Fusion Materials Research

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Materials Science & Technology Division

Oak Ridge National Laboratory, Oak Ridge, TN

Fusion Power Associates Annual Meeting

Fusion Energy: Preparing for the NIF and ITER Era

Oak Ridge, TN, December 4-5, 2007

Contributors: Roger Stoller, Yuri Osetsky, David Hoelzer, Jeremy Busby, Mike Miller, John Vitek, Yoshi Matsukawa (ORNL);

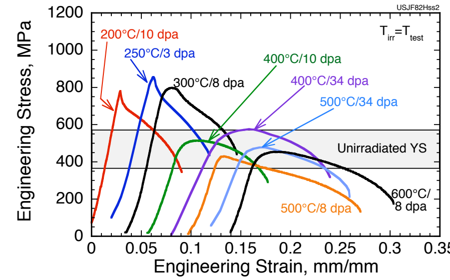
Rick Kurtz (PNNL), Bob Odette (UCSB), Brian Wirth (UCB)

Outline

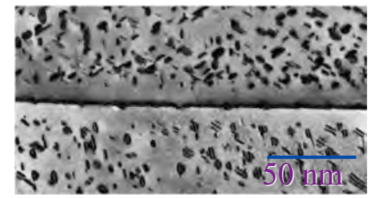
- **Effects of neutron bombardment on structural materials**
  - **"Five scourges" of radiation**
- **Prospects for development of high-performance radiation-resistant materials**
  - **Crucial role of nanoscale architectures**
- **Selected grand challenges for fusion materials science**

Radiation Damage can Produce Large Changes in Structural Materials

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

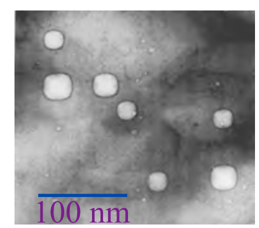


- **Phase instabilities from radiation-induced precipitation (0.3-0.6 T_M, >10 dpa)**

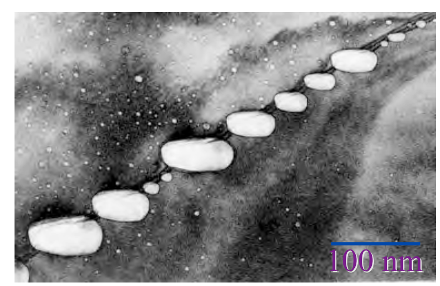


- **Irradiation creep ($<0.45\ T_M$, >10 dpa)**

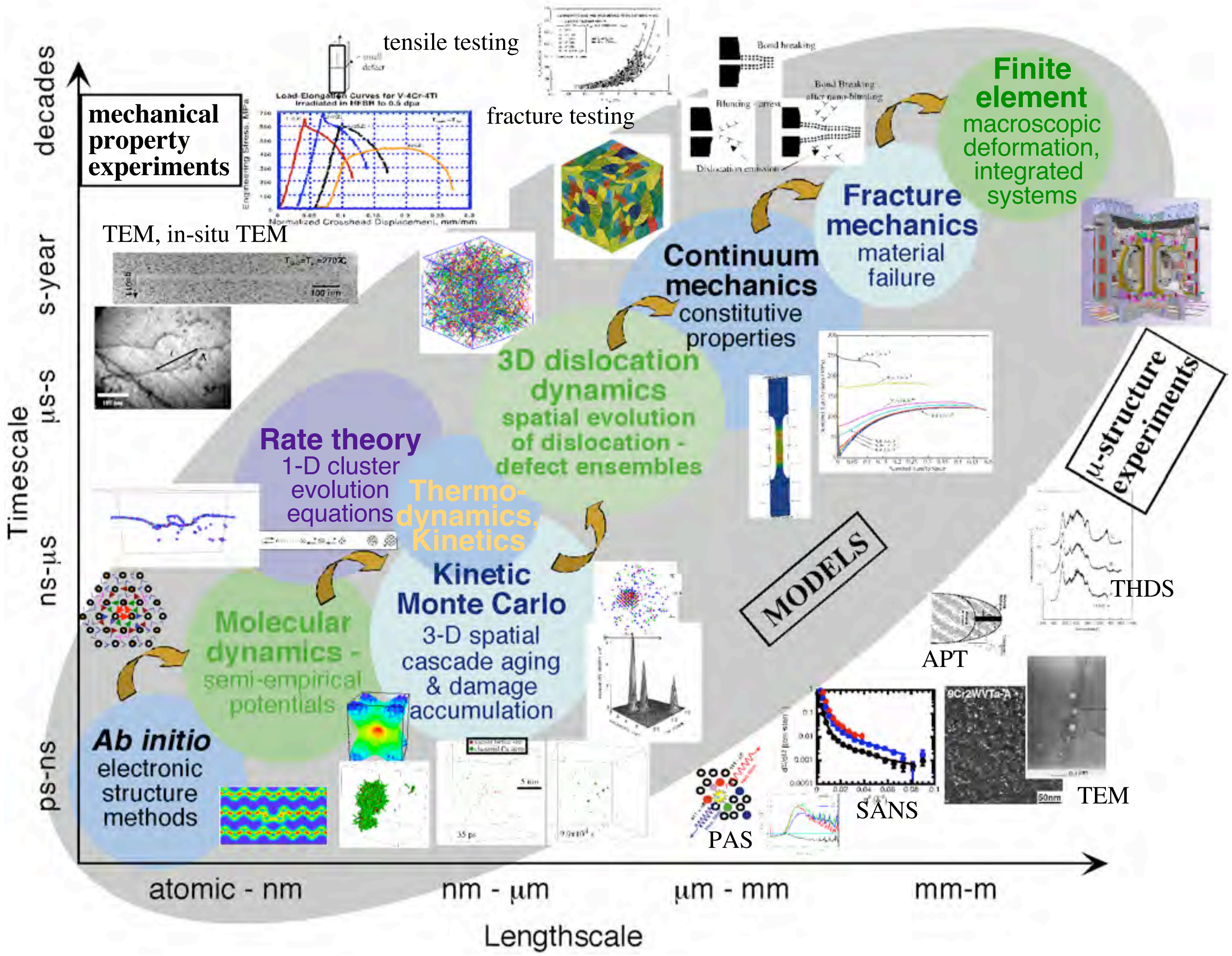
- **Volumetric swelling from void formation (0.3-0.6 T_M, >10 dpa)**



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



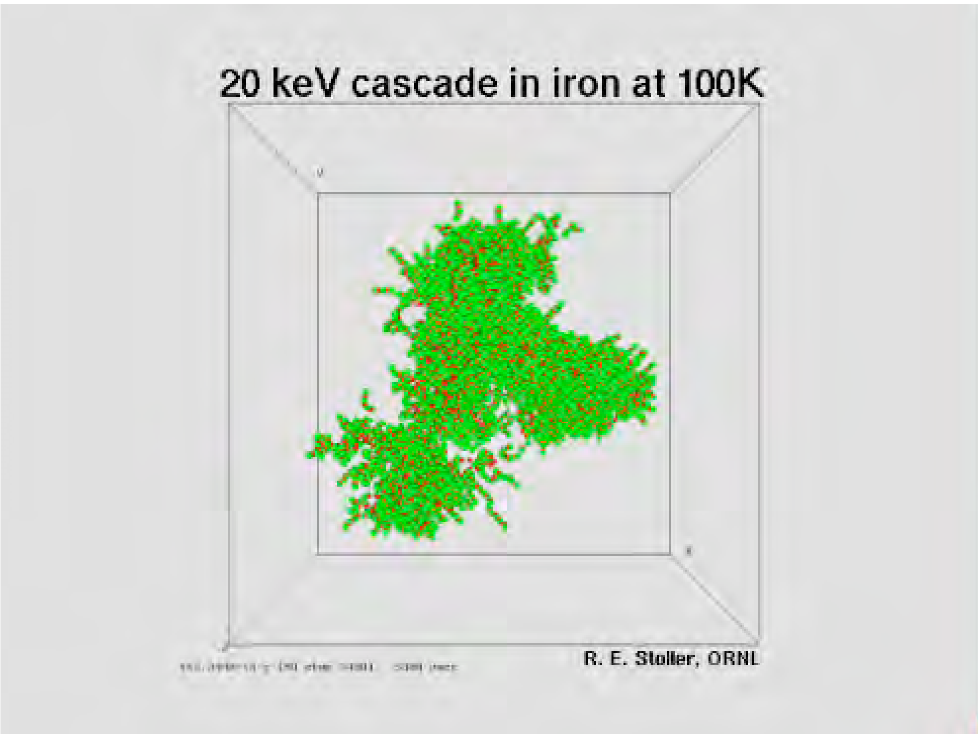
Radiation damage is inherently multiscale with interacting phenomena ranging from fs to decades and nm to m

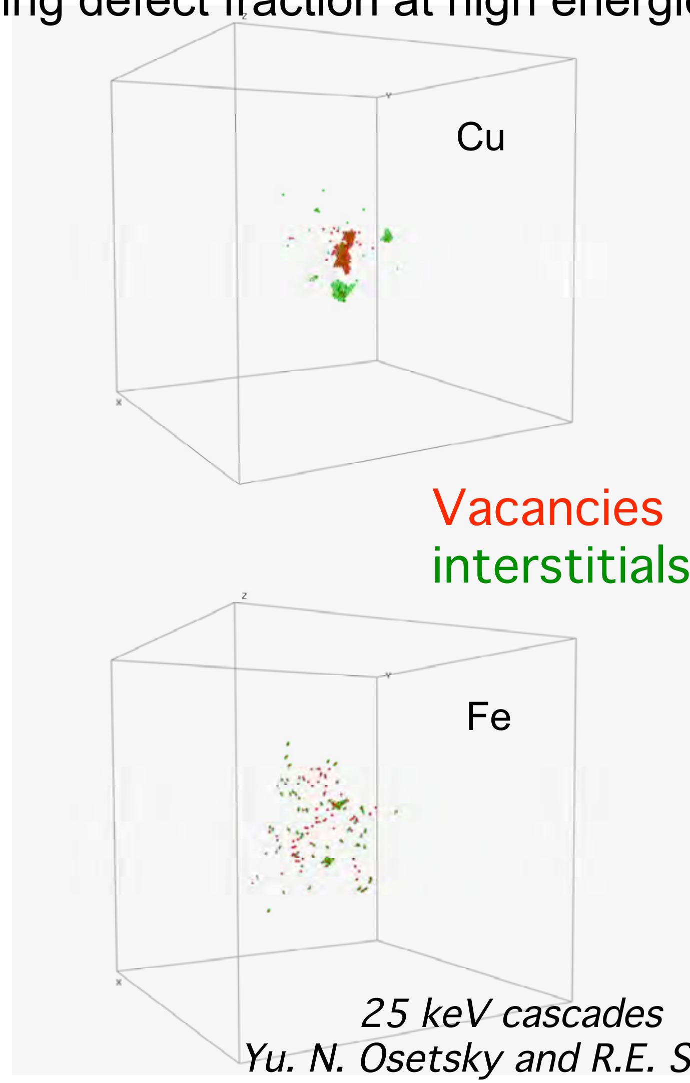


B.D. Wirth, UC-Berkeley

Recent Molecular Dynamics simulations have provided key fundamental information on defect production

