Advanced Structural Materials for Non-Light Water Reactors

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Workshop on Advanced Non-Light Water Reactors: Materials and Component Integrity

Nuclear Regulatory Commission

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THE UNIVERSITY of TENNESSEE KNOXVILLE

OAK RIDGE National Laboratory

Overview

- **High sink strength has been a long-standing scientific tenet for superior radiation resistance in structural alloys**
  - Cold-worked and Ti-modified SS alloys (e.g., D9) developed by LMFBR program in the 1970s
- **Improved structural materials are needed for nuclear power to fully achieve its promise**
  - High burnup, accident tolerant LWRs
  - Fusion and Gen IV reactors
- **Nanostructured alloys enable simultaneous achievement of radiation resistance and high performance (strength)**
  - Radiation resistance ("sink strength"): $S \sim 4\pi RN$
  - Dispersed barrier hardening: $\Delta\sigma_y \sim \alpha\mu b(2NR)^{1/2}$

$\Rightarrow$ For a given precipitate volume $f=4\pi R^3/3$, best radiation resistance and mechanical strength simultaneously occurs for high N, small R

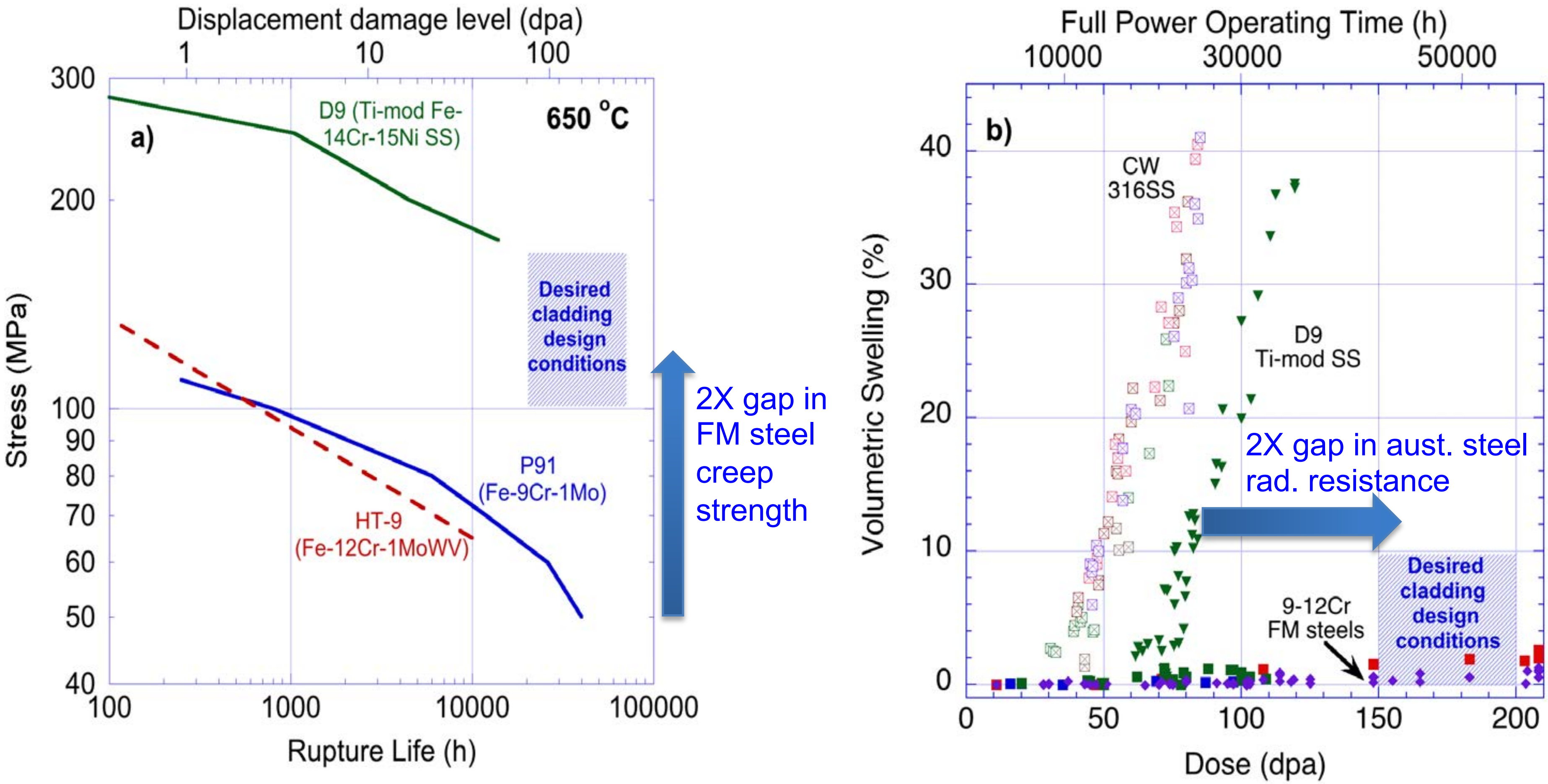
$S \sim N^{2/3}/R^2$ (radiation resistance)

$\Delta\sigma_y \sim f^{1/2}/R$ (mechanical strength)

$\Rightarrow$ High density of uniformly distributed nanoscale precipitates preferred

