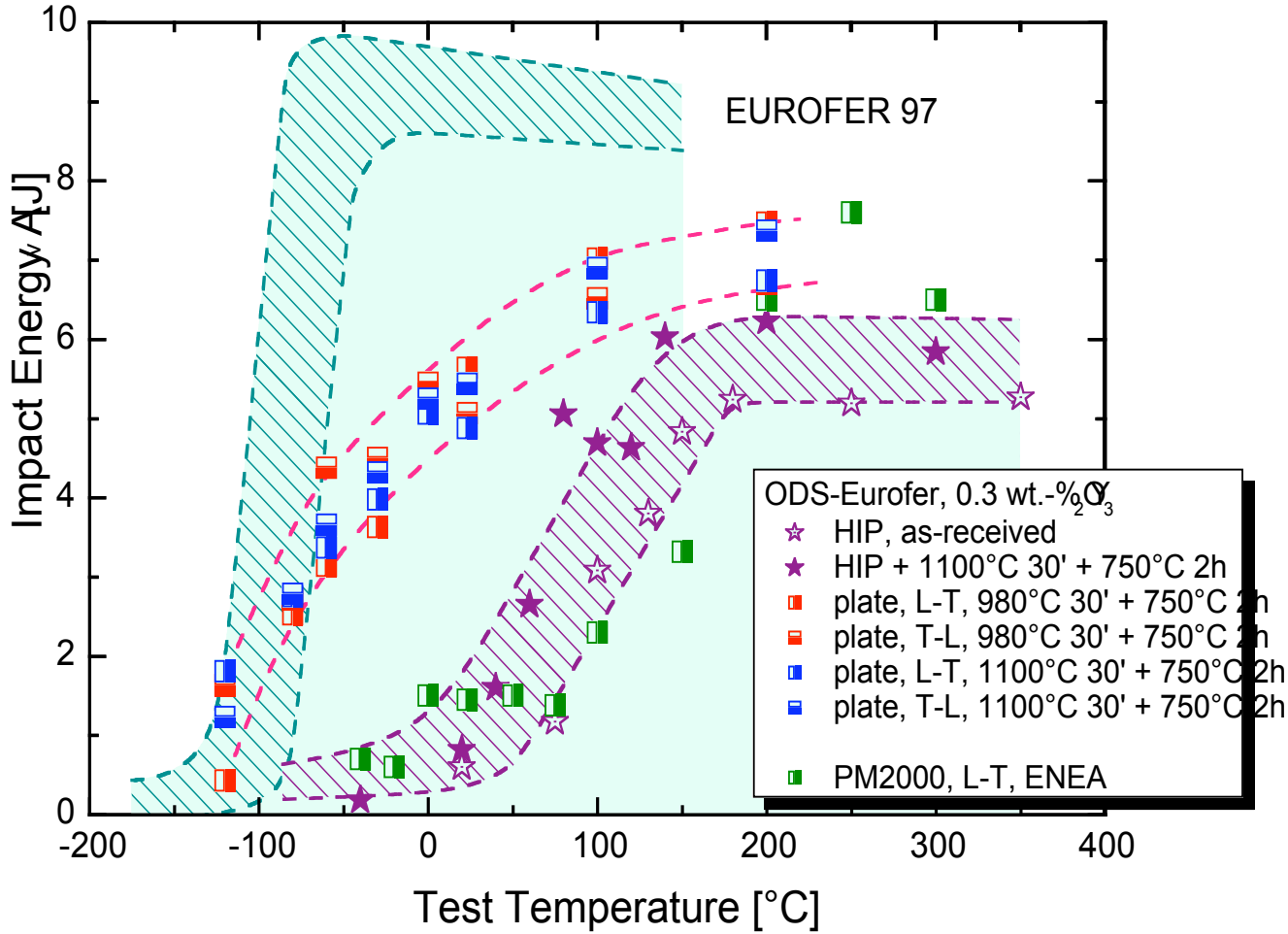
A. Kohyama, ANS TOFE (Madison, WI, 2004)

Creep Behaviour of ODS-EUROFER compared to EUROFER 97



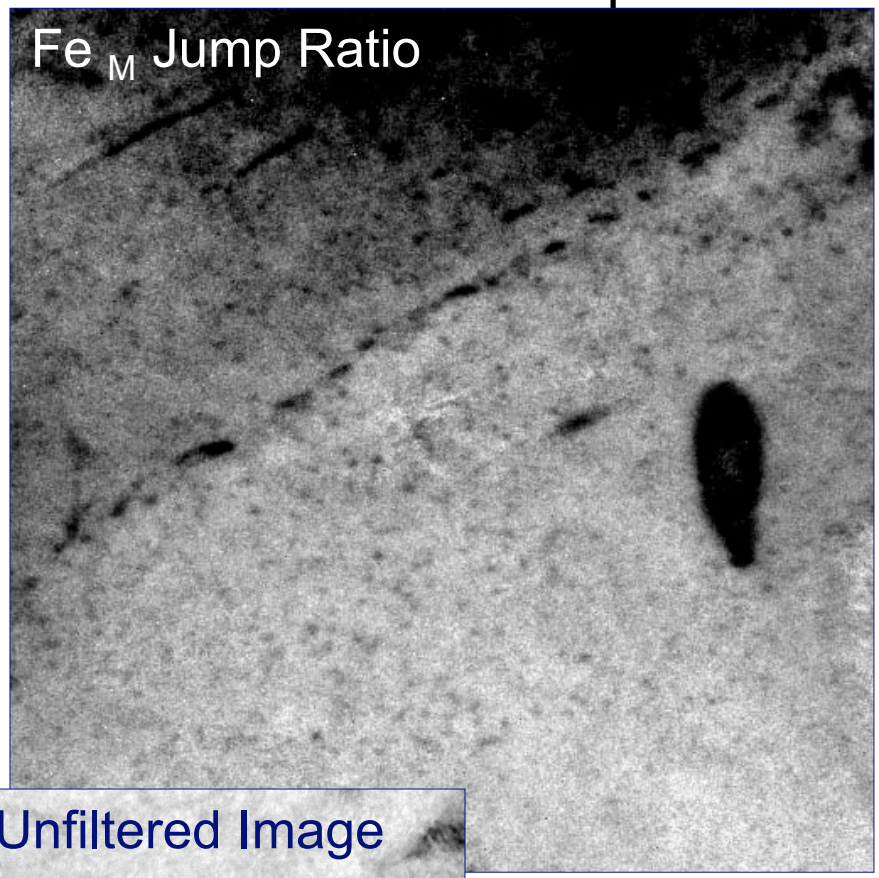
R. Lindau et al., SOFT23, Venice

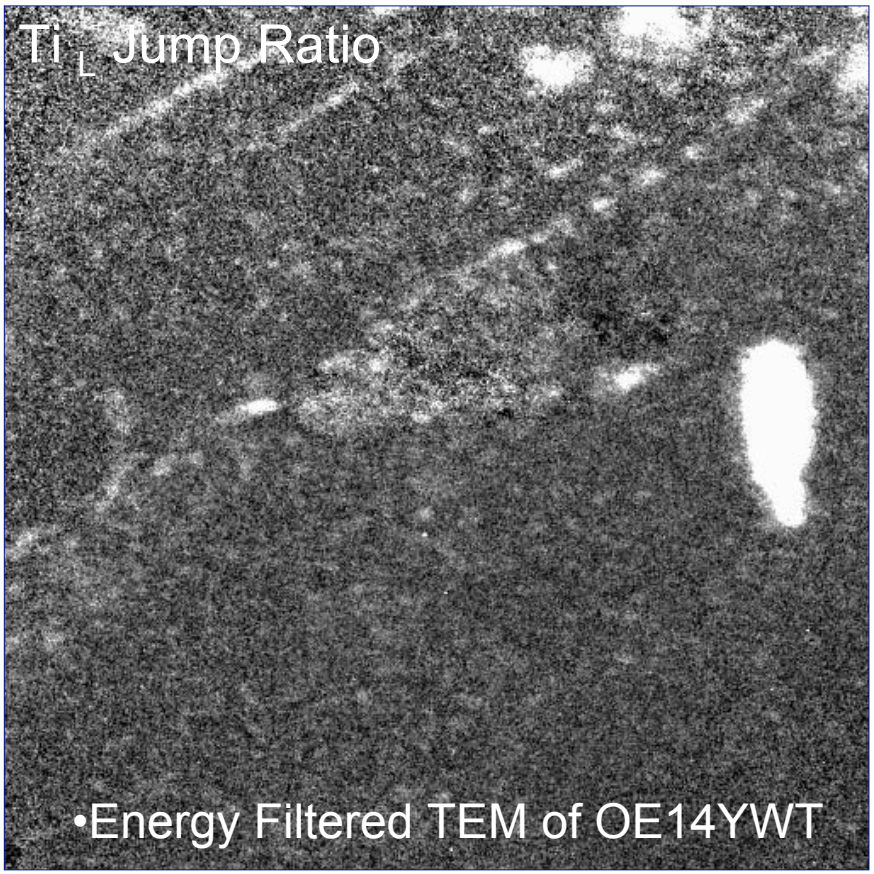
Instrumented Charpy Impact Tests on KLST Specimens: ODS-EUROFER exhibits a brittle-ductile transition between -50 and 100 C depending on heat treatment

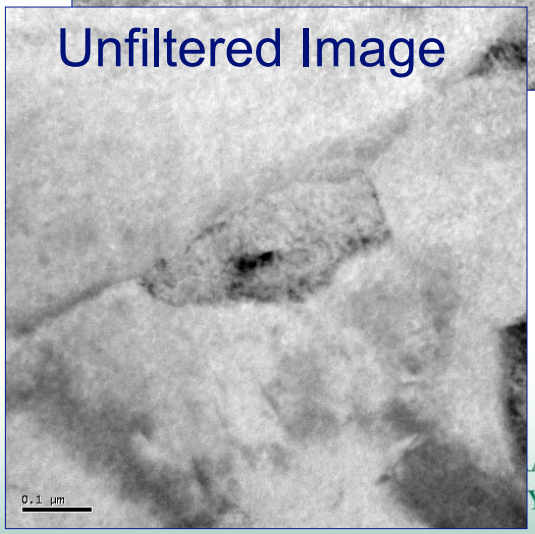


R. Lindau et al., SOFT23, Venice

Nanoparticles Formed During Extrusion of US Experimental ODS Ferritic Steel





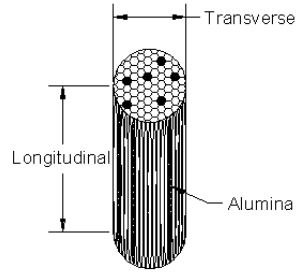


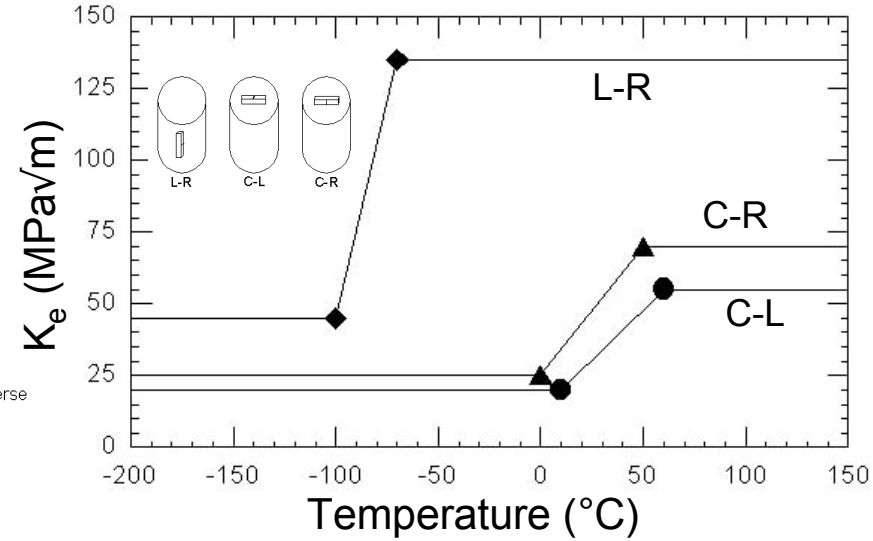
- Nanoparticles are enriched in Ti: Preliminary results of LEAP show particles enriched in Ti, Y, and O
- Nucleation of the nanoparticles occurred on grain boundaries and within grains
- Particle sizes are 2.8 to 7.0nm – (FWHM intensity histogram)