- Effect of knock-on atom energy and crystal structure on defect production
- subcascade formation leads to asymptotic surviving defect fraction at high energies

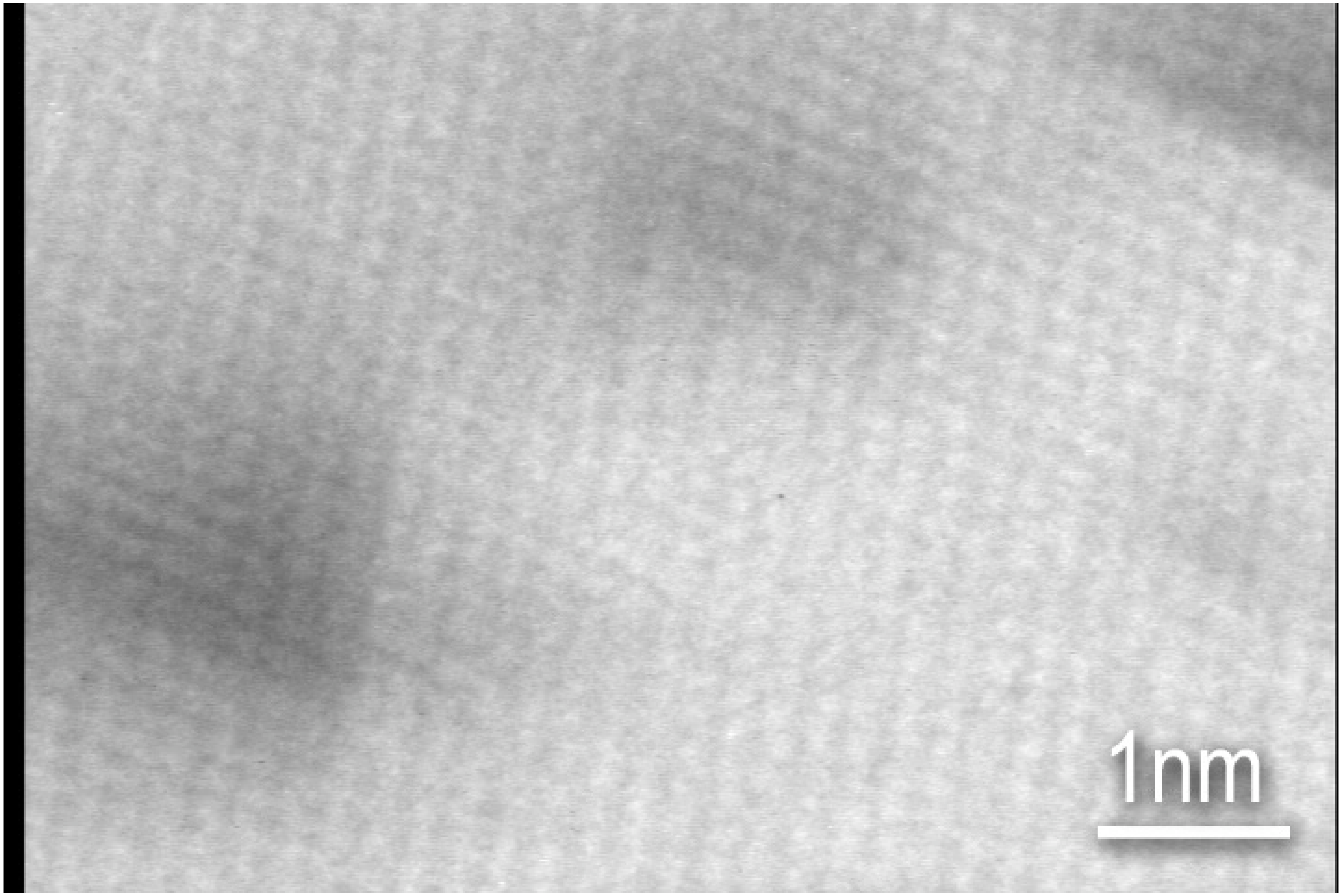




Large vacancy clusters are not directly formed in BCC metal displacement cascades

Experimental validation of Molecular Dynamics prediction of 1-D point defect cluster motion

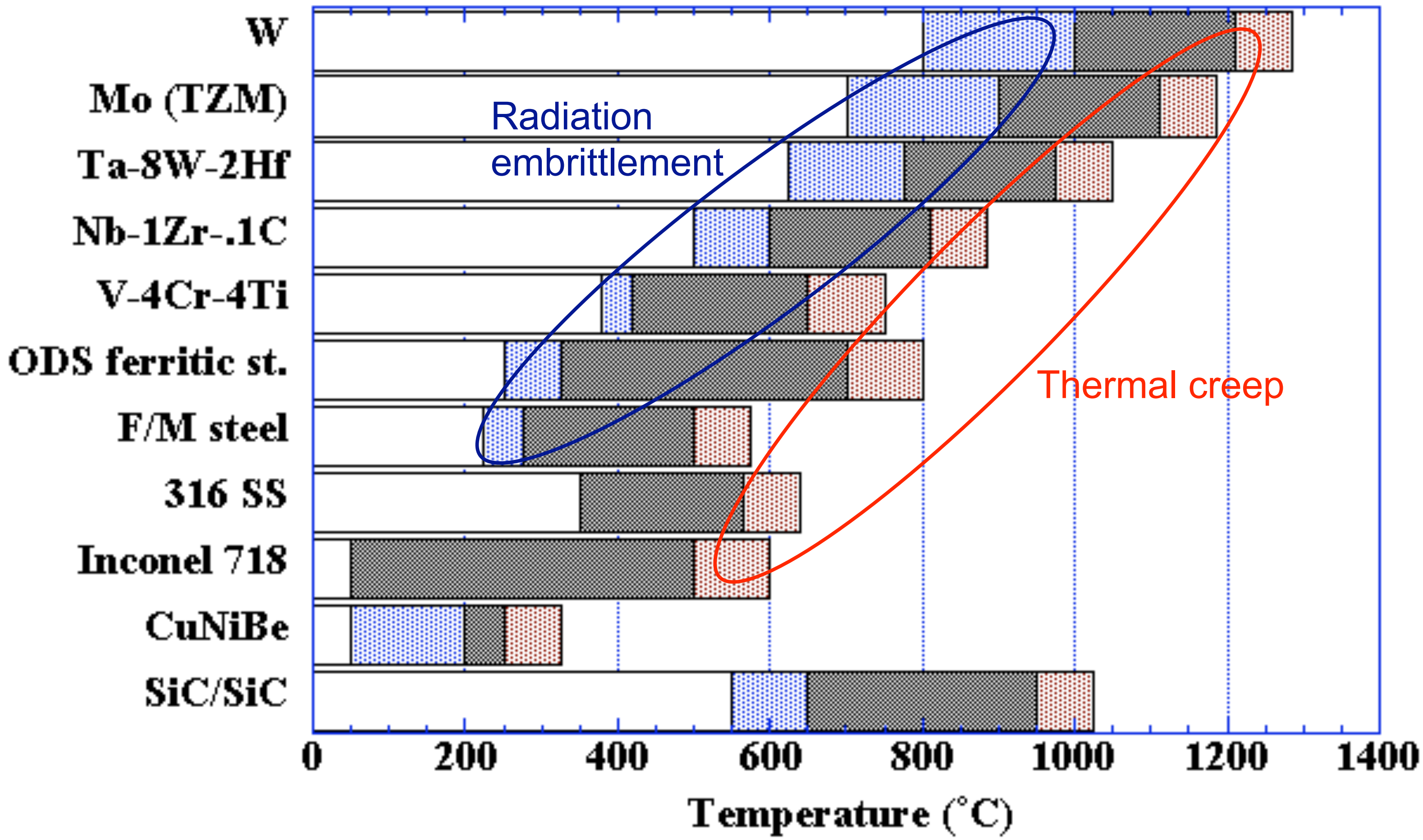
- 1-D glissile vacancy cluster observed to be trapped by stress field of two adjacent SFTs; eventually converts to an SFT



