Progress in Fusion Materials Research

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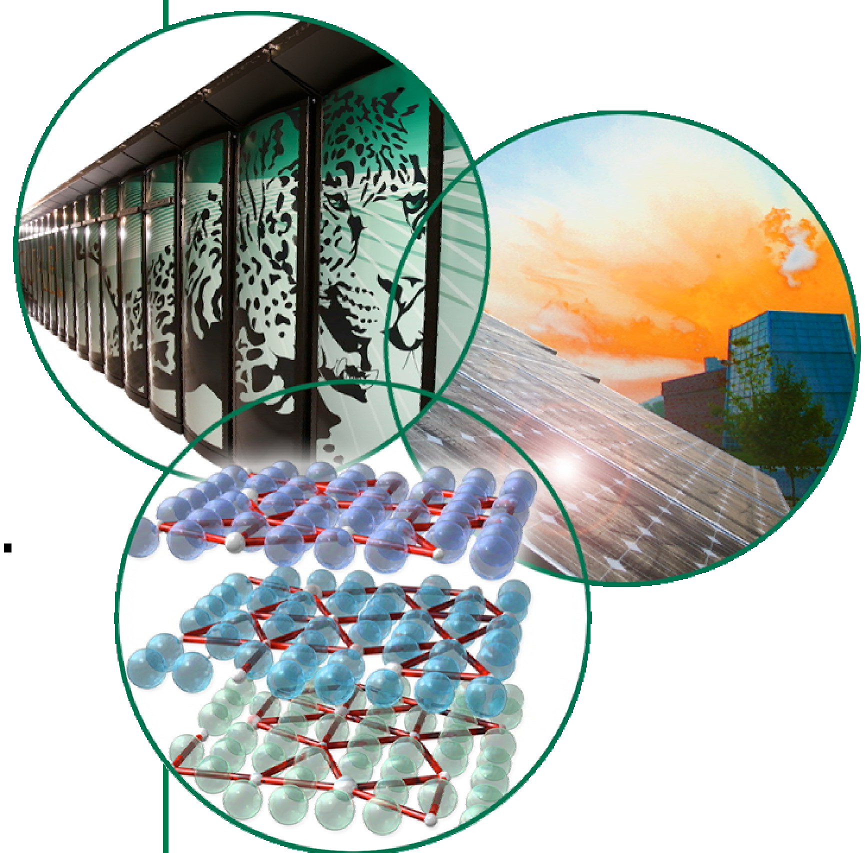
Materials Science & Technology Div.

IEEE/NPSS 23rd Symposium on Fusion Engineering
May 31-June 5, 2009
San Diego, California



U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
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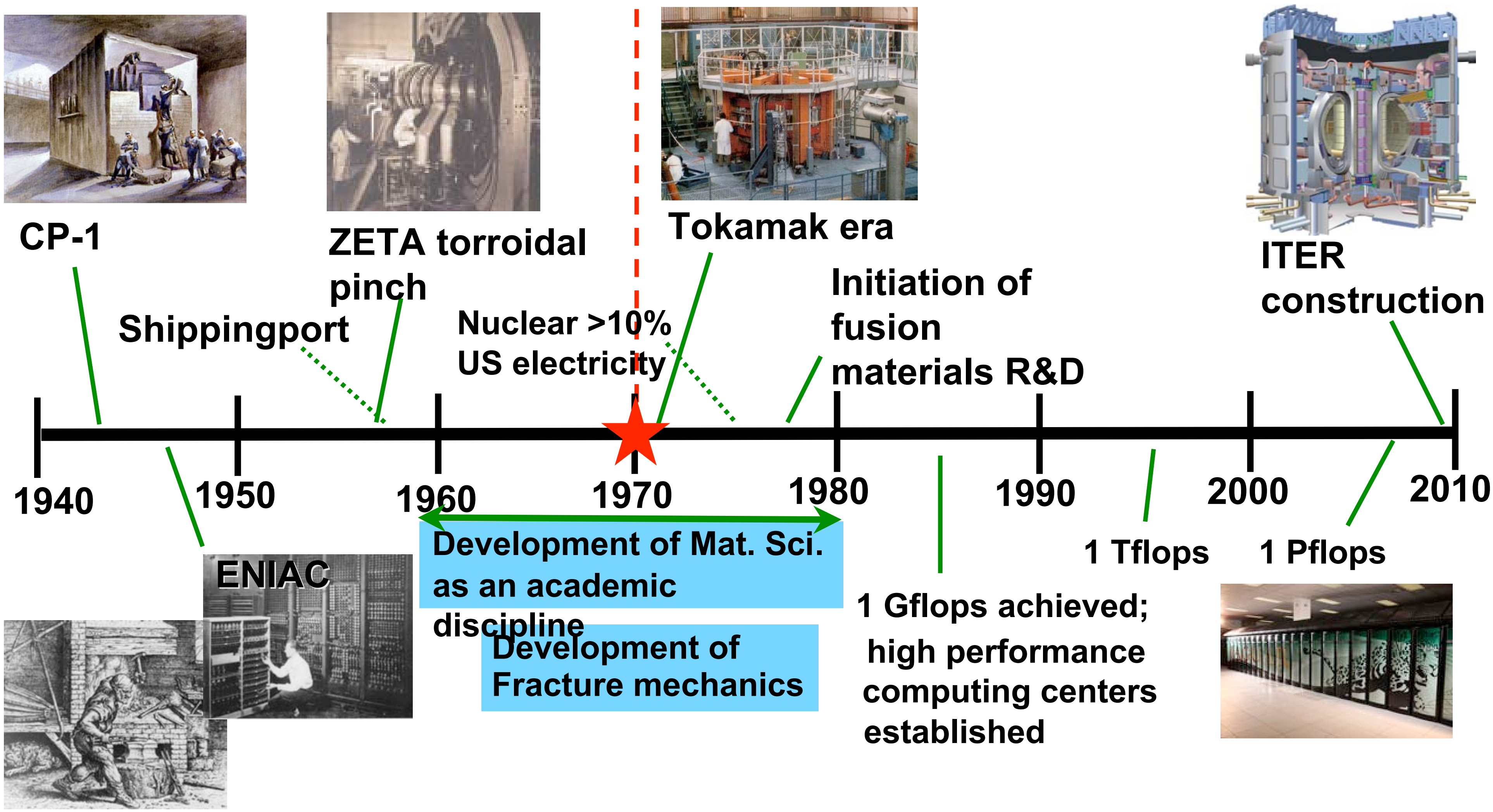
Outline

- Examples of structural materials design data
- Overview of key temperature regimes for radiation damage
  - Amorphization, point defect swelling, void swelling
  - Upper and lower operating temperature limits
- Materials design strategy and prospects for developing new high performance structural materials for fusion energy

The Launching of Fusion Energy Bridges the Development of Modern Materials Science



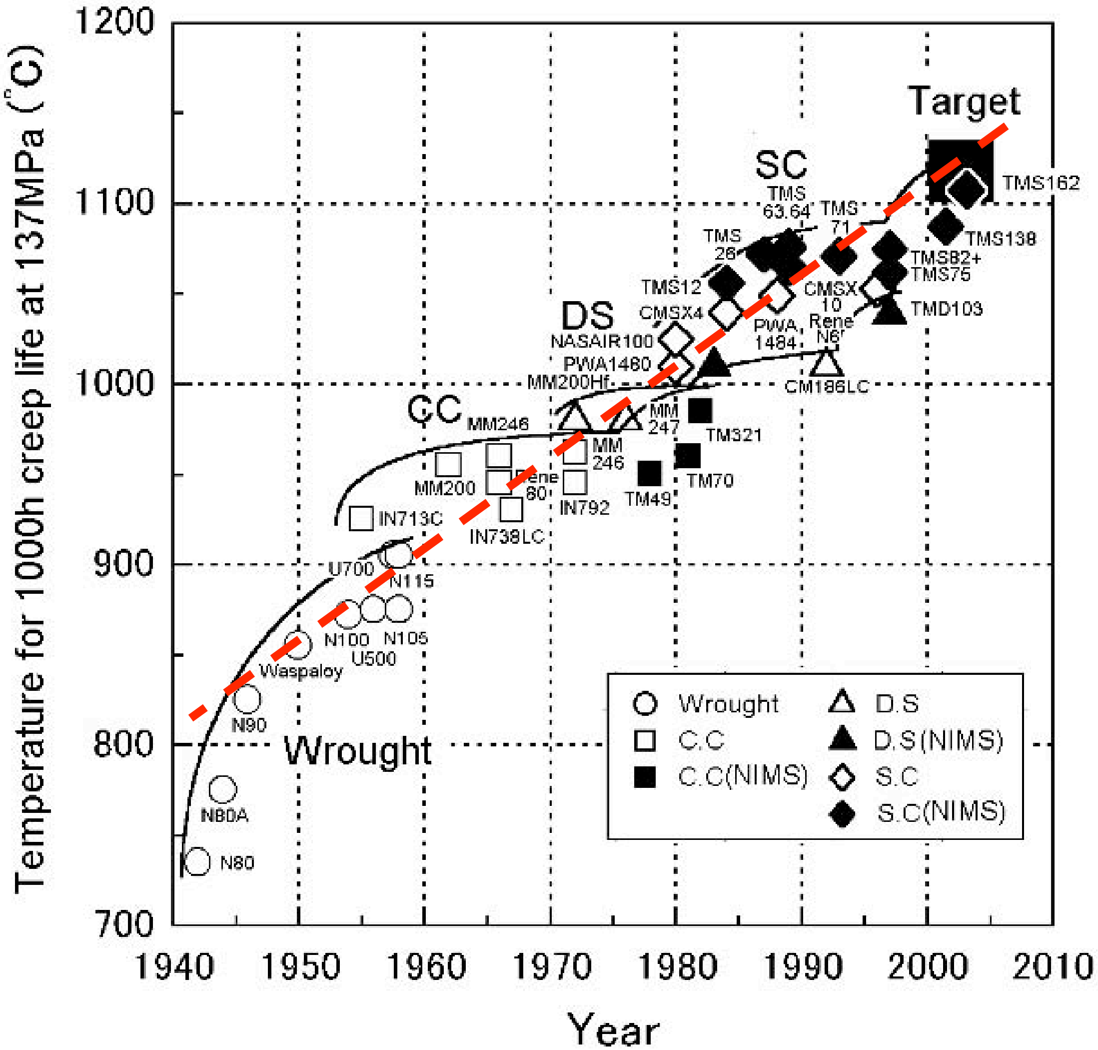
- **Fusion energy systems should take maximum advantage of current and emerging materials and computational science tools**

Development of structural materials for applications involving public safety is historically a long process

- **"When you hear something about a new material, write it down because it will be the best thing you'll ever hear about it"** (Jim Williams, paraphrasing Bob Sprague of General Electric)
- **Aerospace structural materials**
  - Over 50 years to develop TiAl intermetallics from initial studies in 1950s
  - Design cycle times have been reduced to 3-5 years, but development and qualification of new materials still requires >7 years
    - Qualification time dominated by creep and fatigue testing
- **Structural materials for nuclear reactors**
  - Qualification requires all of the mechanical property testing on unirradiated material, plus neutron irradiation and testing of irradiated material
    - Sequential approach would lead to unacceptably long qualification times

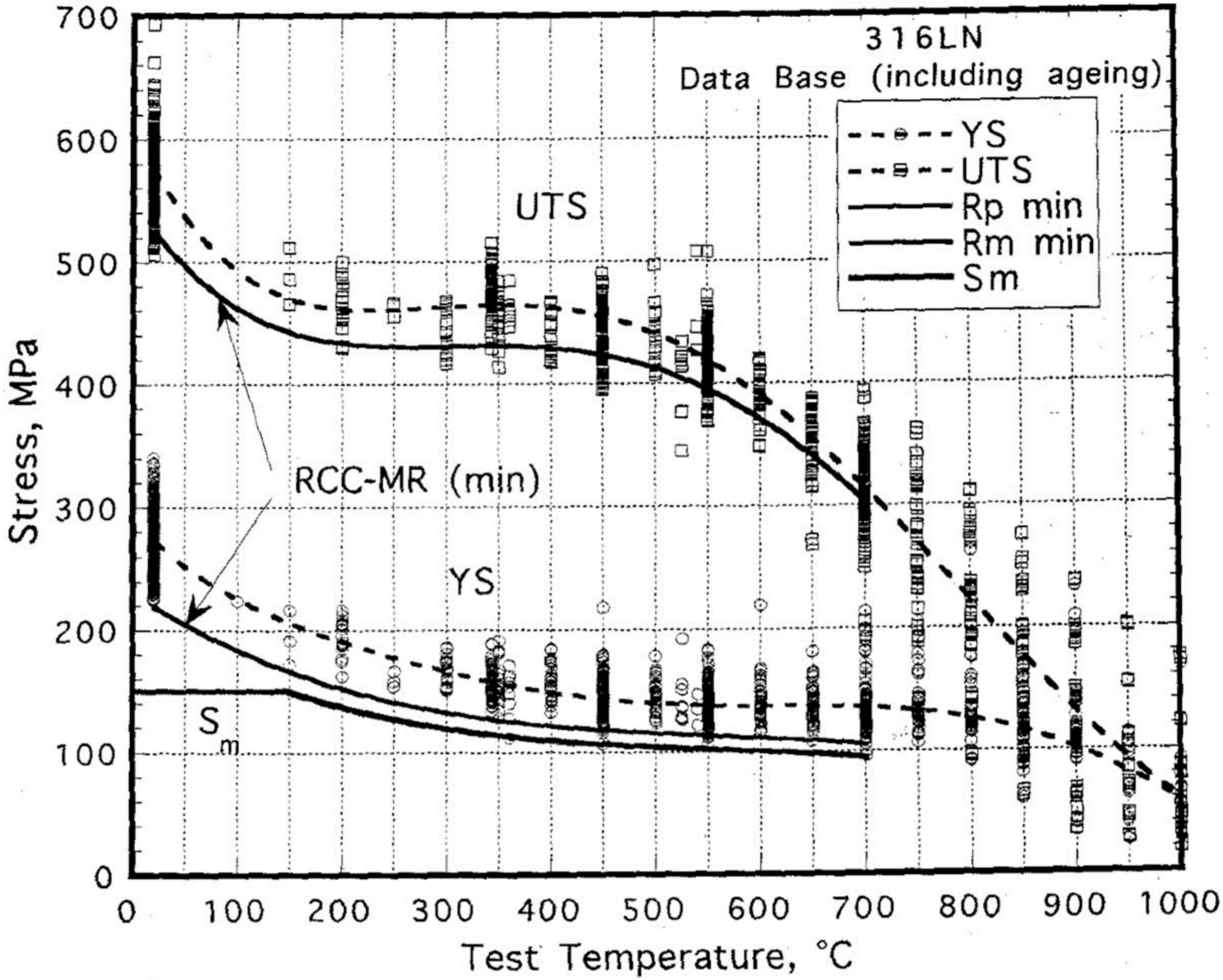
History of improvement in temperature capability of Ni-base superalloys

- **Historical rate of improvement is ~5°C/year**



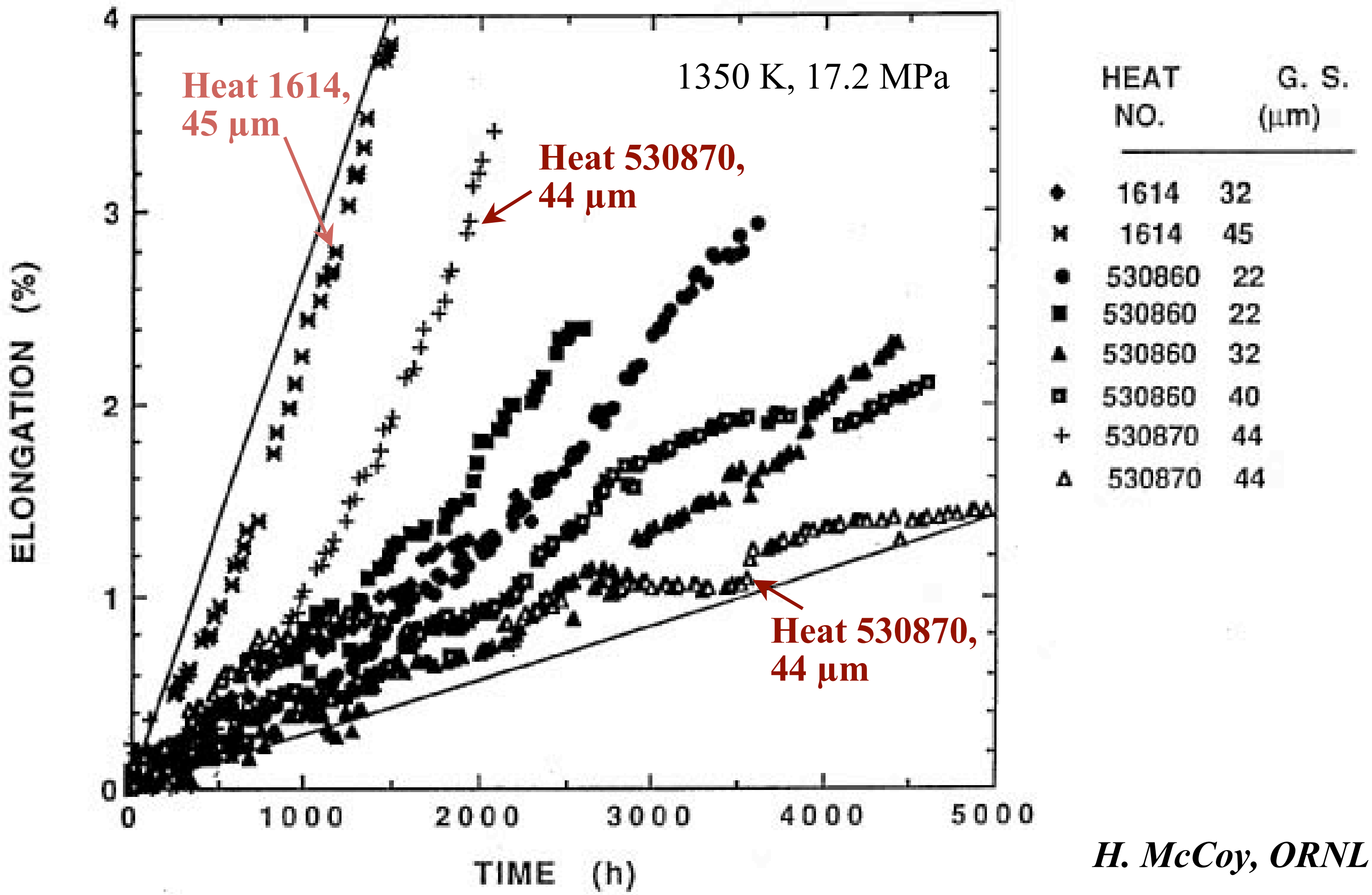
Y. Koizumi et al., Proc. Int. Gas Turbines Conf., 2003, paper TS-119