Fracture Toughness Behavior of MA957 and 12YWT

Fracture toughness of MA957 reflects the microstructural anisotropy that exists parallel to extrusion direction

- *highest toughness is achieved when the crack propagates orthogonal to elongated grains and Al_2O_3 stringers (L-R orientation)*





- Pre-cracked 1/3-sized Charpy Specimens

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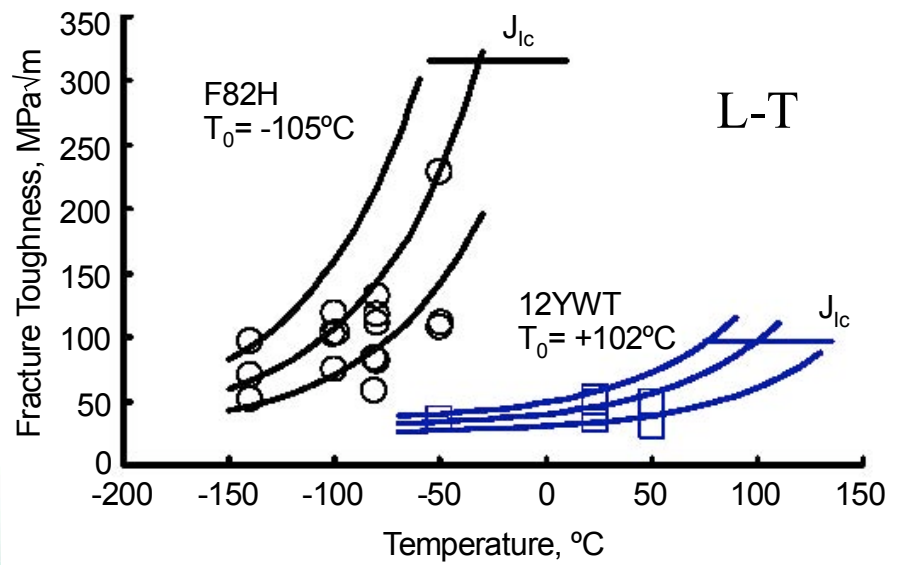
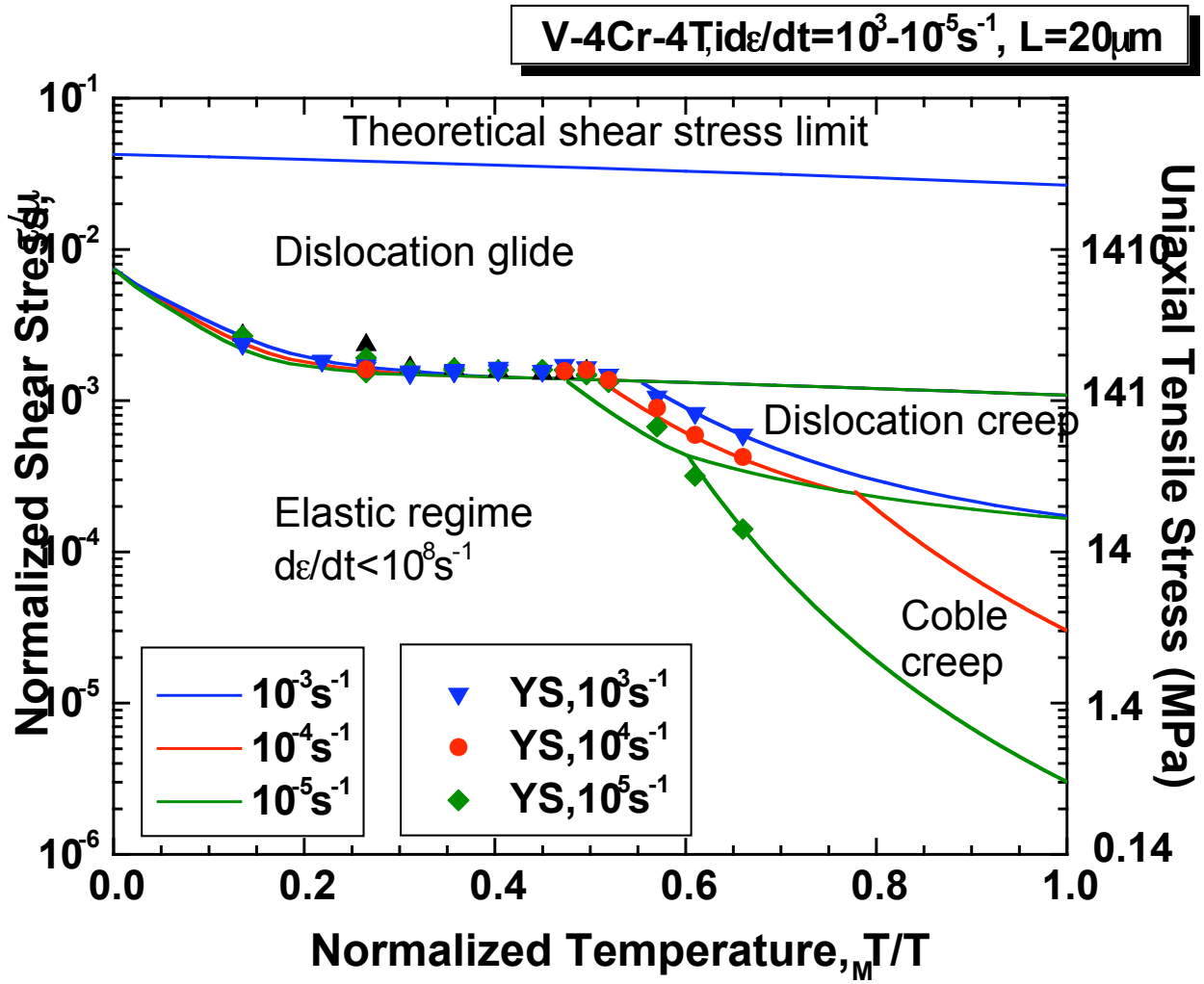


Master Curve Concept Applied to Characterize the Transition Fracture Toughness of 12YWT Alloy

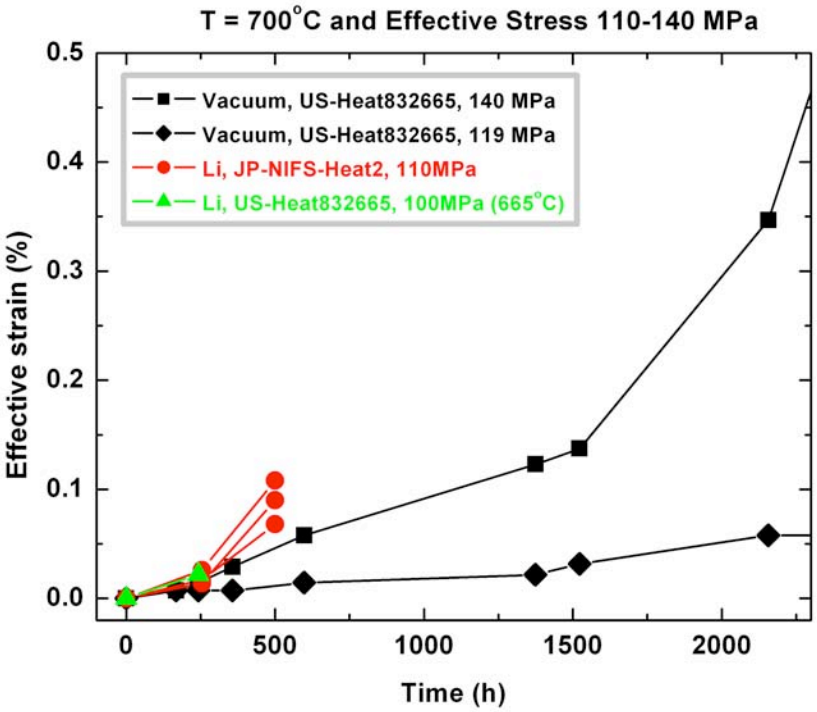
- *12YWT alloy has a much higher transition temperature and much lower upper-shelf compared to typical F/M steel (F82H)*

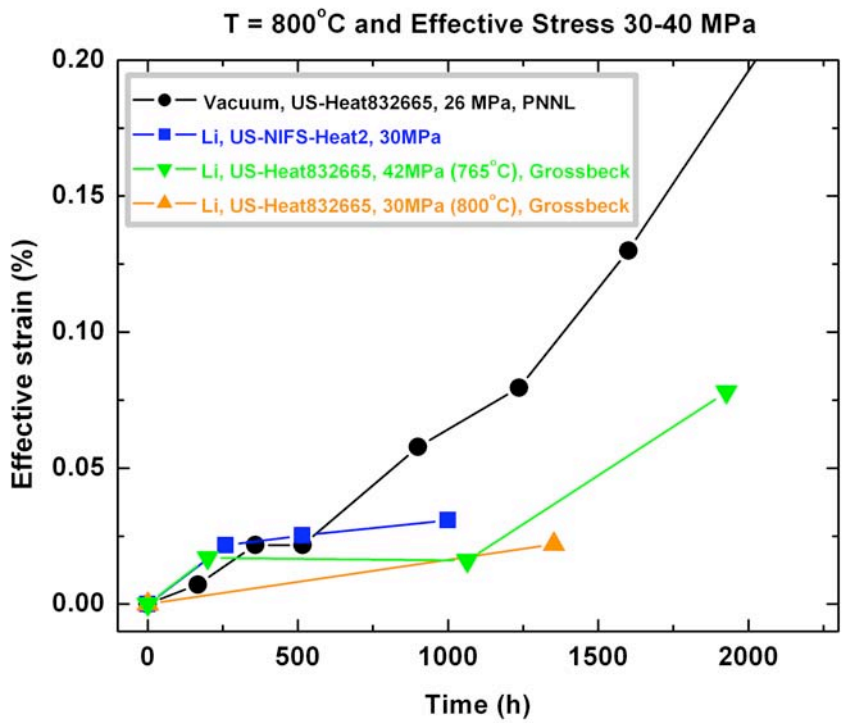
Deformation Mechanism Map for Unirradiated V-4Cr-4Ti at Strain Rates of 10^{-3}-10^{-5} s^{-1}



M. Li et al., J. ASTM International, in press (2004)

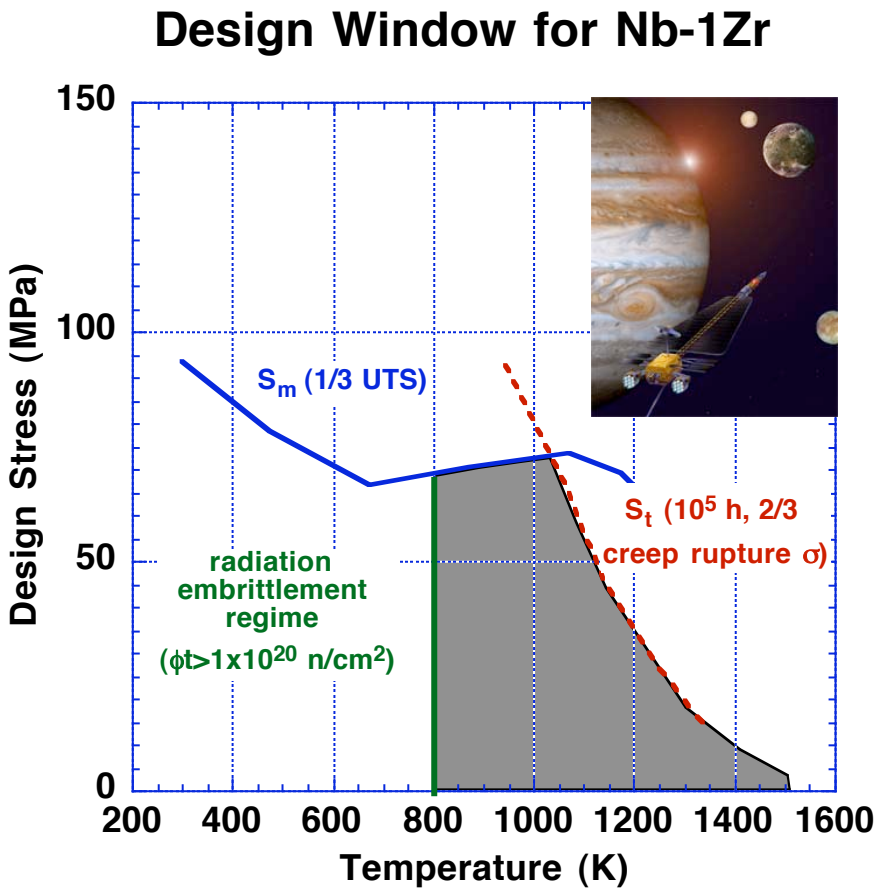
Recent Work Suggests the Upper Temperature Limit for V-4Cr-4Ti based on Thermal Creep is ~700-750 C