Y. Matsukawa and S.J. Zinkle, Science 318 (2007) 959

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

Structural Material Operating Temperature Windows: 10-50 dpa



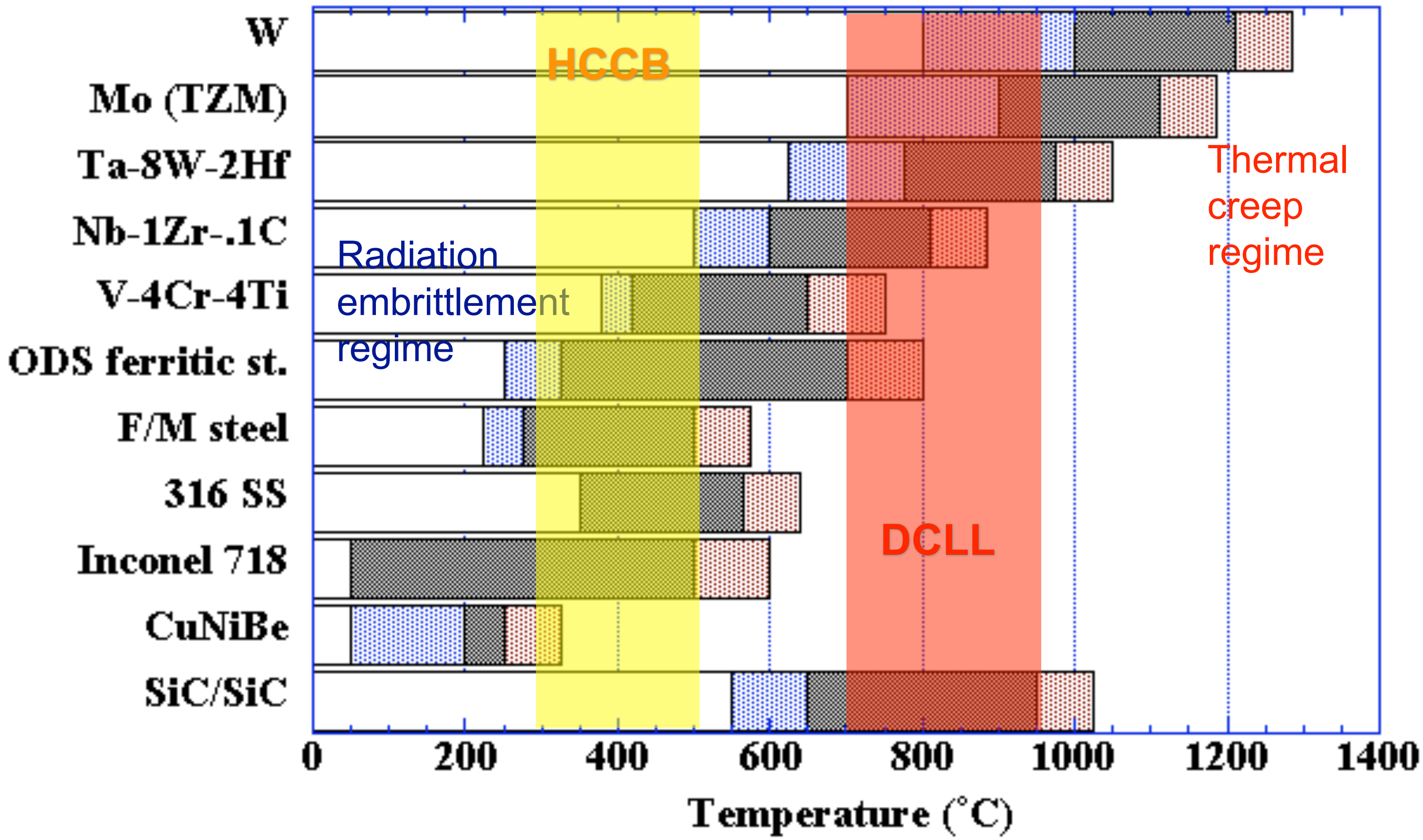
$\eta_{Carnot}=1-T_{reject}/T_{high}$

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

New structural materials with temperature windows >300^{o}C would accelerate exploration of fusion concepts

Structural Material Operating Temperature Windows: 10-50 dpa

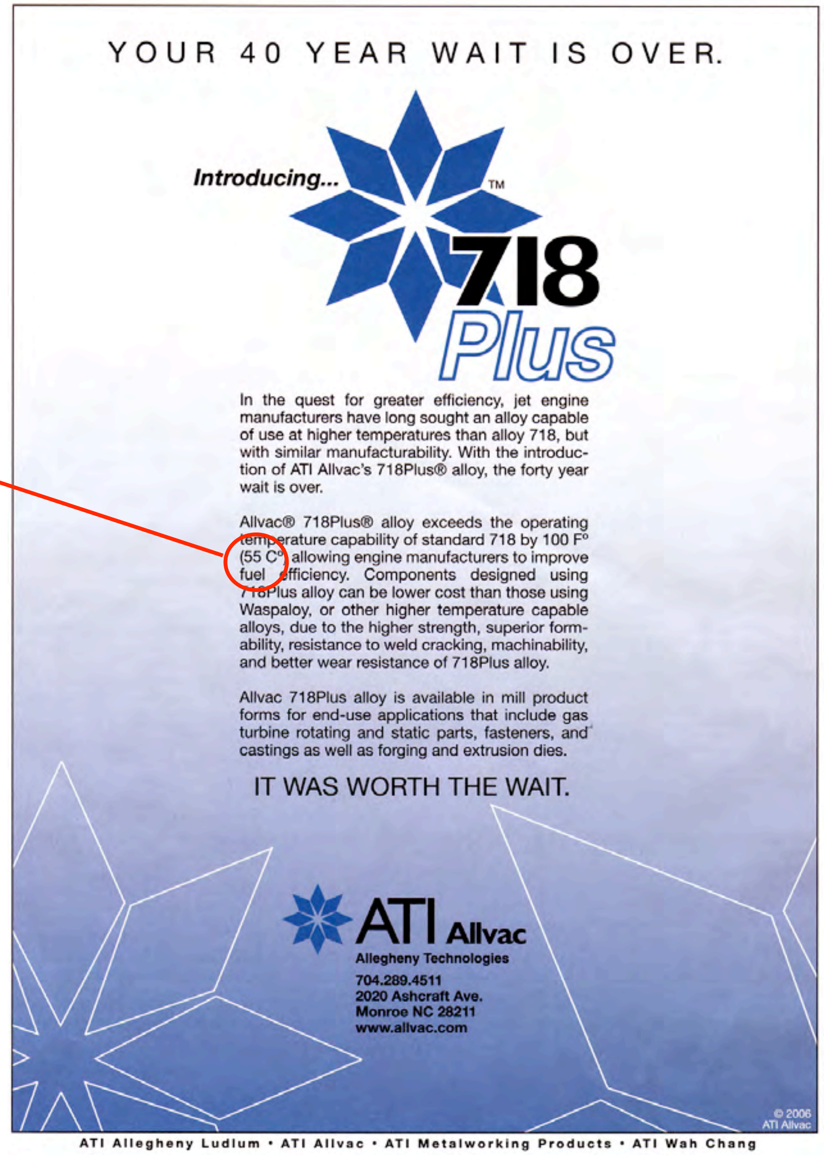


Note: two of numerous proposed fusion concepts are depicted

Conventional Alloy Development is a Slow and Expensive Endeavor

- 55^oC improvement in upper operating temperature limit after 40 years development!!

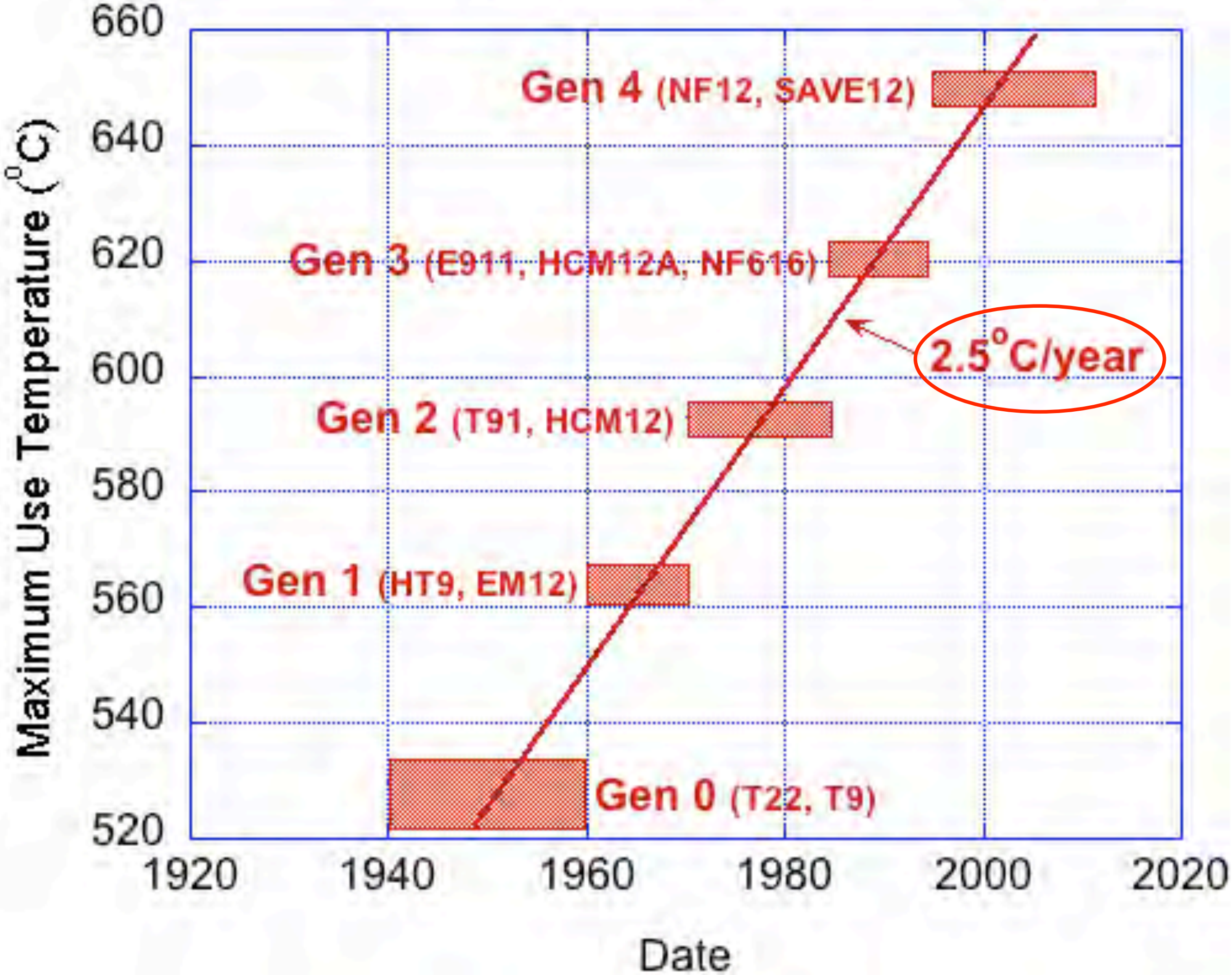
- Improvement in computational thermodynamics could accelerate development of new materials