Design tensile strengths for Type 316 stainless steel



A.A.F. Tavassoli

Large variability in thermal creep behavior for three heats of nominally identical Nb-1Zr

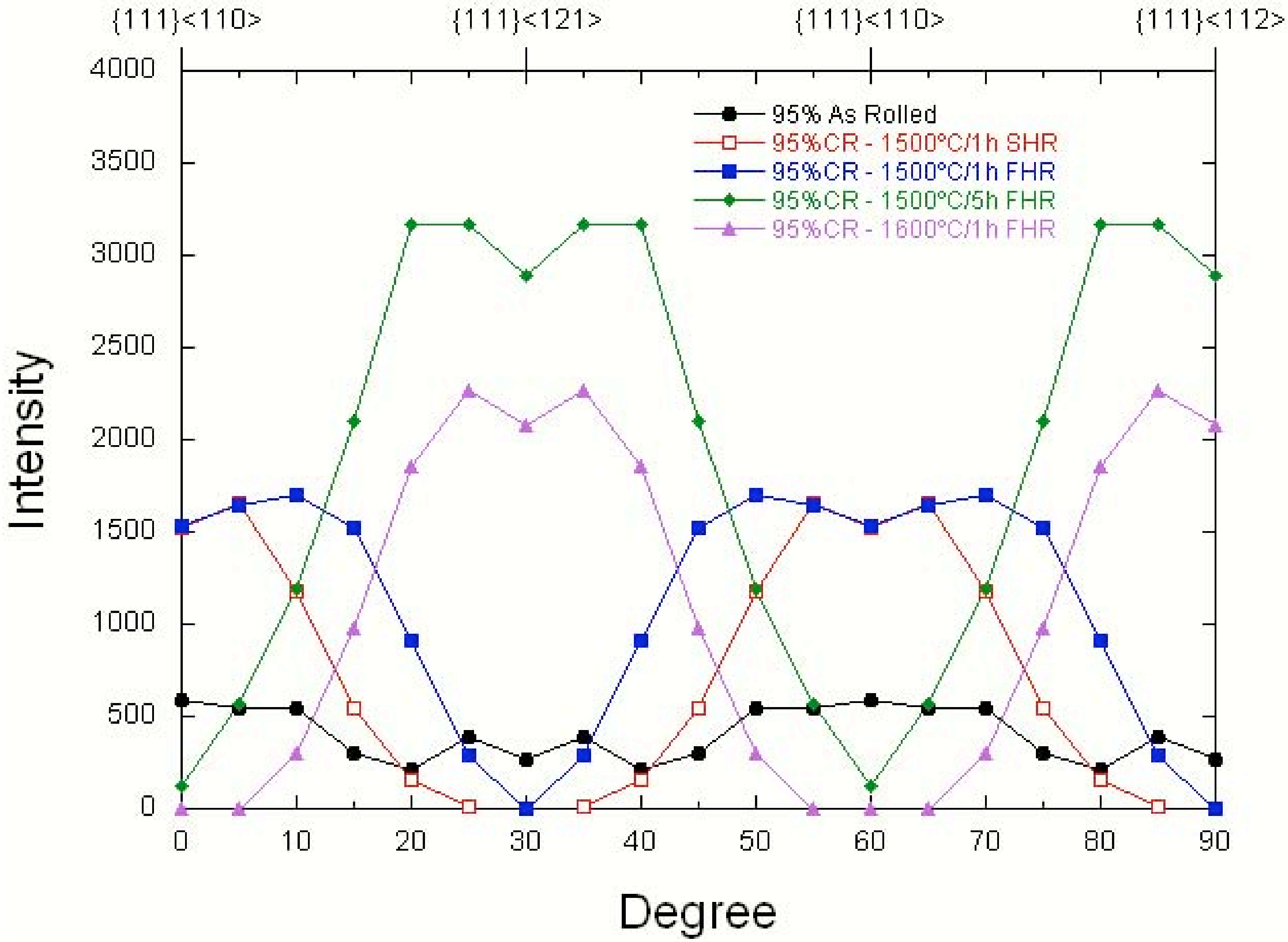


H. McCoy, ORNL

- *In addition to grain size, these results show that* ***other microstructural inhomogeneities*** *can also affect the thermal creep behavior of Nb-1Zr*

Development of Texture in Annealed Nb-1Zr

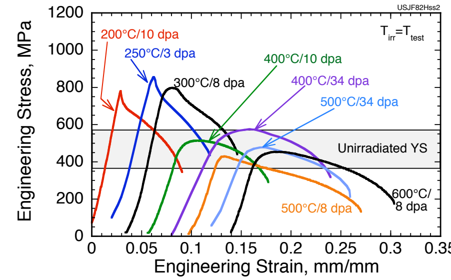
- **Texture pattern in recrystallized Nb-1Zr is strongly dependent on annealing conditions**



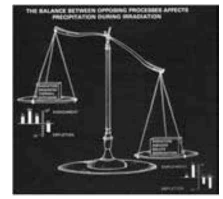
FHR: fast heating rate (>1000˚C/min)
SFR: slow heating rate (10˚C/min)

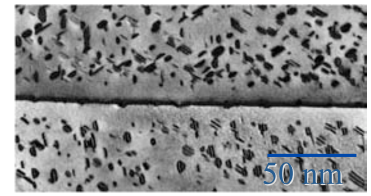
Radiation Damage can Produce Large Changes in Structural Materials

- **Radiation hardening and embrittlement (<0.4 T_M, >0.1 dpa)**



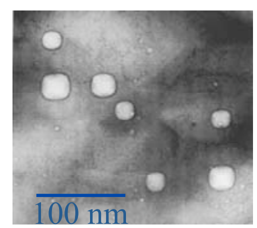
- **Phase instabilities from radiation-induced precipitation (0.3-0.6 T_M, >10 dpa)**

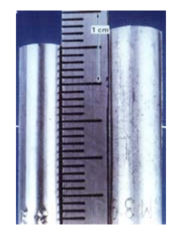




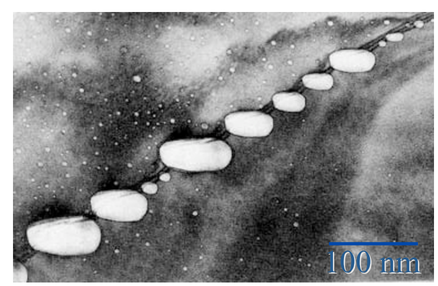
- **Irradiation creep (<0.45 T_M, >10 dpa)**

- **Volumetric swelling from void formation (0.3-0.6 T_M, >10 dpa)**



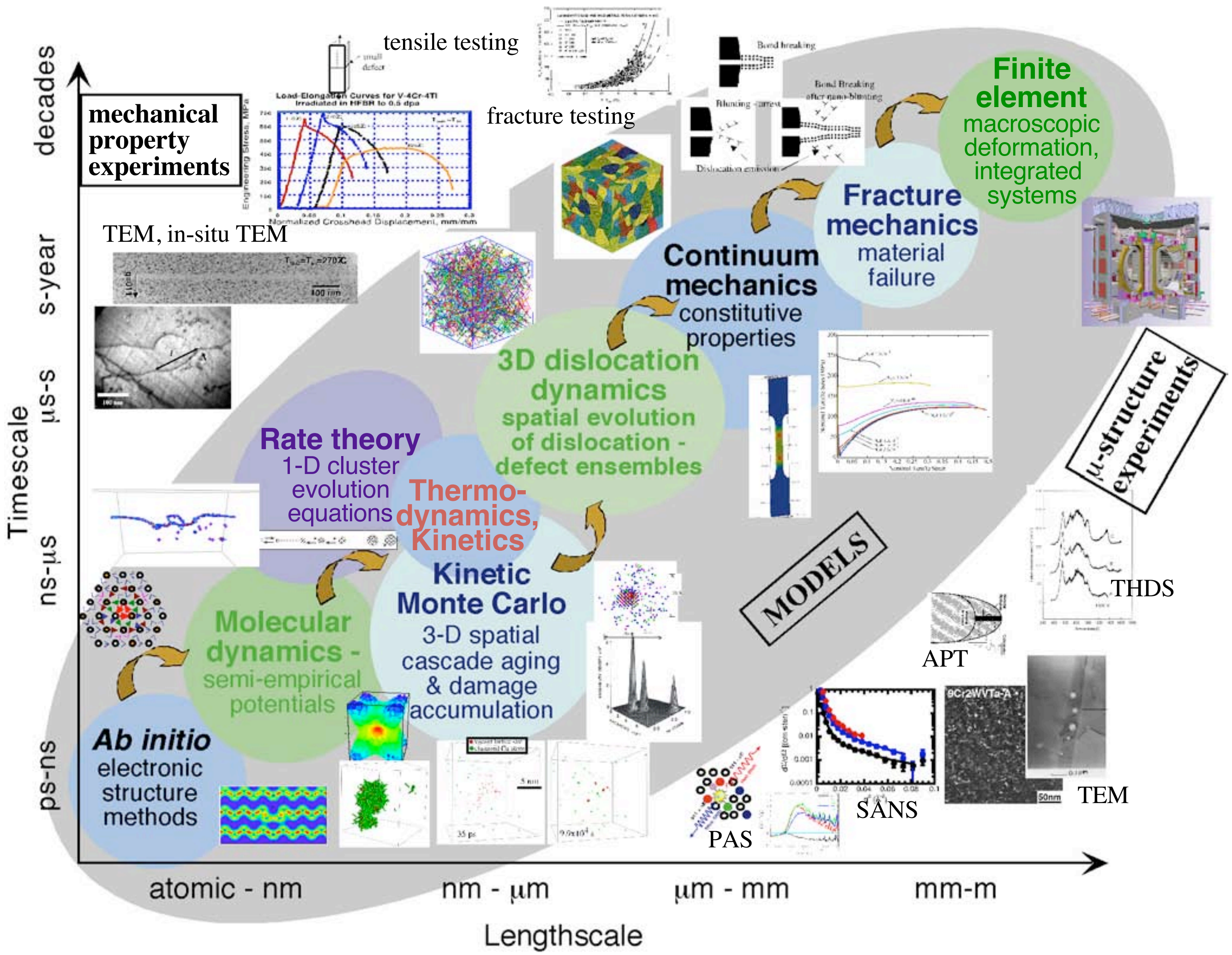


- **High temperature He embrittlement (>0.5 T_M, >10 dpa)**



after S.J. Zinkle, Phys. Plasmas 12 (2005) 058101

Radiation damage is inherently multiscale with interacting phenomena ranging from ps to decades and nm to m



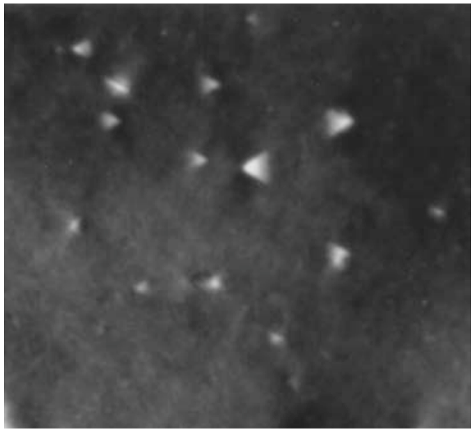
B.D. Wirth, UC-Berkeley

Multidisciplinary Fusion Materials Research has Demonstrated the Equivalency of Displacement Damage Produced by Fission and Fusion Neutrons

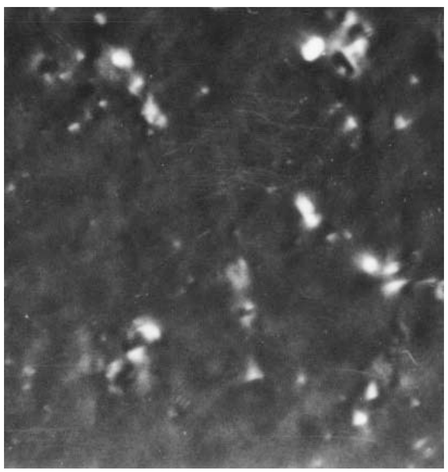
Similar defect clusters produced by fission and fusion neutrons as observed by TEM

Fission

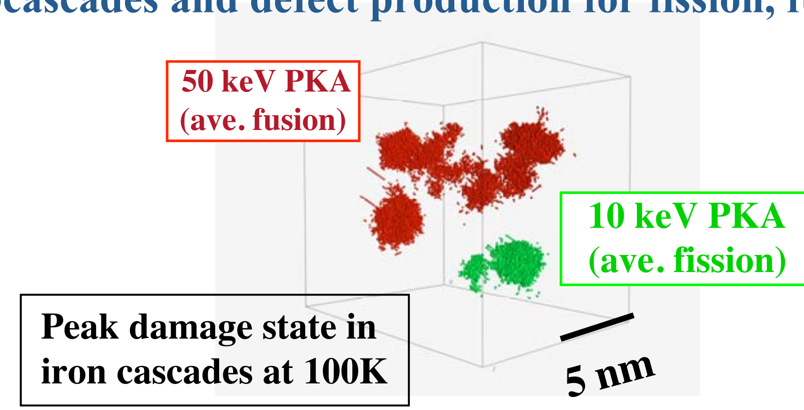
(0.1 - 3 MeV)



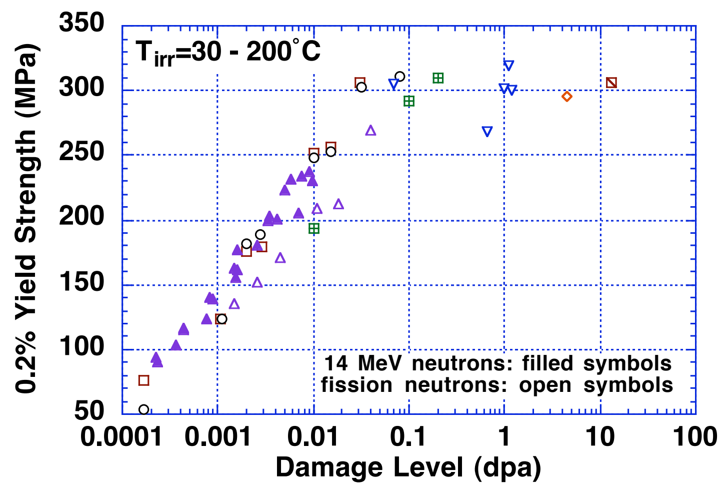
Fusion
(14 MeV)



MD computer simulations predict comparable subcascades and defect production for fission, fusion



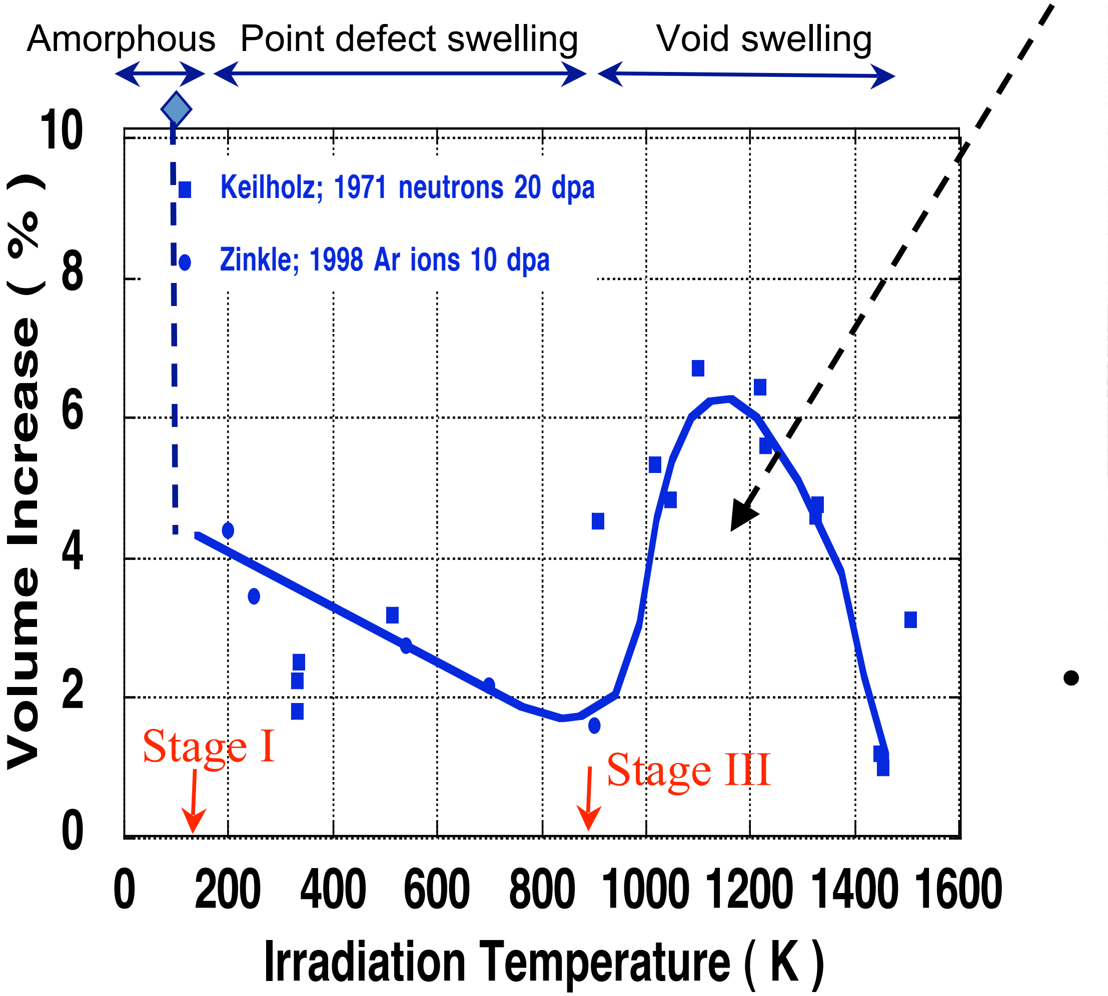
Similar hardening behavior confirms the equivalency