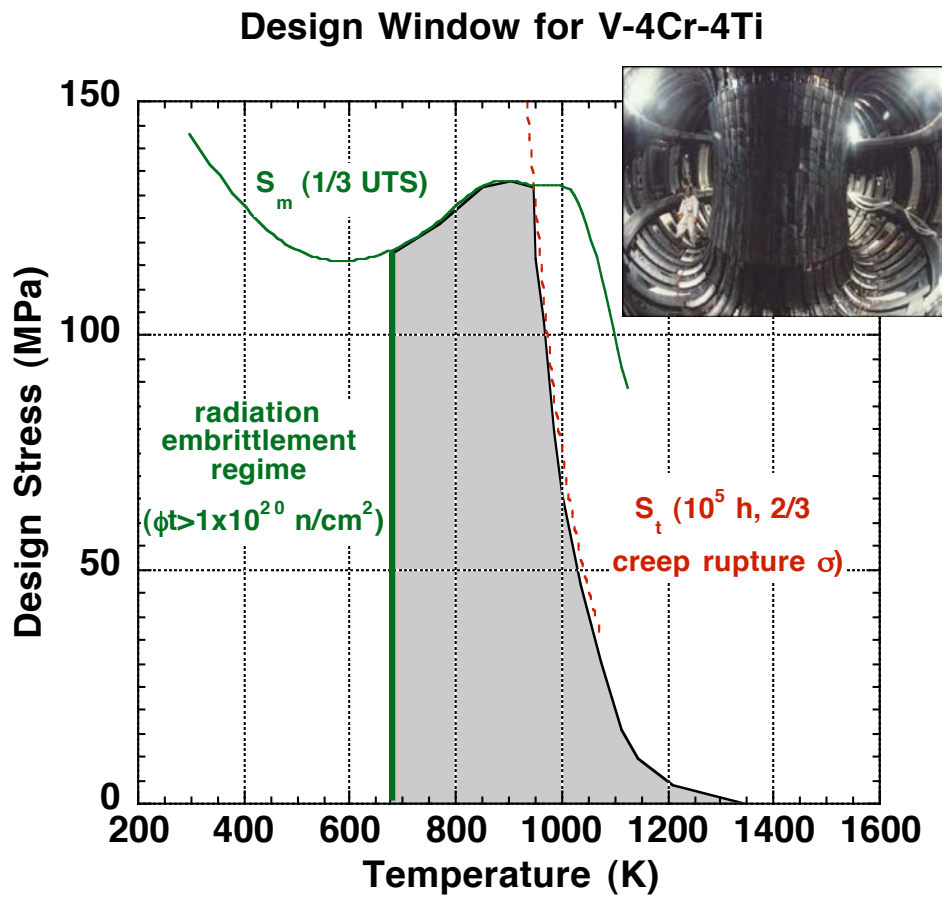




Lower temperature limit due to radiation hardening and embrittlement concerns is ~400 C

Comparison of the Design Window for Nb1Zr and V4Cr4Ti

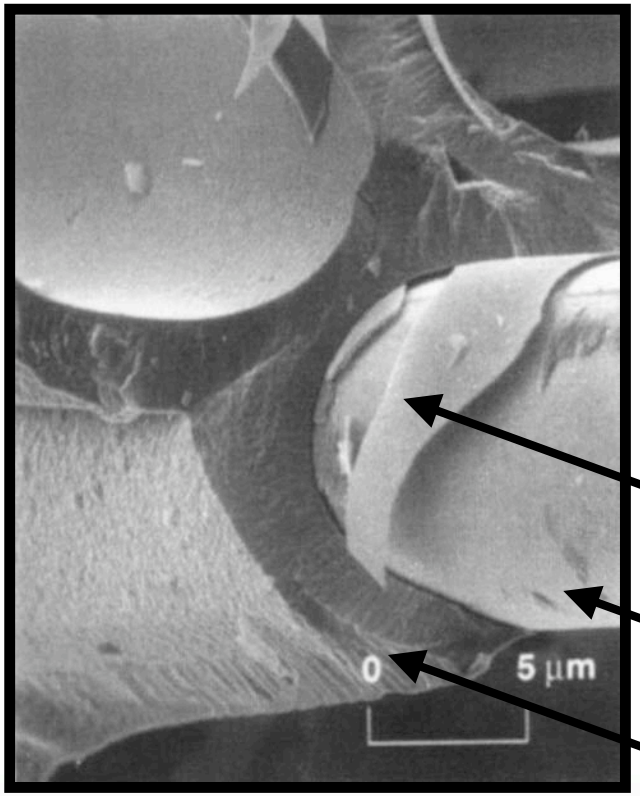




- V4Cr4Ti offers ~factor of two higher stress capability than Nb1Zr
- Maximum temperature capability of V4Cr4Ti is much higher than Nb1Zr on a homolgous temperature basis
  - 0.49 T_M vs. 0.41 T_M for Nb1Zr for a design stress of 50 MPa

Silicon Carbide Composite Development

Silicon carbide composite is the least-developed of the 3 main structural materials being studied in the Fusion Materials Program, but it has the **greatest potential**
Very Low Radioactivation - Very High Temperature Use



Interphase

Fiber

Matrix

<u>Areas being actively studied</u>

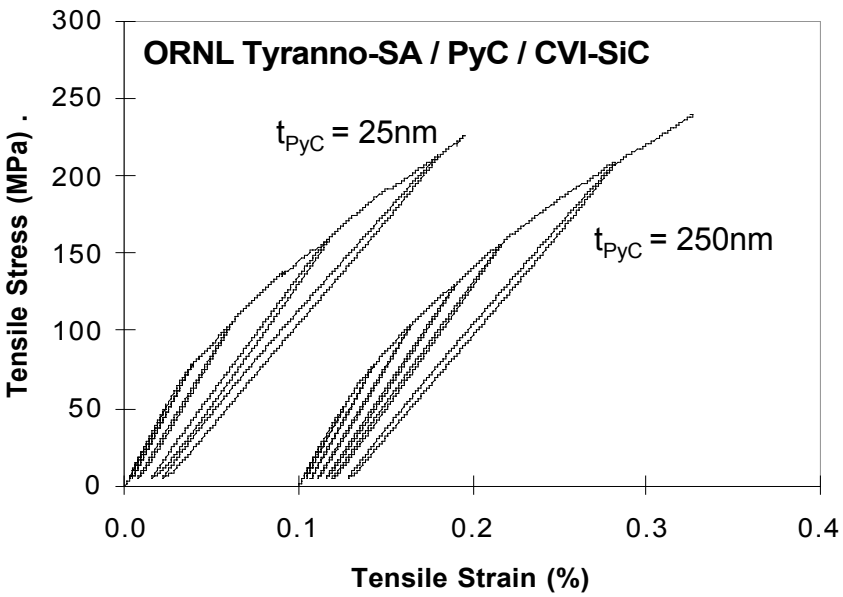
- Acquisition of structural material properties
- Radiation Hardened Composite Development
- Effects of Helium on Mechanical Properties
- Radiation Degradation of Thermal Conductivity
- Swelling, Amorphization and Defect Fundamentals

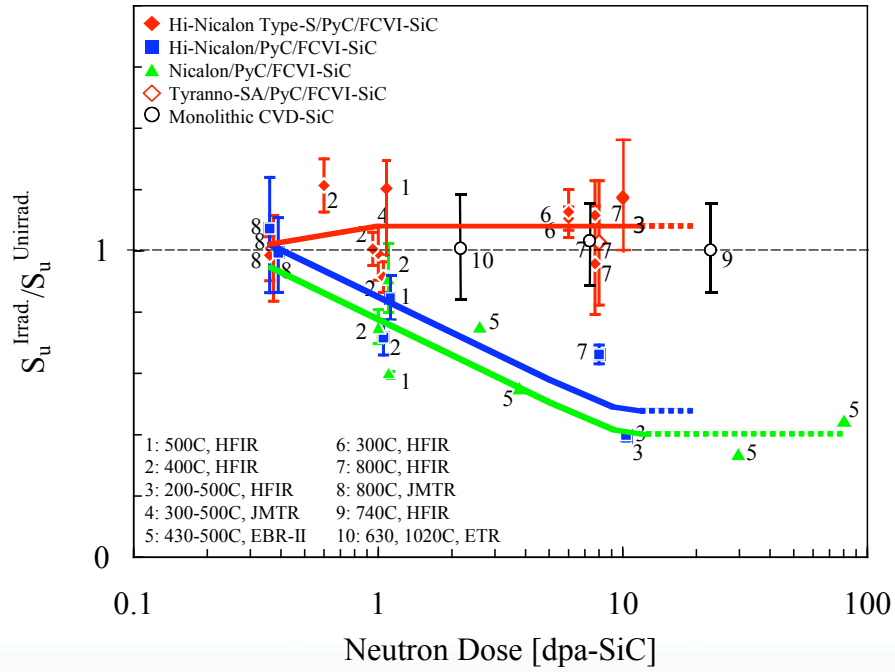
SiC/SiC Composites Development

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.

Bend strengths of irradiated "3rd generation" composites show **no degradation** up to 10 dpa