Advanced Materials & Processes (2006)

Historical development of improved high-temperature steels has exhibited slow and steady progress

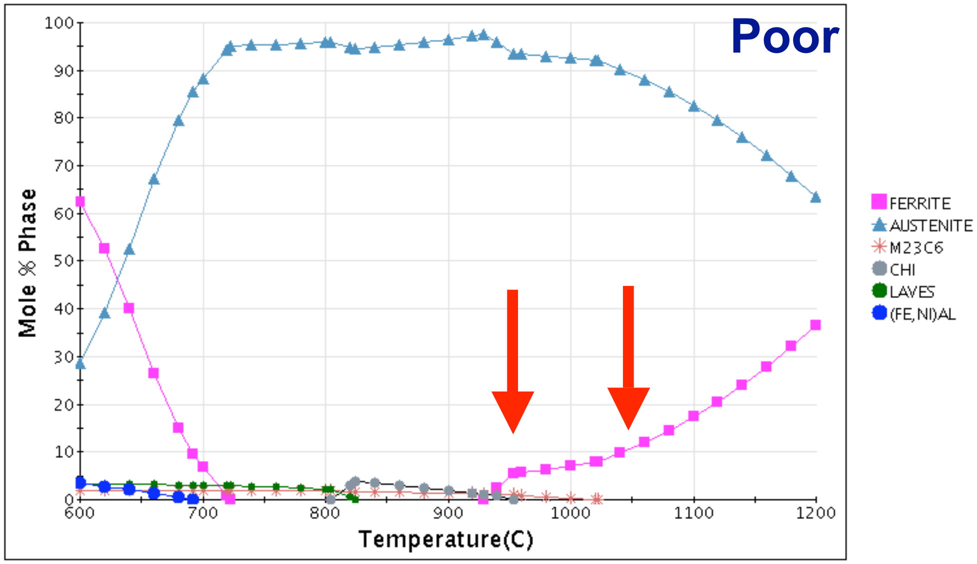
Based on R. Viswanathan, Adv. Mat. Proc. 162 (2004) 73



Modern computational thermodynamics reveals pathway to improve precipitation hardened stainless steels

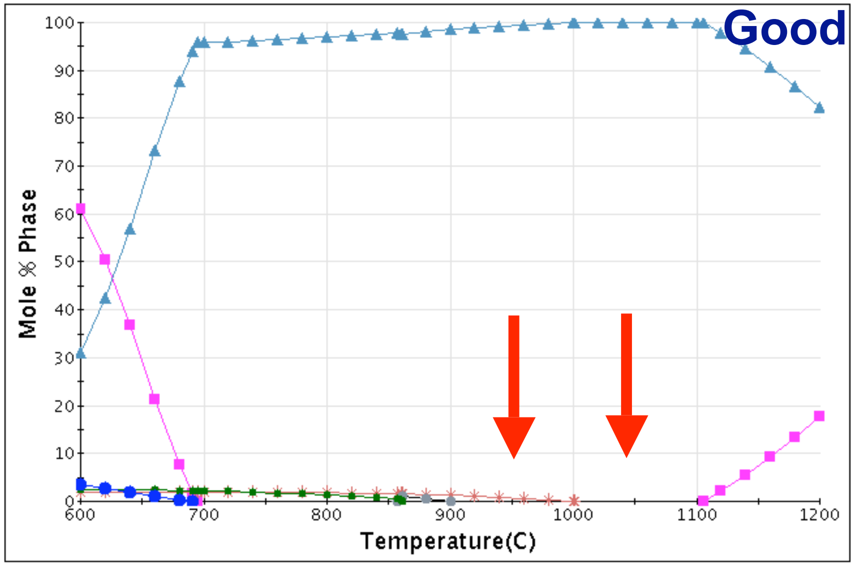
Both 15%Cr-7%Ni alloys are within allowable chemical composition for PH15-7 Mo precipitation hardened stainless steel (UNS S15700)

Fe-1.0Al-0.09C-15.0Cr-1.0Mn-2.5Mo-7.25Ni-1.0Si wt(%)



"average" Cr, Mo, Ni

Fe-1.0Al-0.09C-14.0Cr-1.0Mn-2.0Mo-7.5Ni-1.0Si wt(%)



"low" Cr, Mo and "high" Ni

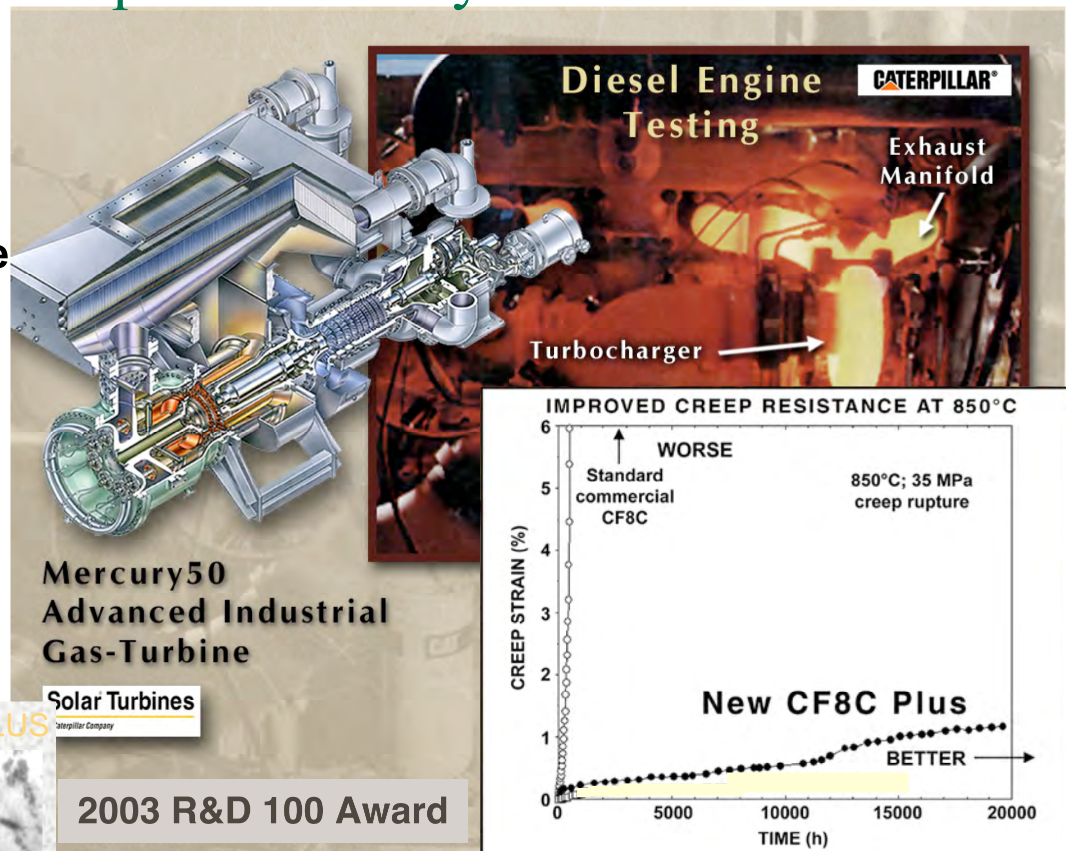
UNS S15700: 14.0-16.0 Cr, 6.50-7.75 Ni, 2.0-3.0 Mo

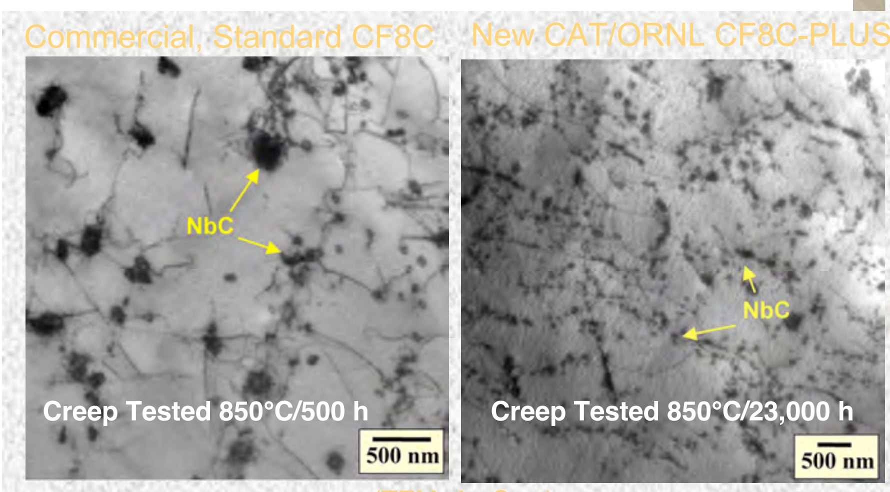
- **Within alloy specifications, large differences can be expected with standard heat treatment**
- **Computational thermodynamics calculations can lead to composition and heat treatment optimization**

J.M. Vitek

Microstructural Evolution In Irradiated Stainless Steels Provided the Key for Developing Improved High Temperature Alloys

- *Reactant Effects* **(ie. Ti, V+Nb enhance MC formation)**
- *Catalytic Effects* **(ie. Si enhances Fe_2Mo or M_6C)**
- *Inhibitor Effects* **(ie. C, P or B retard the formation of Fe_2Mo or FeCr sigma phase during aging, G-phase during irradiation)**
- *Interference Effects* **(ie. N forms TiN instead of TiC; N does not form NbN instead of NbC; therefore C and N can be added with Nb, but not Ti)**





(TEM, As Cast)

Result of microstructural modification:

- **Formation of stable nanoscale MC carbide dispersions to pin dislocations**
- **Resistance to creep cavitation and embrittling grain boundary phases (ie. sigma, Laves)**
- **Resistance to dislocation recovery/ recrystallization**

