Structural materials for advanced nuclear reactors

Steve Zinkle

UT/ORNL Governor's Chair,

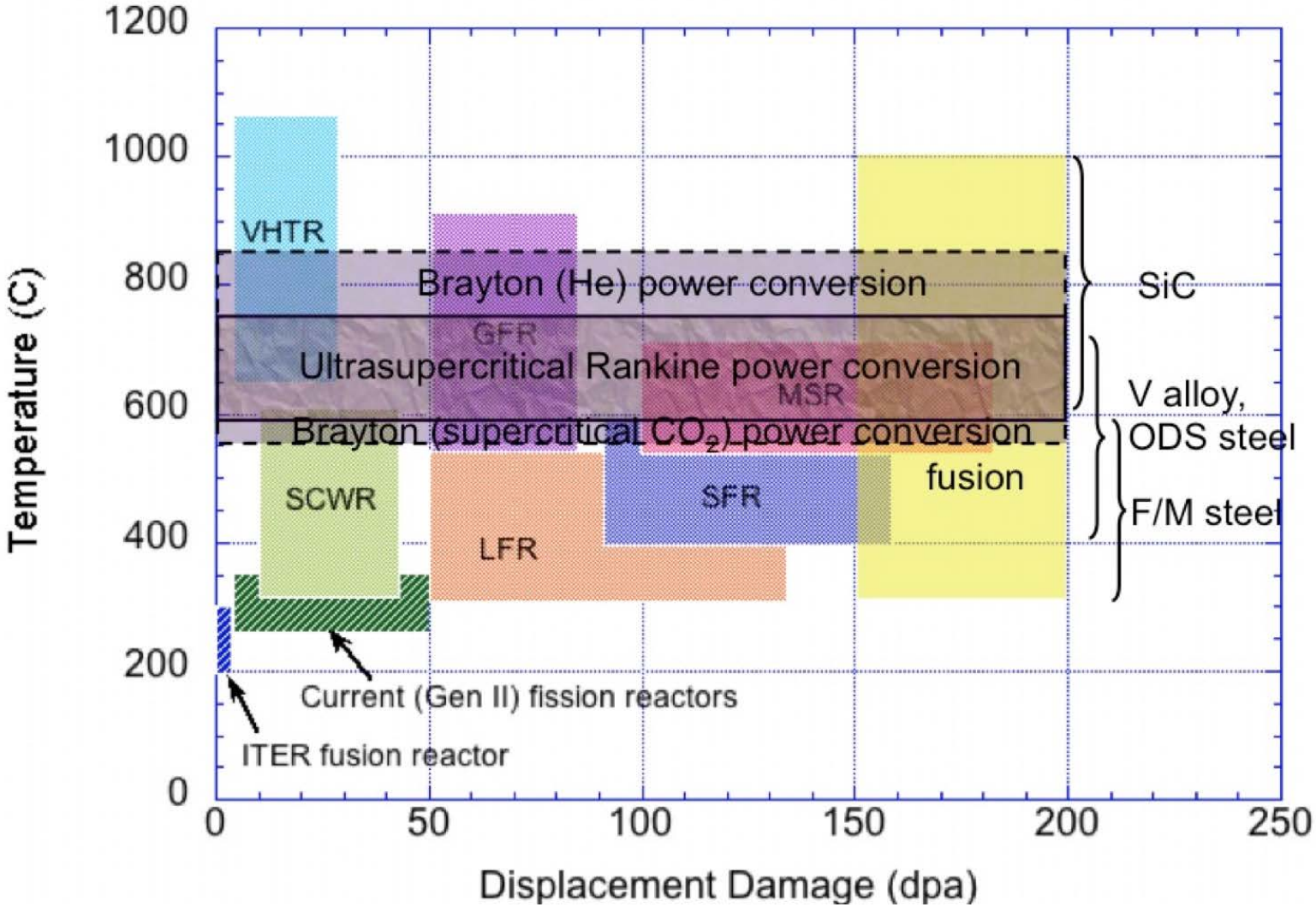
University of Tennessee and Oak Ridge National Laboratory

ARPA-E planning meeting

Washington, DC

March 16-17, 2016

Comparison of Gen IV and Fusion Structural Materials Environments with different power conversion systems