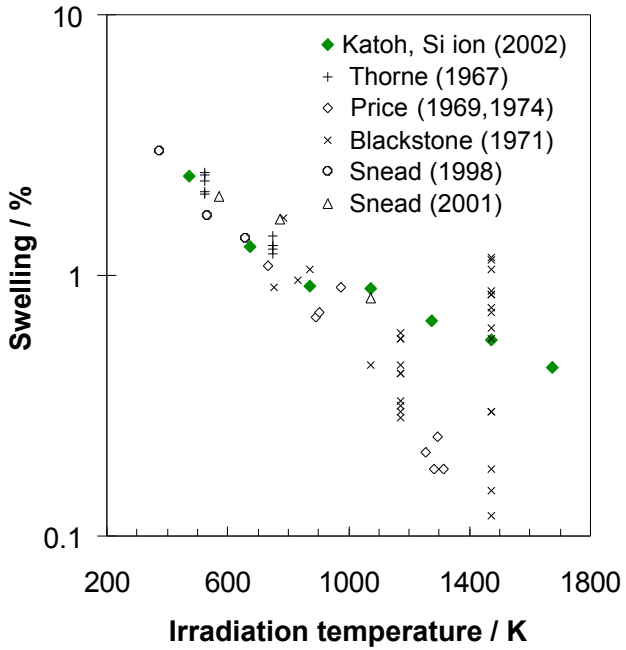




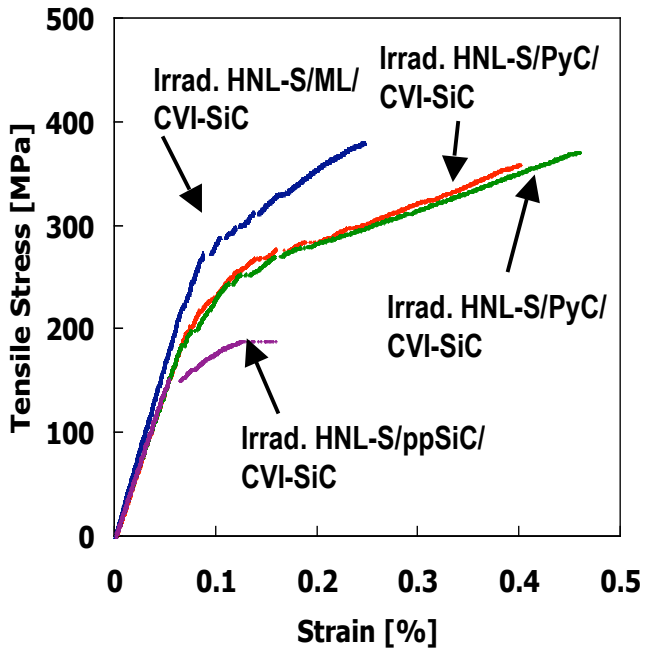
Irradiation Effect Studies in SiC/SiC

Composite Properties

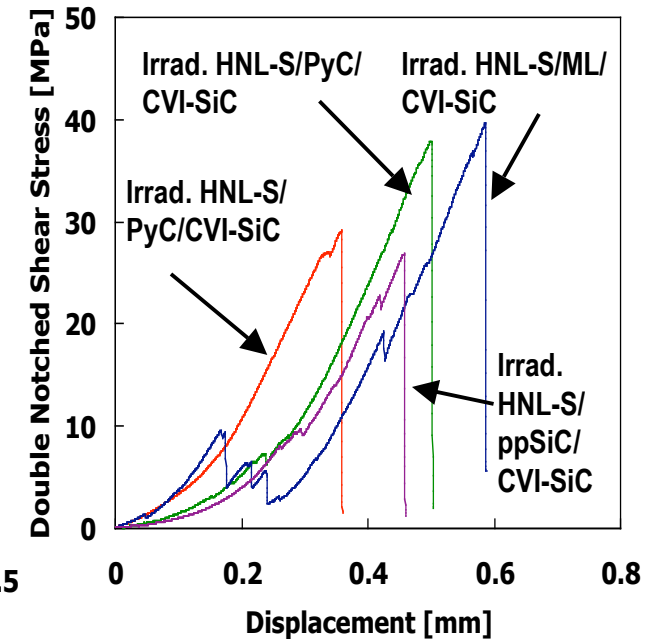
- Various mechanical and thermo-physical properties of irradiated SiC/SiC composites are being evaluated.
- Swelling, thermal conductivity, elastic modulus, tensile strength, shear strength, etc.



Swelling



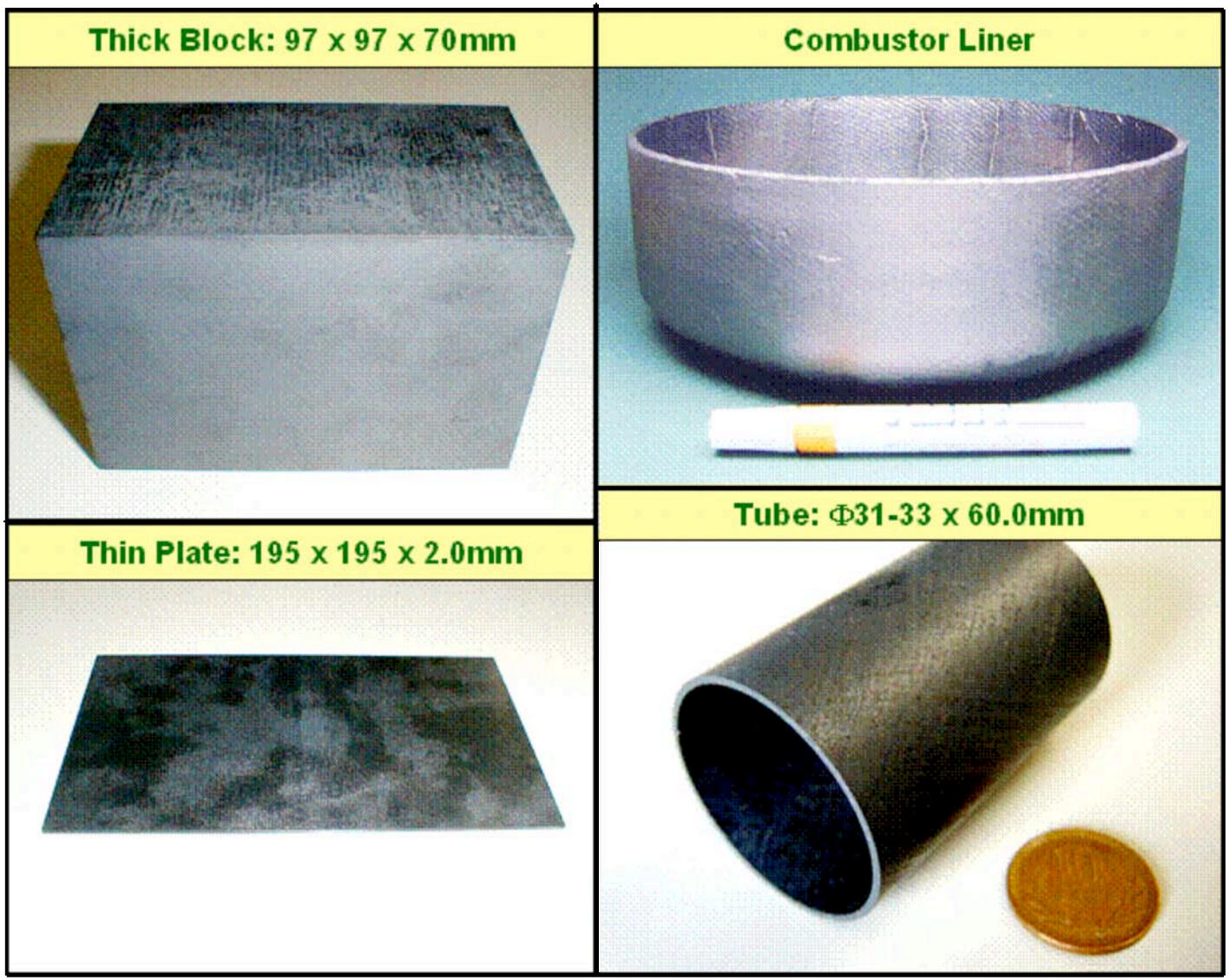
Irradiated tensile properties (800C, 1dpa)



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

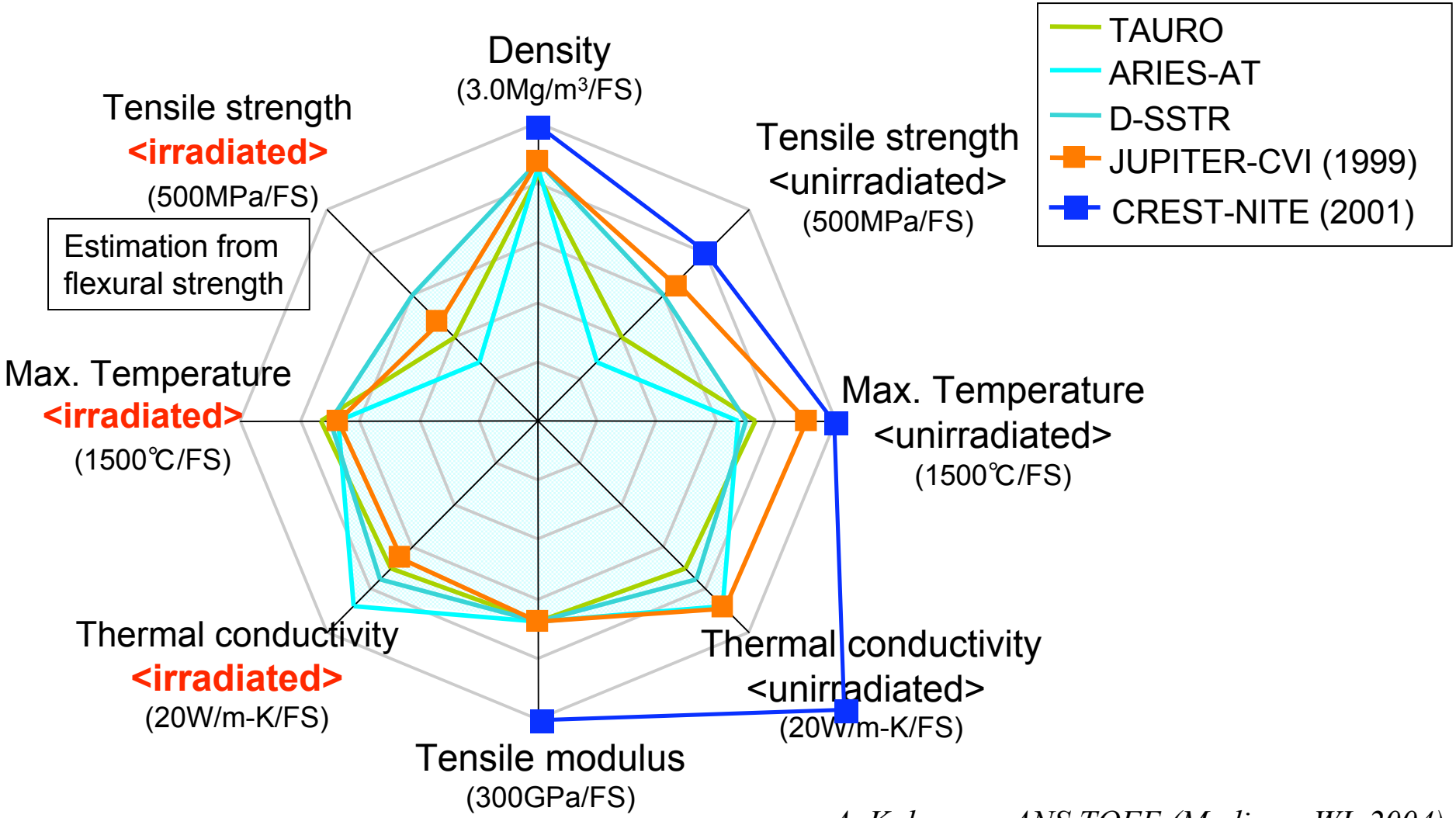
Shape Flexibility of "NITE" SiC/SiC Composites

Based on stoichiometric SiC fibers, nanoscale powder-based slurry infiltration, engineered fiber-matrix interphase



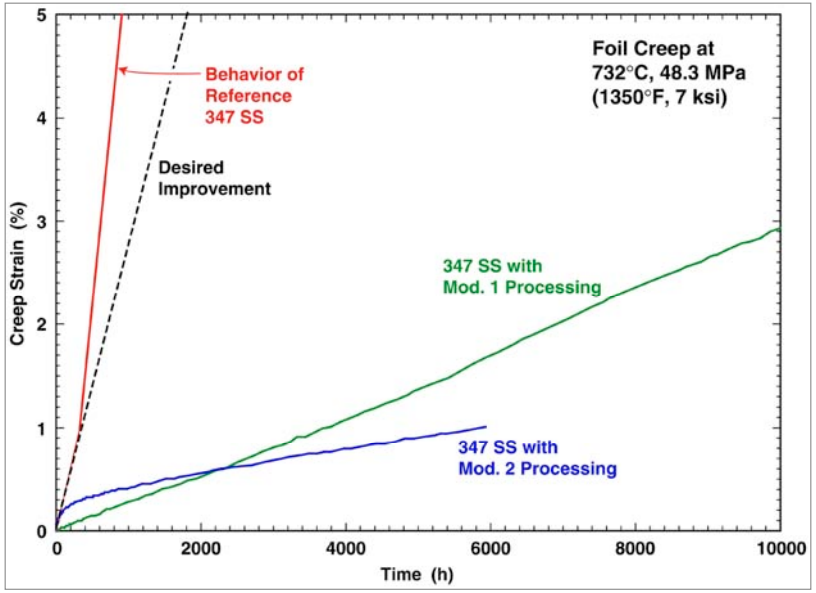
A. Kohyama, ANS TOFE (Madison, WI, 2004)