FreedomCAR and Vehicle Technologies and Distributed Energy and Electricity Reliability Programs of DOE-EERE

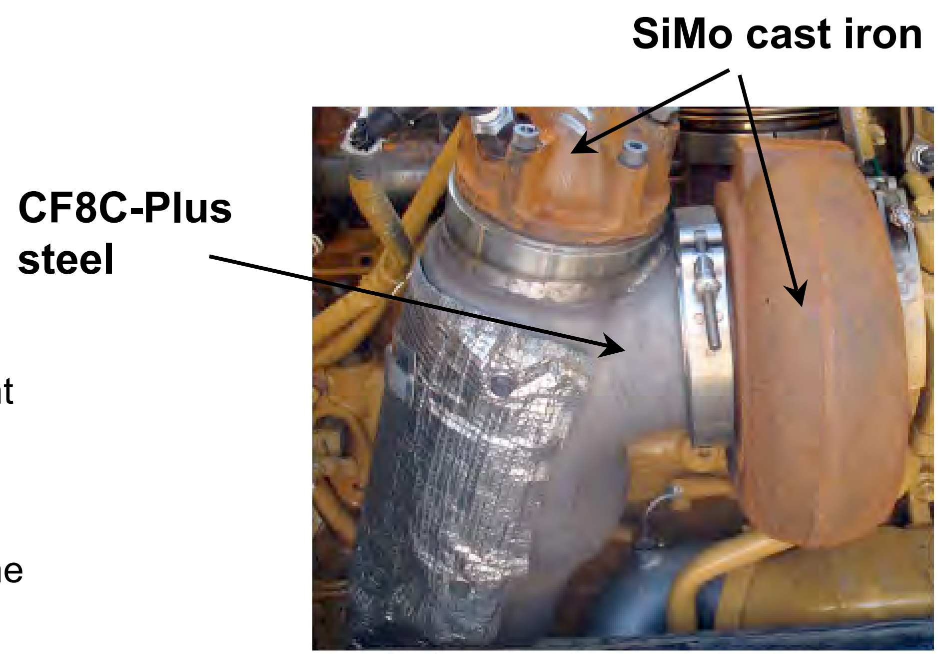
P.J. Maziasz

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

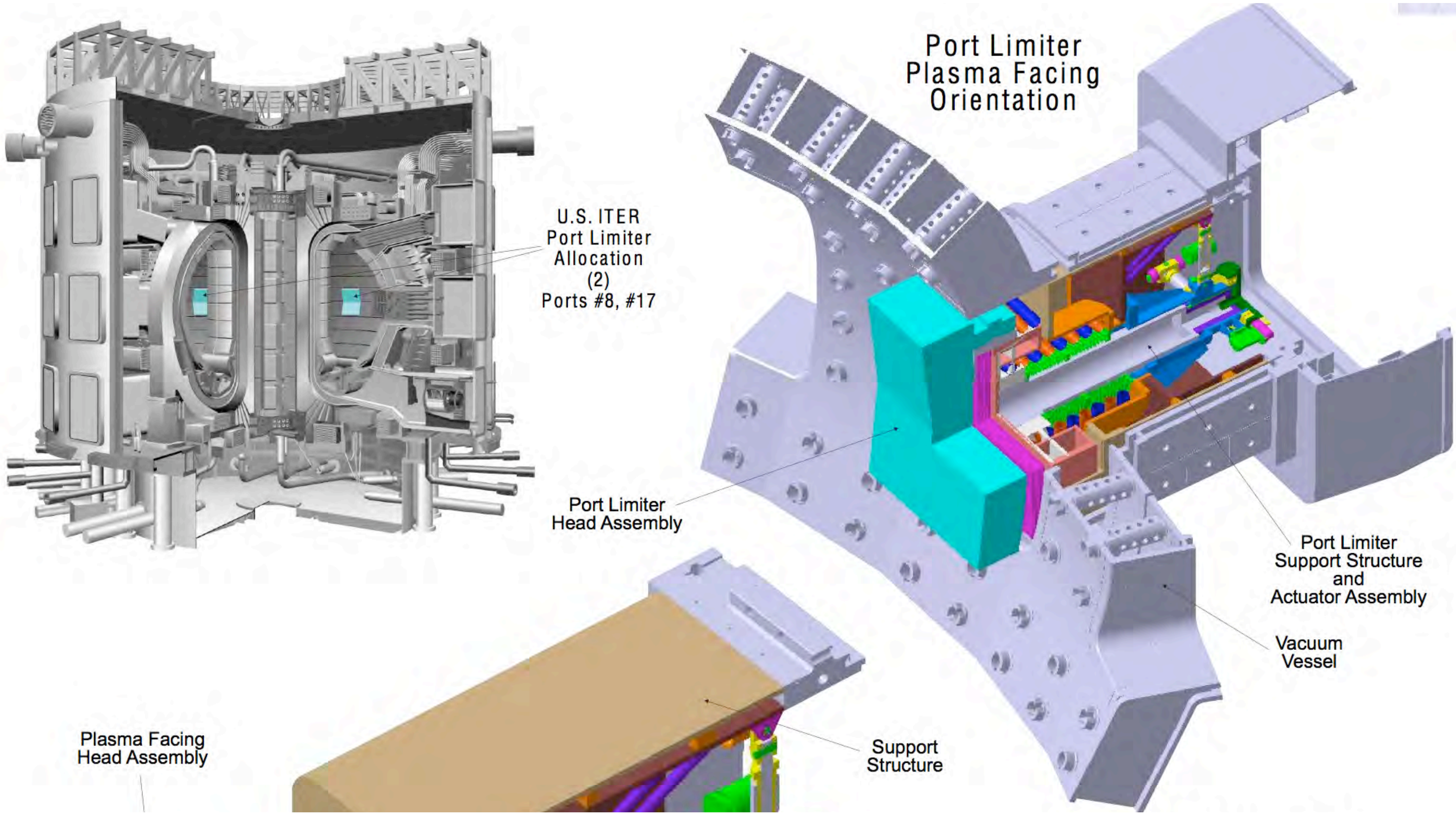
- **MetalTek International, Stainless Foundry & Engineering, and Wollaston Alloys received trial licenses in 2005 (18 months after project start)**
- **Over 350,000 lb of CF8C-Plus steel have been successfully cast to date**
  - **Now used on all heavy-duty truck diesel engines made by Caterpillar (since 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



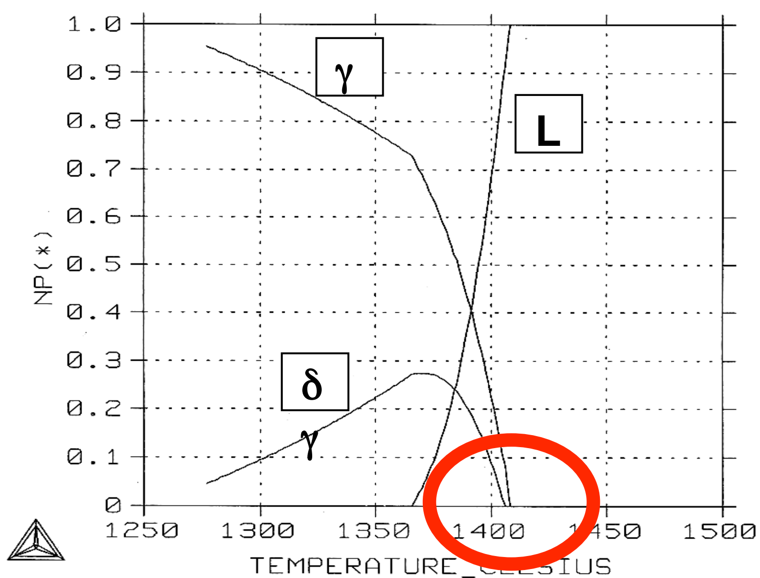
Caterpillar Regeneration System (CRS) Housing

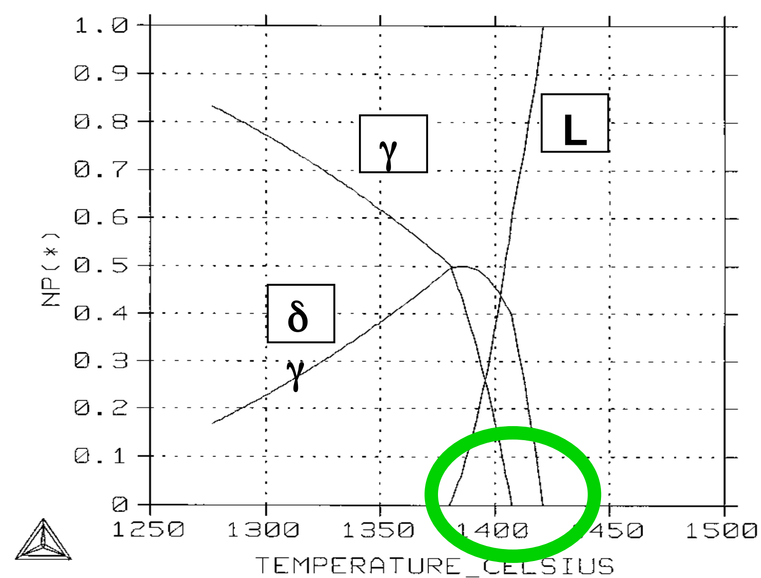
Development of Low-cost, High-performance Cast Stainless Steel for ITER Fusion Reactor Structures



