Technology Issues for Fusion Power

Steve Zinkle

UT/ORNL Governor's Chair,

University of Tennessee and Oak Ridge National Laboratory

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General Comments

- The enormous challenge of developing fusion energy requires multidisciplinary science solutions involving forefront researchers
  - Much can be gained from interactions with the broader scientific community; fusion materials & technology researchers typically have strong connections to these communities
- Many of the critical path items for DEMO are associated with fusion materials and technology issues (PMI, etc.)
  - Low-TRL issues can often be resolved at low-cost
- Alternative energy options are continuously improving
  - Passively safe fission power plants with accident tolerant fuel that would not require public evacuation for any design-basis accident
  - Small modular fission reactors to minimize construction cost/ schedule overruns and "right-sized" for incremental power growth
  - Low-cost solar (coupled with low-cost energy storage); distributed vs. concentrated power production visions

Baseload energy for the long run: What's new with fission reactor concepts?

- **Small modular reactors to enable in-factory construction (bigger is not necessarily better)**
  - **Complexity of large fission construction projects often introduces cost overruns; large fusion energy systems will also be susceptible**
- **Improved public safety & environmental attractiveness**
  - **Zero Emergency evacuation planning zone region (No adverse public consequences for design basis accidents)**
  - **Deep burn fuel cycles/ closed fuel cycles (Reduced long-term radiological waste disposal burden)**
- **Improved economic competitiveness**
  - **LWRs: very high ($\geq$90%) and predictable availability**
  - **High component lifetime (MTBF) and short repair times**
  - **High thermodynamic efficiency for Gen IV concepts**

Fusion materials challenges and opportunities

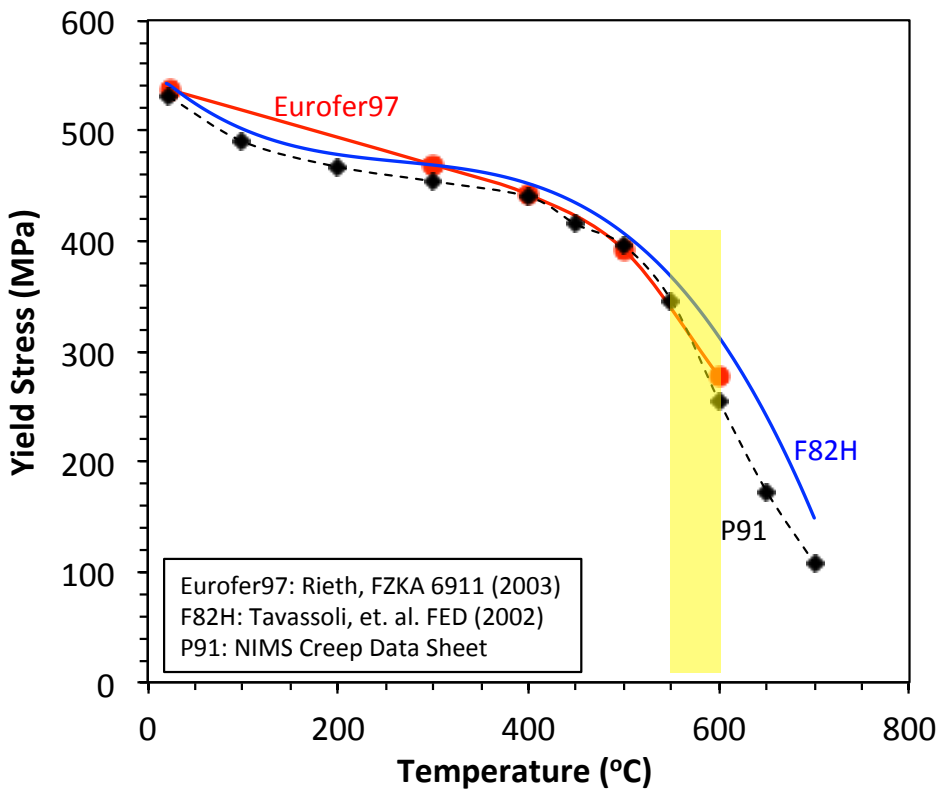
- **Challenges**
  - **Plasma facing components**
    - **Will tungsten work?**
  - **Tritium containment and online extraction/fuel reprocessing**
  - **Nonstructural materials lifetime in a DT fusion environment**
    - **Plasma diagnostics (optical fibers, electrical insulators, etc.)**
    - **Plasma heating feedthrough insulators**
    - **Next generation magnet systems (insulation, HTC superconductors)**
    - **Ceramic breeders**
  - **Structural materials**
    - **T_2 sequestration in radiation-induced cavities**
    - **Is there a viable option beyond 5 MW-yr/m^2? (50 dpa)**