Current Status of SiC/SiC Composites

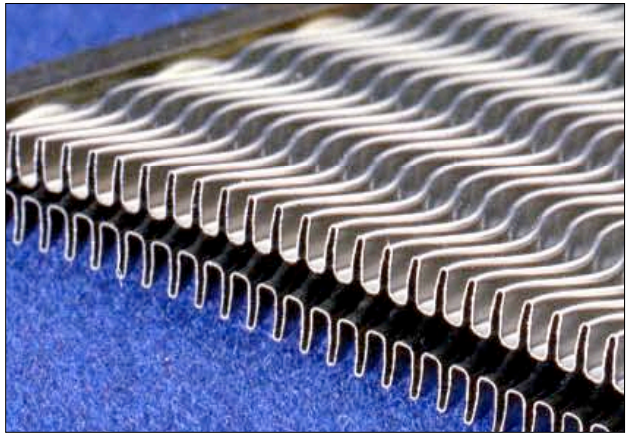


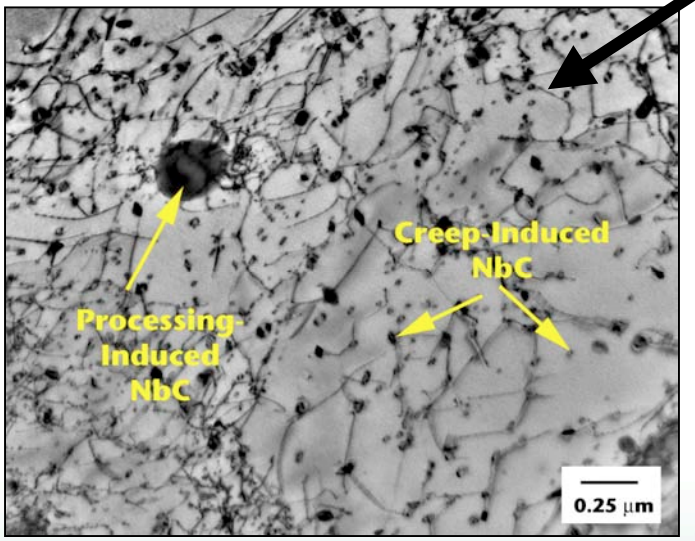
A. Kohyama, ANS TOFE (Madison, WI, 2004)

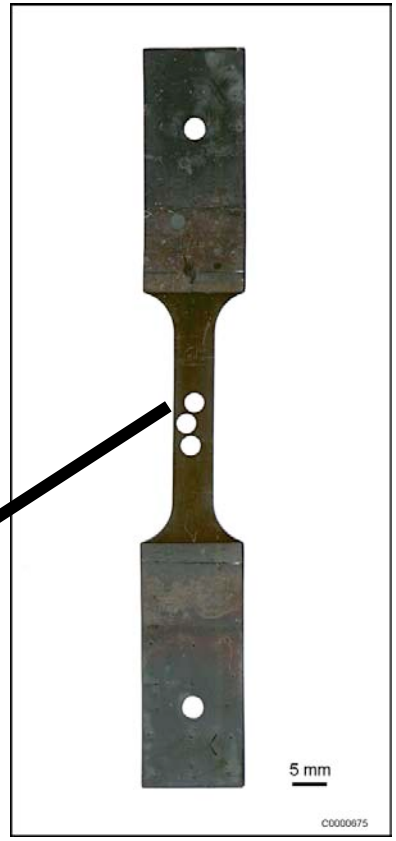
Microstructure-Mechanical property knowledge derived from Fusion Materials Science investigations is being transferred to US Industry



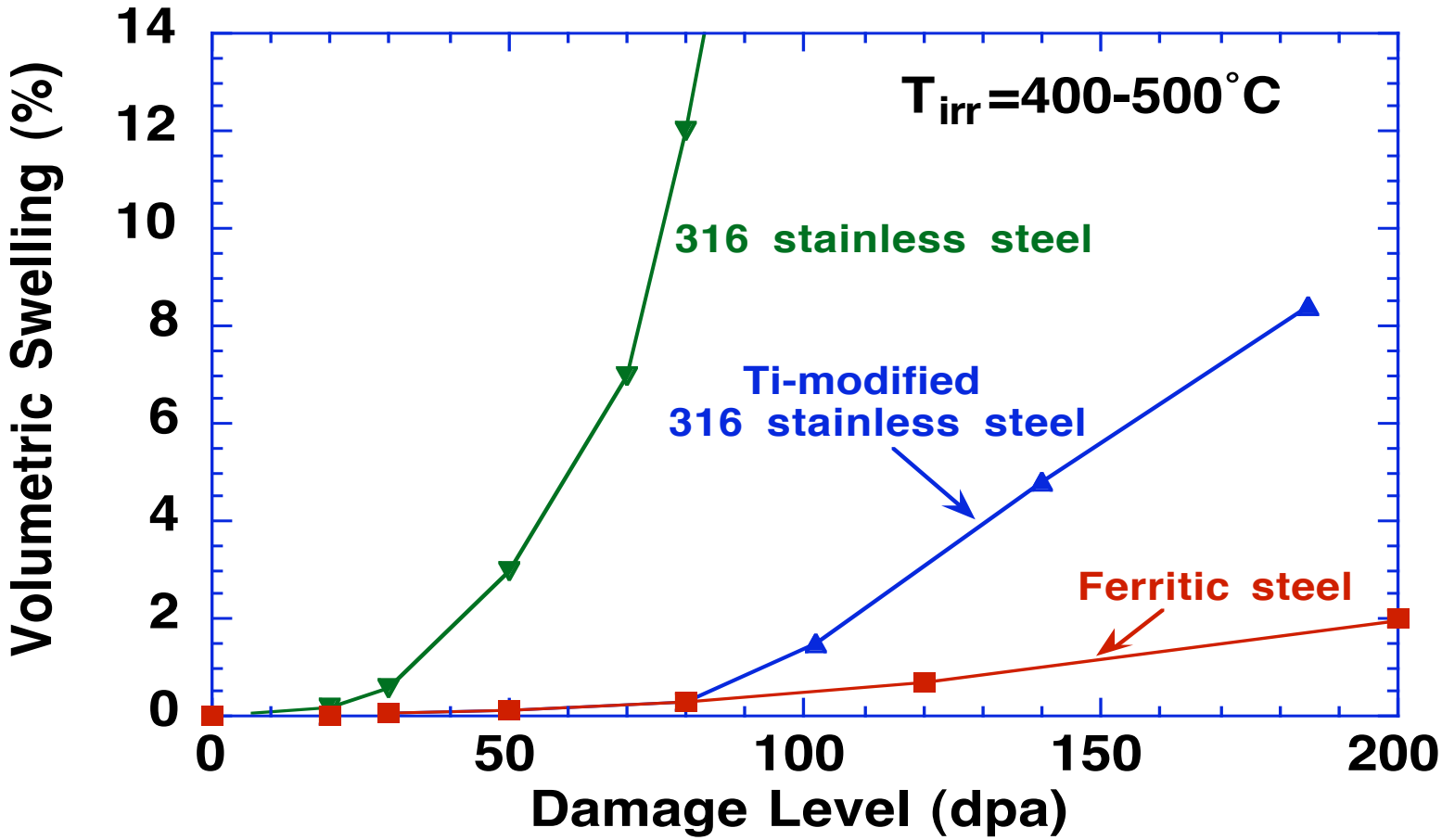
Precipitate stability knowledge derived from radiation effects studies can be used to develop highly creep resistant alloys (microturbine recuperator)





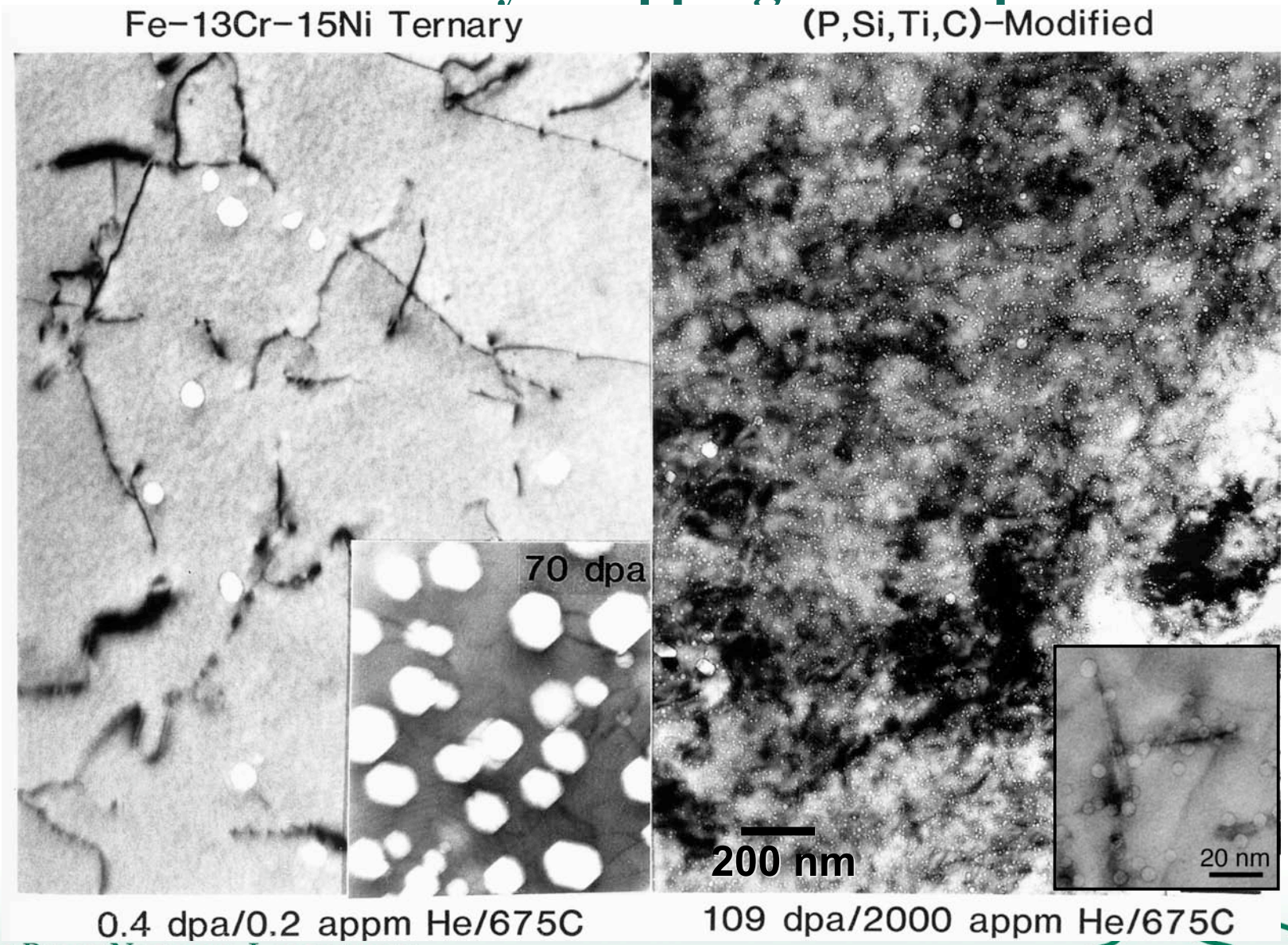


Swelling resistant alloys have been developed via international collaborations



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

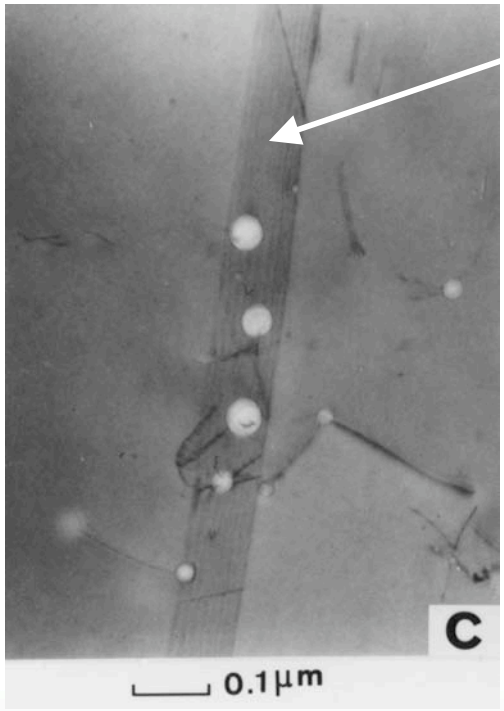
Swelling Resistant Alloys can be developed by Controlling the He Cavity Trapping at Precipitates



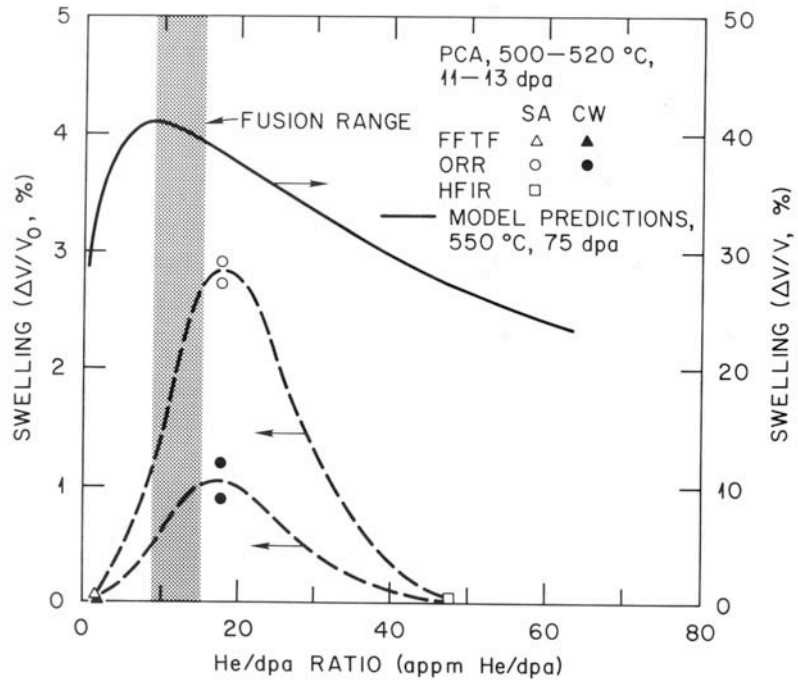
Why Is He/dpa Ratio an Important Parameter for Fusion Materials R&D?