Predicting solidification behavior in stainless steel welds is critical

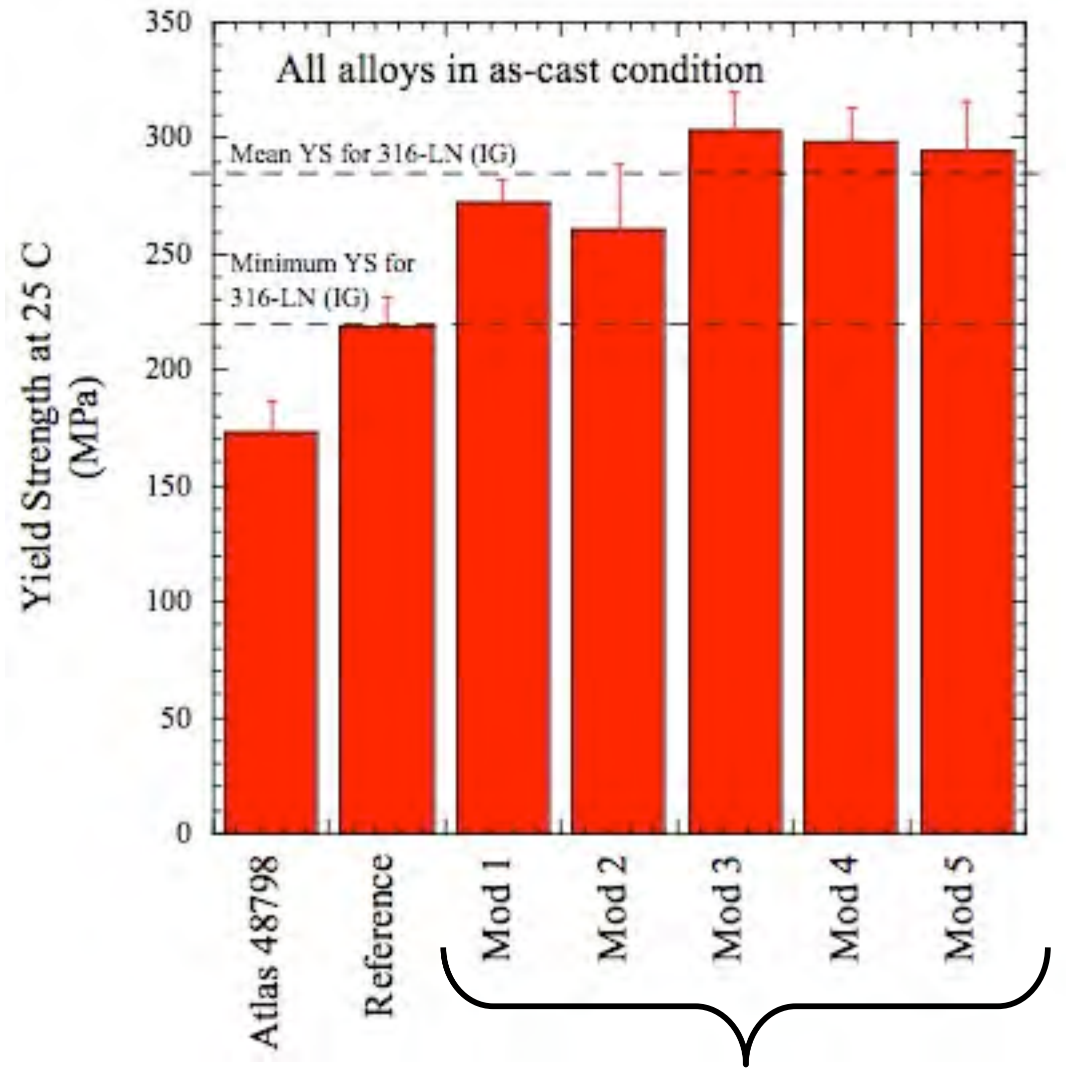
- Primary ferrite formation is needed to avoid cracking
- Small changes may be critical





Stainless steels with 17.5Cr, 1.5Mn, 0.75Si and
(left) 12.2Ni, 2.35Mo, 0.04C vs (right) 10.2Ni, 2.05Mo, 0.02C

High strength cast stainless steel has been fabricated, within chemical specifications for ITER-grade 316SS

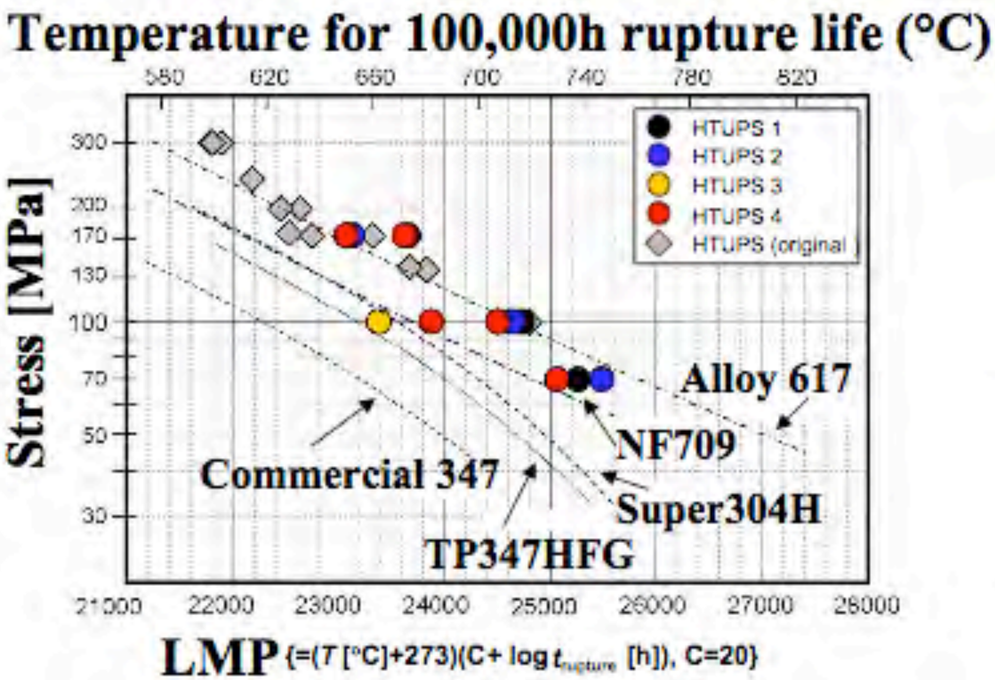


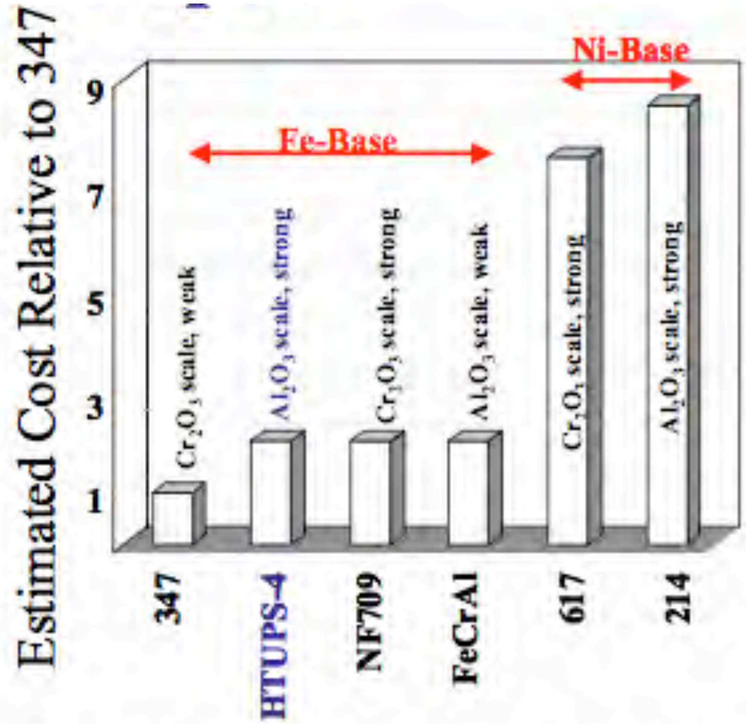
New ORNL alloys

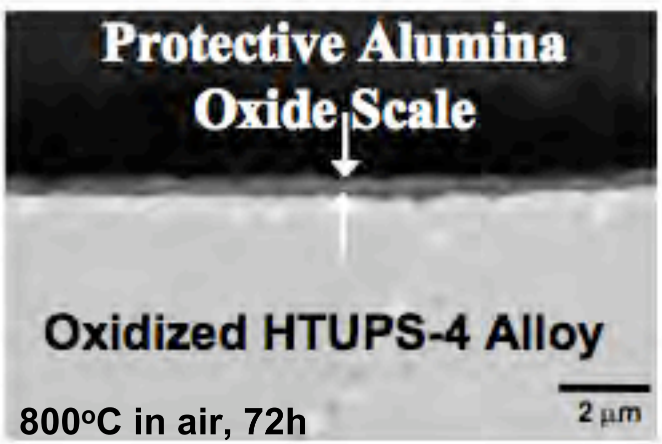
Impact sample of Mod3 alloy

Tested at 200ºC. Sample exhibited high ductility and did not fail with 270 J test.

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





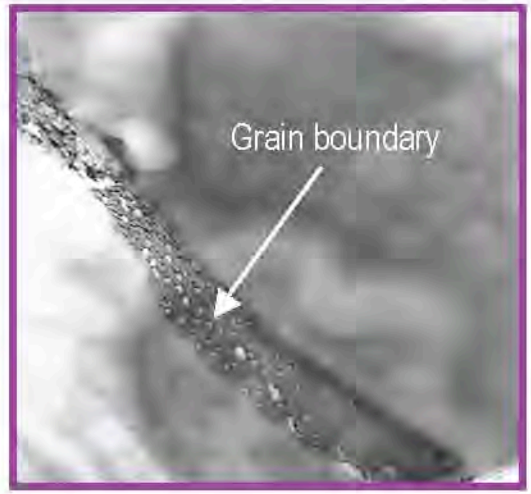


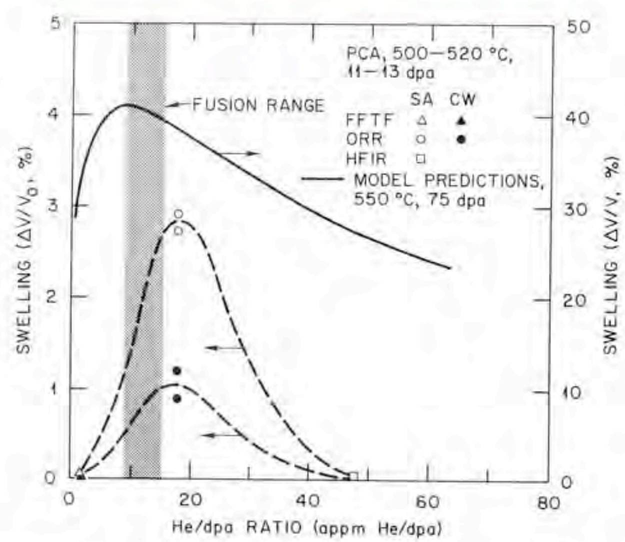
- Designed for 600-800°C structural use under aggressive oxidizing conditions
  - superior oxidation resistance to conventional chromia-forming alloys
- Comparable cost to current heat-resistant austenitic stainless steels

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

Grand Challenge: Impact of He-Rich Environment on Neutron Irradiated Materials

- A unique aspect of the DT fusion environment is substantial production of gaseous transmutants such as He and H.
- Accumulation of He can have major consequences for the integrity of fusion structures such as:
  - Loss of high-temperature creep strength.
  - Increased swelling and irradiation creep at intermediate temperatures.
  - Potential for loss of ductility and fracture toughness at low temperatures.
- Trapping at a high-density of tailored interfaces is a key strategy for management of He.