Increasing opportunities for leveraging broader mater. sci. community

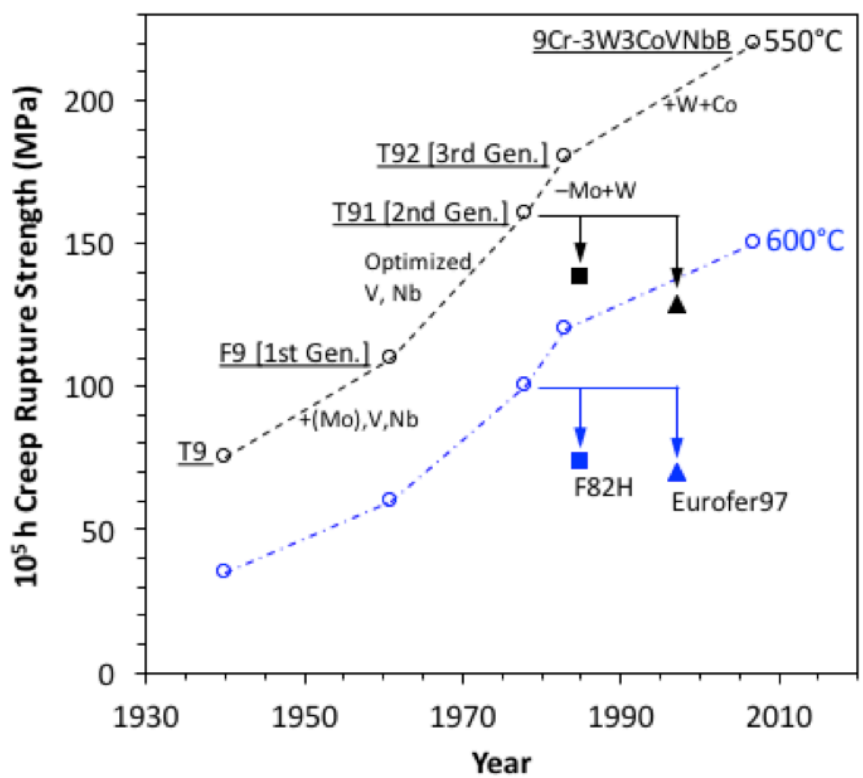
Development of Reduced Activation FM Steels

- **USA, Japan, and European Union initiated development of RAFM steels in 1980s, and came up with respective alloys such as 9Cr-2WVTa, F82H, and Eurofer97 (adopted in 1997). China, India, Korea, etc. started relevant R&D activities afterwards.**

- **Despite comparable tensile properties as compared with the ASME codified Grade 91, RAFM steels have significantly lower creep strength at temperatures above ~500°C.**