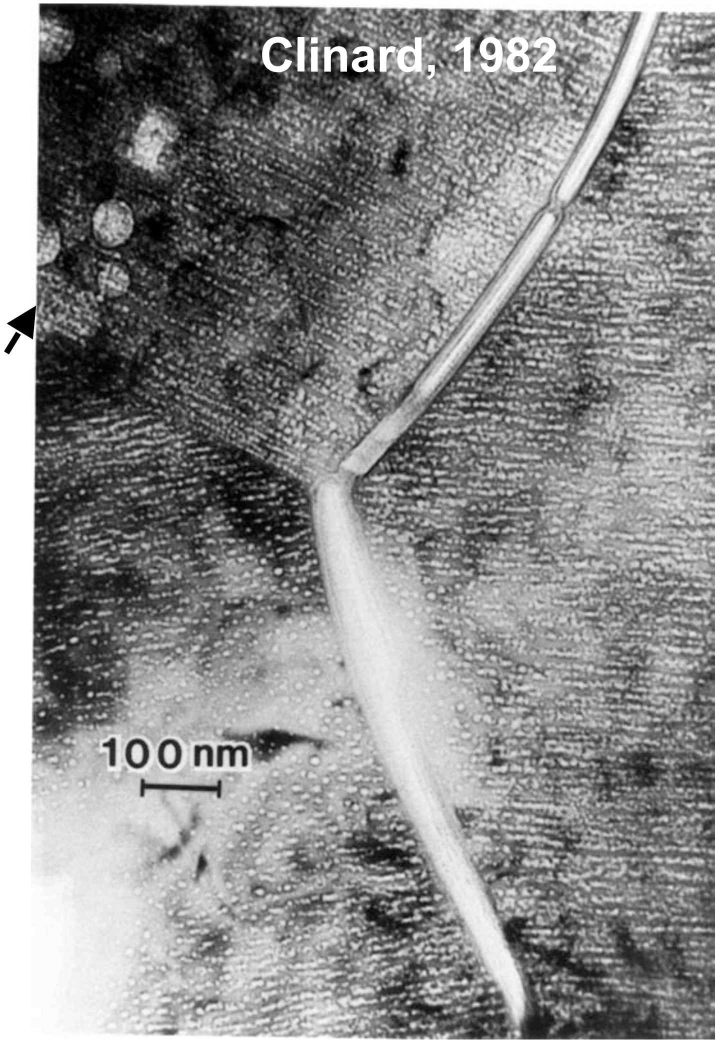


A critical unanswered question is the effect of higher transmutant H and He production in the fusion spectrum

Al_2O_3 Swelling

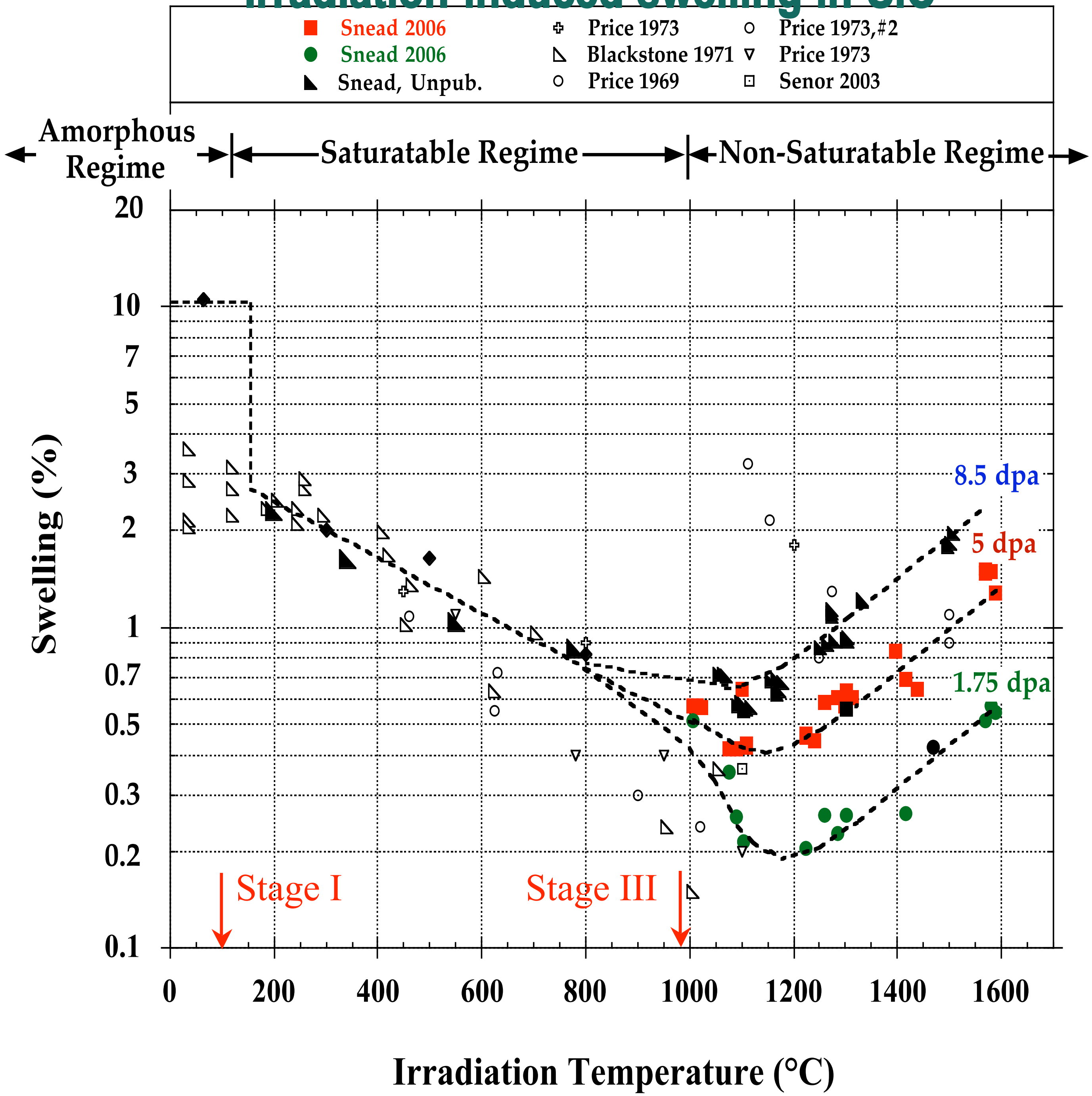
- 3 distinct swelling regimes are observed in irradiated Al_2O_3



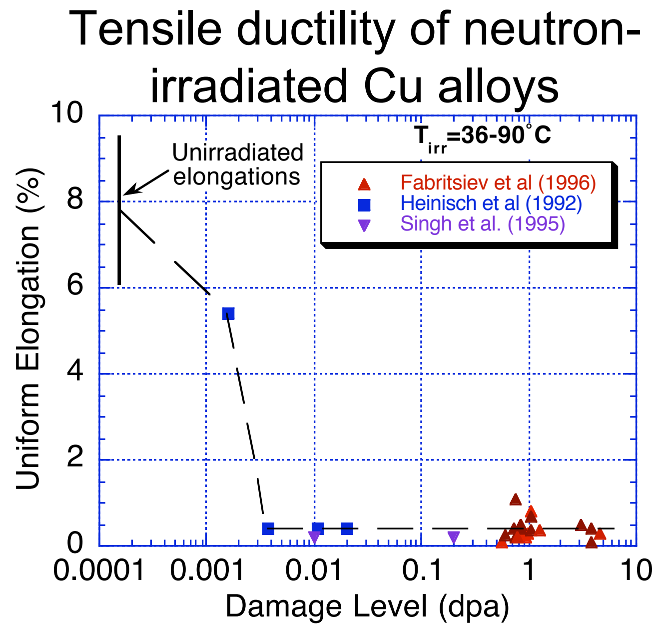


- Activation Energies:
  - Al vacancy; 1.8-2.1 eV
  - O vacancy; 1.8-2 eV
  - Al, O interstitial; 0.2-0.8 eV

Irradiation-induced swelling in SiC



Low tensile ductility in FCC and BCC metals after irradiation at low temperature is due to formation of nanoscale defect clusters



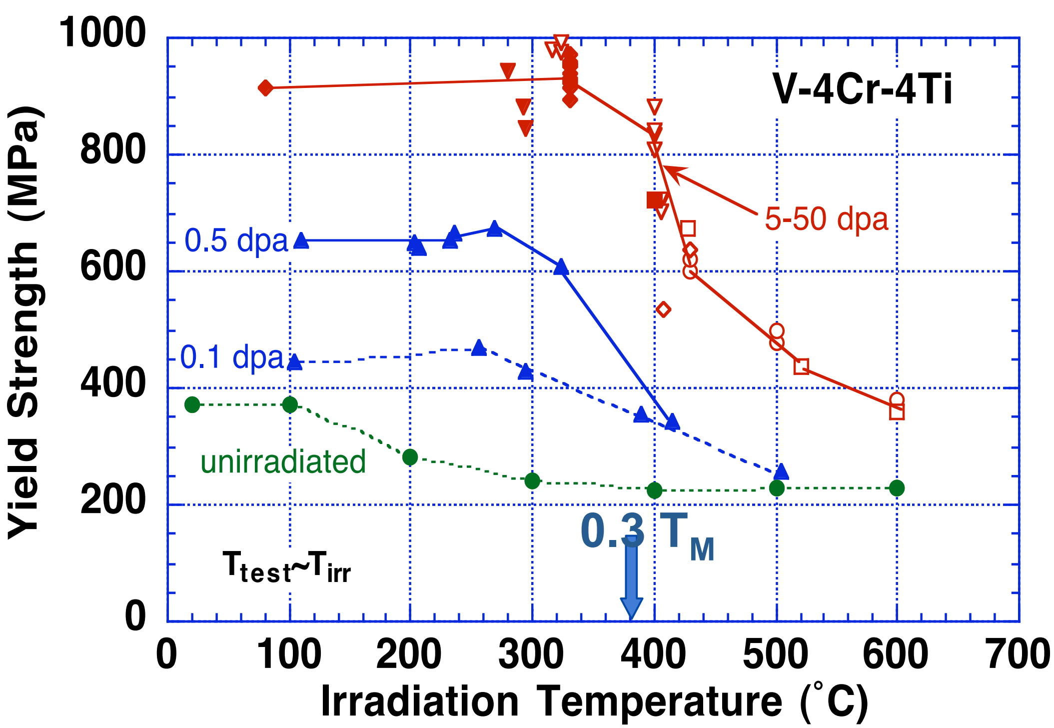
Outstanding questions to be resolved include:

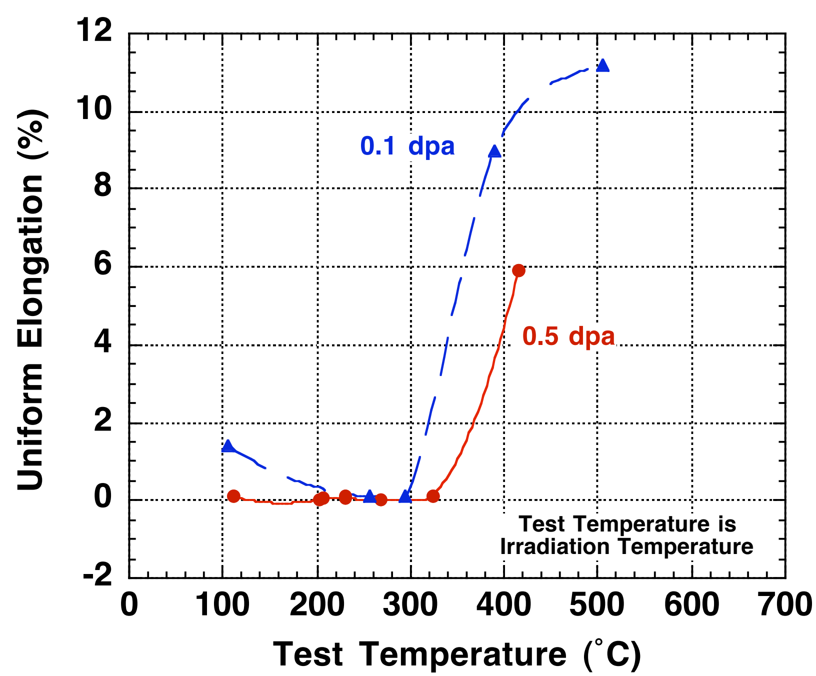
- Can the defect cluster formation be modified by appropriate use of nanoscale 2nd phase features or solute additions?
- Can the poor ductility of the irradiated materials be mitigated by altering the predominant deformation mode? (e.g., twinning vs. dislocation glide)

Oak Ridge National Laboratory

Radiation hardening in V-4Cr-4Ti

High hardening and loss of uniform elongation occurs for irradiation and test temperatures <0.3 T_M