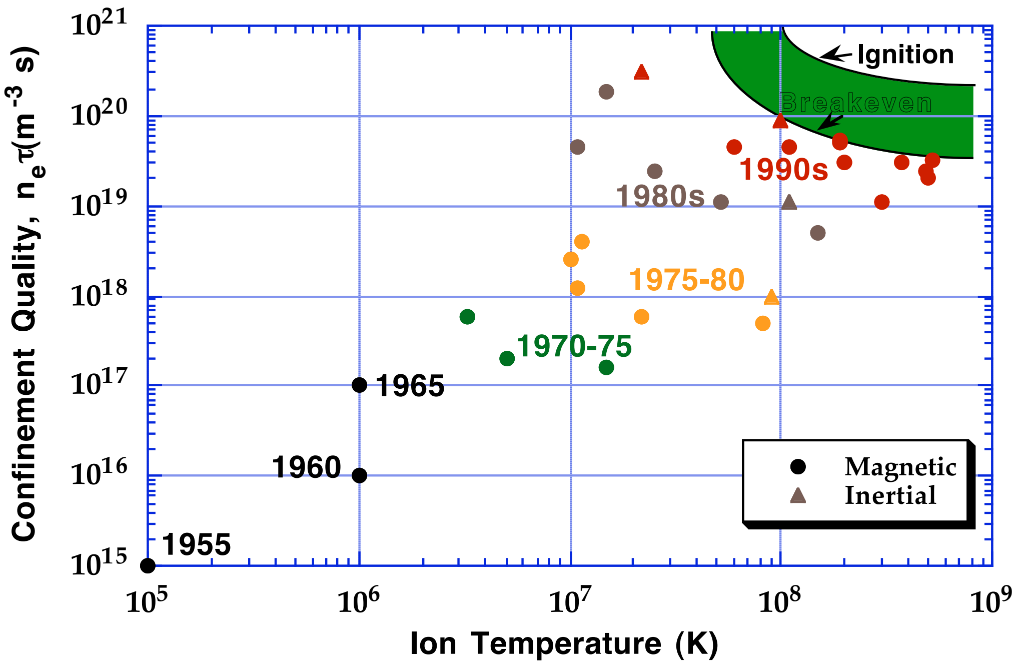




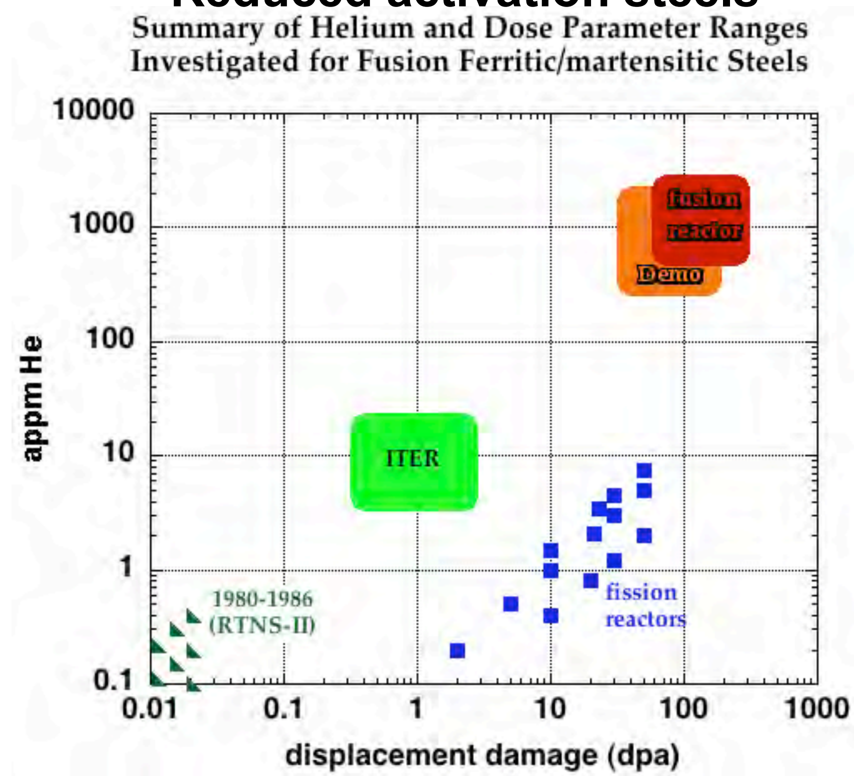
Swelling in stainless steel is maximized at fusion-relevant He/dpa values.

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 science than for plasma physics program**



Reduced activation steels



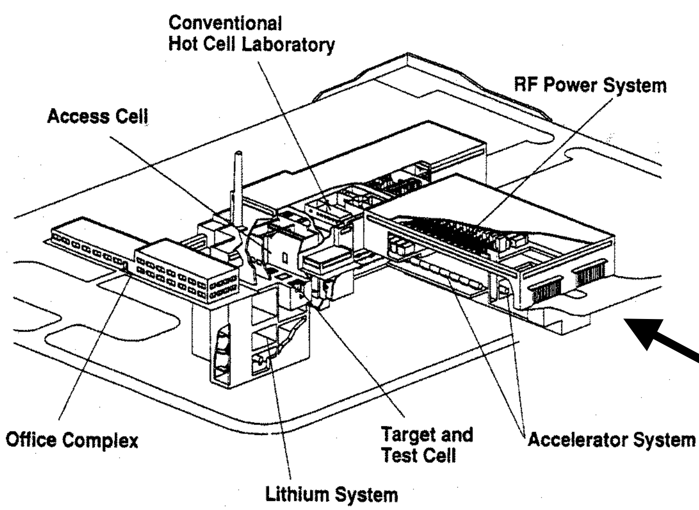
Lack of intense neutron source emphasizes the need for coordinated scientific effort combining experiment, modeling & theory to develop fundamental understanding of radiation damage

Fusion Materials Irradiation Facilities

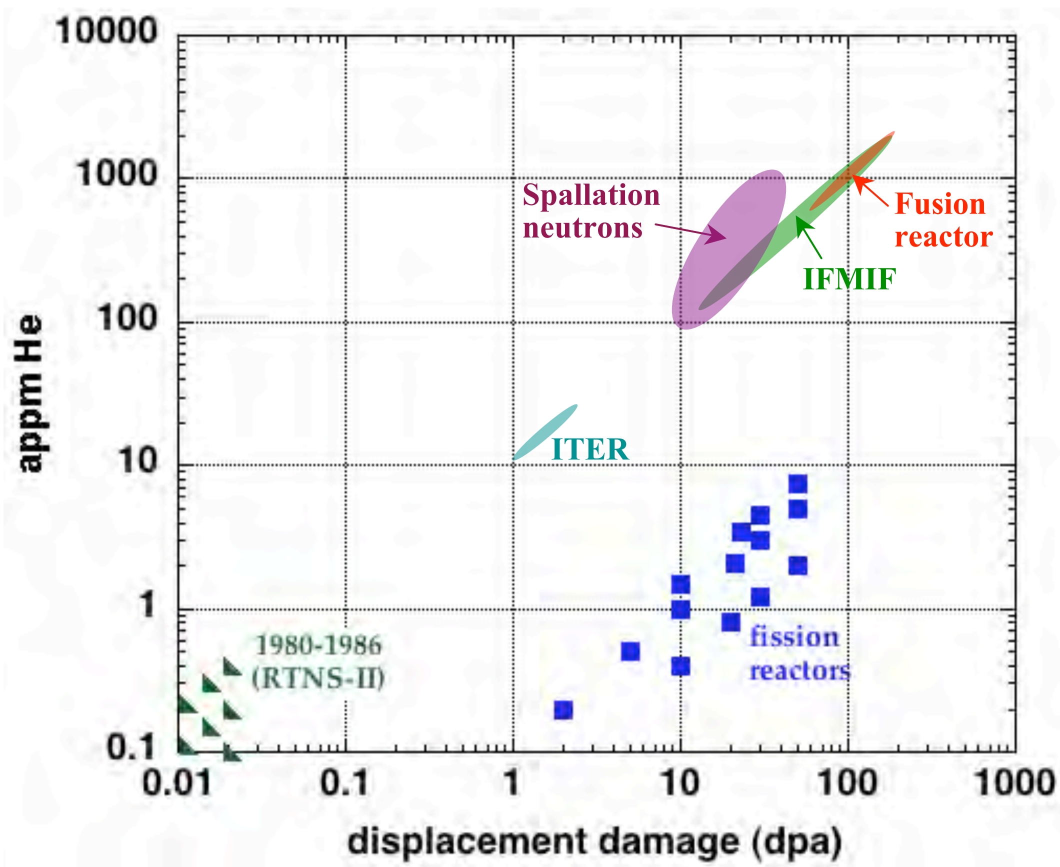
Radiation stability is strongly dependent on exposure temperature, displacement damage (dpa), damage rate, solute transmutation (H, He, ...)