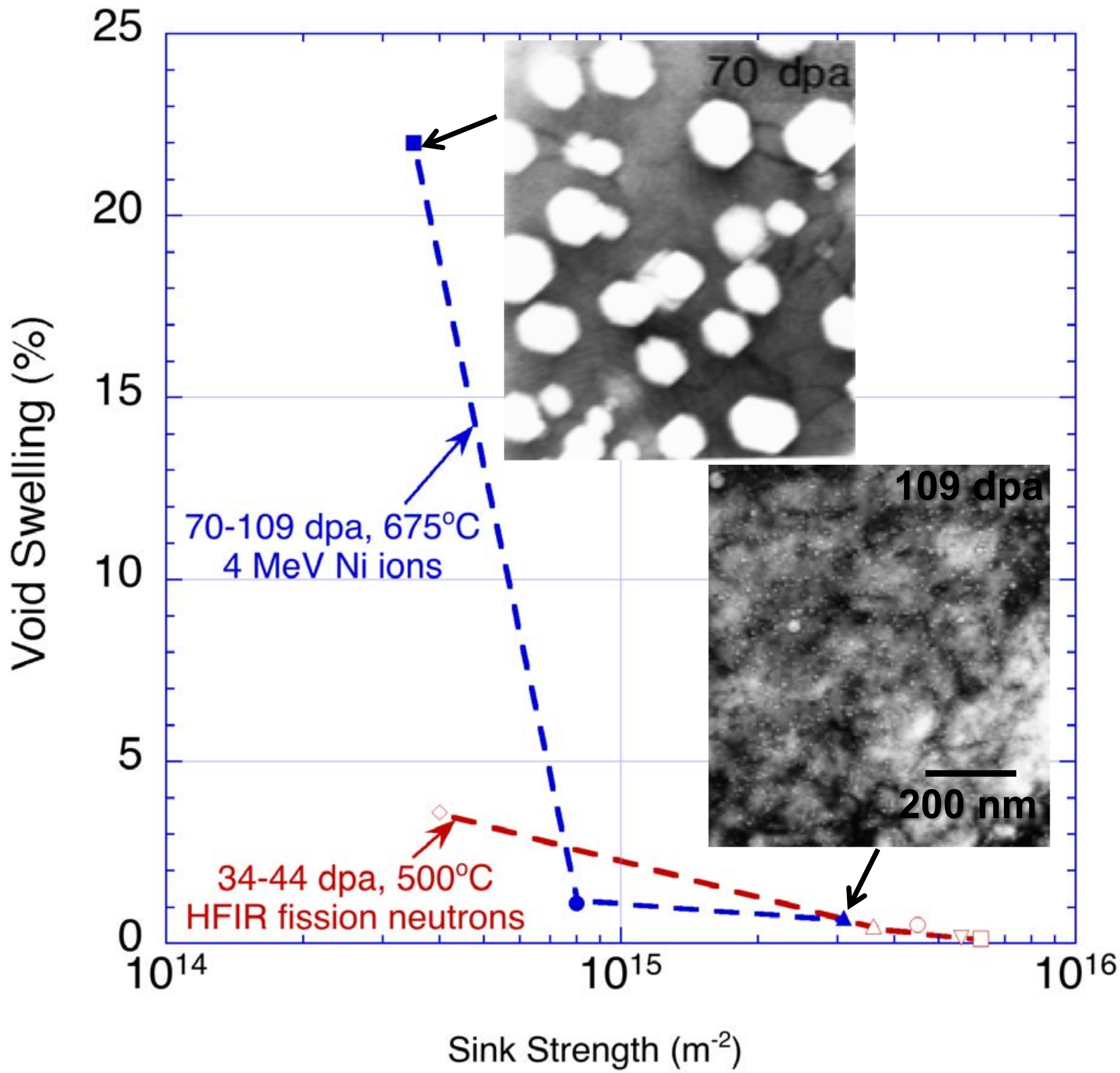
Thermal creep and void swelling in sodium-cooled fast reactor cladding is problematic for conventional steels

Current “either/or” dilemma if structural alloy selection is limited to conventional steels



S.J. Zinkle, K.A. Terrani, L.L. Snead,
Current Opin. Sol. State & Mater. Sci. 20 (2016) 401

Effect of initial sink strength on the volumetric void swelling of irradiated FeCrNi austenitic alloys



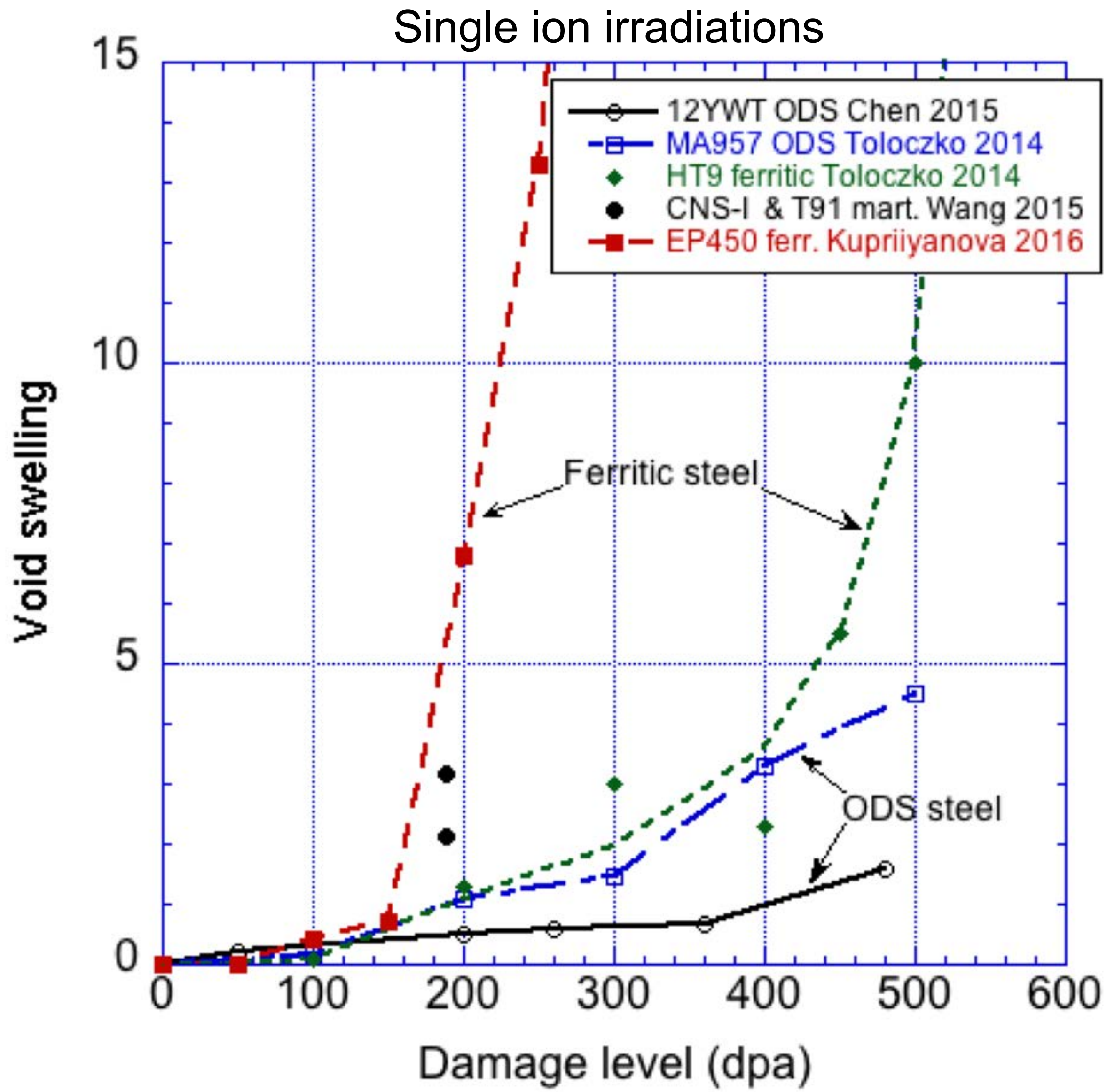
Dramatic reduction in void swelling occurs when average spacing between voids is >10x average spacing between defect sinks