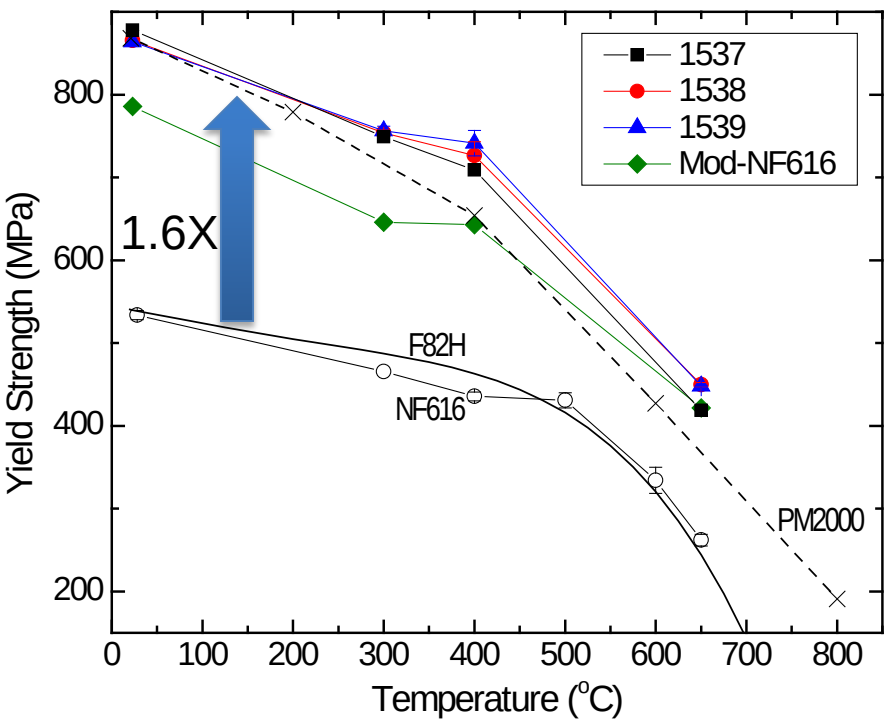


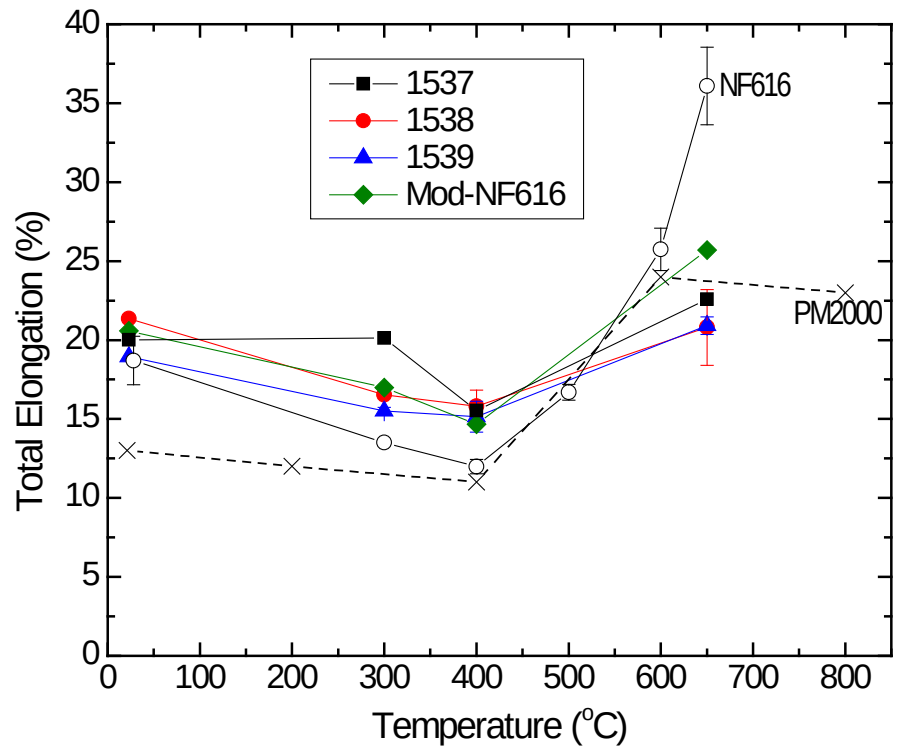
S.J. Zinkle & J.T. Busby, Mater. Today 12 (2009) 12

All Gen IV and Fusion concepts pose severe materials challenges

New steels designed with computational thermodynamics exhibit superior mechanical properties compared to conventional steel

- Three new reduced activation FM steel heats (1537, 1538, 1539) and an optimized-Gr.92 heat (C3=mod-NF616) were investigated
- Tensile strengths of the new thermomechanical treated (TMT) steels were much higher than conventional steels
- Dramatic improvement in thermal creep strength also observed