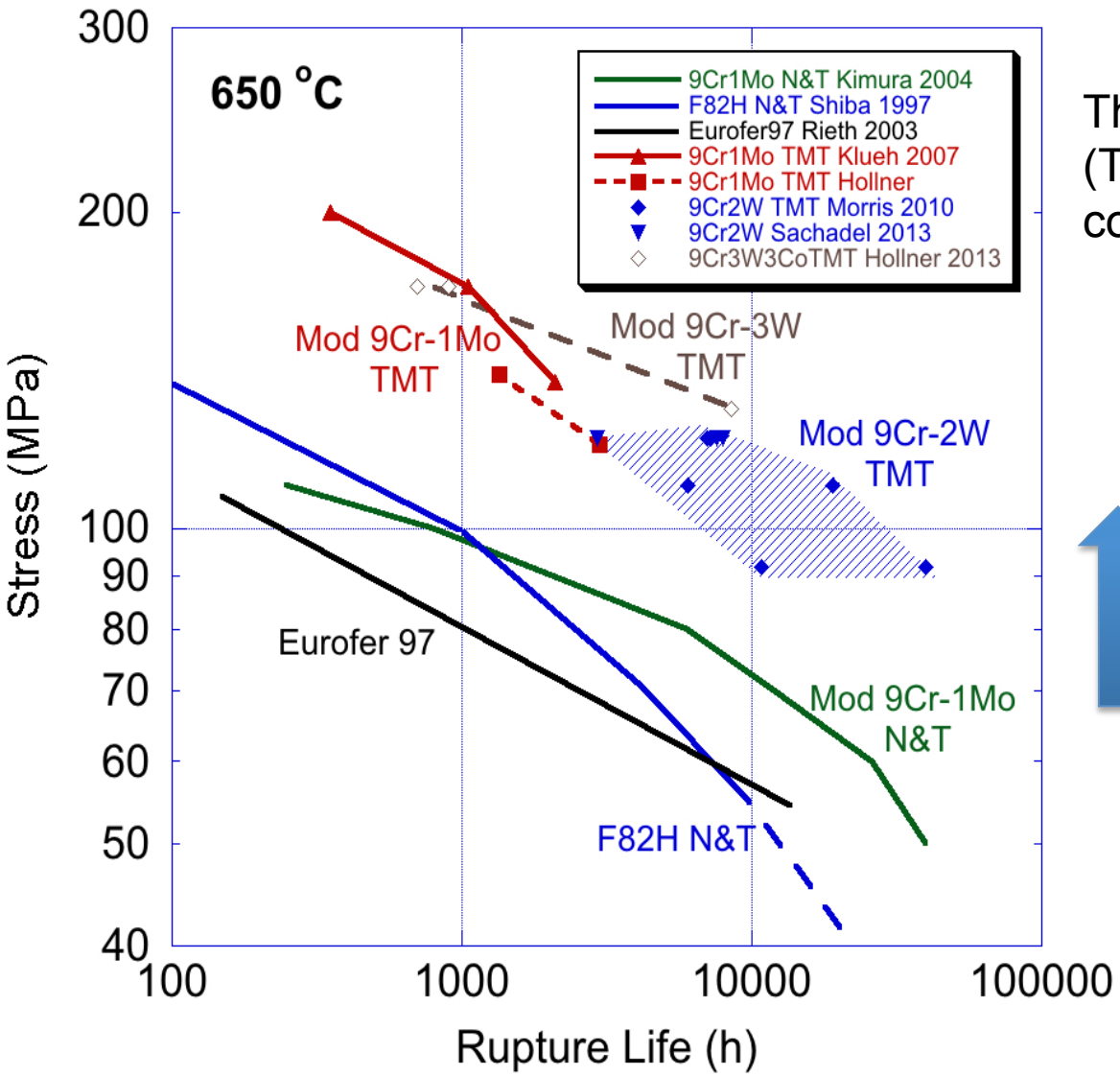


L. Tan, ORNL. ICFRM17



S.J. Zinkle et al., Nucl. Fusion 57 (2017) 092005

Creep rupture behavior for TMT vs. conventional 9Cr steels



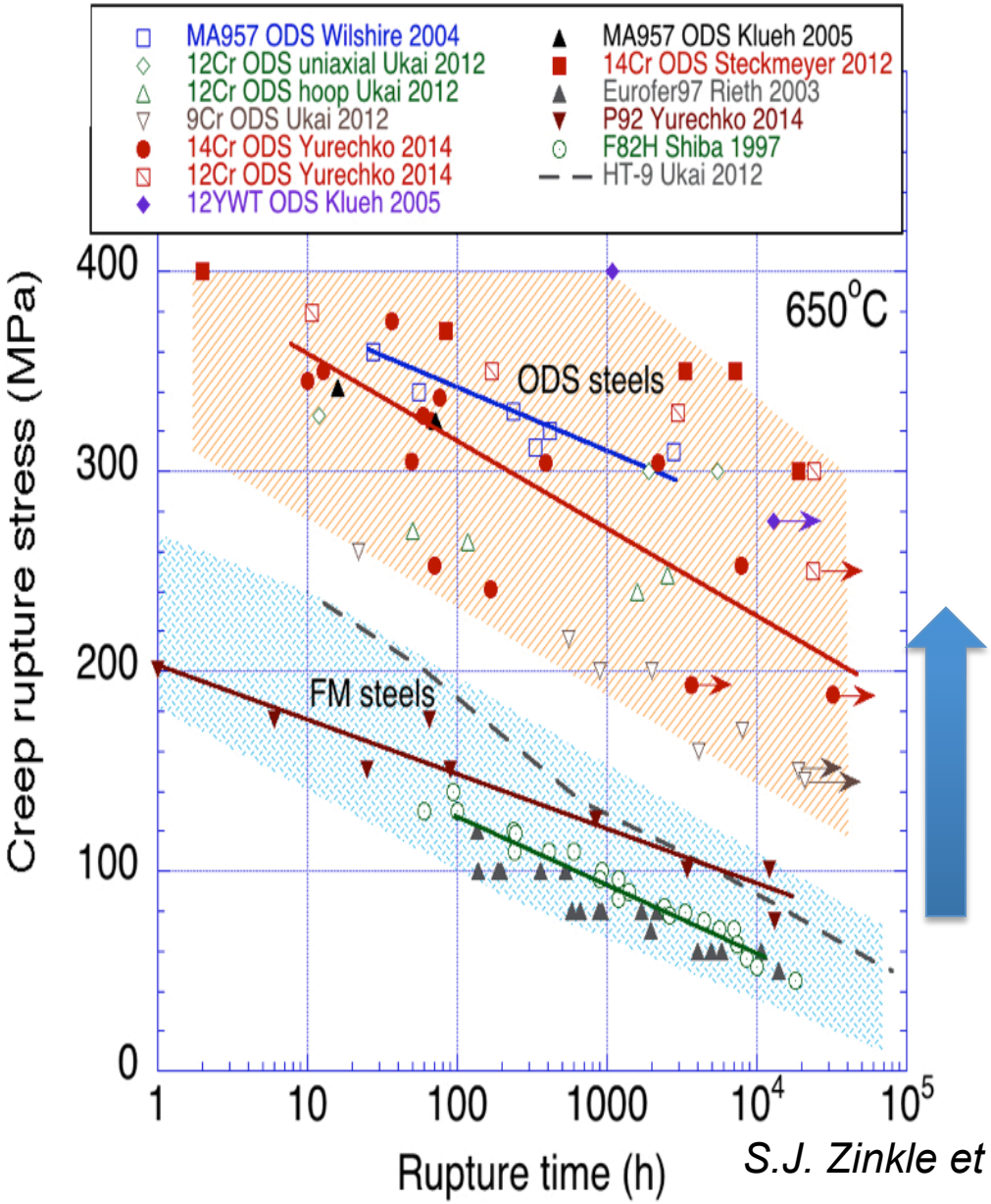
Thermo-mechanical treatment (TMT) 9Cr steels designed using computational thermodynamics

50-100% improvement in creep rupture strength for newly designed reduced activation steels

Predicted significant improvement in radiation resistance as well due to high precipitate density