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

For void swelling resistance, sink strengths $>10^{15}/m^2$ are generally sufficient for fission reactors; fusion reactor irradiation may require even higher sink strengths ($>10^{16}/m^2$?) due to transmutant He production

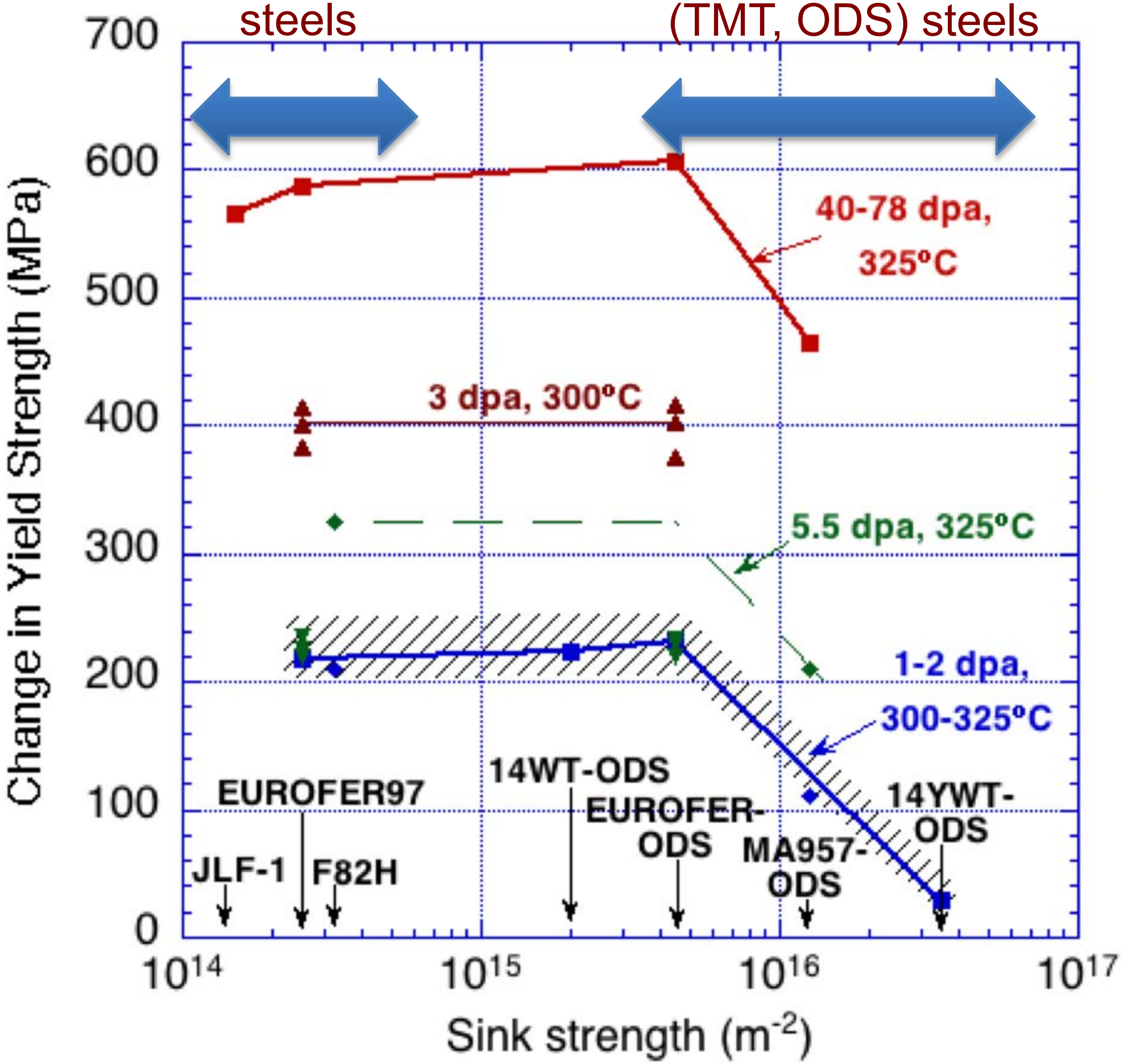
S.J. Zinkle and L.L. Snead, Ann Rev. Mat. Res., 44 (2014) 241

ODS steels provide improved void swelling resistance compared to standard ferritic/martensitic steels