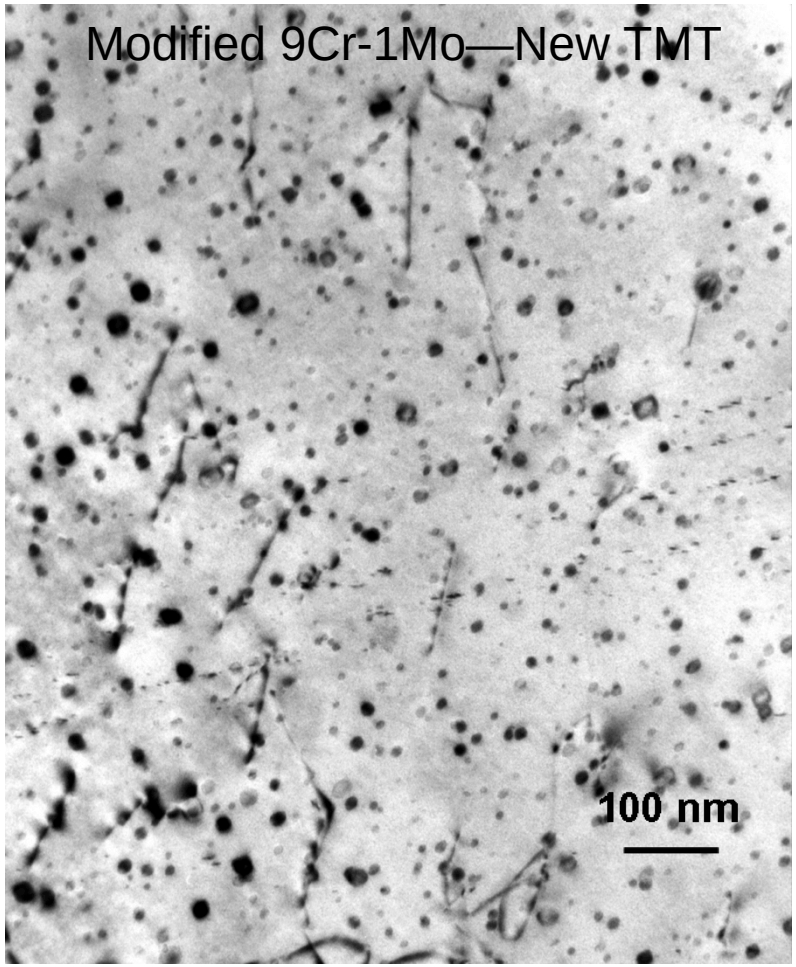




L. Tan, Y. Yang & J.T. Busby, J. Nucl. Mater. 442 (2012) S13

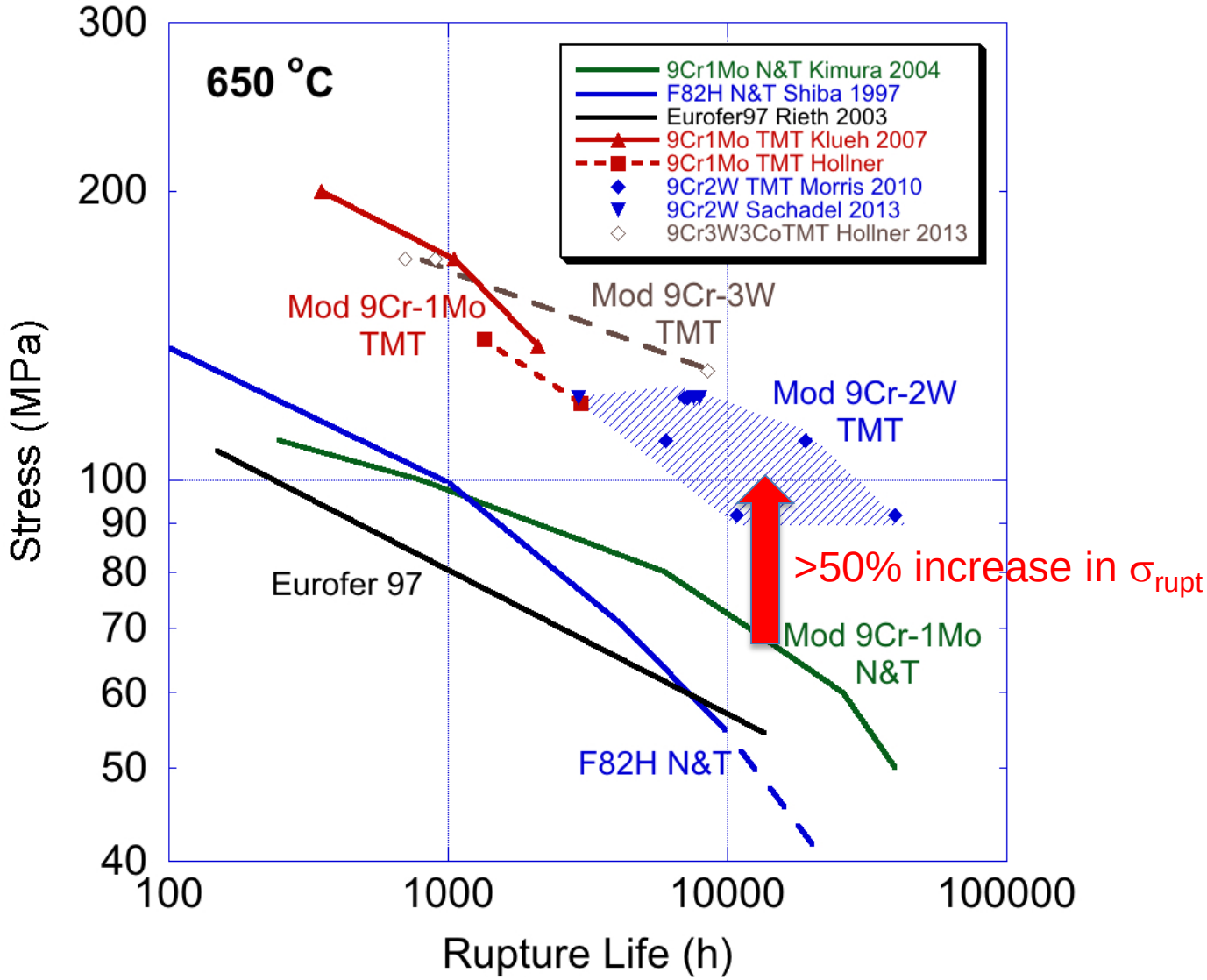
New Thermomechanical treatment (TMT) Applied to Commercial 9-12%Cr Steels Yields Improved Microstructure