- He generation can alter the microstructural evolution path of irradiated materials
  - Cavity formation
  - Precipitate and dislocation loop formation

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



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

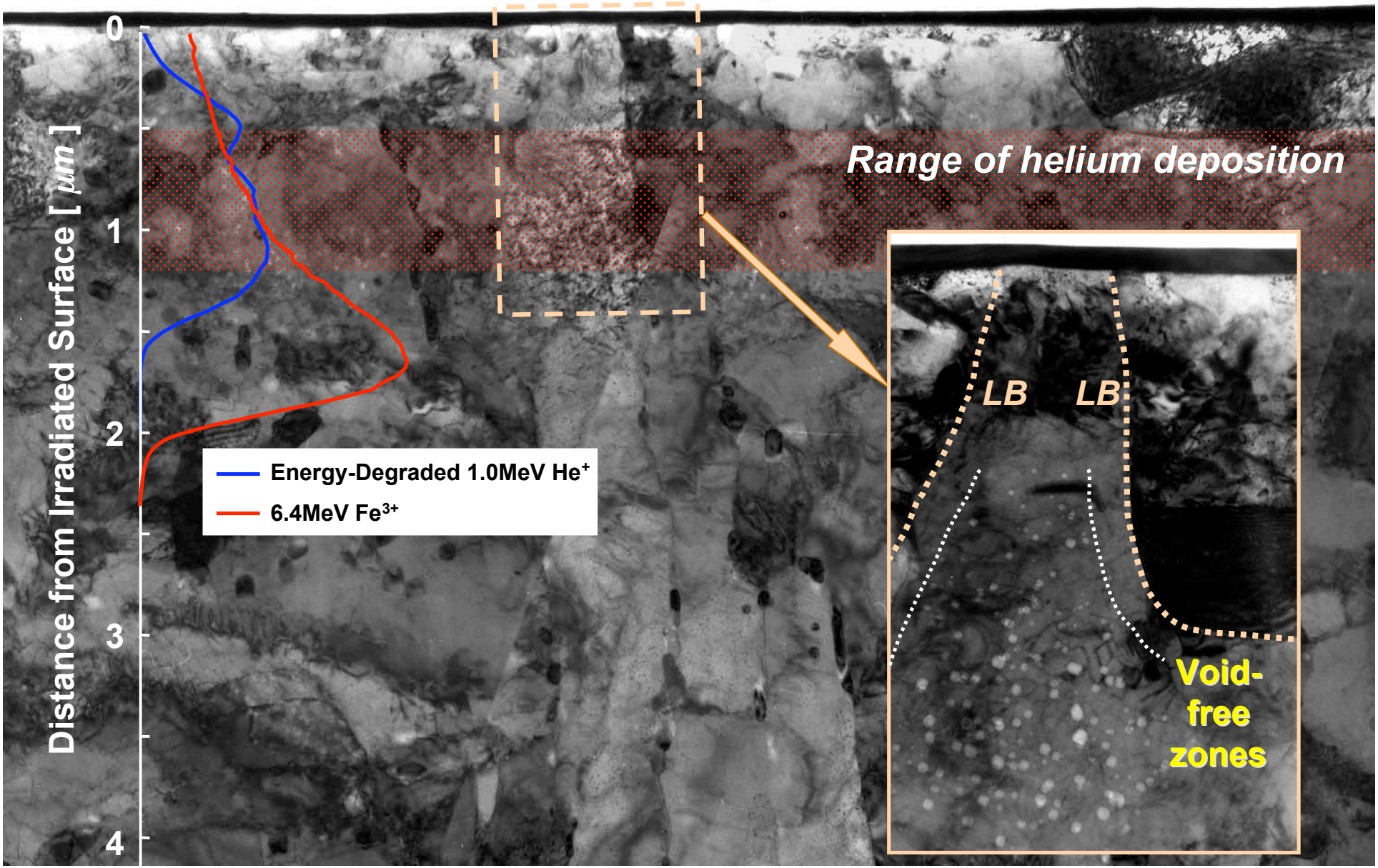


Management of He transmutation products (matrix trapping at engineered 2nd phases) is a key factor for fusion materials

Cavity formation in JLF-1 by dual-beam irradiation

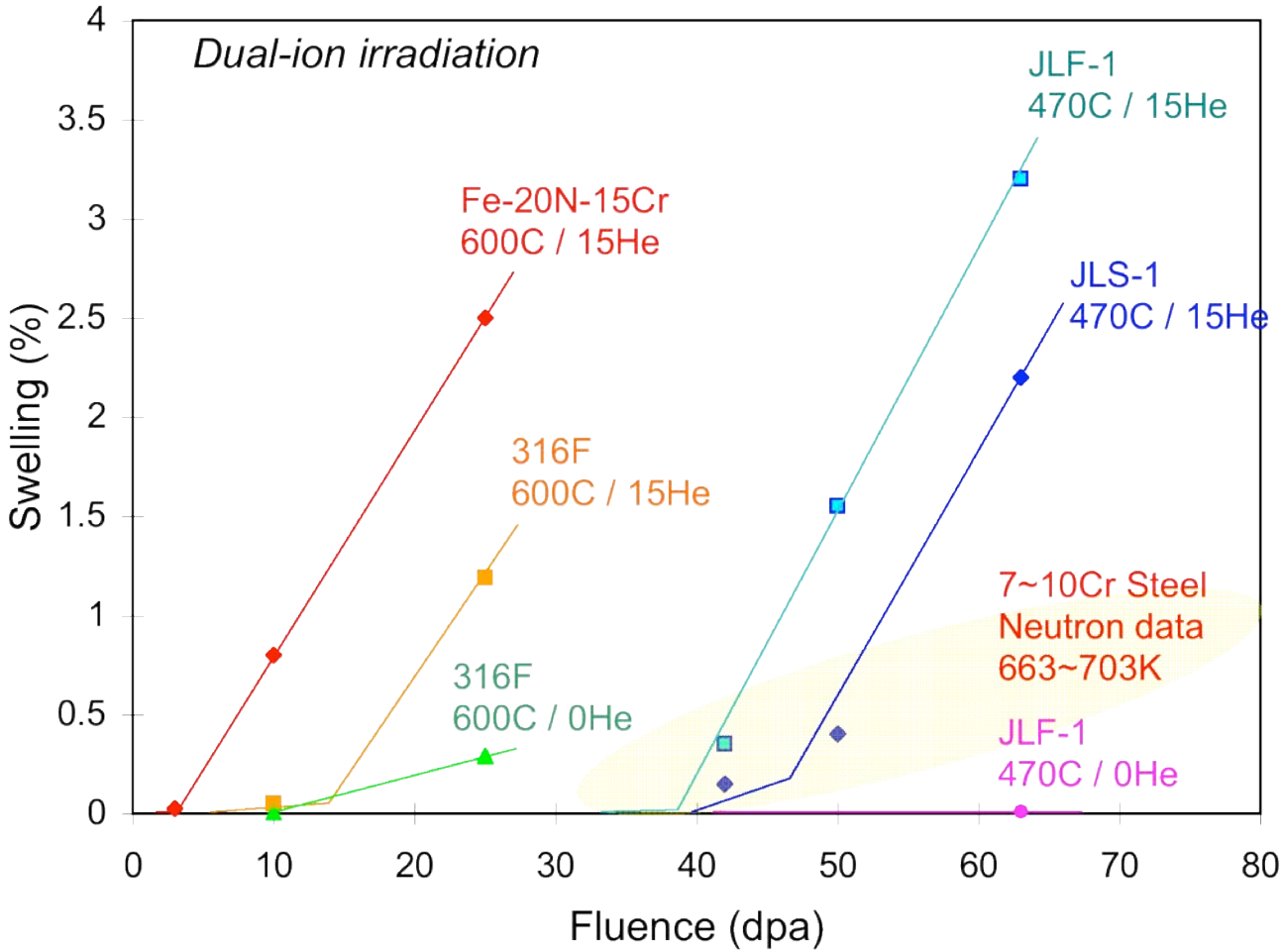
_ 6.4 MeV Fe^{3+} _ Energy-Degraded 1.0 MeV He^{+} , 20 dpa at 743 K _

Y. Katoh et al., J. Nucl. Mater. 323 (2003) 251



Swelling behavior of austentic and ferritic stainless steels

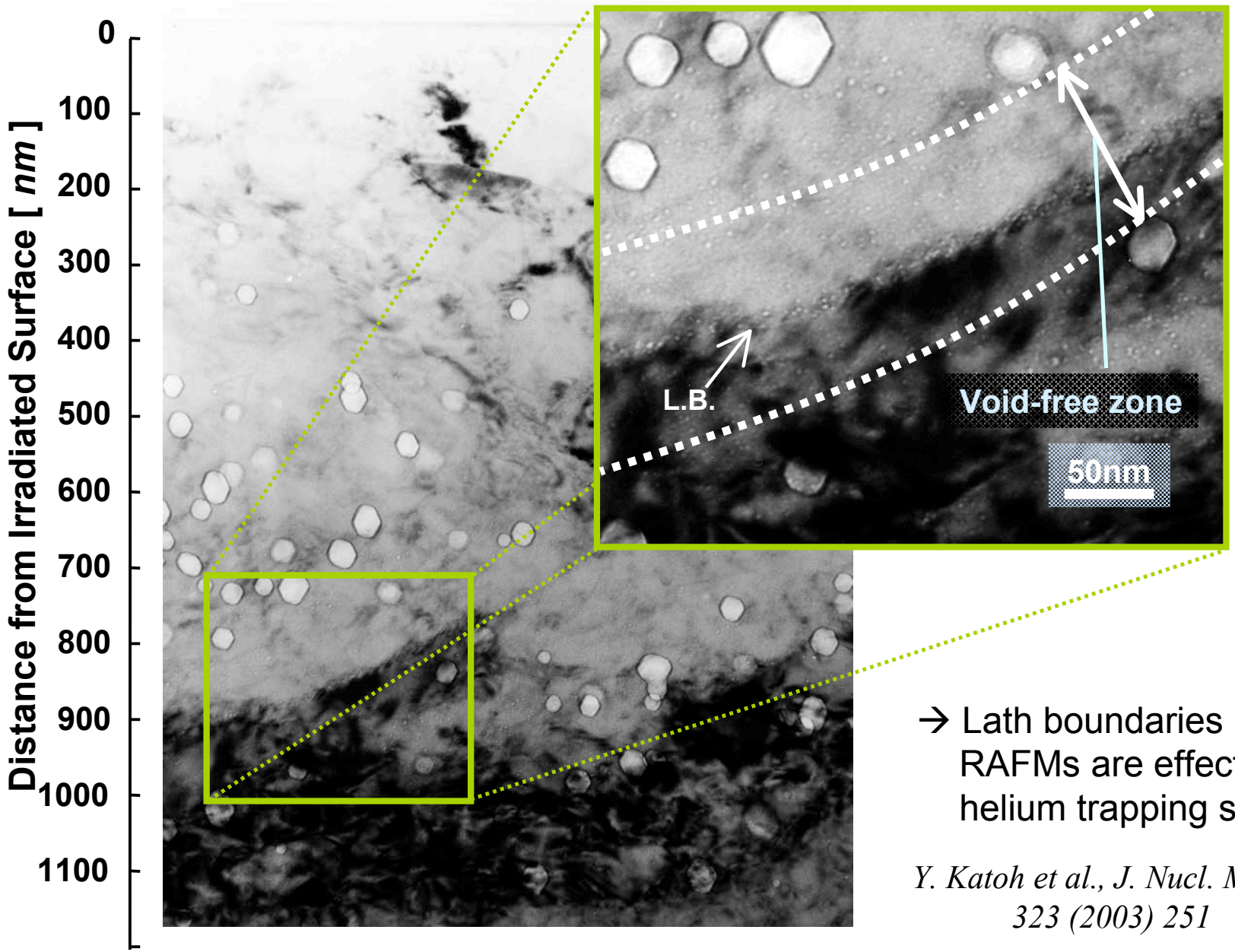
Y. Katoh et al., J. Nucl. Mater. 323 (2003) 251



- Swelling behavior of RAFMs and austenitics near peak-swelling temperatures are similar in the presence of helium, except for incubation dose.