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

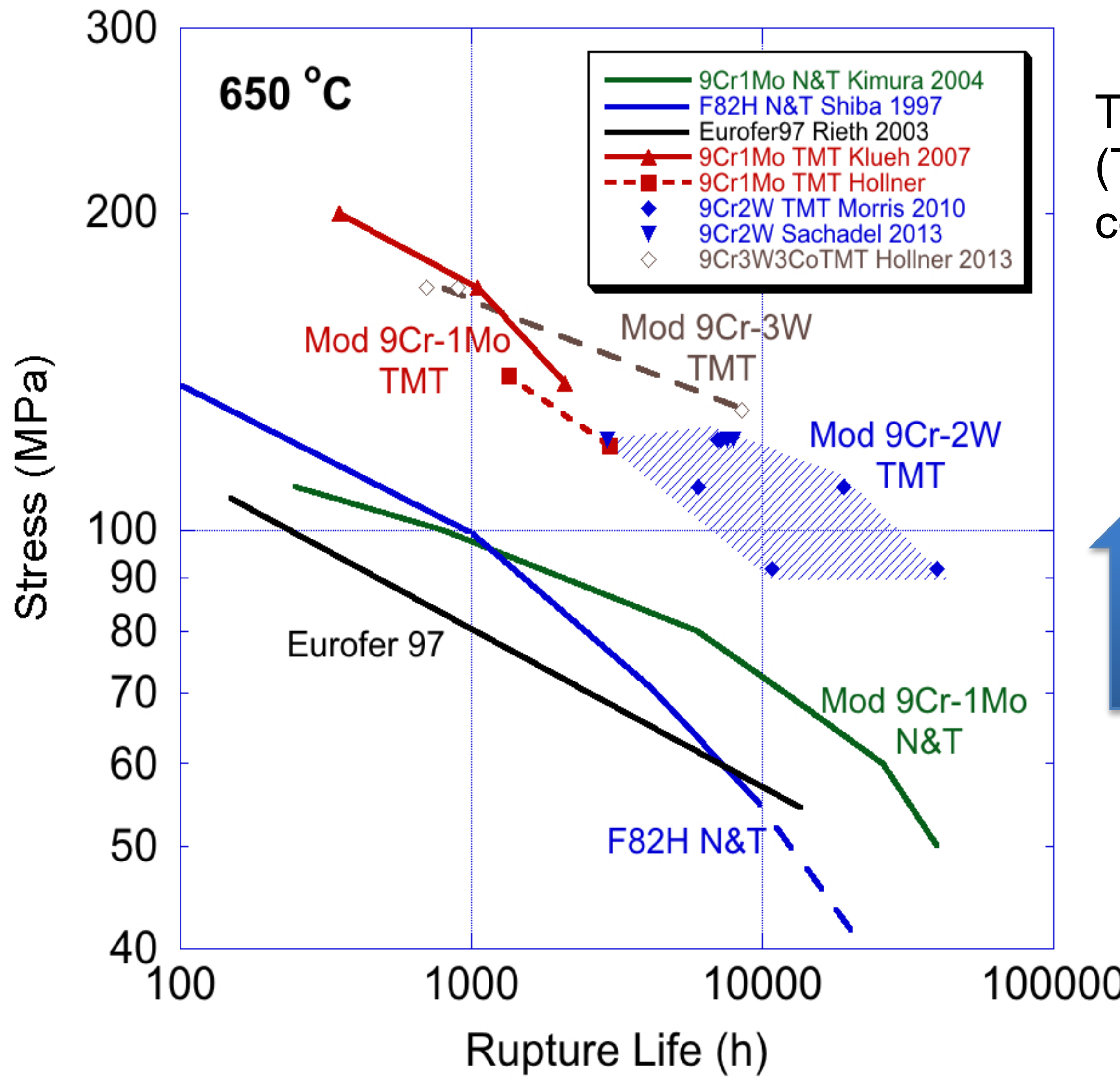
$N_{loop}^{-1/3} >> S_{tot}^{-1/2}$

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

Creep rupture behavior for TMT vs. conventional 9Cr steels



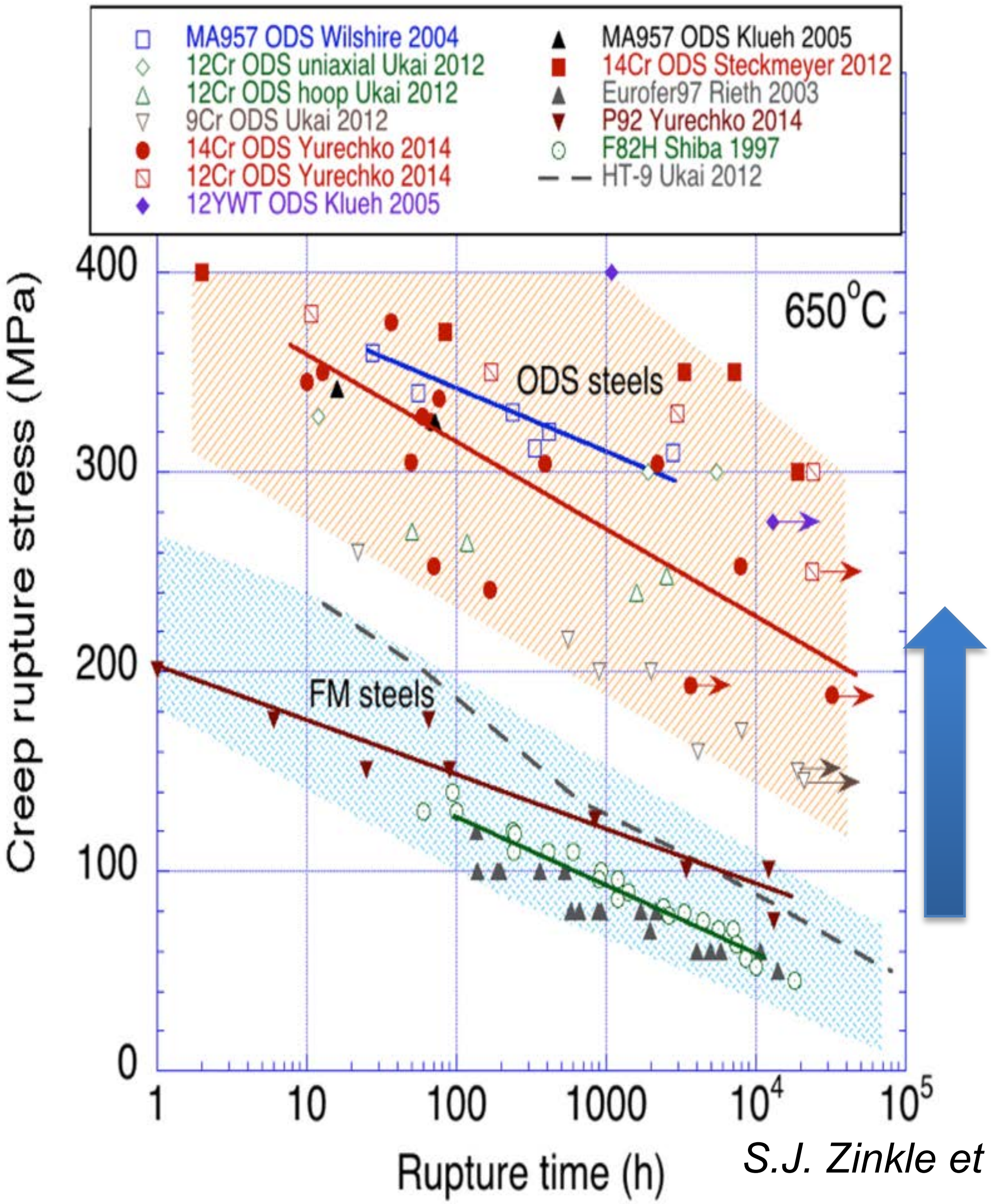
Thermo-mechanical treatment (TMT) 9Cr steels designed using computational thermodynamics