- Commercial 9Cr-1Mo and 12 Cr steels were processed
- TMT (hot rolling) on 25.4–mm plates
  - Several TMT conditions were investigated
- Precipitates formed on dislocations introduced by hot rolling
- Precipitate dispersion is much finer than observed in conventionally processed 9-12Cr steel
  - Up to 1000X increase in density (TMT precipitate density is $0.2\text{-}1 \times 10^{22}/m^3$; d~4-8 nm)



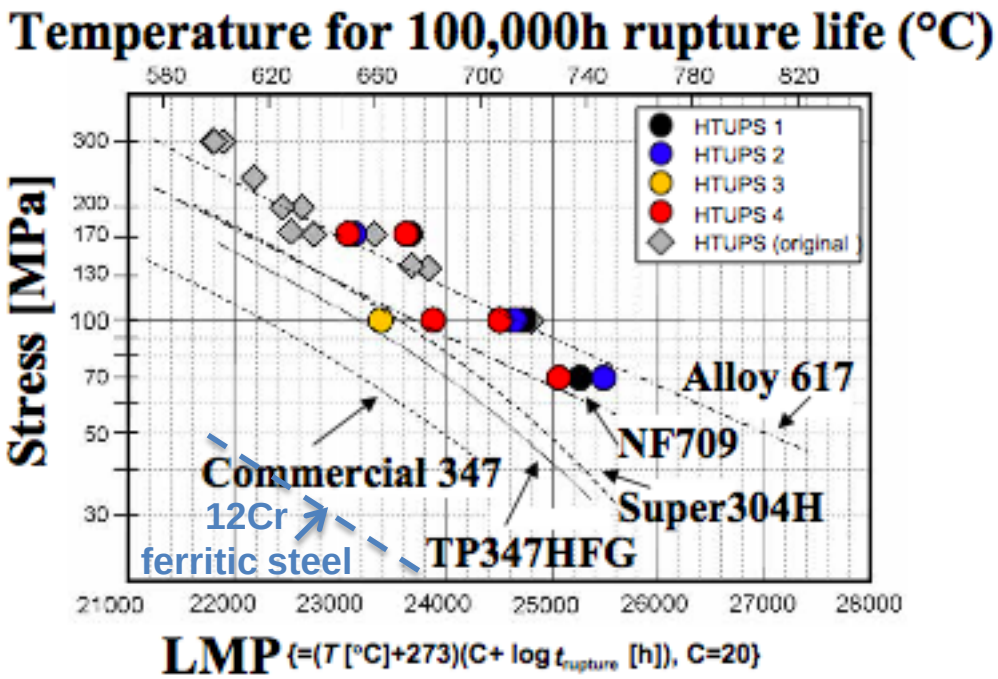
R.L. Klueh et al., J. Nucl. Mat. 367-370 (2007) 48; Scripta Mat. 53 (2005) 275

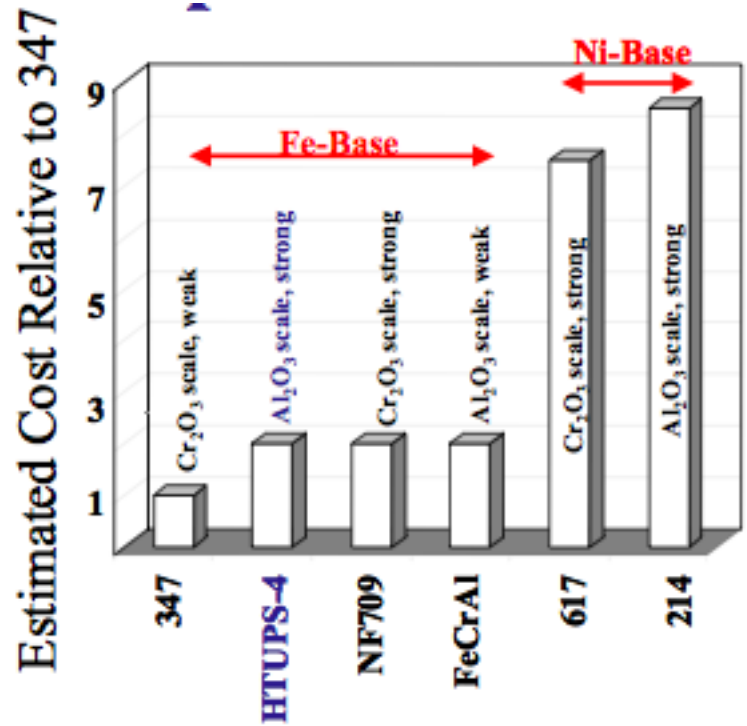
Creep rupture behavior for TMT vs. conventional 9Cr steels