=> He/dpa ratio is a useful radiation effects metric for fusion materials

- Fission sources
  fusion-relevant displacement damage
  low He generation (except Ni alloys, etc.)
- Ion accelerators
  generally limited to microstructural studies
  typically very high damage rates
- Spallation sources
- D-Li stripping source



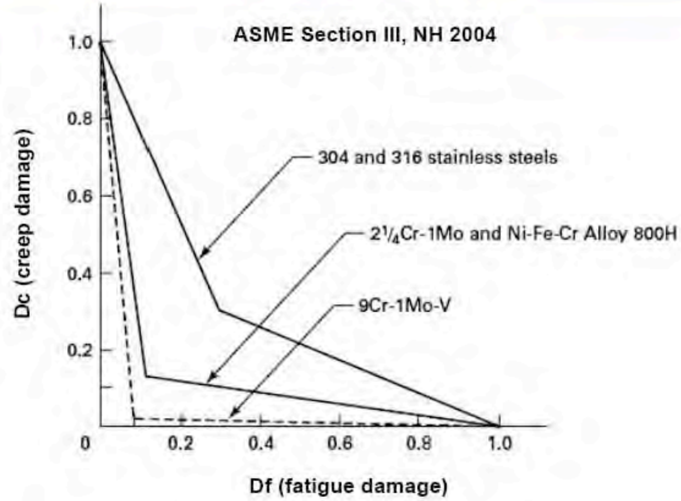
Summary of Helium and Displacement Damage Levels for Ferritic Steels



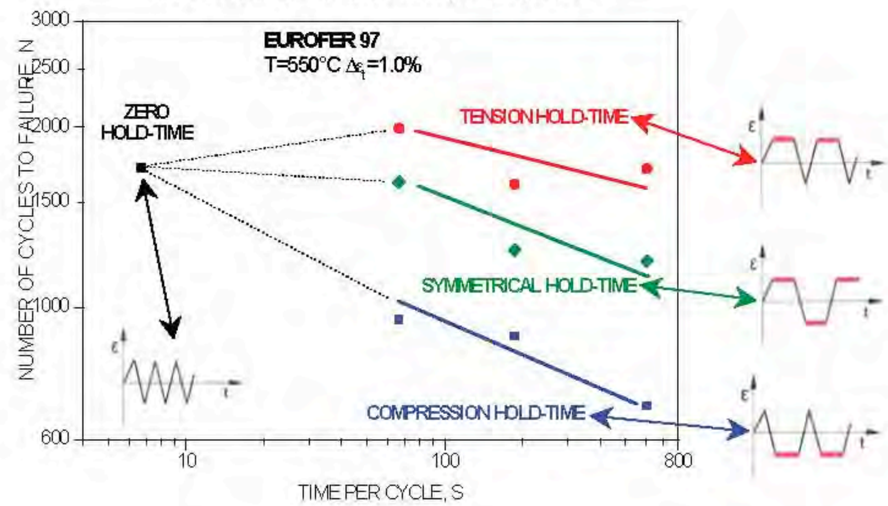
under planning: **IFMIF**

Grand Challenge: Science-Based High-Temperature Design Methodology

- Current high-temperature design methods are largely empirically based.
- Cyclic plastic loading is far more damaging than monotonic loading.
- New models of high-temperature deformation and fracture are needed:
  - Creep-fatigue interaction.
  - Elastic-plastic, time-dependent fracture mechanics.
  - Materials with low ductility, pronounced anisotropy, composites and multilayers.

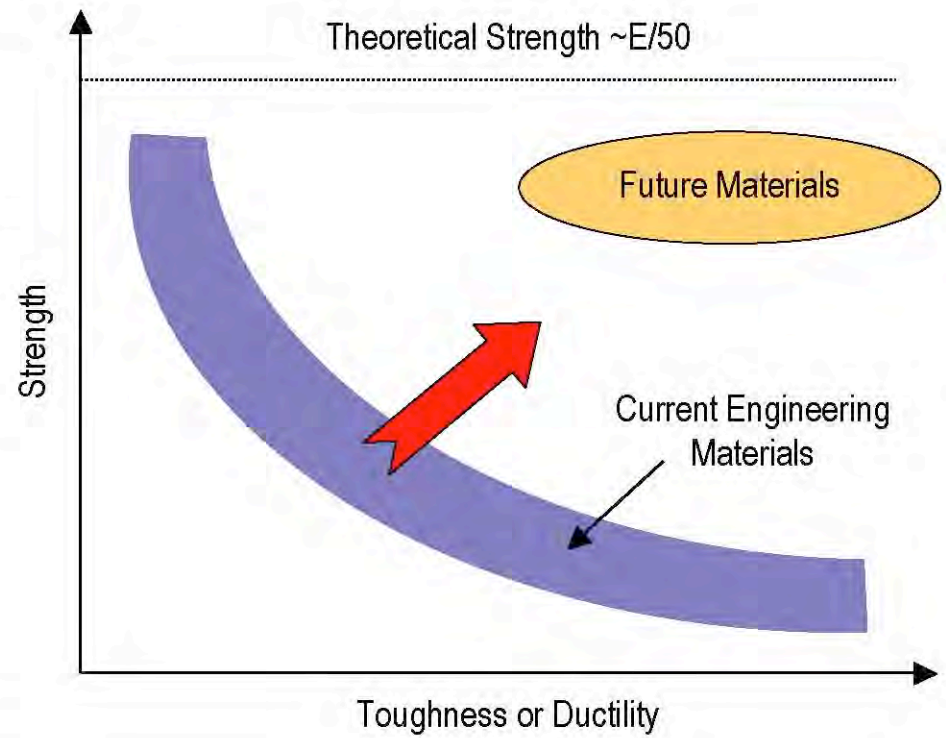


J. Aktaa & R. Schmitt, FZK, 2004

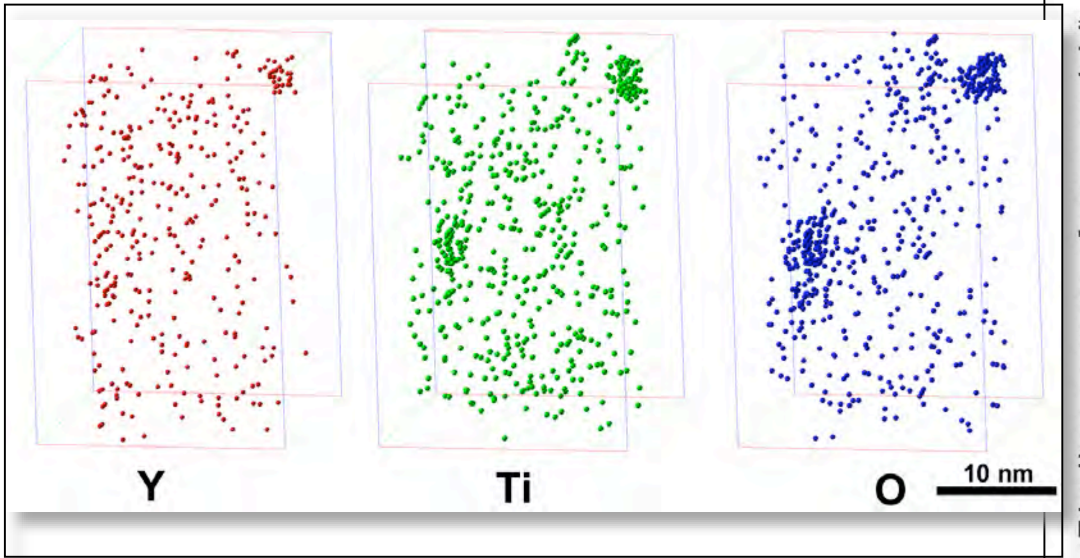


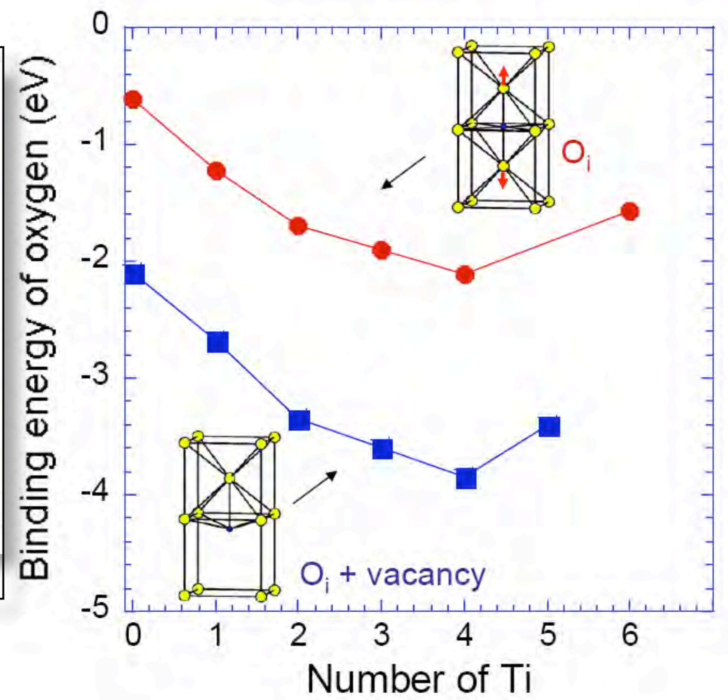
Grand Challenge: Breaking the High Strength-Low Toughness/Ductility Paradigm

- A general feature of engineering materials is increased strength tends to be offset by losses of toughness (resistance to crack growth) and ductility.
- Strength increases may result from alloying, material processing, or radiation damage.
- Loss of toughness and ductility is a loss of margin against structural failure.
- Simultaneous achievement of high-strength and high toughness/ductility would provide enormous benefits for fusion, but also many other areas (e.g., transportation, magnets, robotics, etc.).



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 (by C. L. Fu and M. Krcmar).

Conclusions

- Existing structural materials face Gen IV reactor design challenges 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 advanced fission reactors
- Continued utilization of modern materials science techniques would be valuable to uncover new phenomena associated with localized corrosion, ultra-high toughness ceramic composites, ultra-high strength alloys, etc.