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

Predicted 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

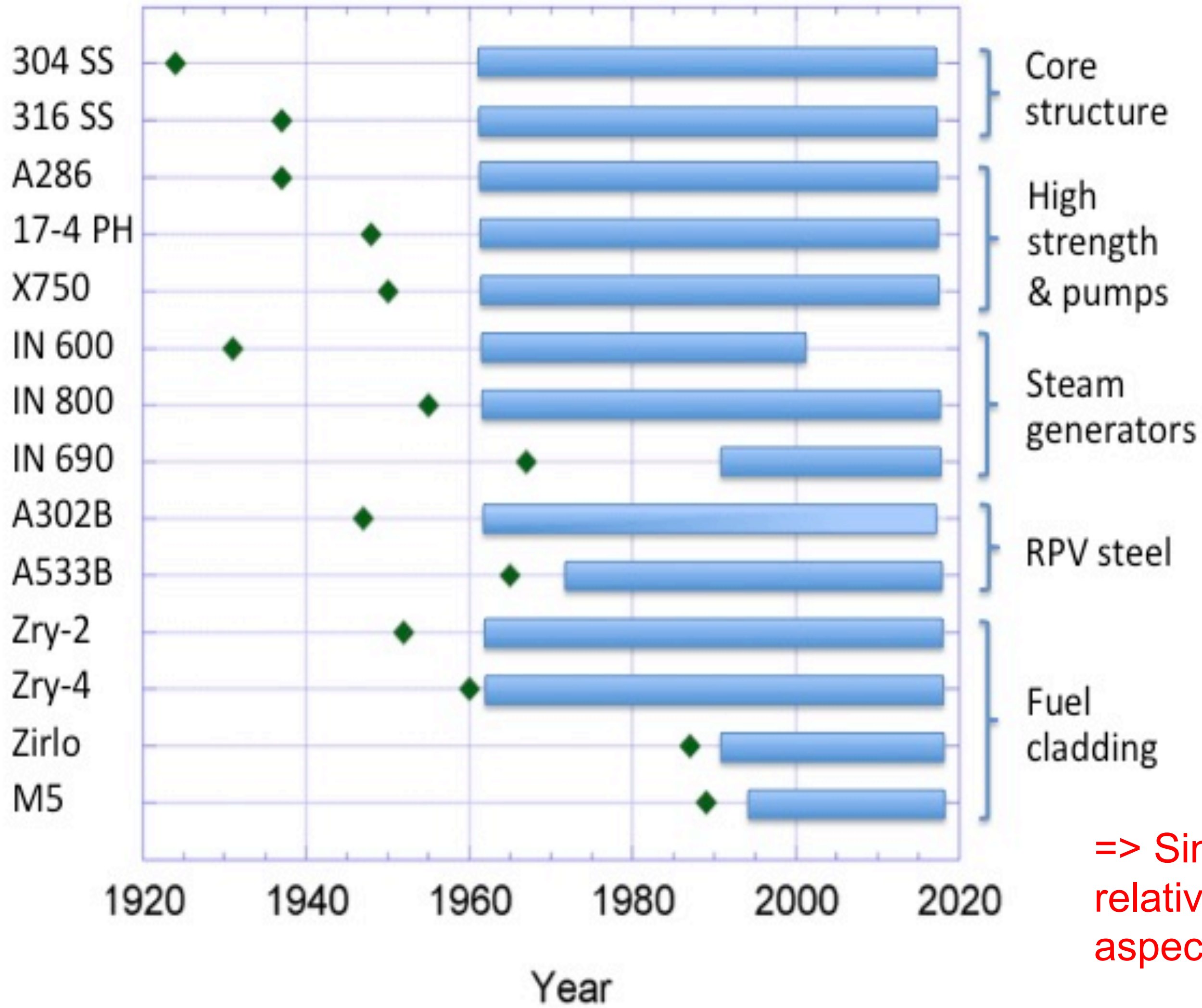
Predicted improvement in radiation resistance as well due to high dispersoid density

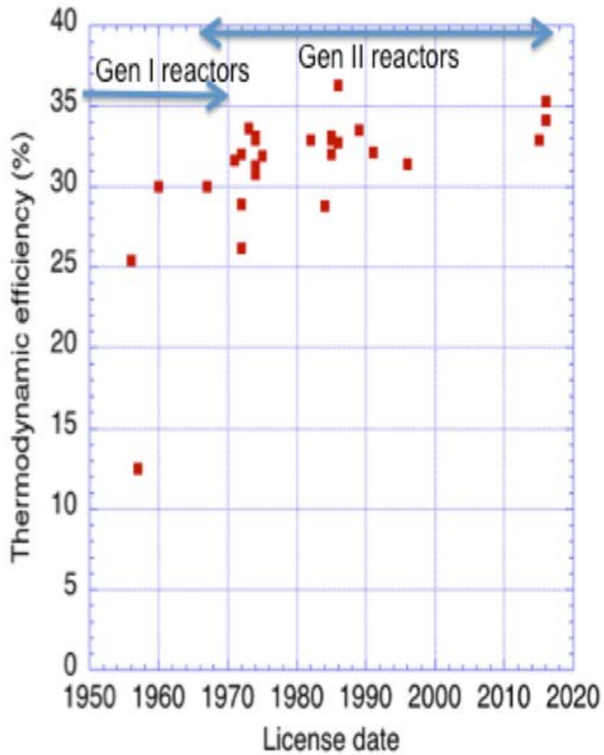
S.J. Zinkle et al., Nucl. Fusion 57 (2017) 092005