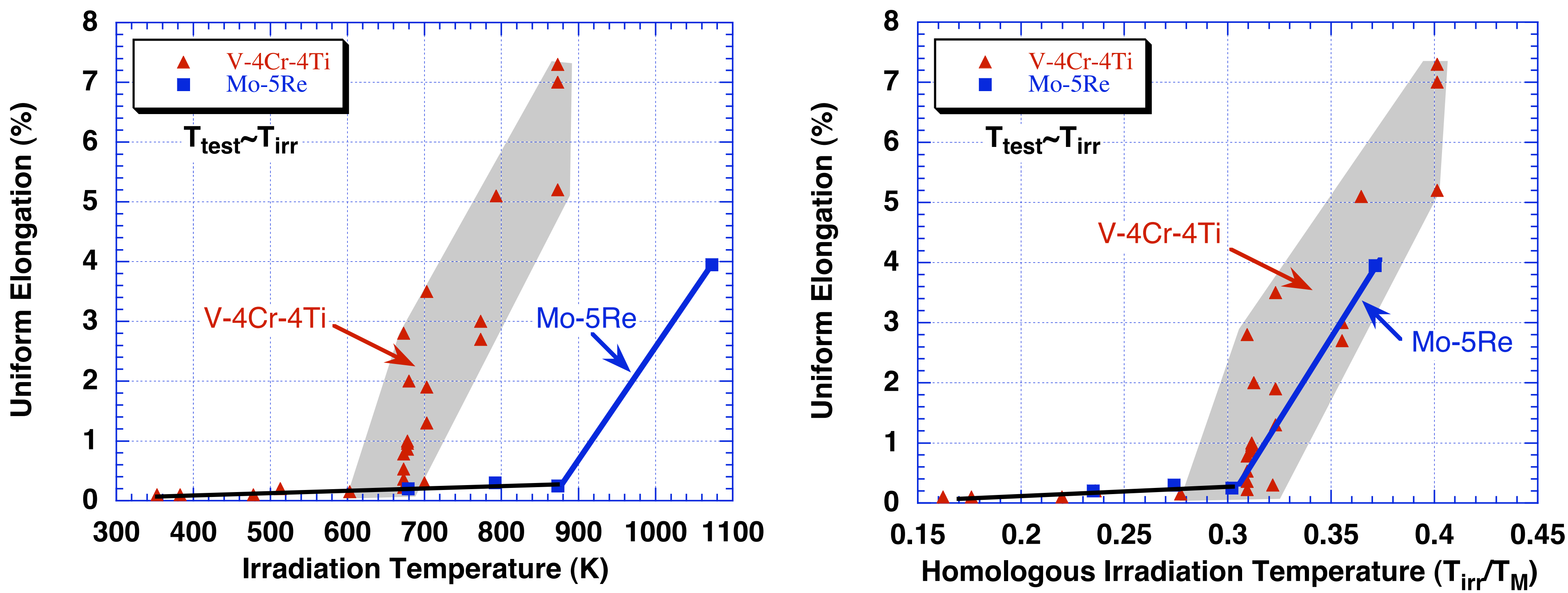




 Managed by UT-Battelle
for the U.S. Department of Energy

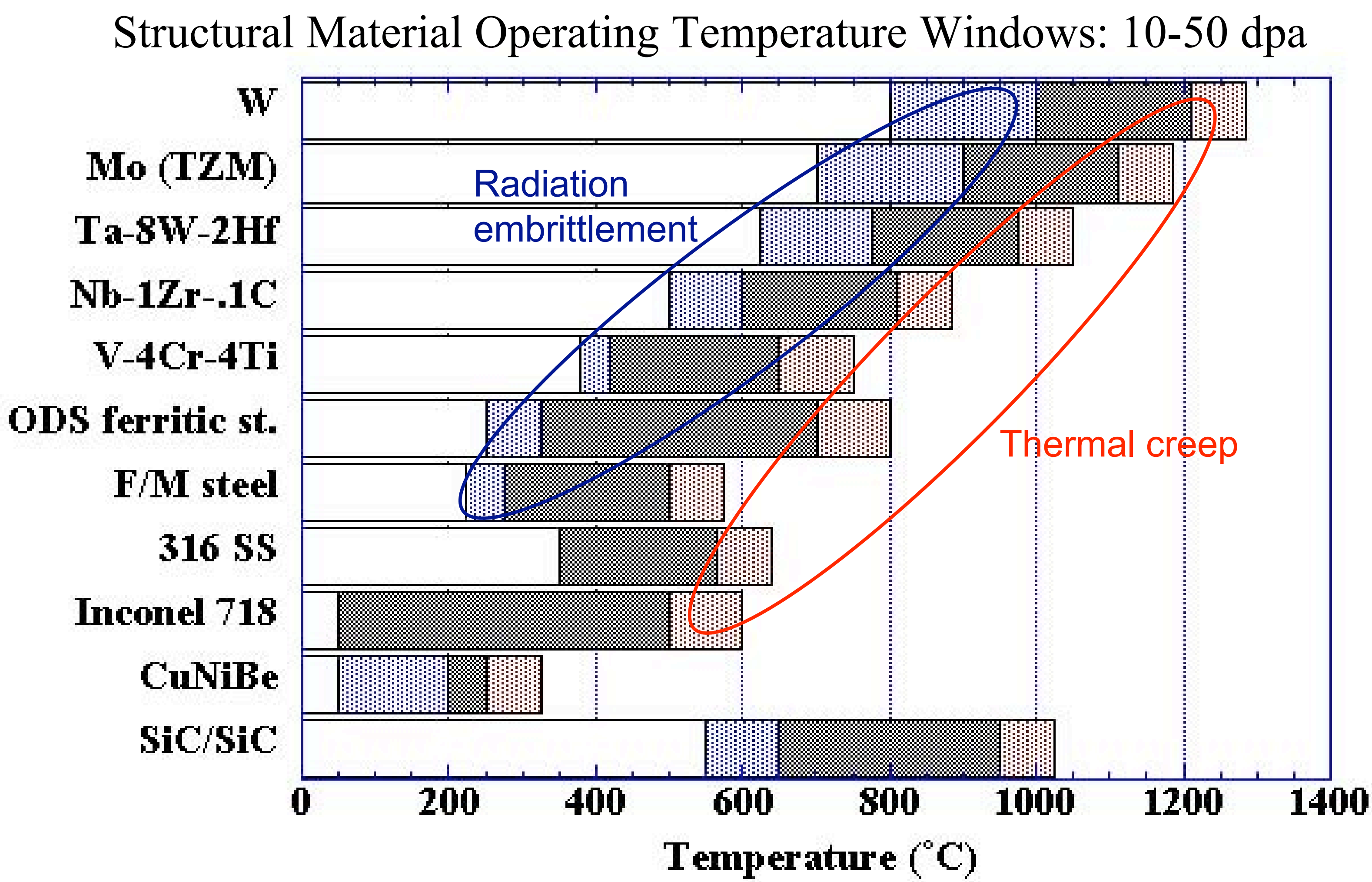
Comparison of the uniform elongation of neutron irradiated vanadium and molybdenum alloys

- Radiation-induced flow localization occurs for irradiation temperatures below 0.3 T_M



Corresponding critical temperature for W alloys is ~830°C

Can we break the shackles that limit conventional structural materials to ~300^{o}C temperature window?



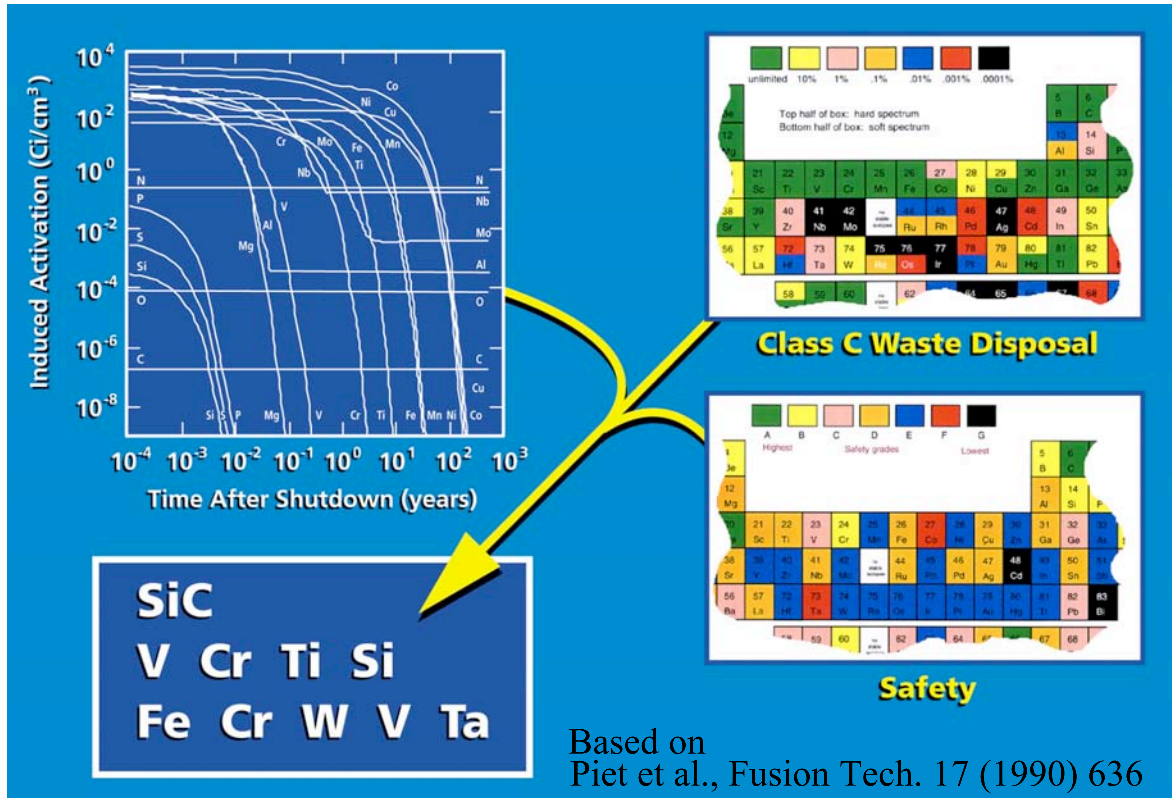
η_{Carnot}=1-T_{reject}/T_{high}

Additional considerations such as He embrittlement and chemical compatibility may impose further restrictions on operating window

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

The Overarching Goals for Fusion Power Systems Narrow the Choices and Place Significant Demands for Performance of Structural Materials

- **Safety**
- **Minimization of Rad. Waste**
- **Economically Competitive**
  - **High thermal efficiency (high temperatures)**
  - **Acceptable lifetime**
  - **Reliability**

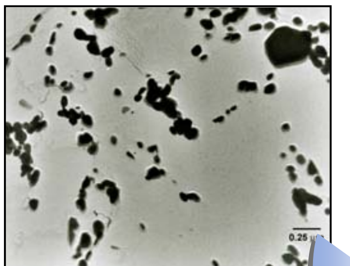


Fe-9Cr steels: builds upon 9Cr-1Mo industrial experience and materials database (9-12 Cr ODS steels are a higher temperature future option)
V-4Cr-4Ti: Higher temperature capability, targeted for Li self-cooled blanket designs
SiC/SiC: High risk, high performance option (early in its development path)
W alloys: High performance option for PFCs (early in its development path)

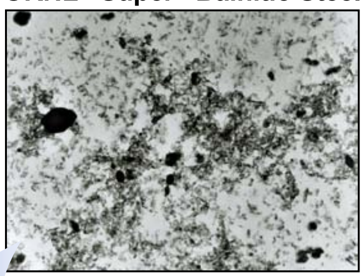
Modern Materials Science Applied to "Old" Alloys Yields Dramatic Improvements in Performance and New Applications

Alloy composition is changed to produce a microstructure of fine, stable precipitates

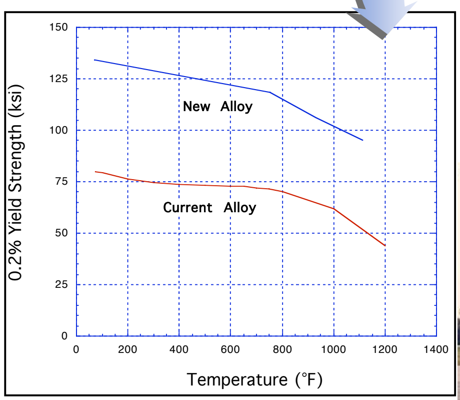
Commercial Bainitic Steel



ORNL "Super" Bainitic Steel

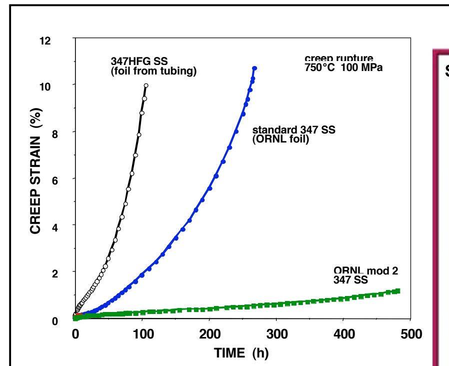


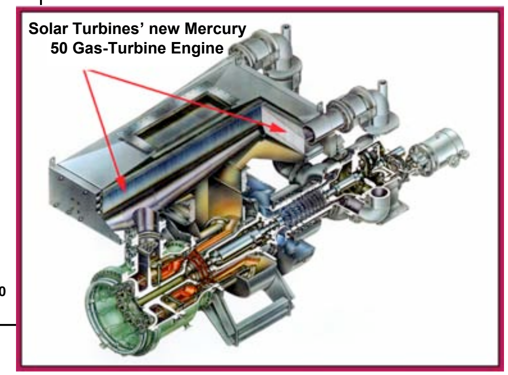
Old **New**



Low chromium steels for chemistry and energy industry applications

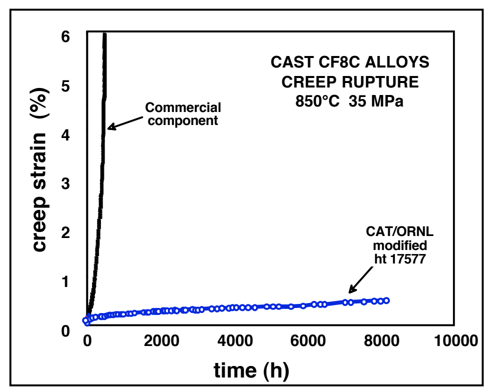
Similar Scientific Microstructural Design Produces:

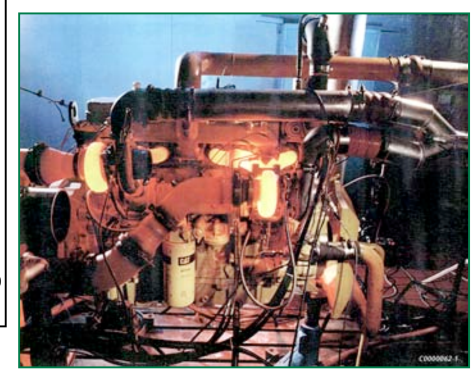




Solar Turbine Corp. Microturbine

New austenitic stainless steels for microturbine recuperators, and





High Performance Diesel Engine

New cast austenitic steels for automotive and heavy vehicle exhaust components

Technology Transfer of CF8C-Plus Cast Stainless Steel

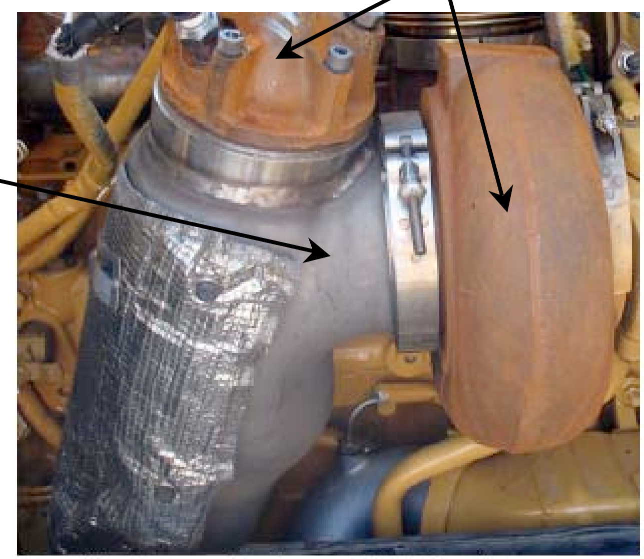
6,700 lb **CF8C-Plus** end-cover cast by MetalTek for Solar Turbines Mercury 50 gas turbine

- **MetalTek International, Stainless Foundry & Engineering, and Wollaston Alloys received trial licenses in 2005 (18 months after project start)**
- **Over 350,000 lb of CF8C-Plus steel have been successfully cast to date**
  - **Now used on all heavy-duty truck diesel engines made by Caterpillar (since Jan. 2007)**
  - **Solar Turbines (end-cover, casings), Siemens-Westinghouse (large section tests for turbine casings), ORNL, and a global petrochemical company (tubes/piping).**
  - **Stainless Foundry has cast CF8C-Plus exhaust components for Waukesha Engine Dresser NG engines**

80 lb **CF8C-Plus** exhaust component cast by Stainless Foundry for Waukesha NG reciprocating engine