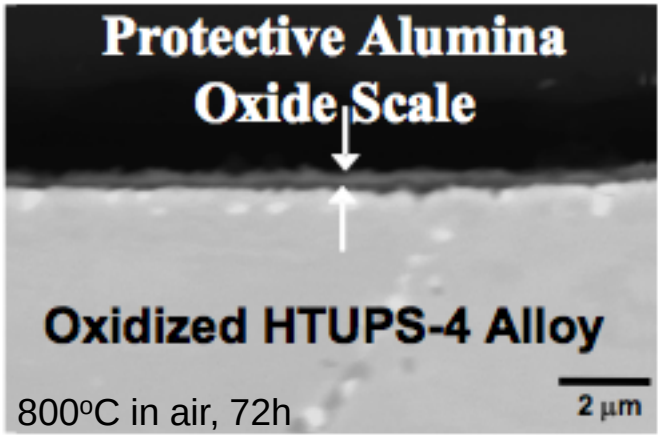


S.J. Zinkle et al., Nucl. Fusion (2016) in press

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

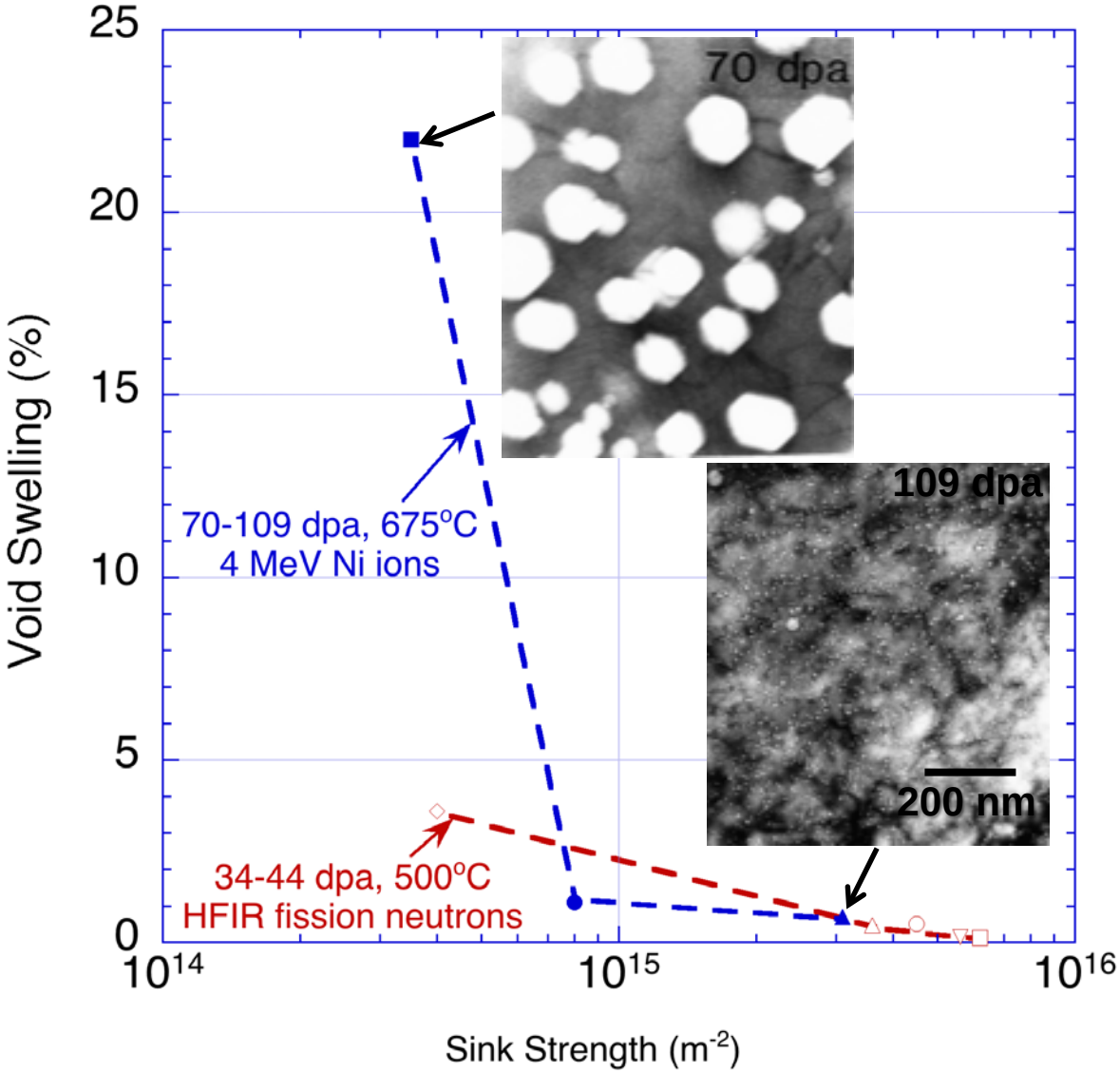
Y. Yamamoto, M.P. Brady et al., Science 316 (2007) 433