Conclusions

- Nanostructured (high sink strength) alloys are promising options for the structural materials in next-generation fission reactors
  - Enables simultaneous superior radiation resistance and superior mechanical property performance
- ASME code qualification is needed to enable their deployment
  - Currently in “boutique” materials stage

Timeline of structural materials used in light water reactors



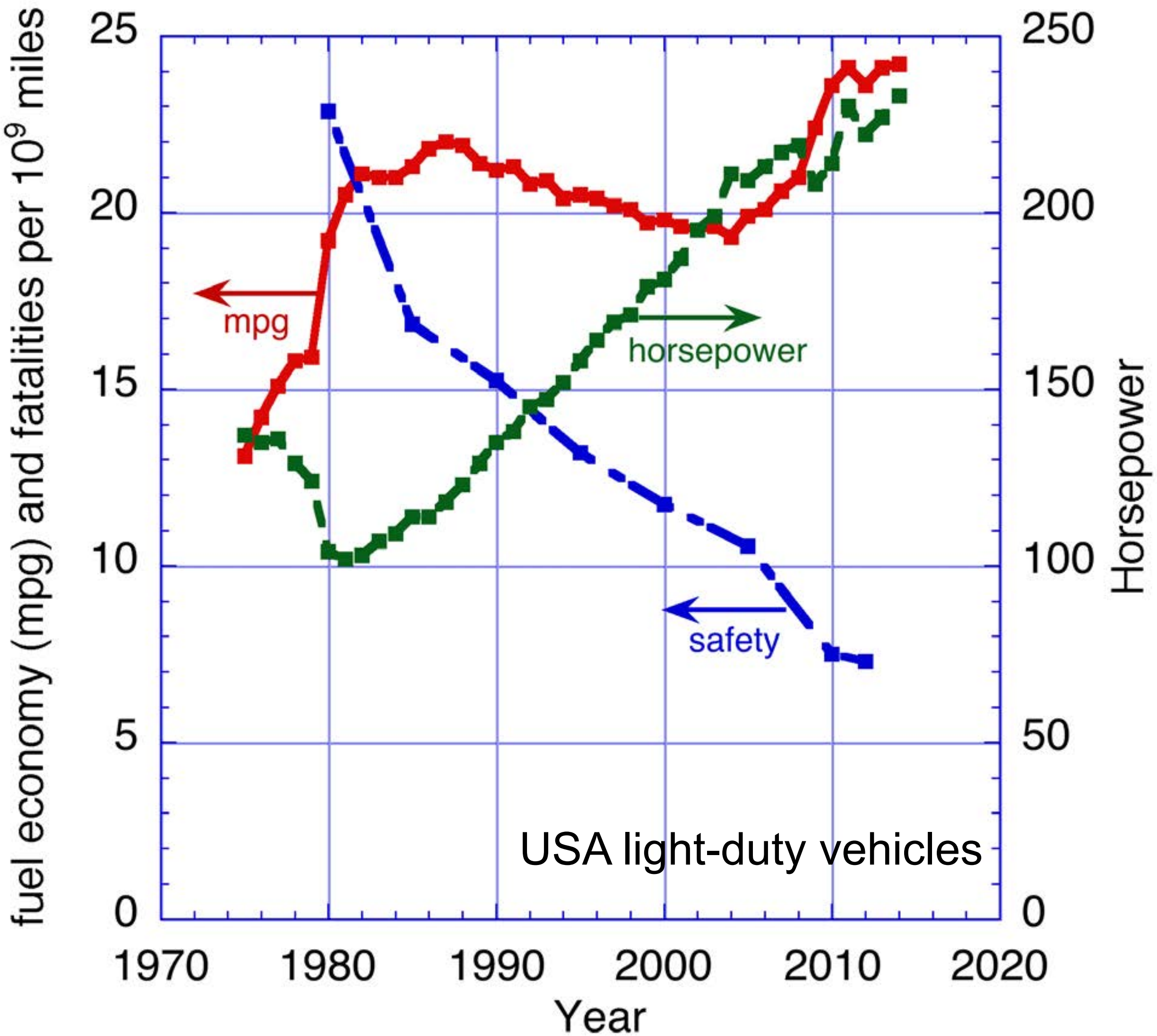


=> Since the 1960s, there has been relatively little modification of materials aspects for LWRs

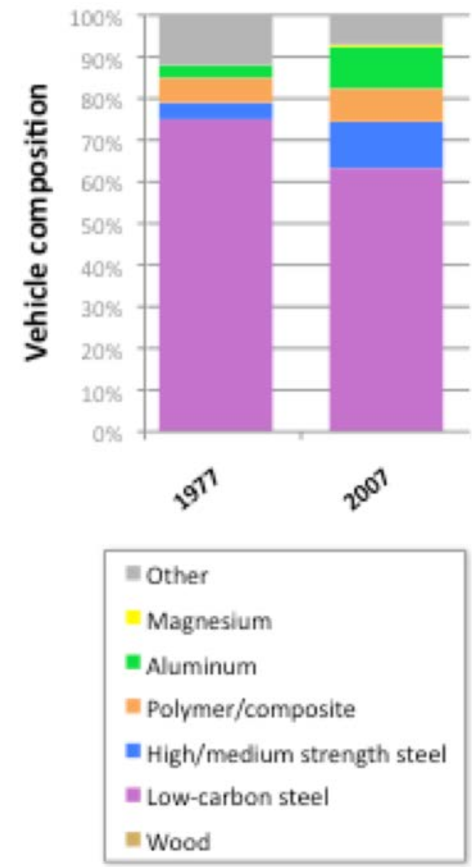
S.J. Zinkle, K.A. Terrani, L.L. Snead, Current Opin. Sol. State & Mater. Sci., 20 (2016) 401