S.J. Zinkle et al., Nucl. Fusion 57 (2017) 092005

Creep rupture behavior for ODS vs. conventional 9Cr steels

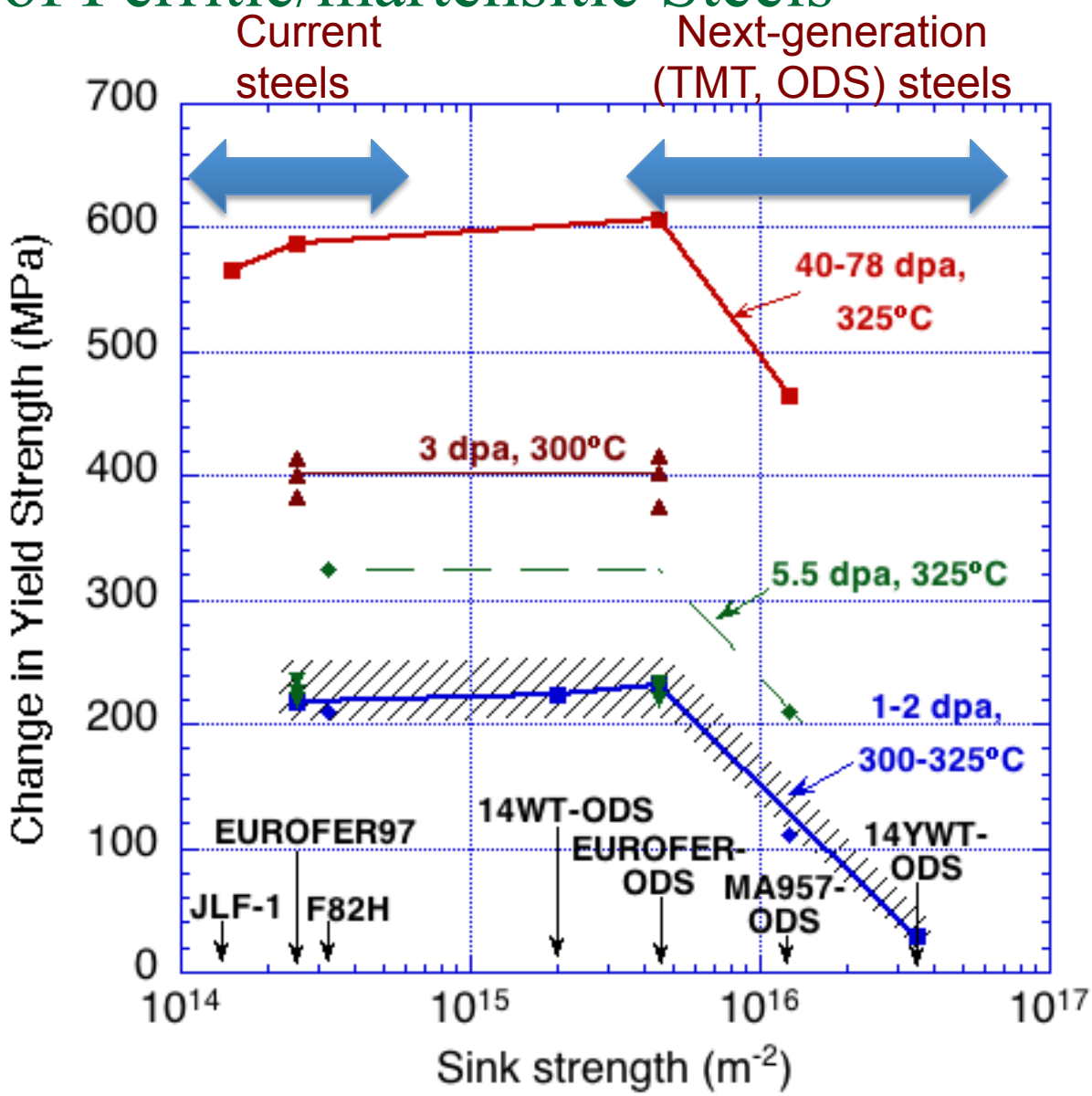


~100% improvement in creep rupture strength for ODS steels

Predicted dramatic improvement in radiation resistance as well due to very high dispersoid density

S.J. Zinkle et al., Nucl. Fusion 57 (2017) 092005

Effect of Initial Sink Strength on the Radiation Hardening of Ferritic/martensitic Steels



Dramatic reduction in radiation hardening occurs when average spacing between defect cluster nuclei (dislocation loops, etc.) is much greater than average spacing between defect sinks

$N_{loop}^{-1/3} >> S_{tot}^{-1/2}$

or equivalently,

$S_{tot} >> S_{rad\ defects}$

S.J. Zinkle and L.L. Snead, Ann Rev. Mat. Res., 44 (2014) 241;
S.J. Zinkle et al., Nucl. Fusion 57 (2017) 092005

Materials-tritium issues require additional investigation

- Identification of a robust, efficient and economic method for extraction of tritium from high temperature coolants
  - Large number of potential tritium blanket systems is both advantageous and a hindrance
- Current materials science strategies to develop radiation-resistant materials may (or may not) lead to dramatically enhanced tritium retention in the fusion blanket
  - Fission power reactors (typical annual T_2 discharges of 100-800 Ci/GW_e; ~10% of production) are drawing increasing scrutiny
    - >70% of US reactor sites (>50% in last 10 years) have reported T_2 groundwater contamination levels exceeding EPA safe drinking water limits*
  - A 1 GW_e fusion plant will produce ~10^9 Ci/yr; typical assumed releases are ~0.3 to 1×10^5Ci/yr (<0.01% of production)
  - Nanoscale cavity formation may lead to significant trapping of hydrogen isotopes in the blanket (and FW/divertor) structure