Options for designing radiation resistance

- Three general strategies for radiation resistance can be envisioned:
  - Utilize materials with negligible point defect mobility at desired operating temperatures
    - Amorphization with an accompanying volume change may occur if all point defects are immobile => select temperature range where vacancies are immobile but interstitials are mobile
  - Use materials with intrinsic resistance to radiation damage accumulation (e.g., BCC alloys, high entropy alloys?, noncrystalline materials?)
  - Materials with a high density of nanoscale recombination centers
    - Volumetrically-distributed precipitates or nanolayered structures

Zinkle & Snead, Ann. Rev. Mater. Res. 44 (2014) 241

Effect of Sink Strength on the Volumetric Void Swelling of Irradiated FeCrNi Austenitic Alloys



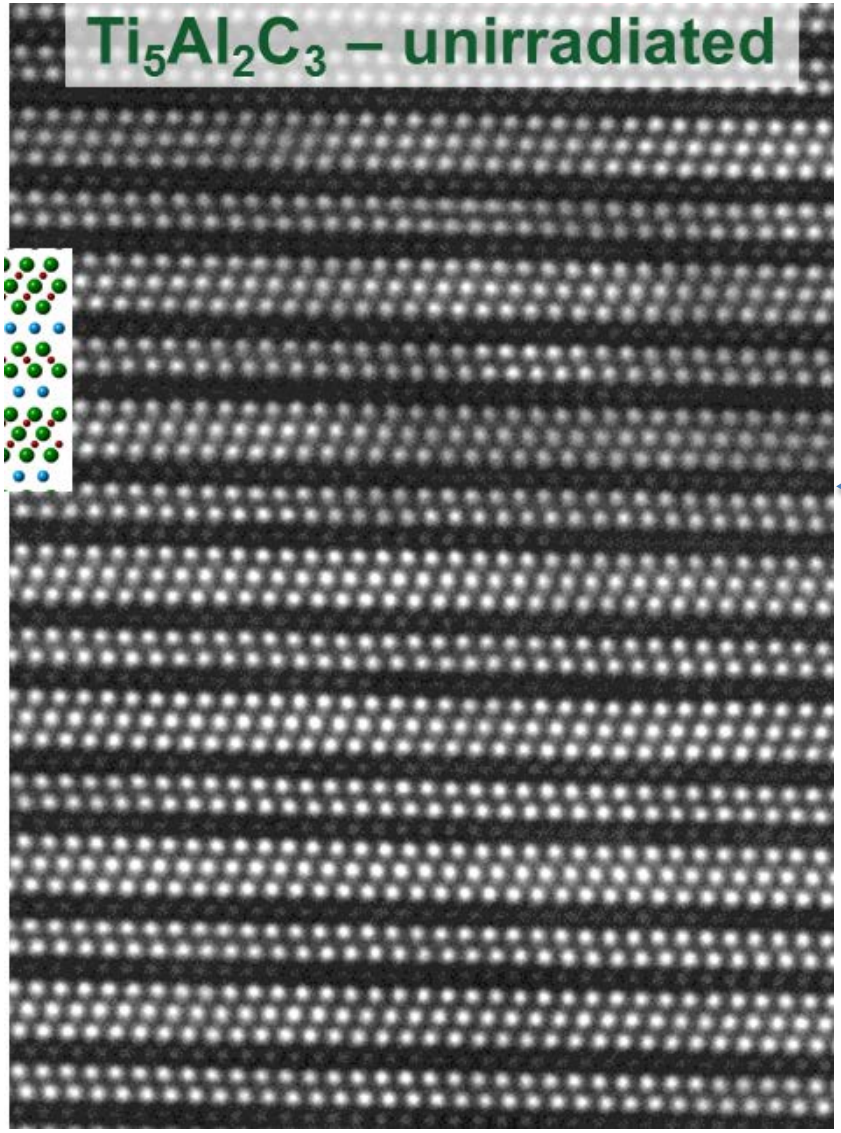
Dramatic reduction in void swelling occurs when average spacing between voids is >10x average spacing between defect sinks