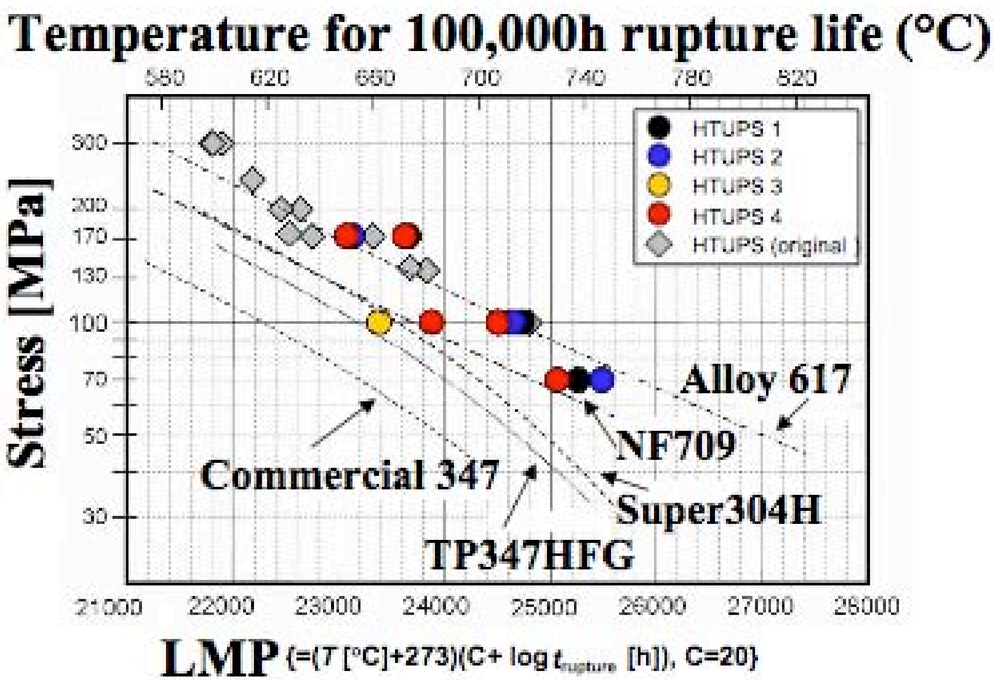
SiMo cast iron

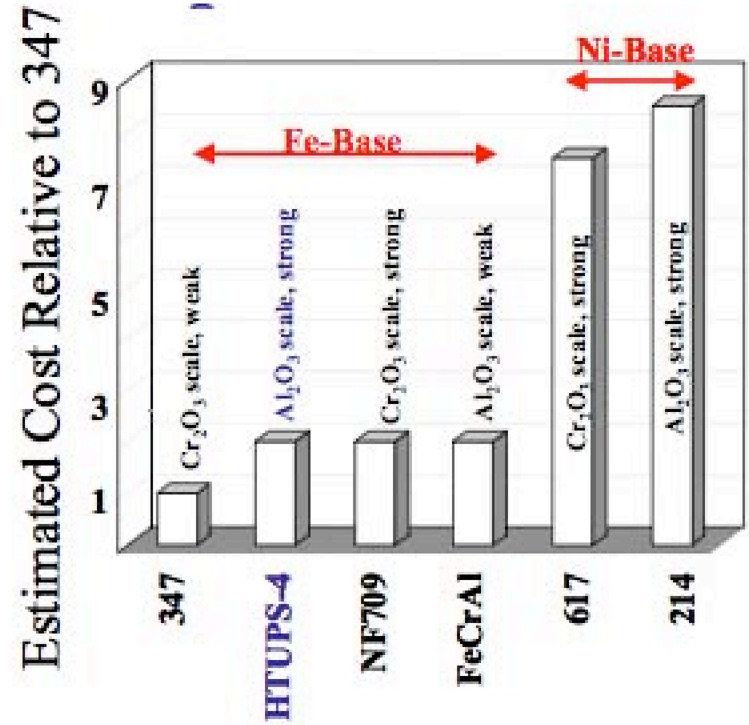
CF8C-Plus steel

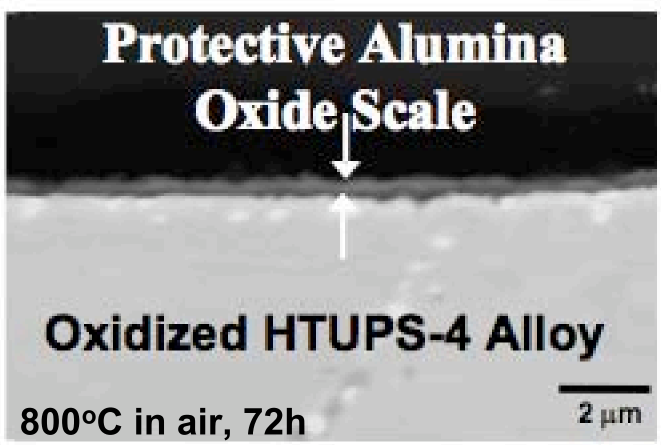


Caterpillar Regeneration System (CRS) Housing

Development of New Alumina-Forming, Creep Resistant Austenitic Stainless Steel



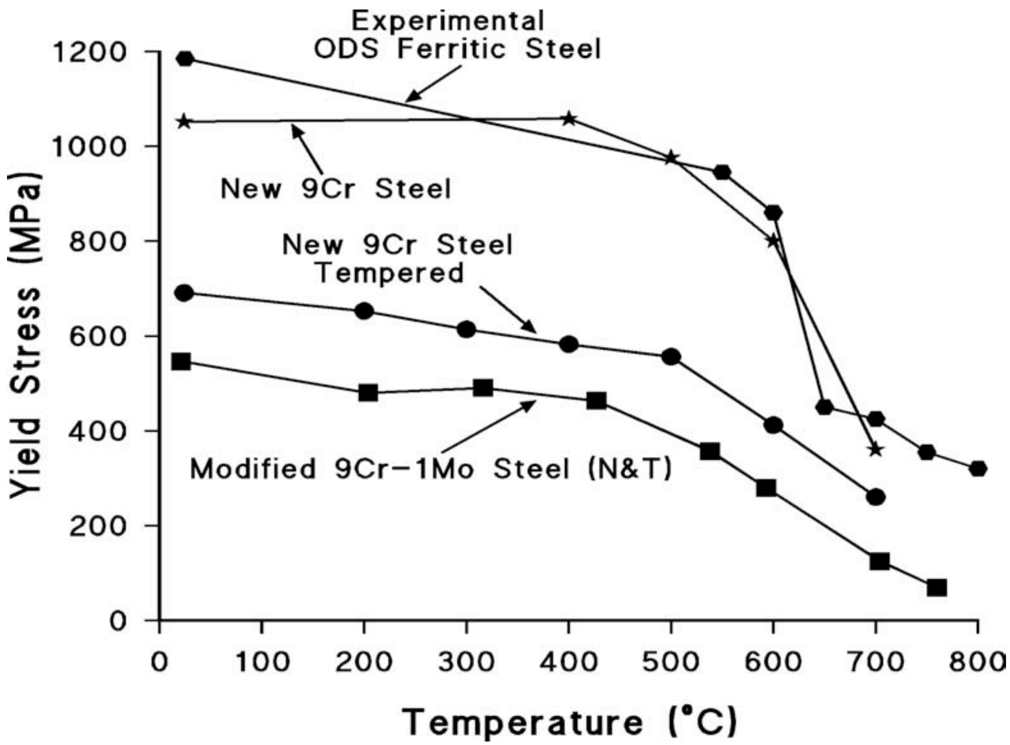




- Designed for 600-800°C structural use under aggressive oxidizing conditions
  - superior oxidation resistance to conventional chromia-forming alloys
- Comparable cost to current heat-resistant austenitic stainless steels

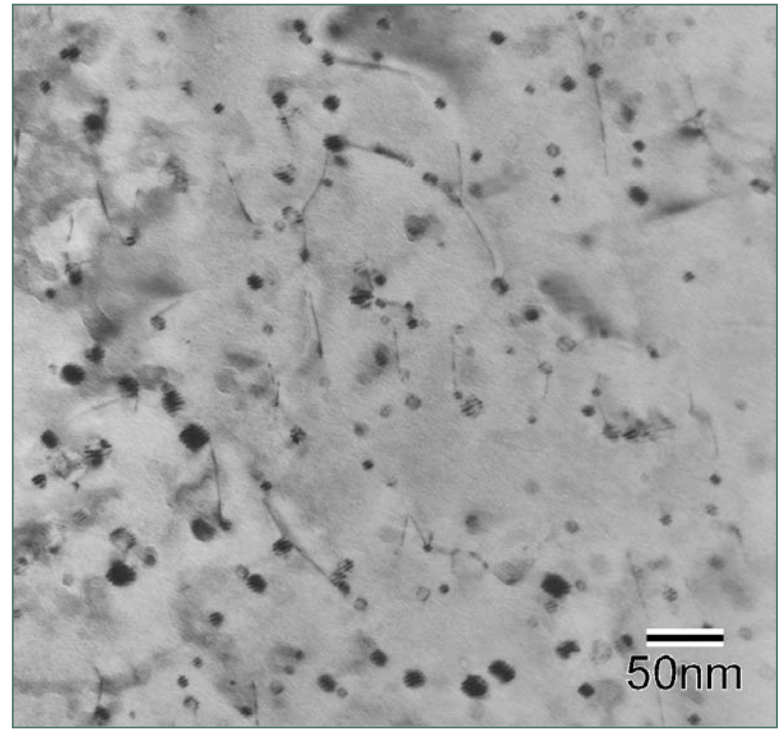
Y. Yamamoto, M.P. Brady et al., Science 316 (2007) 433

Modified chemistry and thermomechanical treatment procedure for new 9Cr ferritic/martensitic steels produces high strength



Modified thermomechanical treatment of 9Cr-1Mo steel introduces fine-scale precipitates

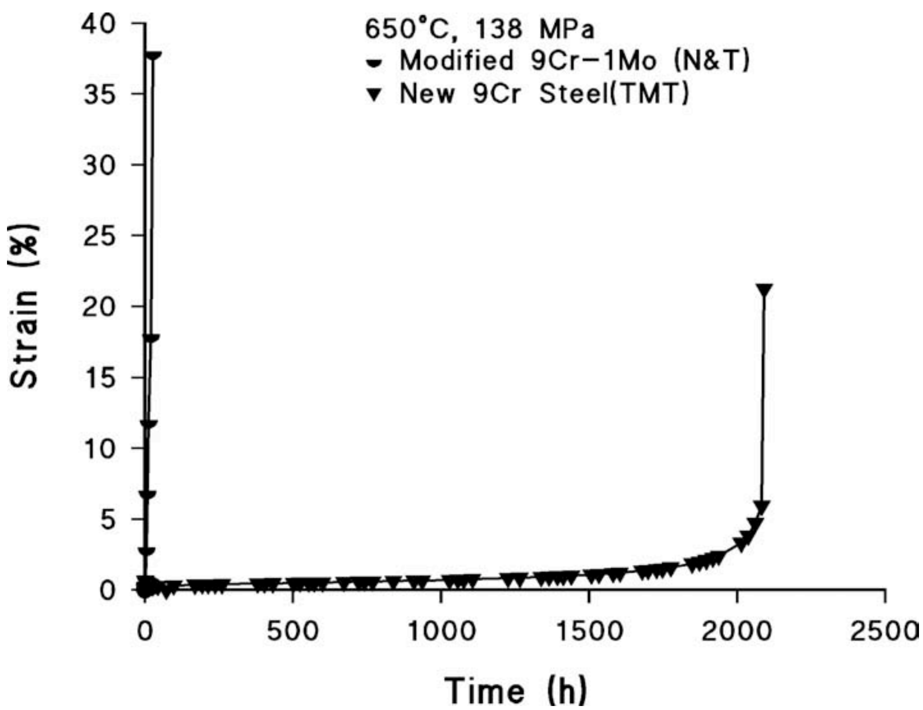
R.L. Klueh et al., J. Nucl. Mat. 367-370 (2007) 48; Scripta Mat. 53 (2005) 275

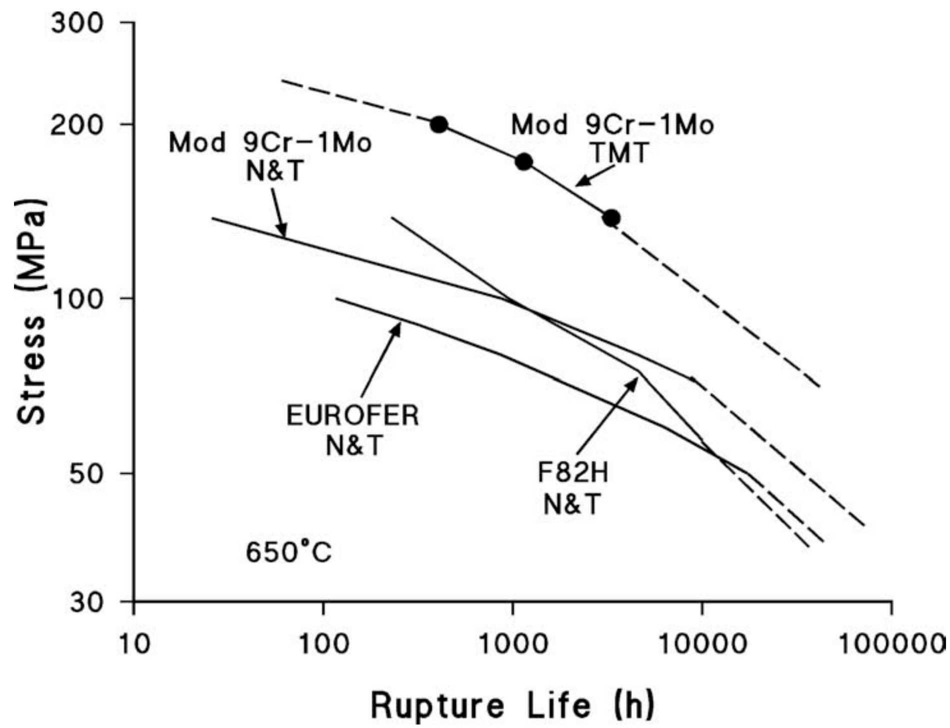


- **Good toughness and high temperature strength are also produced in dispersion-strengthed Fe-9.5Cr-3Co-1Ni-0.6Mo-0.3Ti-0.07C steel due to high number density of nano-size TiC precipitates**

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

Large Increase in Rupture Life of Modified 9Cr-1Mo at 650°C





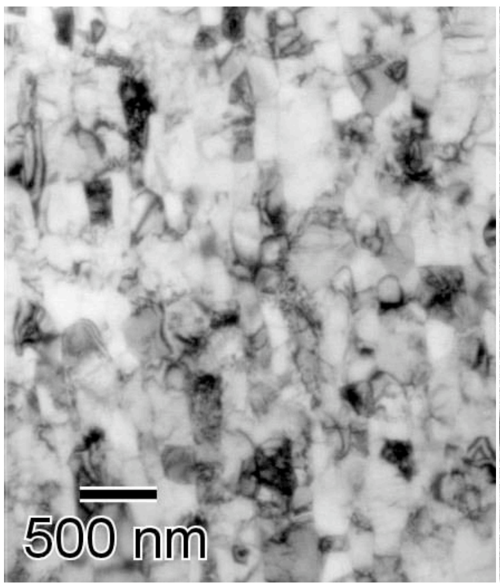
- **Thermo-mechanical treatment (TMT) of modified 9Cr-1Mo produced steel with over an order-of-magnitude increase in rupture life**

R.L. Klueh et al., J. Nucl. Mat. 367-370 (2007) 48; Scripta Mat. 53 (2005) 275

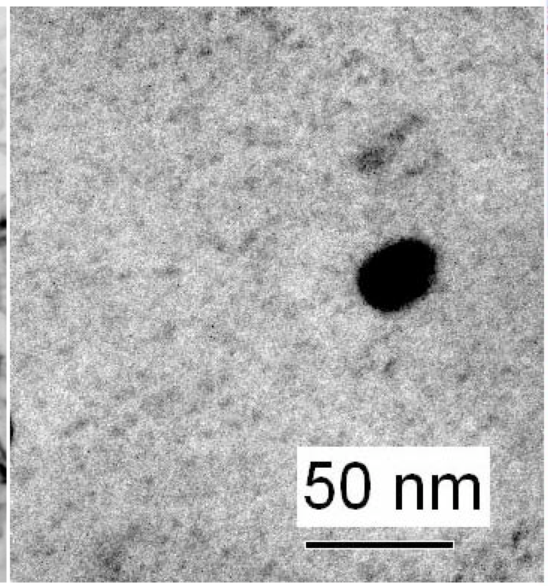
Nanostructuring Achieves Good Fracture Toughness and High-Strength Properties

NFA 14YWT Developed at ORNL

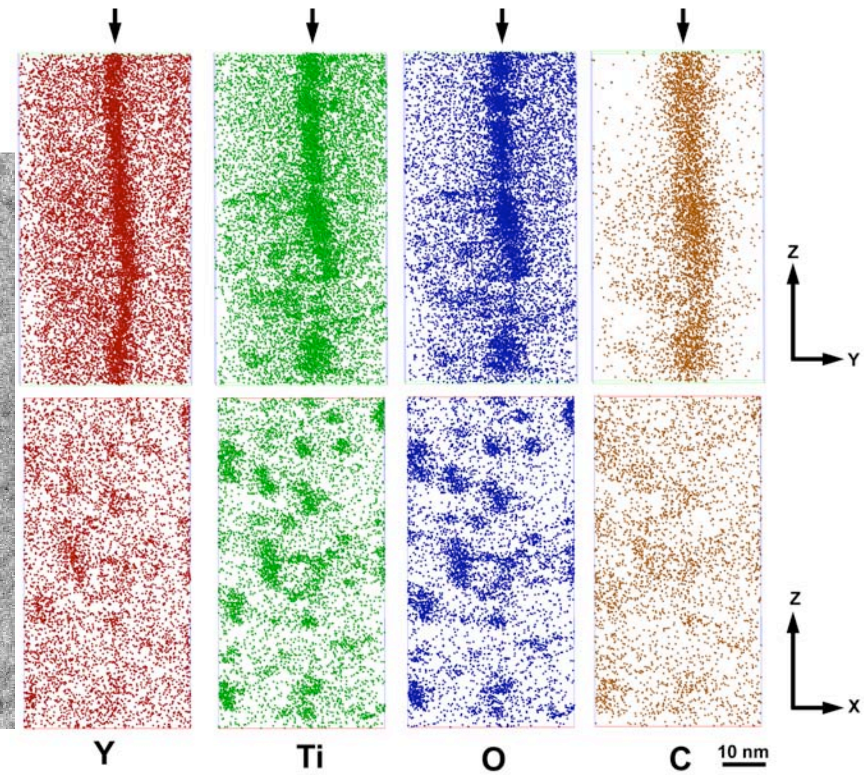
BF TEM



Fe M Jump Ratio

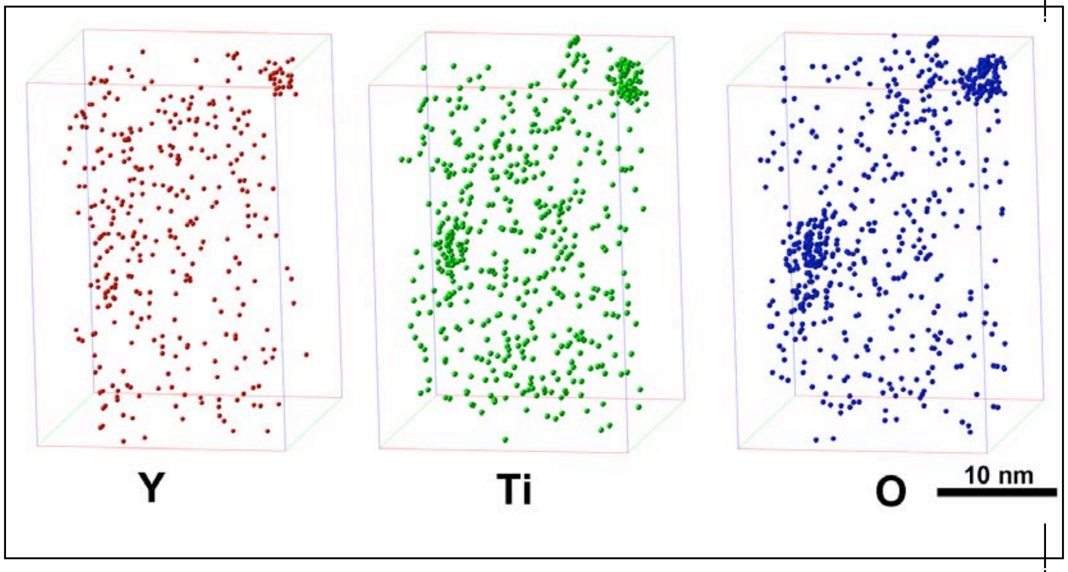


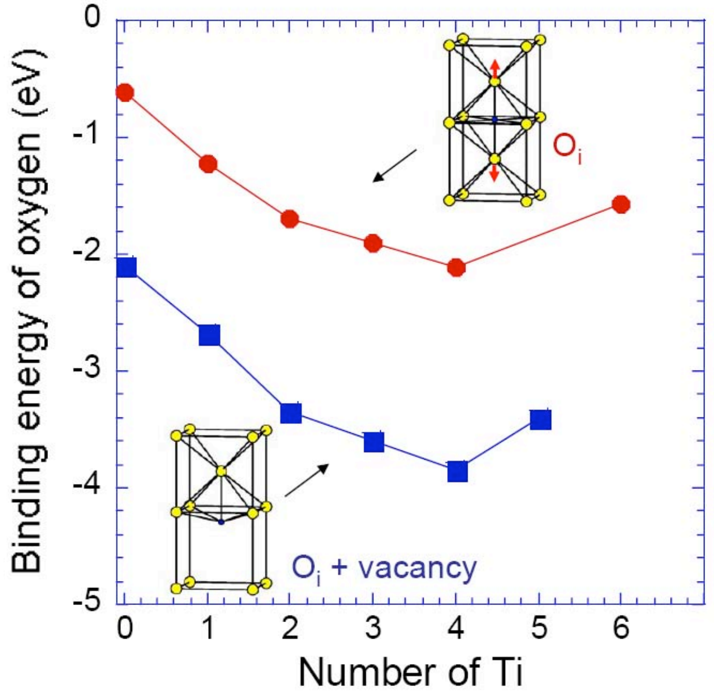
Grain boundary nucleation of NC



- Nano-size grain size with very high grain boundary interfacial area
- High number density of NC in-matrix with λ = 10-15 nm
- High number density of NC decorating grain boundaries