*https://www.nrc.gov/docs/ML1723/ML17236A511.pdf (Sept. 2017)

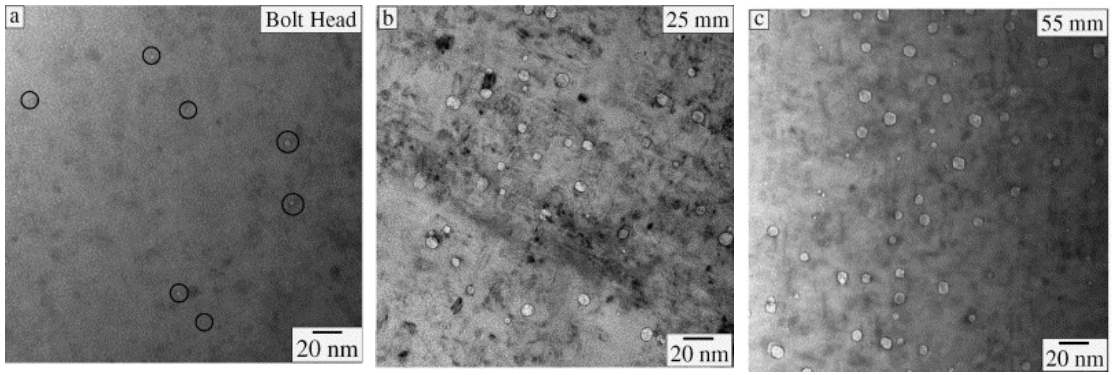
H retention increases dramatically in the presence of cavity formation

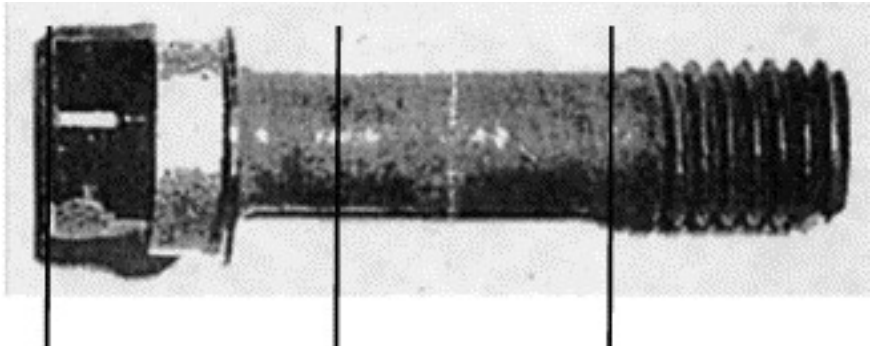
3 to 5x increase in retained hydrogen when cavities are present, even with 2-3x reduction in neutron dose

=> Fusion may need to avoid operation at conditions that produce fine-scale cavities in structural materials

500-700 appm H (few cavities)

1700-3700 appm H (rad.-induced cavities present)