$$N_v^{-1/3} > 10\ S_{tot}^{-1/2}$$

S.J. Zinkle and L.L. Snead, Ann Rev. Mat. Res., 44 (2014) 241

Internal multilayers in MAX phase ceramics: Example for $Ti_5Al_2C_3$

Ti: green
Al: blue
C: red



TiC
Al
TiC

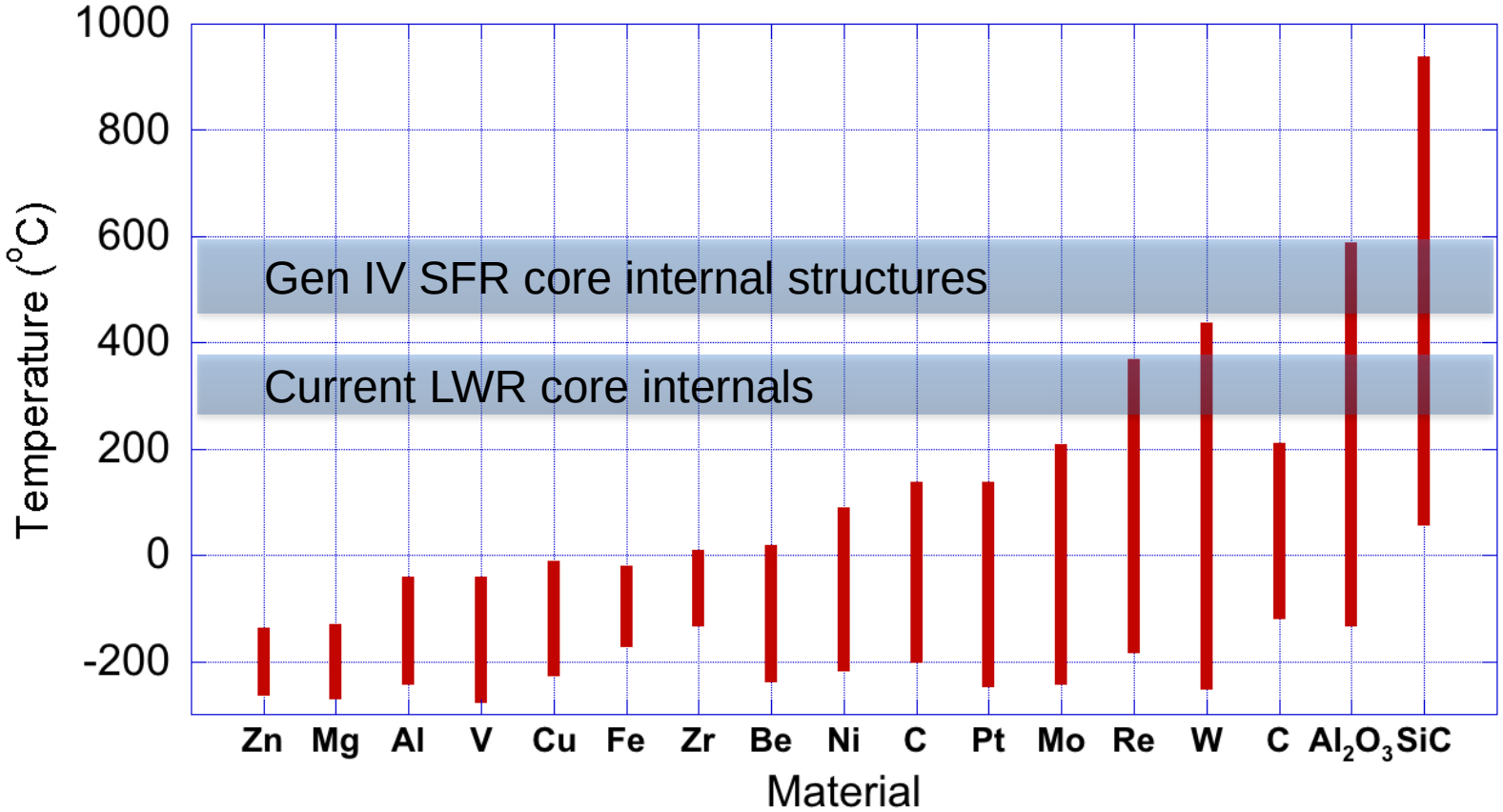
5 nm

Bulk nanolaminates:
If interfaces are ideal point defect sinks,
$S>10^{19}/m^2$

Chad Parish, ORNL

Approaches for radiation resistance 1: Immobile defects

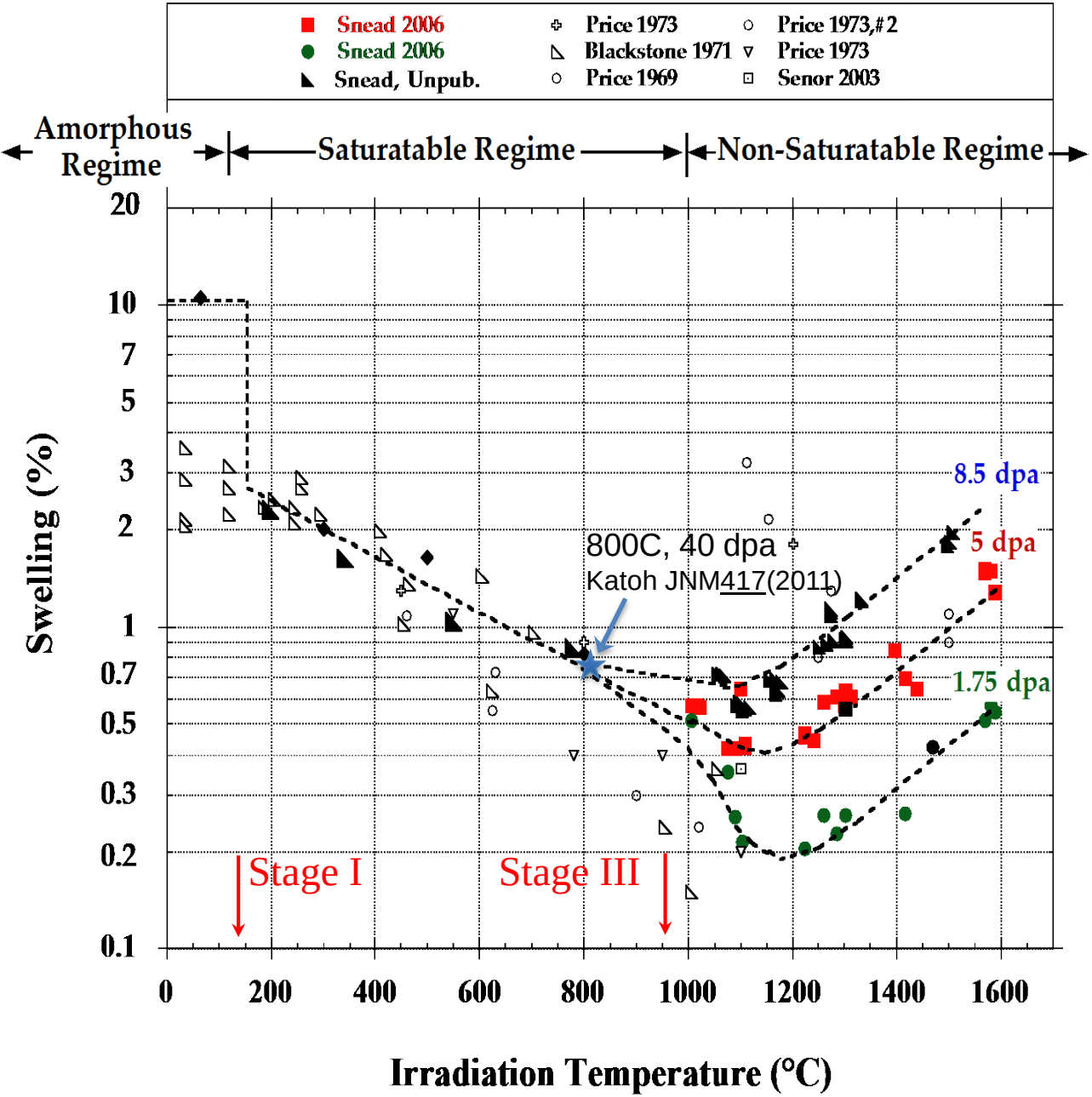
- Defect accumulation is limited if one or more defect types are immobile
  - Utilize materials with negligible point defect mobility at desired operating temperatures
  - A key potential consequence (particularly in ordered alloys and ceramics) is amorphization, with accompanying significant volumetric and property changes



- Regime with intrinsically high point defect recombination typically occurs at too low of temperatures for power generation applications (except SiC and possibly Al_2O_3, W, Re)