Lath-boundary bubble formation in 9Cr-2W steel (JLF-1)

6.4 MeV Fe^{3+} He^{+} , 60 dpa at 743 K

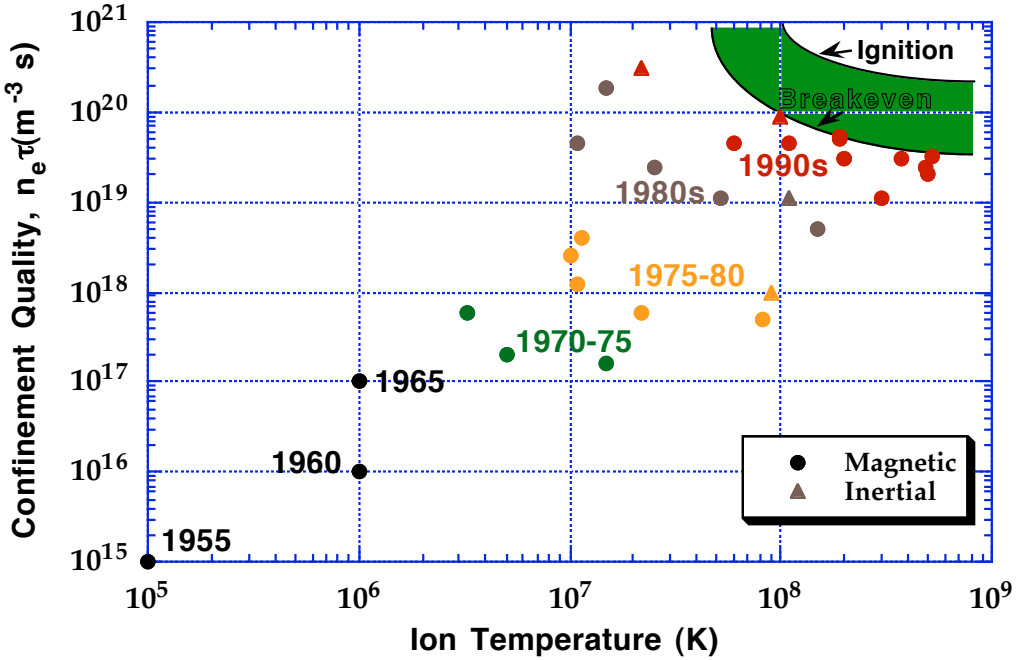


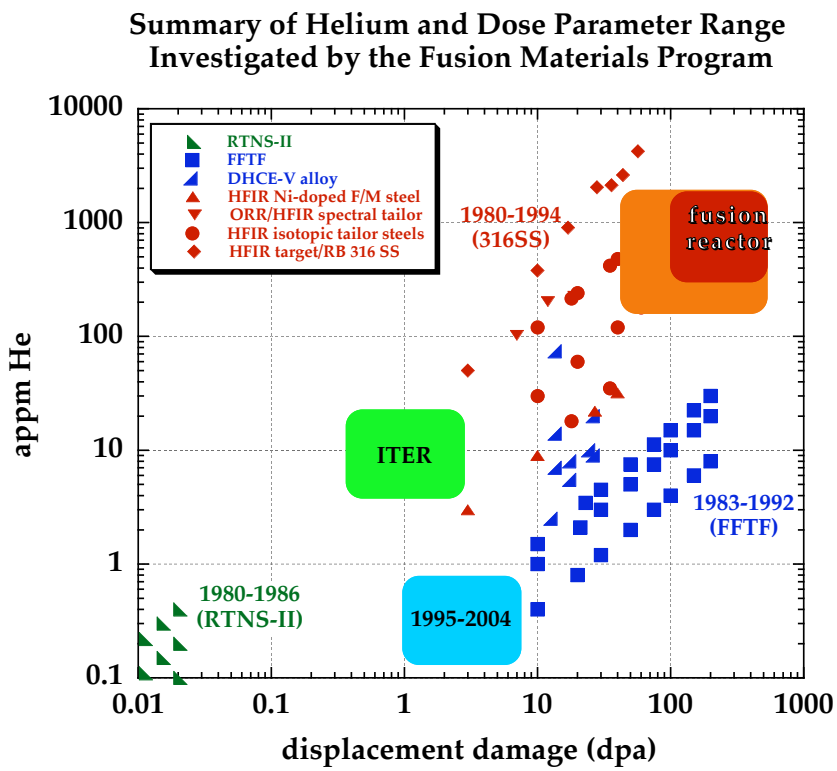
→ Lath boundaries in RAFMs are effective helium trapping sites

Y. Katoh et al., J. Nucl. Mater. 323 (2003) 251

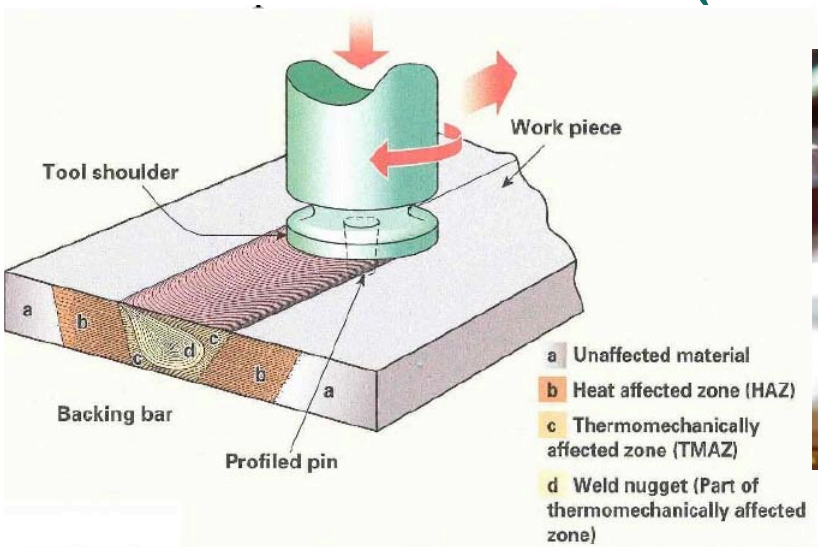
The knowledge base on materials exposed to fusion-relevant operating conditions is very limited

- Extrapolation from currently available parameter space to fusion regime is much larger for fusion materials than for plasma physics program
- An intense neutron source such as IFMIF is needed to develop and qualify fusion structural materials
- Theory and modeling will accelerate the development of fusion materials, but does not replace the need for a dedicated neutron source such as IFMIF
  - R.E. Stoller et al., ORNL/TM-2004/132 (June 2004), Workshop on Advanced Computational Materials Science: Application to Fusion and Generation IV Fission Reactors (http://www.csm.ornl.gov/meetings/SCNEworkshop/)

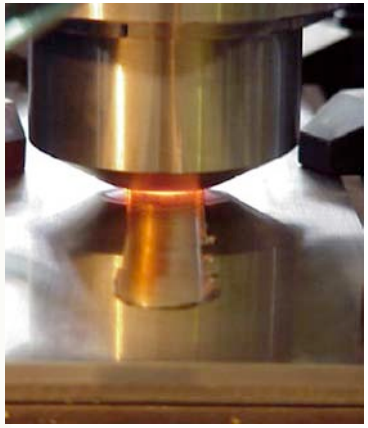




Friction Stir Welding may enable joining of numerous advanced materials (ODS steels, He-containing metals, etc.)