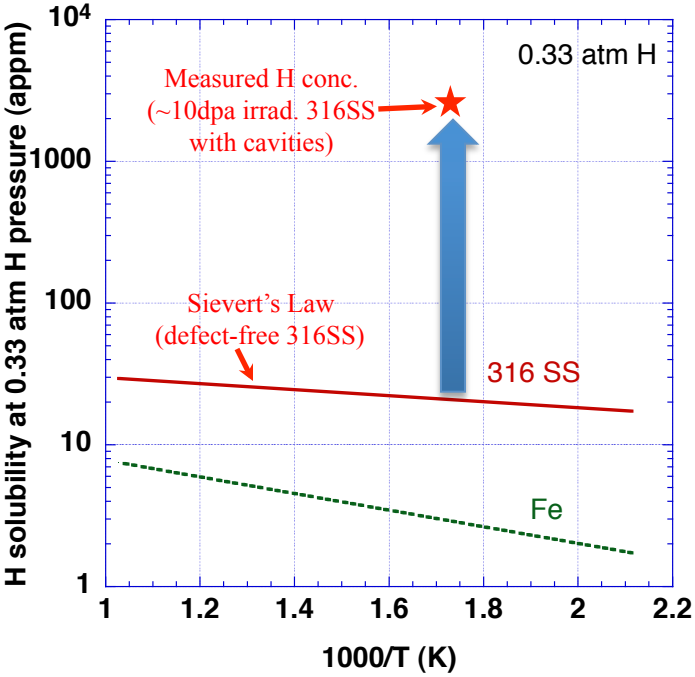


Bolt head
1 mm
320°C, 19.5 dpa

Bolt shank
25 mm
343°C, 12.2 dpa

Near threads
55 mm
333°C, 7.5 dpa

Retained H level is ~100x higher than expected from Sievert's law solubilities



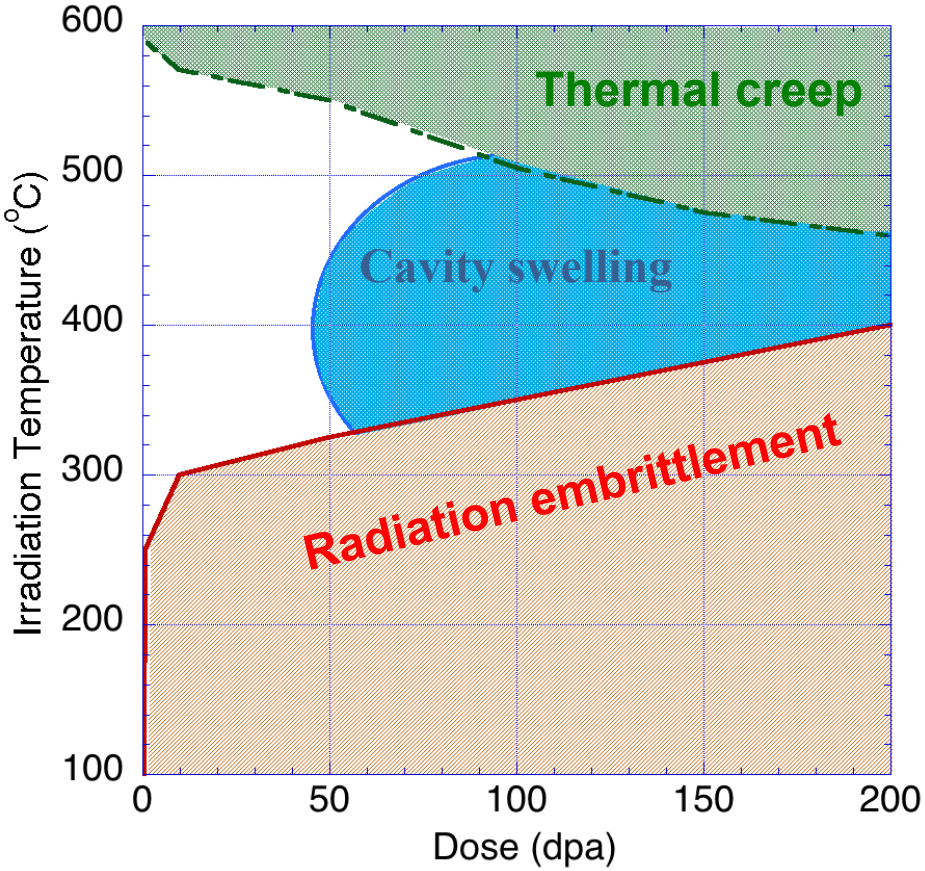
Baffle-former bolt removed from Tihange-1 (Belgium) pressurized water reactor

Type 316 austenitic stainless steel

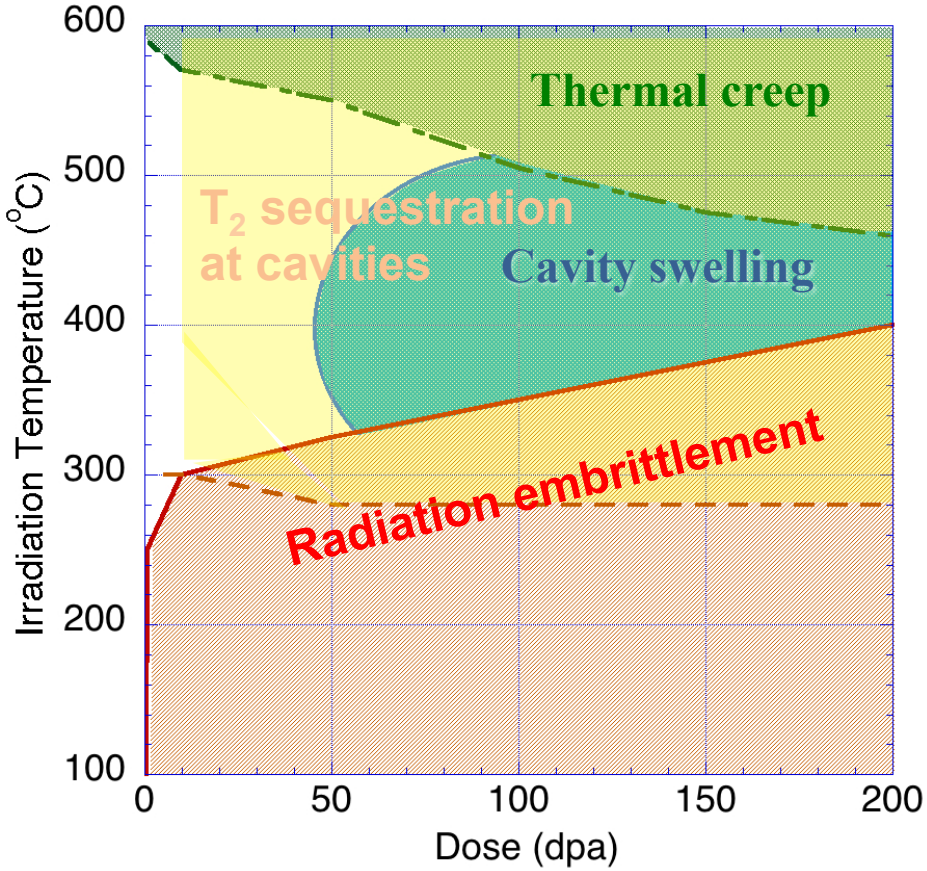
F.A. Garner et al., J. Nucl. Mater. 356 (2006) 122

Notional operating temperature windows for ferritic martensitic steels in fusion reactors