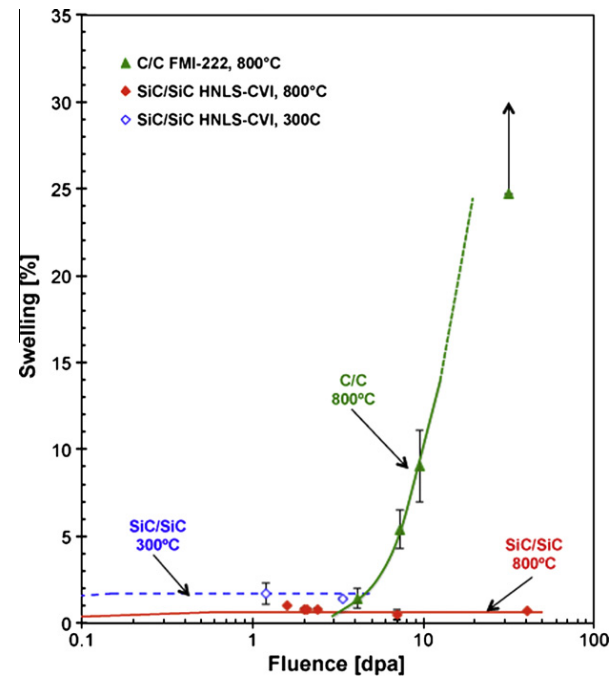
Zinkle & Snead, Ann. Rev. Mater. Res. 44 (2014) 241

Radiation resistance depends on temperature: example of swelling in SiC



Good radiation stability when interstitials are immobile & vacancies mobile: $S>10^{19}/m^2$. Similar behavior occurs in MAX phase ceramics, etc.

-cf. D.W. Clark et al., Acta Mater. 105 (2016) 130



L.L. Snead et al., JNM 367-370 (2007) 677

Conclusions

- Advances in materials science have paved the way for a suite of new materials with significant performance improvements
  - E.g., >50% improvement in creep rupture strength or >10X improvement in creep rupture lifetime for ferritic/martensitic steels
- The same microstructural features that provide good mechanical properties also provide superior radiation resistance
- Enhanced performance, durability and safety is possible
- Looking forward to working with reactor design teams to implement these high-performance cost-effective materials