Evolution in light duty personal vehicles

Greatly improved safety, along with improved performance (horsepower, fuel economy)



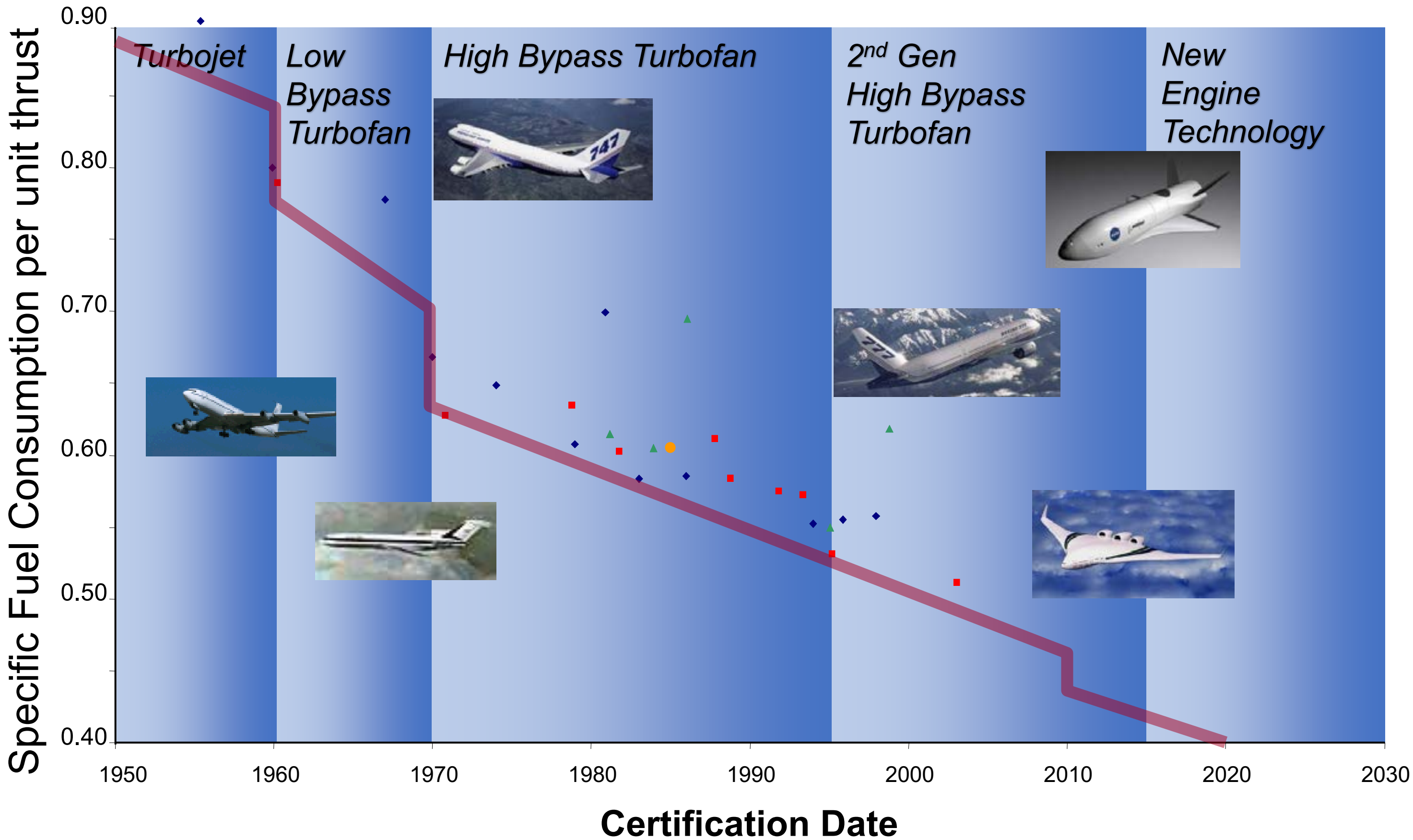
Source: US Dept. of Transportation and Environmental Protection Agency



A. Taub et al., JOM 59, 2 (2007) 48

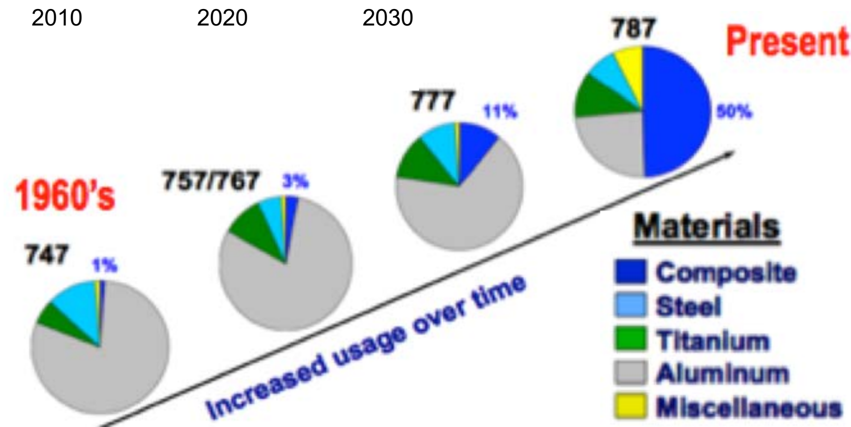
New Propulsion Materials and Architectures Have Driven Marked Improvements in Jet Engine Fuel Efficiency