Traditional operating window



Potential impact of T2 sequestration in blanket structure



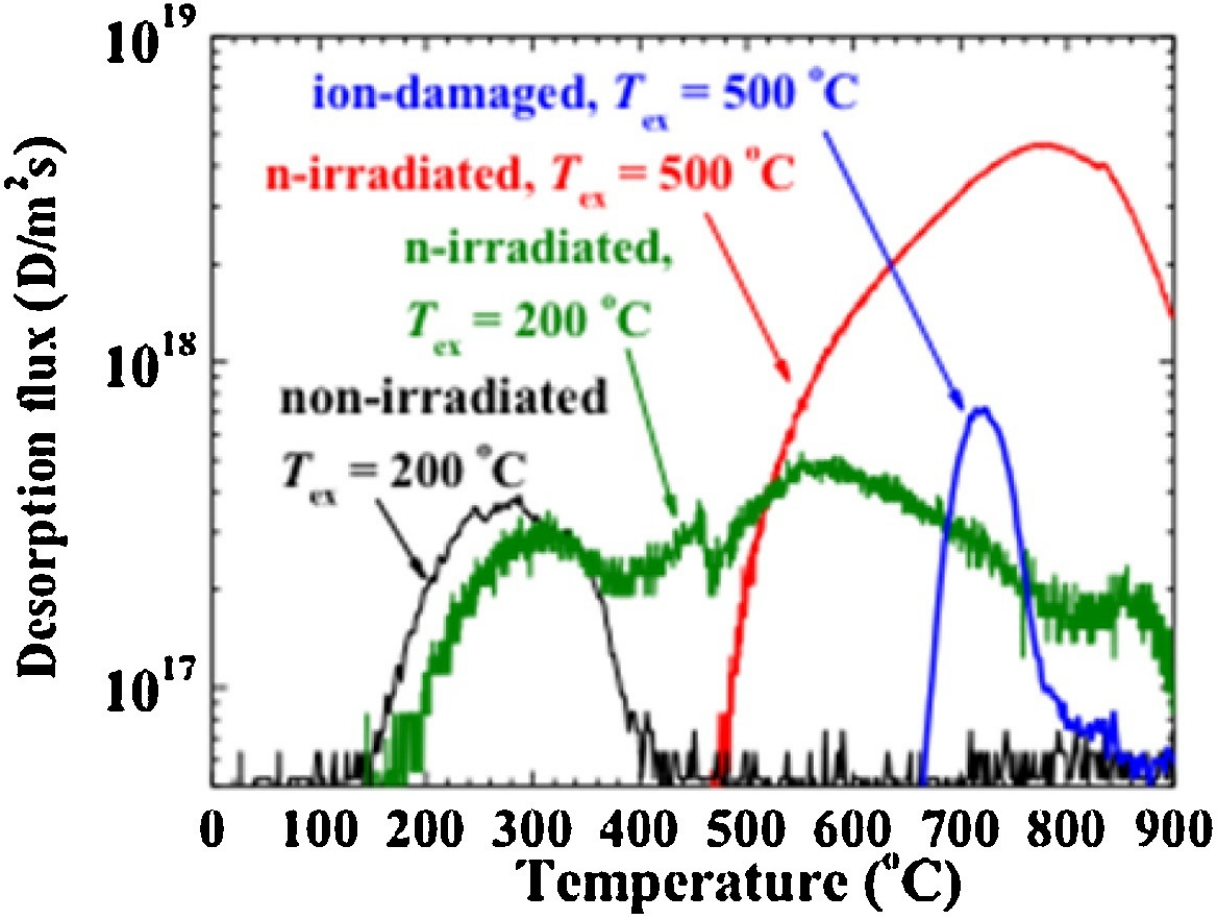
Zinkle & Ghoniem Fus. Eng. Des. 51-52 (2000) 55;
A. Hishinuma et al. J. Nucl. Mat. 258-263 (1998) 193

Concluding Comments

- Multiple options are available for high performance structural materials for nuclear environments
  - High confidence of suitability for fission neutron environments
  - Uncertain suitability of FM steels for fusion beyond ~5 MW-yr/m^2
  - Potential impact of tritium retention in cavities needs to be assessed (requires systems-level analysis for specific blanket concepts)
- Many of the critical path items for DEMO are associated with fusion materials and technology issues (PMI, etc.)
  - Low-TRL issues can often be resolved at low-cost
- Alternative energy options are continuously improving
  - Passively safe fission power plants with accident tolerant fuel that would not require public evacuation for any design-basis accident
  - Lower-cost solar, wind (coupled with lower-cost energy storage)

Effect of irradiation temperature on H trapping in neutron and ion irradiated tungsten