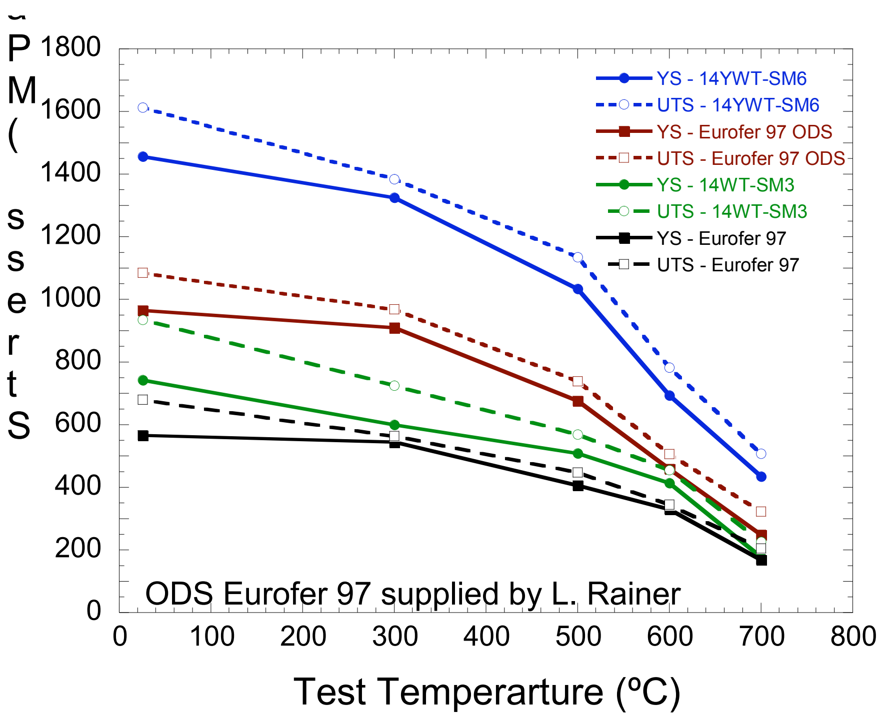
Theory Has Shown That Vacancies Play a Pivotal Role in the Formation and Stability of Nanoclusters in ODS steel

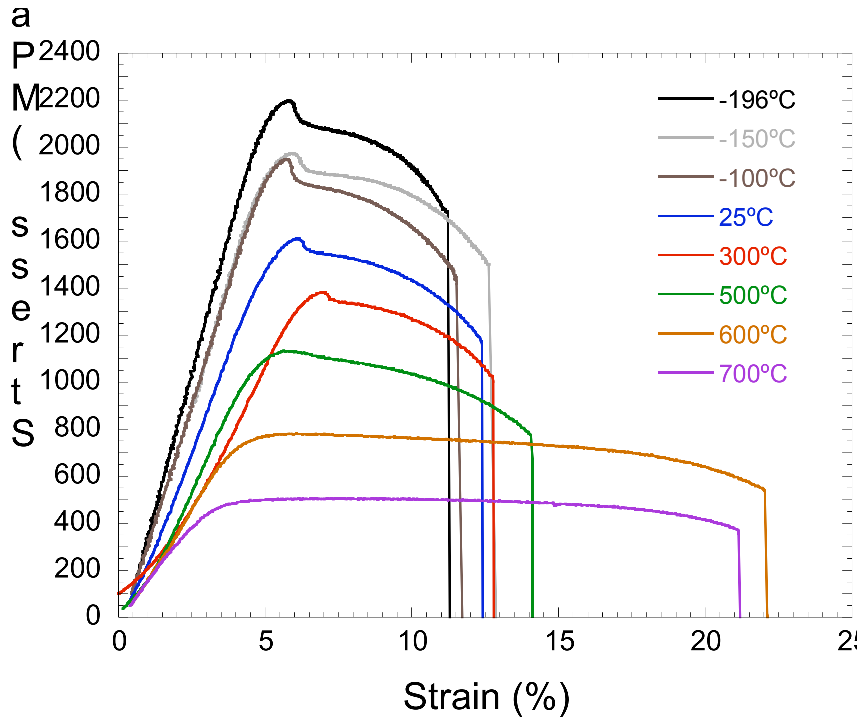




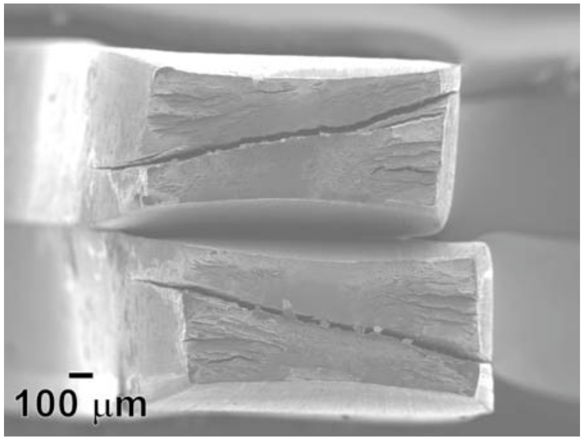
The presence of Ti and vacancy has a drastic effect in lowering the binding energy of oxygen in Fe *(C. L. Fu and M. Krcmar).*

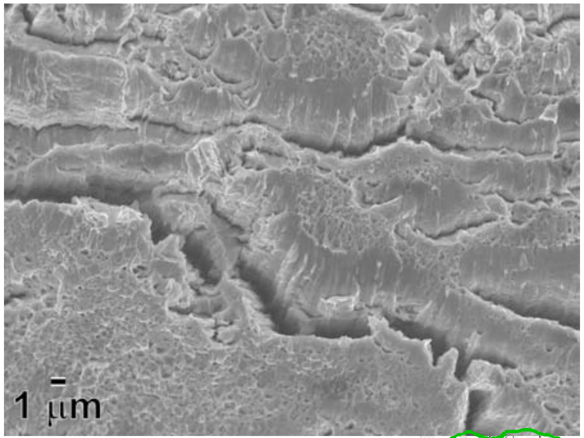
14YWT Shows High Strength and Some Ductility to -196ºC





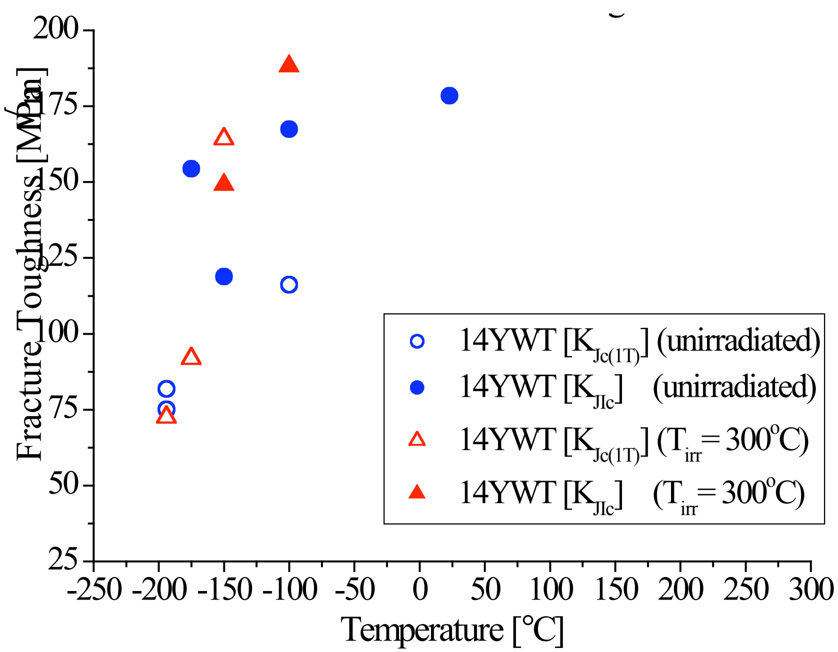
- At -196ºC ($\varepsilon = 10^{-3}s^{-1}$)
  - mixed mode dimple rupture-cleavage failure
  - reduction in area = 43%
  - σ_f = 3.0 GPa
  - T.E. = ~7%

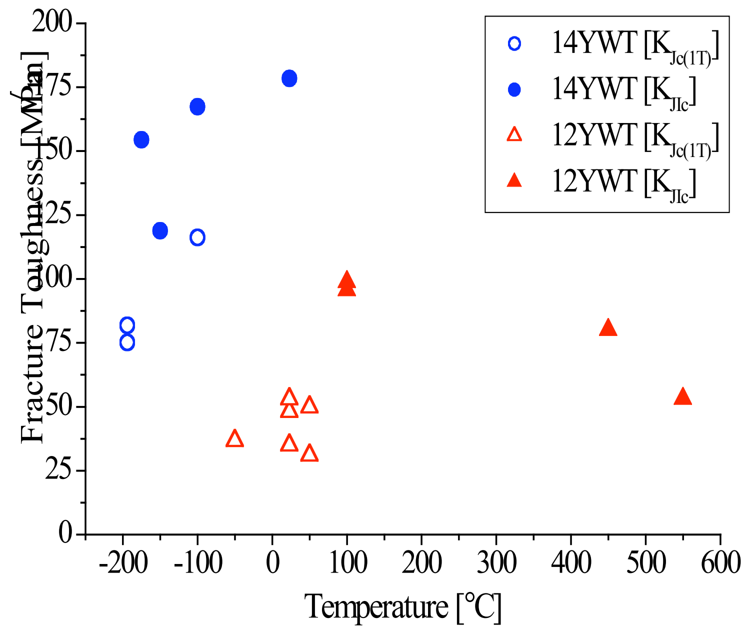




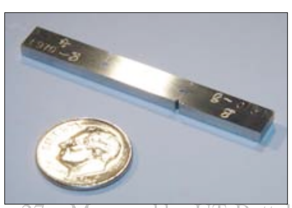
High Fracture Toughness Achieved in 14YWT

- The fracture toughness of 14YWT is much better than that of 12YWT
- The DBTT is shifted from ~75 ºC for 12YWT to -150 ºC for 14YWT



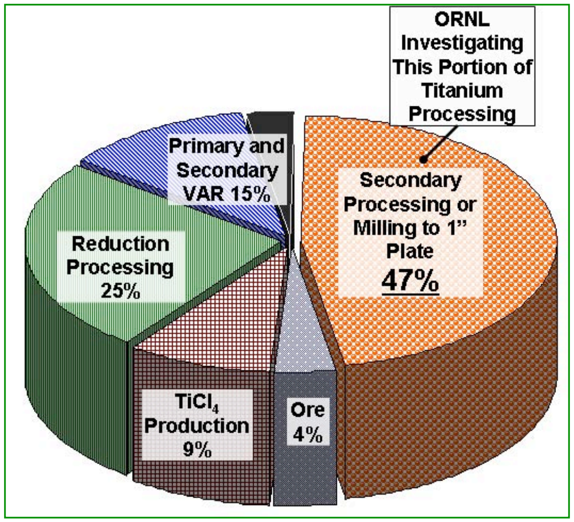


- Neutron irradiation to 1.5 dpa at 300ºC does not degrade the fracture toughness
- More testing is required though…



- L-T Orientation
- Pre-cracked: crack length to width (a/w) ratio of 0.5
- Tested using the unloading compliance method (ASTM 1820-06)
- K_{Jc} for brittle cleavage calculated from critical J-integral at fracture, adjusted to 1-T reference specimen $K_{Jc(1T)}$
- K_{JIc} for ductile deformation behavior calculated from critical J-integral at onset of stable crack growth

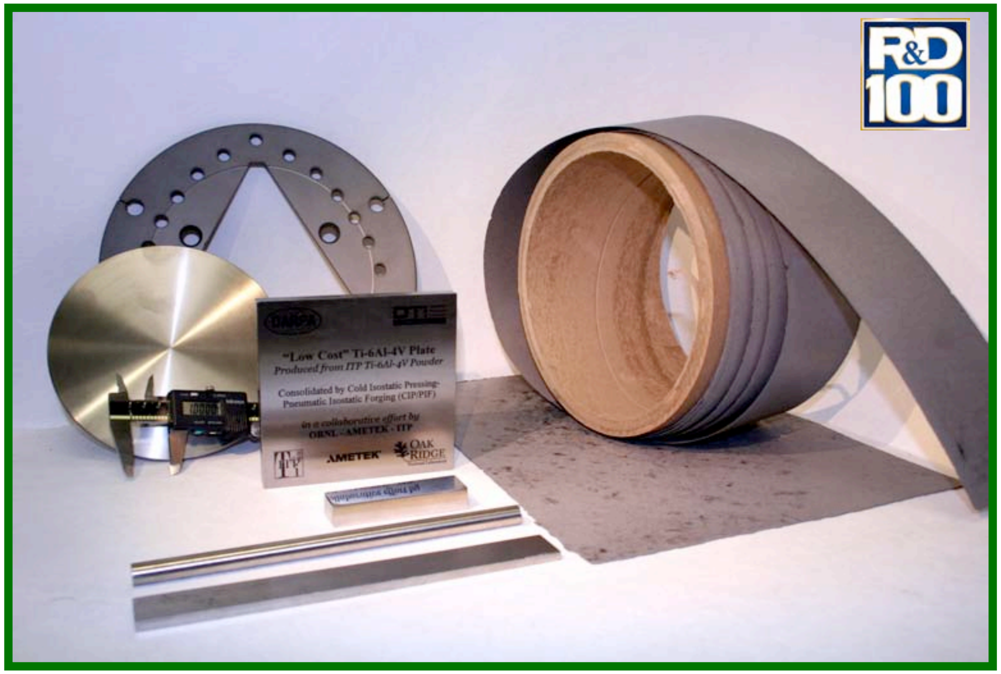
Solid State Consolidation of "Low-Cost" Titanium Powders



Cost Break Down to Produce 1" Thick Titanium Plate Using Kroll – VAR Melted Ti

A.D. Hartman et al. ,JOM September 1998. pp. 16-19

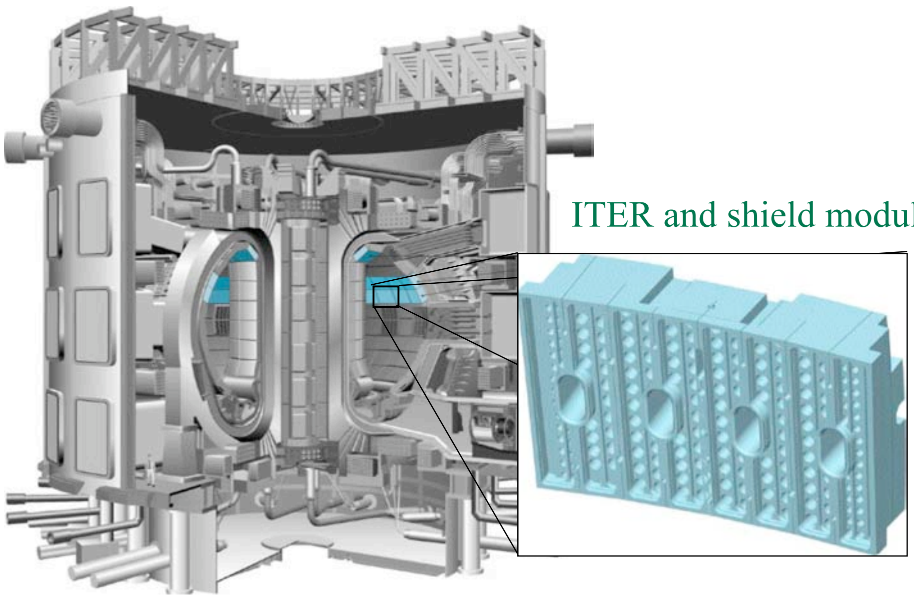
- **Potential reduced cost of plate, sheet, and near net shapes by 50 to 90%**
- **Scrap reduced from 50% (conventional material) to less than 5% for new low cost titanium**
- **Demonstrated and exceeded "wrought" material performance parameters**

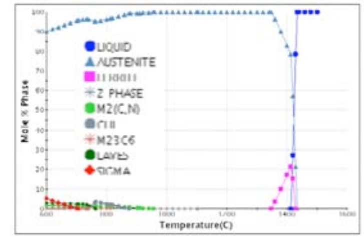


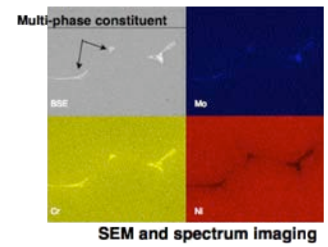
Solid State Consolidated Plate, Bar, Sheet, and Net Shape Components Produced from New "Low Cost" Titanium Powders

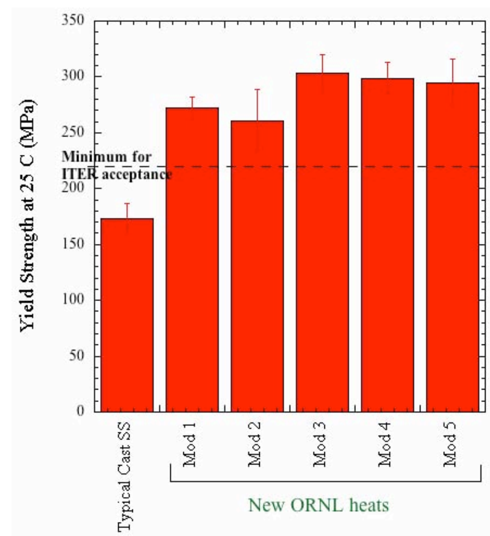
W.H. Peter, C.A. Blue, et al.