Sketch provided by TWI



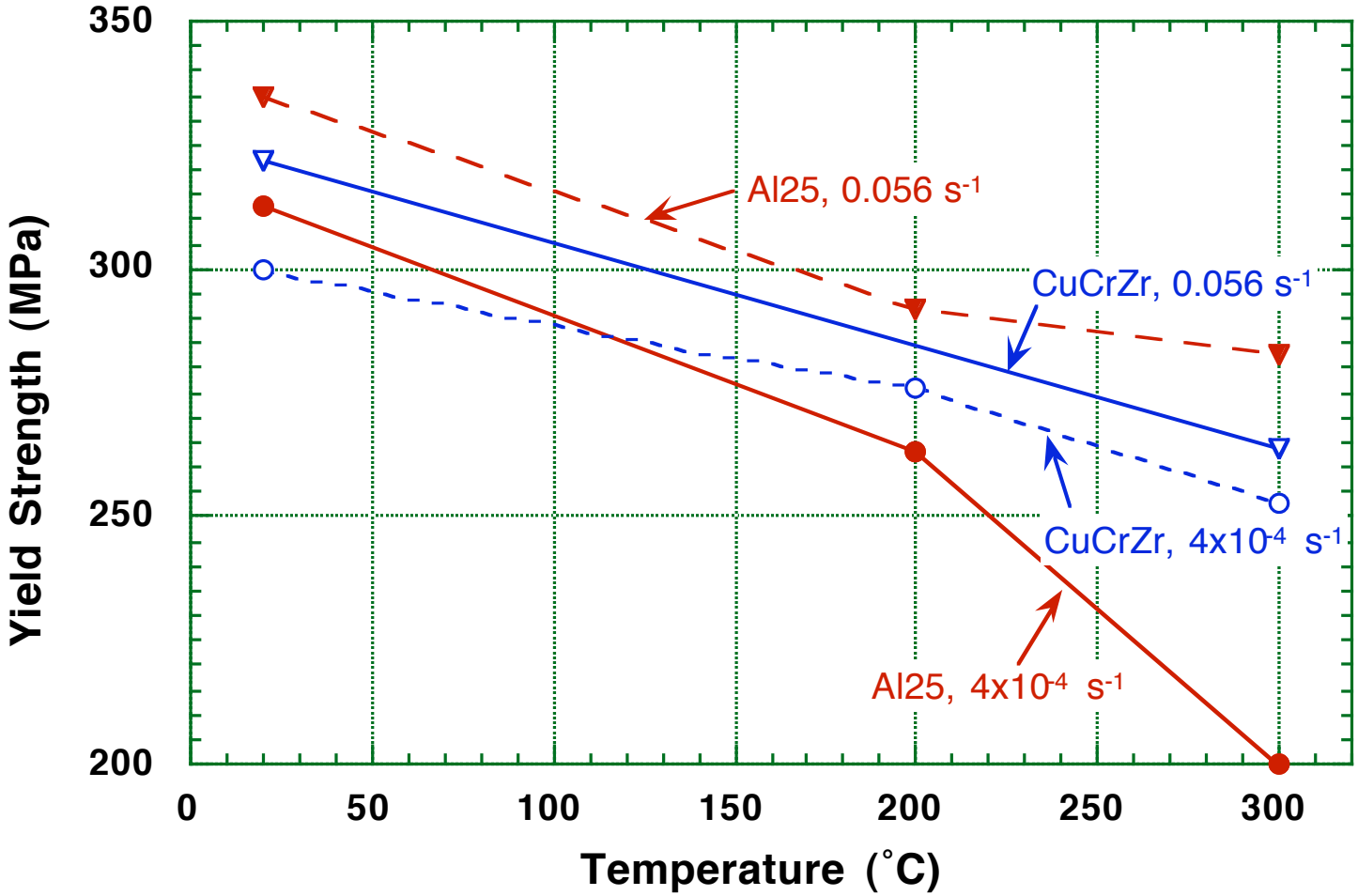
SS304 stainless steel

- 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

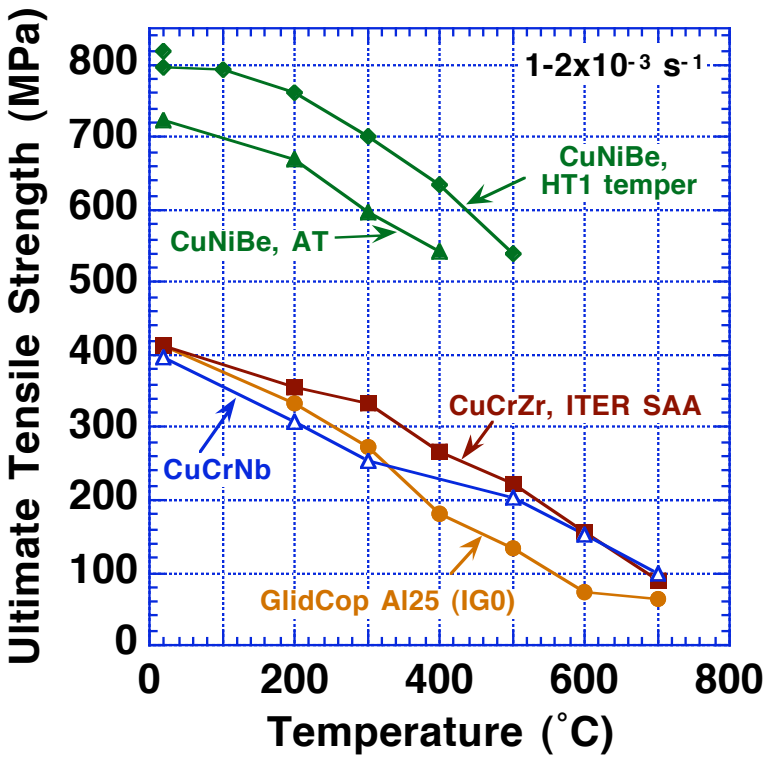
- Development of structural materials for demanding environments such as fusion is a long-term endeavor
  - Must be based on advanced materials science principles
  - Alloying strategy based on precipitate or dispersion hardening generally improves both thermal creep strength and radiation resistance
- Several options exist for advanced ferritic steels
  - Evolutionary ingot-based precipitate or dispersion strengthened steels (bainitic, ferritic/martensitic, or ferritic structures)
  - Oxide dispersion strengthened ferritic/martensitic or ferritic steels
- Vanadium alloys offer attractive high temperature capability from a conventional ingot metallurgy process
- SiC/SiC composite R&D has progressed from initial qualitative screening studies to measurement of engineering-relevant mechanical properties (unirradiated and irradiated)
- An intense neutron source such as IFMIF is needed to develop and qualify fusion structural materials

Comparison of the yield strengths of CuCrZr (IG) and GlidCop Al25 (Al_2O_3-dispersion strengthened copper)

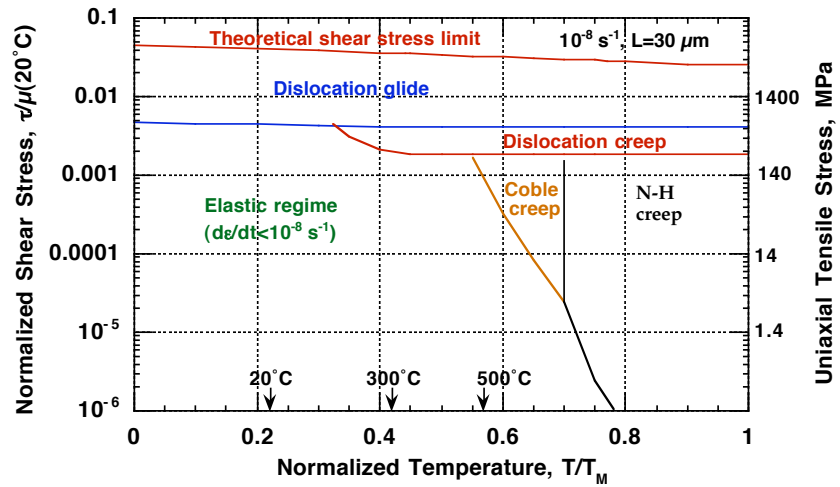


•GlidCop Al25 Cu-Al_2O_3 alloy has a high strain rate sensitivity, in part due to grain boundary sliding phenomena at T>250˚C

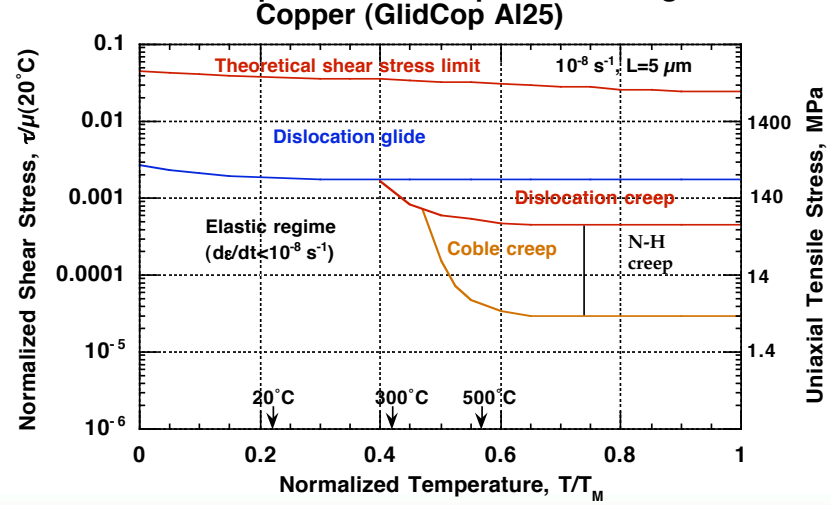
Mechanical behavior of copper alloys can be understood on the basis of current materials science models of deformation



Deformation Map for CuNiBe (Brush-Wellman Hycon 3HP)

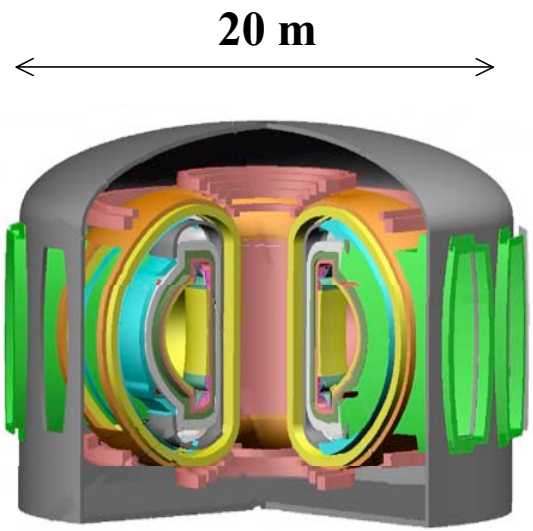


Deformation Map for Oxide Dispersion-strengthened Copper (GlidCop Al25)



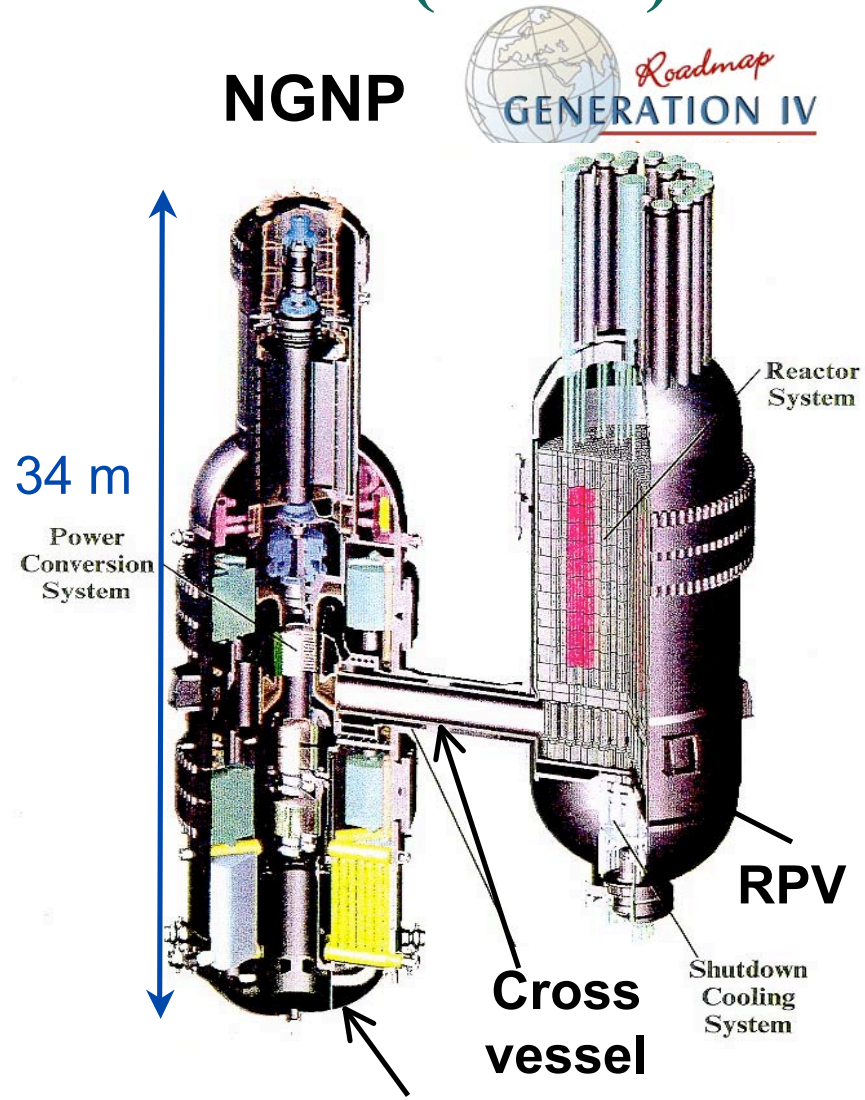
Applications to US industry (e.g., USCAR) as well as fusion energy sciences program

The ARIES-AT reactor design is similar size as proposed Gen-IV Next Generation Nuclear Plant (NGNP)



Correctly scaled size of ARIES AT fusion reactor

Correctly scaled size of typical PWR RPV



- Improved safety and performance (e.g., H_2 production) offset higher capital costs for future reactors

Materials Research and the Path to Fusion Power

Plasma Physics Confinement

Fusion Reactor Concept Definition

ITER

Demo Conceptual Designs

Demo Final Design and Construction

- **Materials research to identify candidate FW/B structural materials**
  - **Thermal conductivity and expansion**
  - **Activation**
  - **High temperature mechanical properties**
  - **Compatibility with coolants and T breeders**
  - **Irradiation damage issues**
  - **Joining and fabrication issues**

- **Identify and demonstrate approaches to improve material performance**
- **Identify concept specific issues and demonstrate proof-of-principle solutions, e.g.**
  - **design with ferromagnetic material**
  - **MHD-insulator for V-Li concept**
  - **methods for design of large thermal**
  - **mechanically loaded composite structures**

- Development of materials with acceptable performance and demonstrate to goal life (dpa and He)
- Demonstrate solution to concept specific issues on actual structural materials and prototype components
- Develop design data base, constitutive equations, and models to describe all aspects of material behavior required for design and licensing

Ion Accelerators

RTNS

Fission Reactors

IFMIF

Component Test Facility

Confirmation & Modification of Performance With Actual Fusion Environment Test Results

Fusion Power