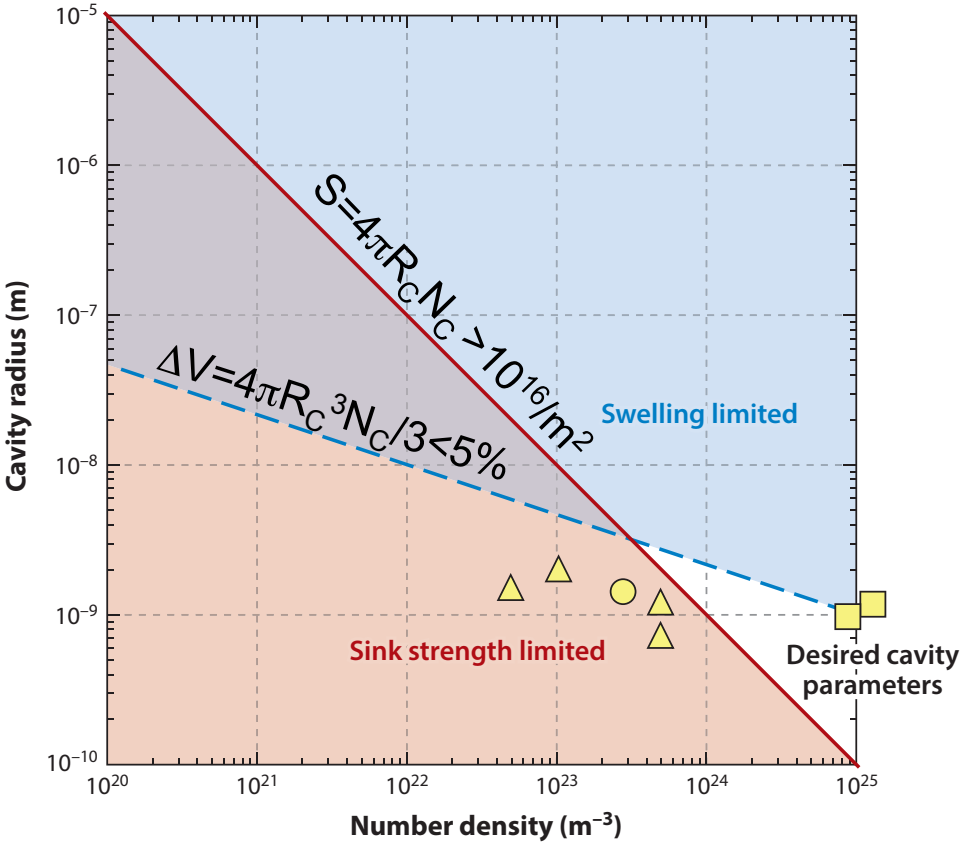
H trapping at irradiation defects is enhanced for irradiation at temperatures where cavity formation occurs (500°C vs. 200°C)

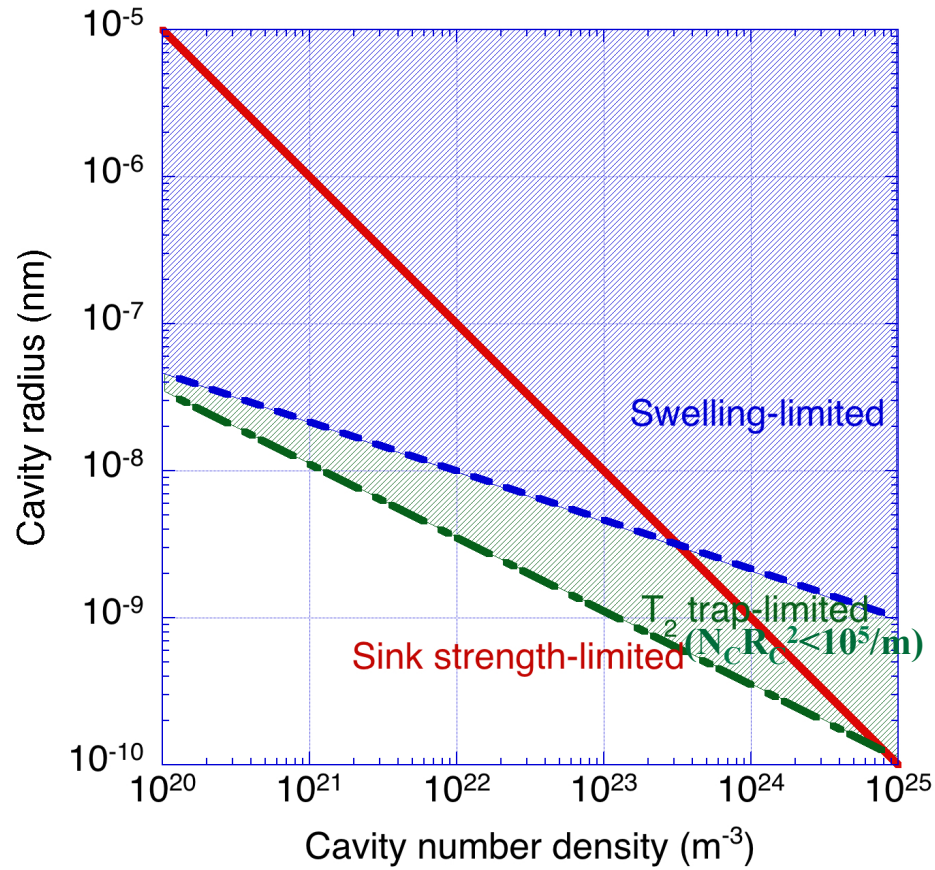


0.025 dpa n irr.
0.5 dpa ion irr

Y. Oya et al., Fus. Eng. Des. 113 (2016) 211

Does the mainstream approach for designing radiation resistance cause unacceptable tritium sequestration in DT fusion energy structures?





T_2 trap limit assumes monolayer coverage on cavities in ITER PFC tiles only (850 m^2 surface, 1 cm thick)

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