Development of low-cost, high-performance cast stainless steel for ITER structures


ITER and shield module







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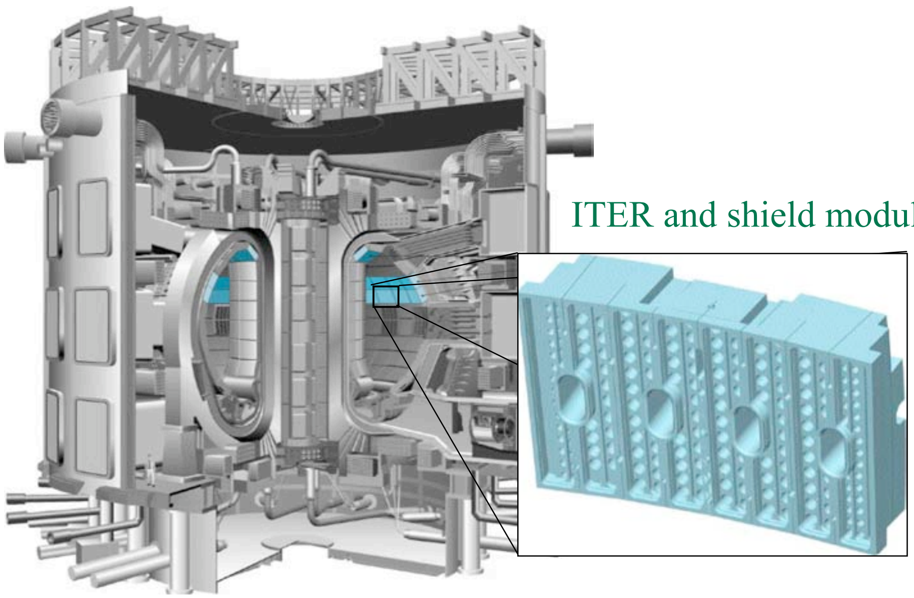

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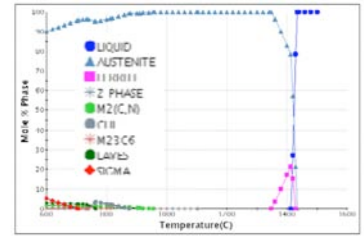
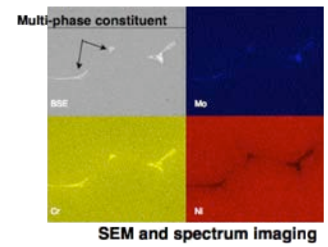
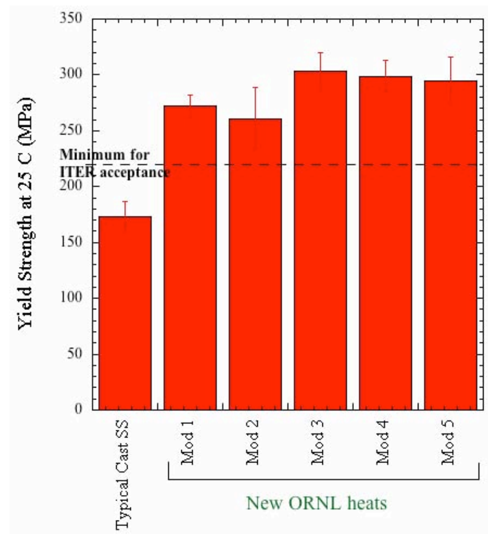
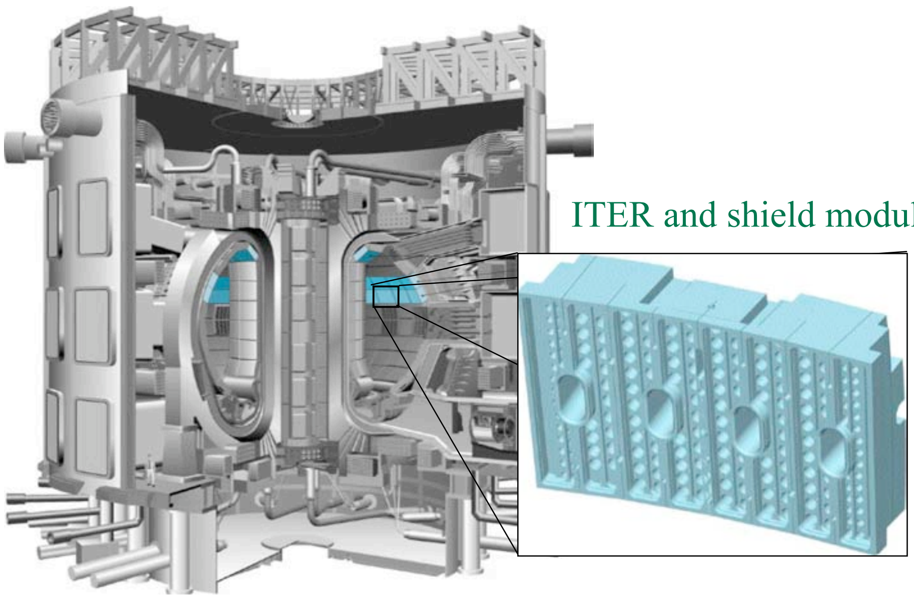






- The US contribution to the ITER project involves many complex stainless steel components.
- Casting methods may considerably reduce time and cost associated with fabrication.
- However, greater strength is needed for the cast material to be accepted for use in ITER.

Development of low-cost, high-performance cast stainless steel for ITER structures



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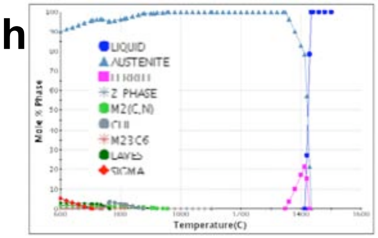

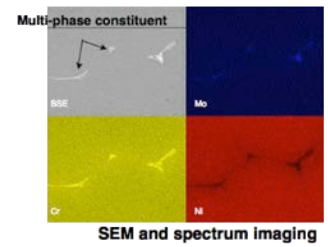

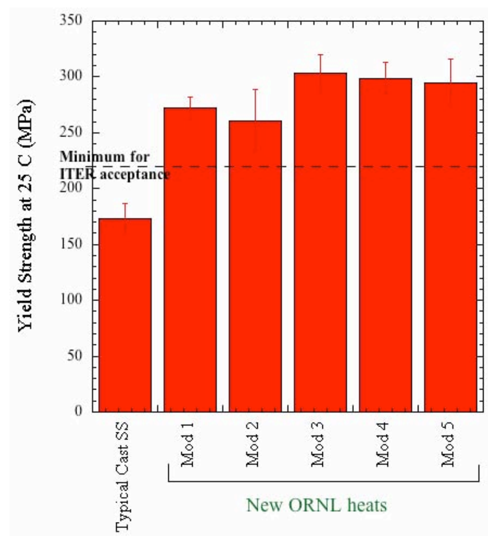

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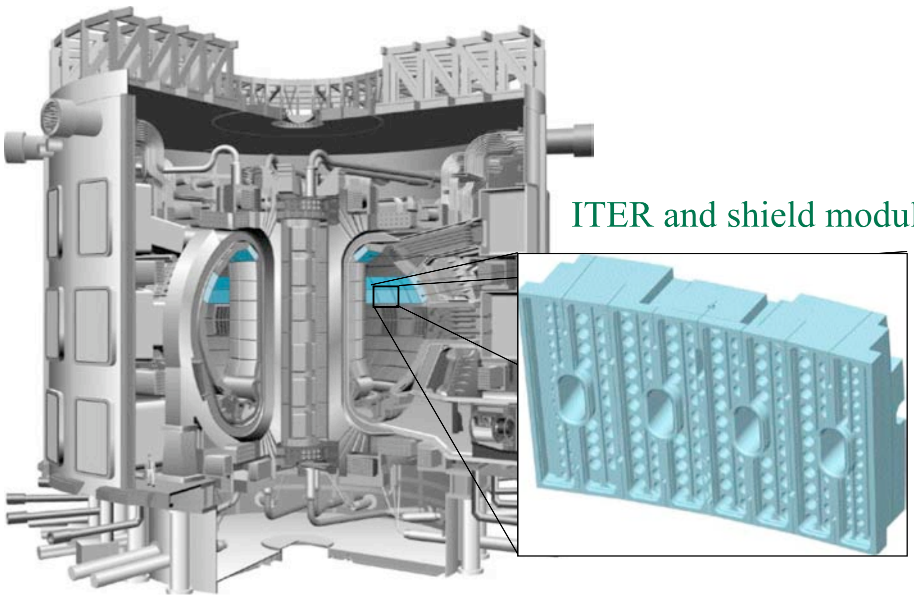

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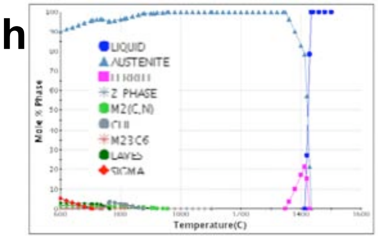
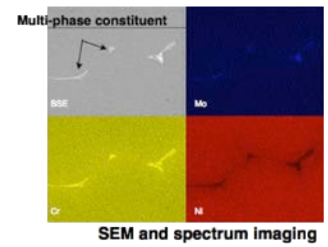
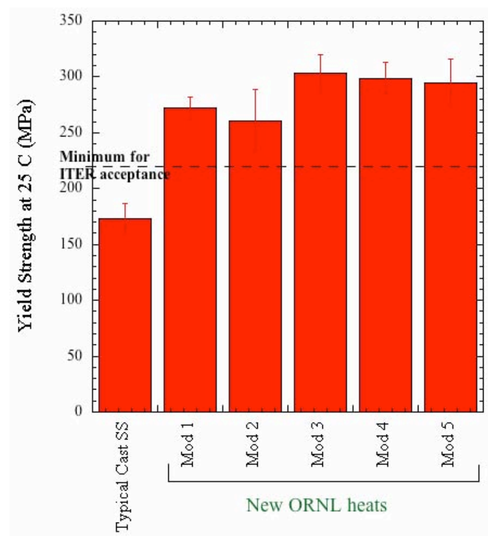
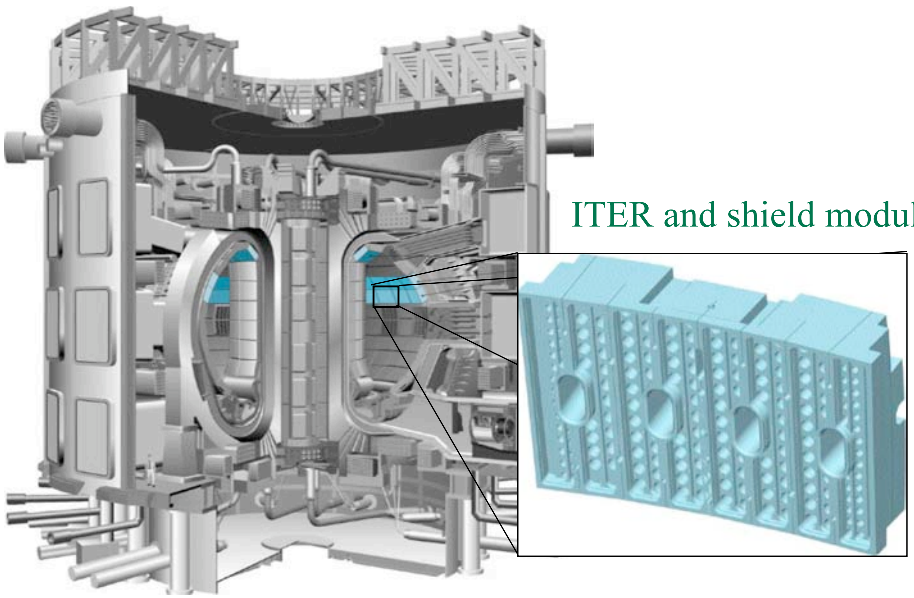






Impact testing at 200-300°C. Samples do not break.

Development of low-cost, high-performance cast stainless steel for ITER structures



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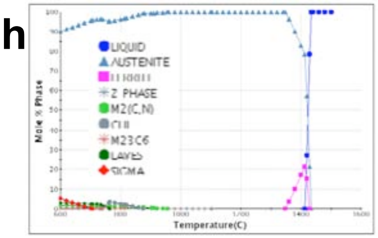
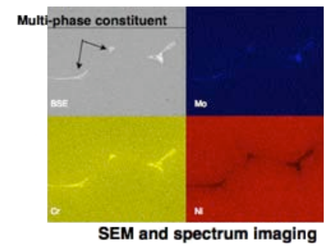
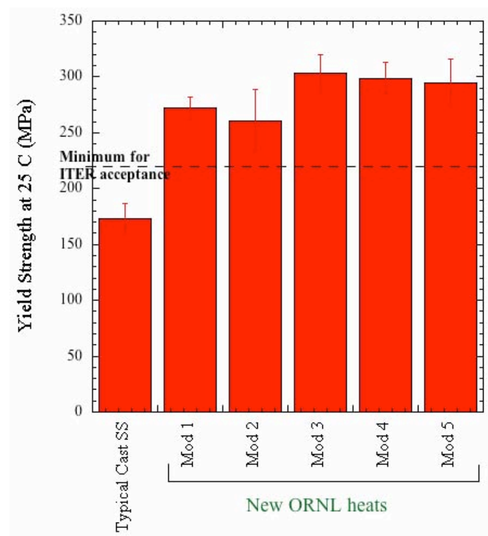


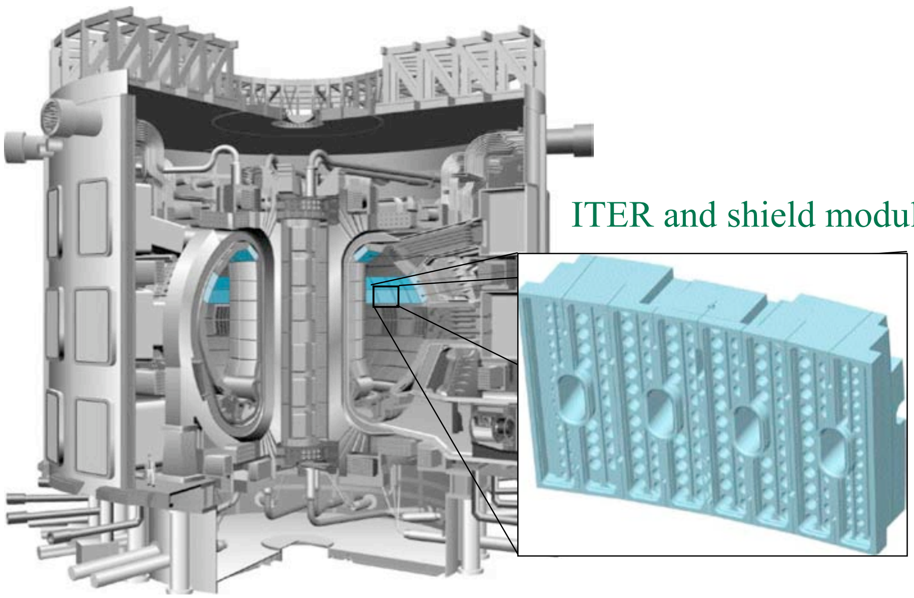




Impact testing at 200-300°C. Samples do not break.

•Improved steels exhibit greater strength and performance than typical cast grades and meet ITER criteria.

Development of low-cost, high-performance cast stainless steel for ITER structures



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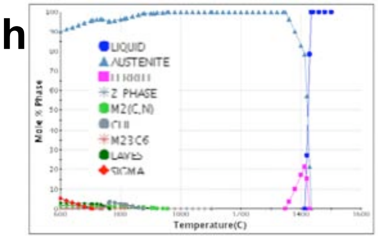
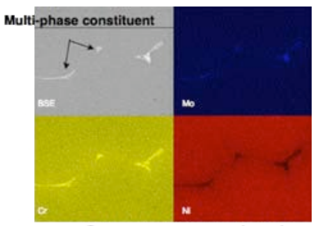
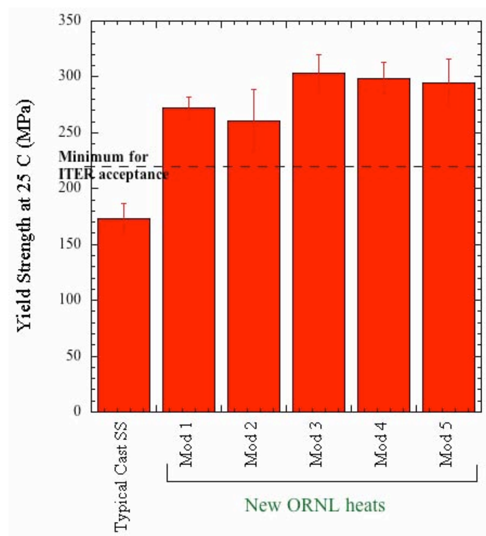




SEM and spectrum imaging



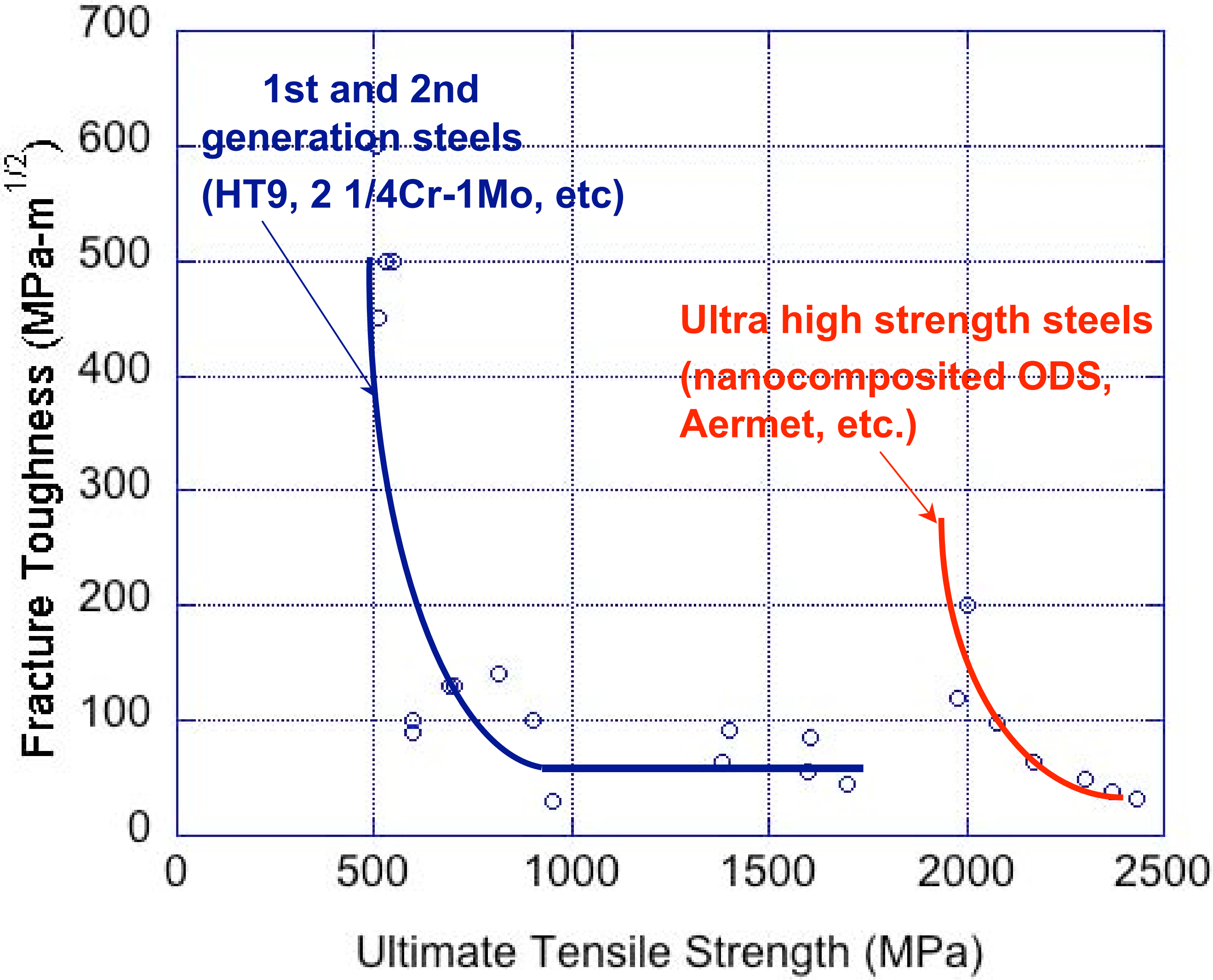
Tensile tests at 25°C

Impact testing at 200-300°C. Samples do not break.

•Improved steels exhibit greater strength and performance than typical cast grades and meet ITER criteria.

Recent research suggests high-strength steels that retain high-toughness are achievable

- Generally obtained by producing high density of nanoscale precipitates and elimination of coarse particles that serve as stress concentrator points



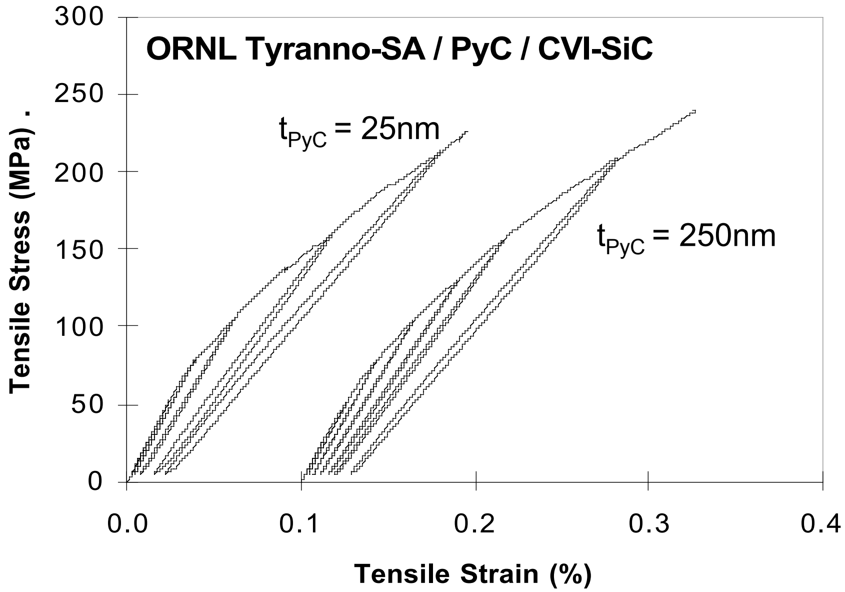
Potential Alloy Development Options for Tungsten

- Solute additions that beneficially modify the elastic constants (Poisson ratio effect) in order to improve ductility and fracture toughness
- Nanoscale engineering of internal boundaries
  - Coherent twin boundaries for strengthening (instead of grain boundaries); cf. K. Lu et al., Science 324 (2009) 349
- Create a high density of nanoscale precipitates for radiation resistance

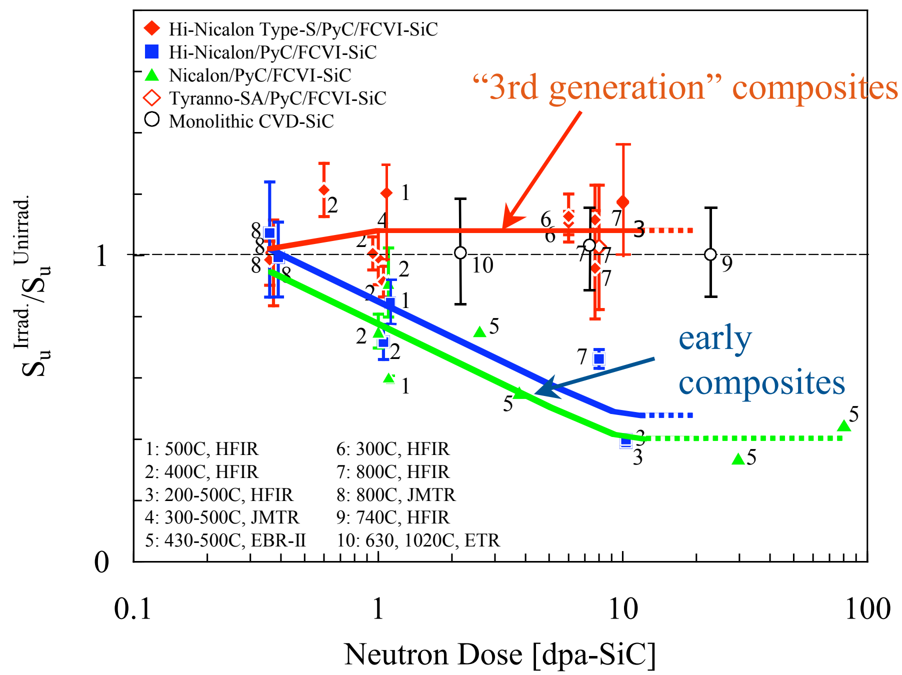
SiC/SiC Composites Development (fusion program)

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**
- **Extensive engineering data generation for irradiated properties (including statistical strength) is planned (prior studies utilized simple qualitative screening tests)**



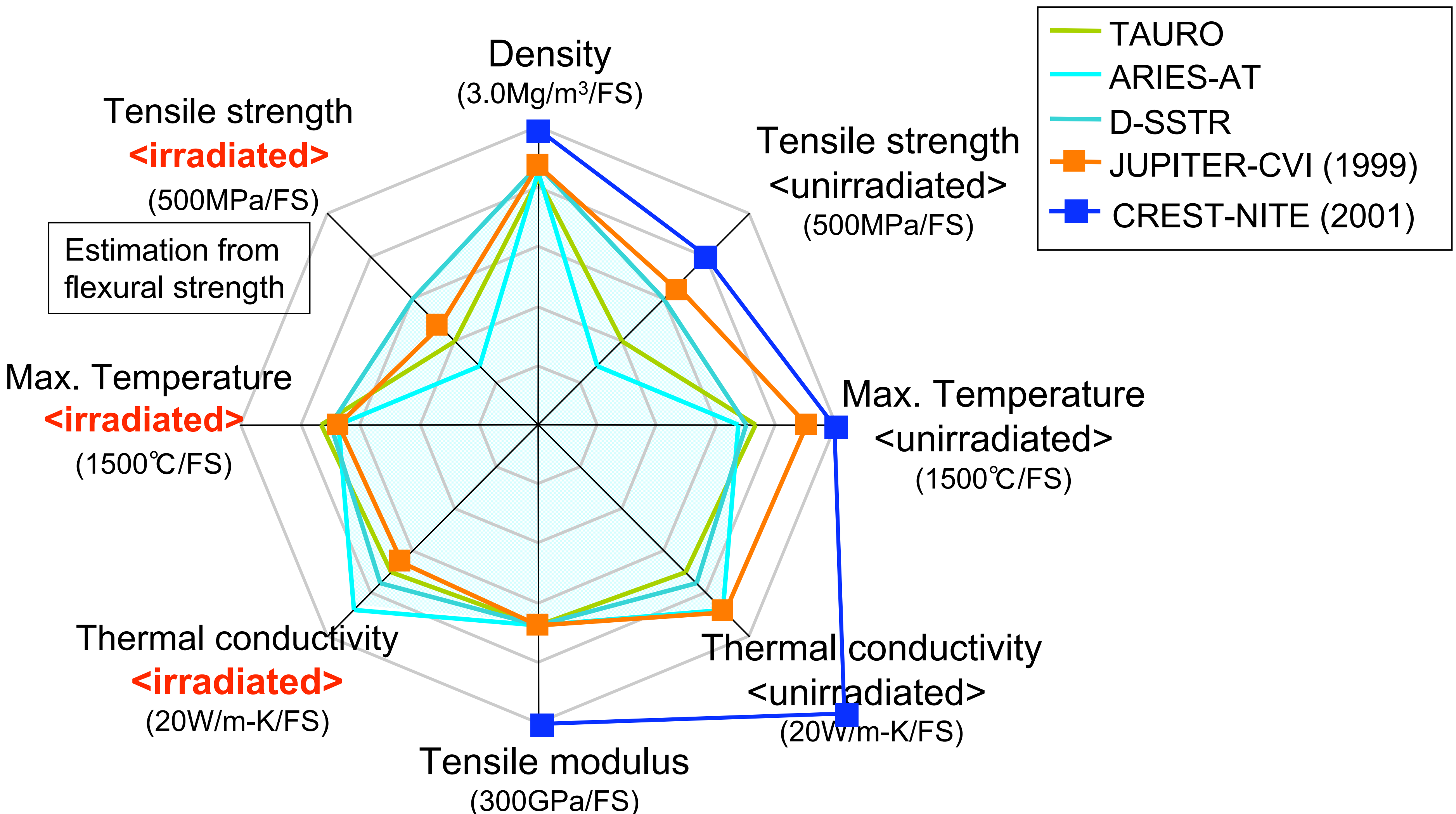
Bend strengths of irradiated "3rd generation" composites show **no degradation** up to 10 dpa



L.L. Snead, Y. Katoh, T. Nozawa et al.

Future work: advanced matrix infiltration R&D; joining; hermetic coatings; SiC/graphite composites, etc.

Current Status of SiC/SiC Composites

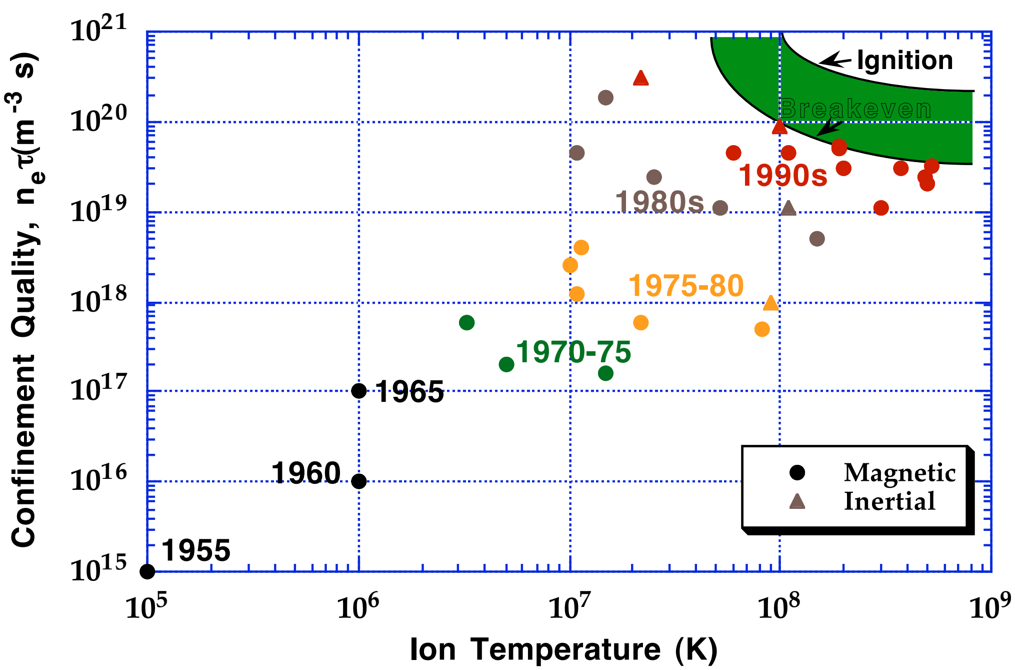


A. Kohyama

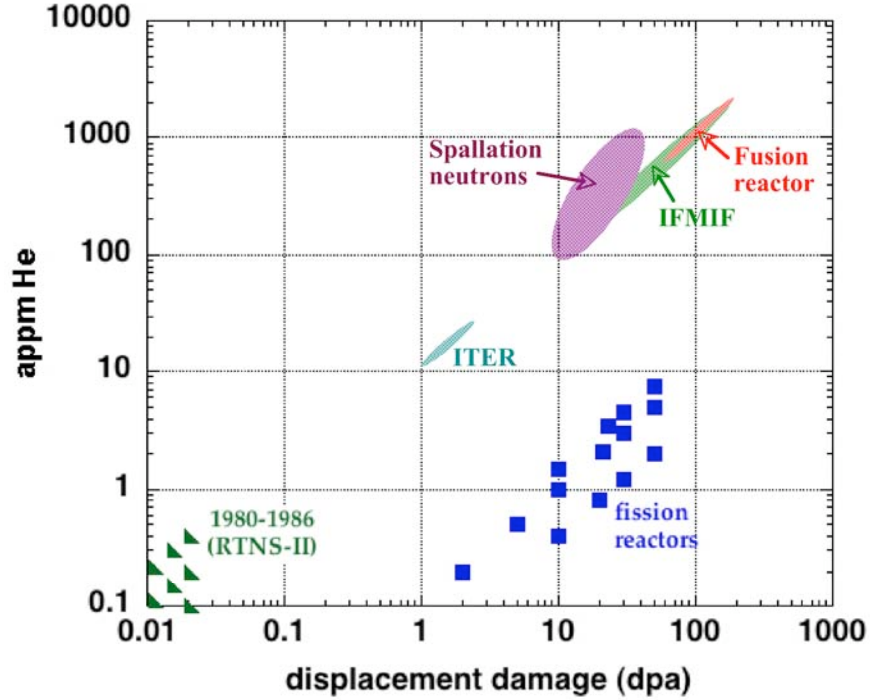
Fusion materials research must rely heavily on modeling due to inaccessibility of fusion-relevant operating regime

- **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**

Plasma physics experimental achievements



Summary of Helium and Displacement Damage Levels for Ferritic Steels



Conclusions

- Existing structural materials are not ideal for advanced nuclear energy systems due to limited operating temperature windows
  - May produce technically viable design, but not with desired optimal economic attractiveness
- Substantial improvement in the performance of structural materials can be achieved in a timely manner with a science-based approach
- Design of nanoscale features in structural materials confers improved mechanical strength and radiation resistance
  - Such nanoscale alloy tailoring is vital for development of radiation-resistant structural materials for fusion energy systems
  - Experimental validation will ultimately require testing in appropriate fusion-relevant facilities