Plus: 40x improvement in durability; 10x improvement in in-flight shutdown rate



R.E. Schafrik, personal communication

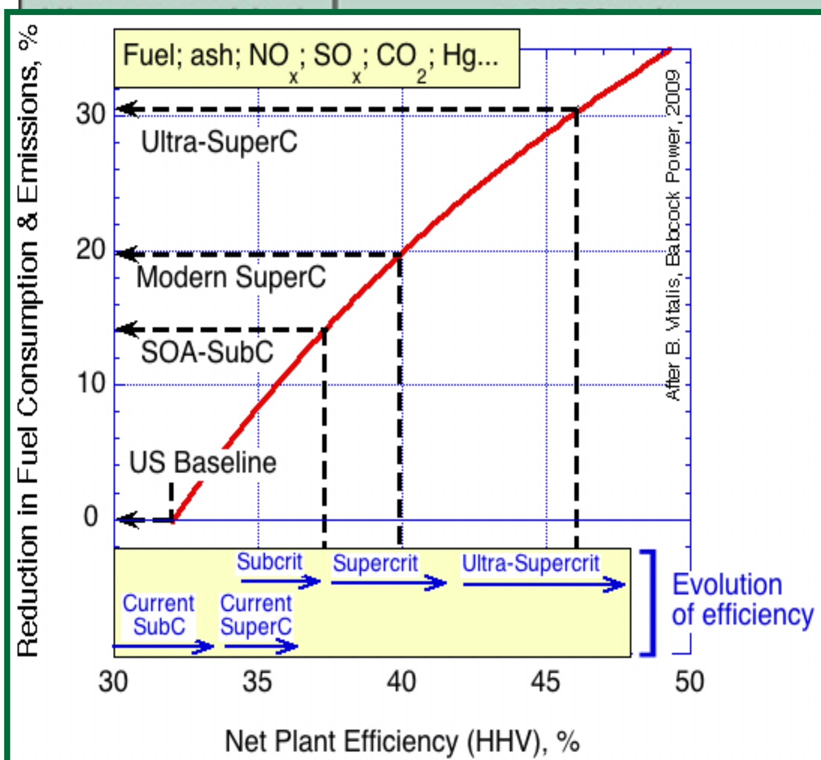
W.G. Roeseler et al., in 16th Int. Conf. on Composite Materials, Kyoto, Japan (2007)



Near-term Importance of Advanced Steam

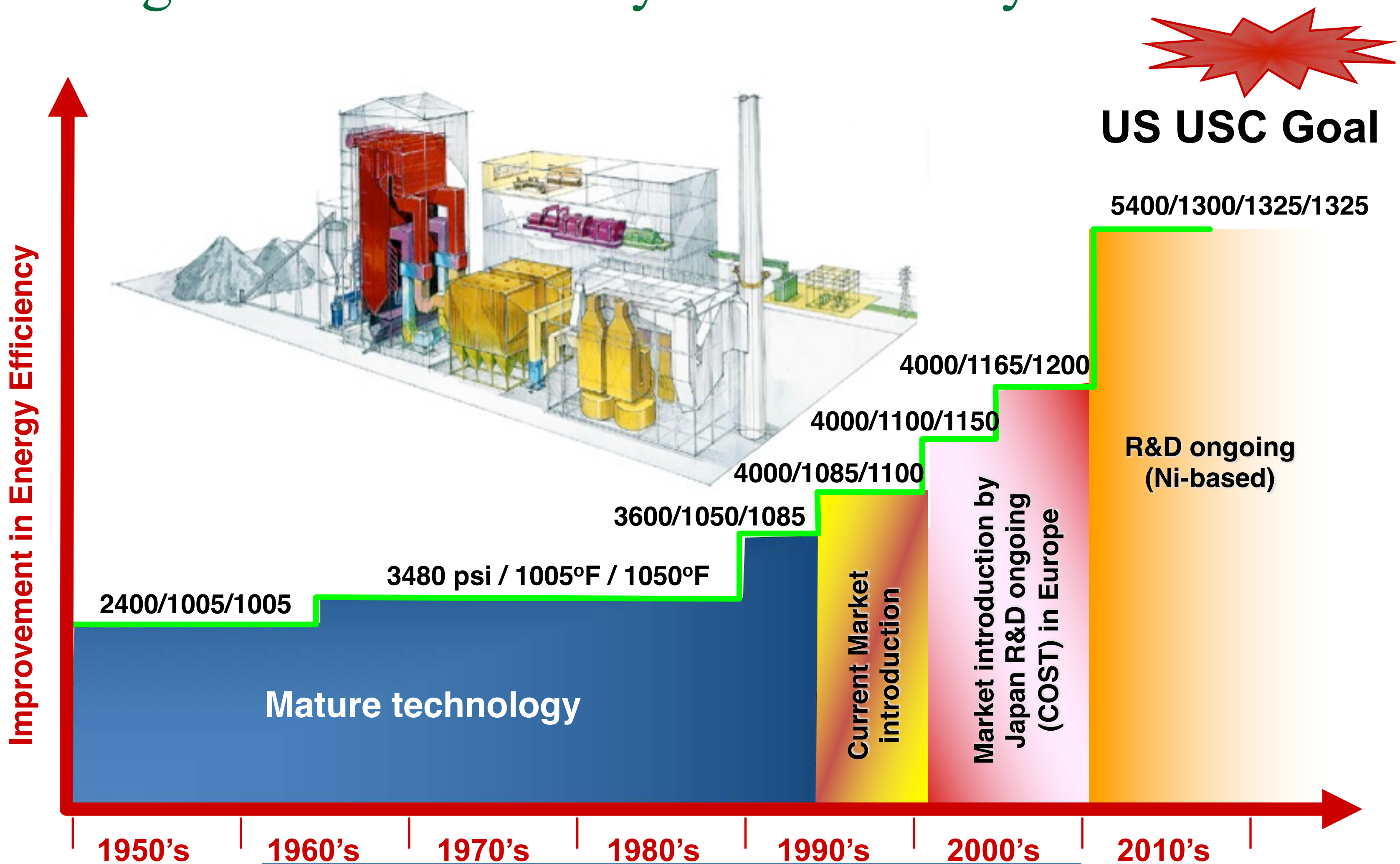
Nomenclature	Conditions	Net plant efficiency (%)	Net plant heat rate (HHV)
Subcritical	2,400 psi 1,050F/1,050F	35	9,751 Btu/kWh
Supercritical	>3,600 psi 1,050F/1,075F	38	8,981 Btu/kWh
		>42	8,126 Btu/kWh
		>45	7,757 Btu/kWh

Source: Electric Power Research Institute



essential to reduce cost of CCS

Advanced Steam Conditions Push Metallurgical Limits of Alloys in Use Today

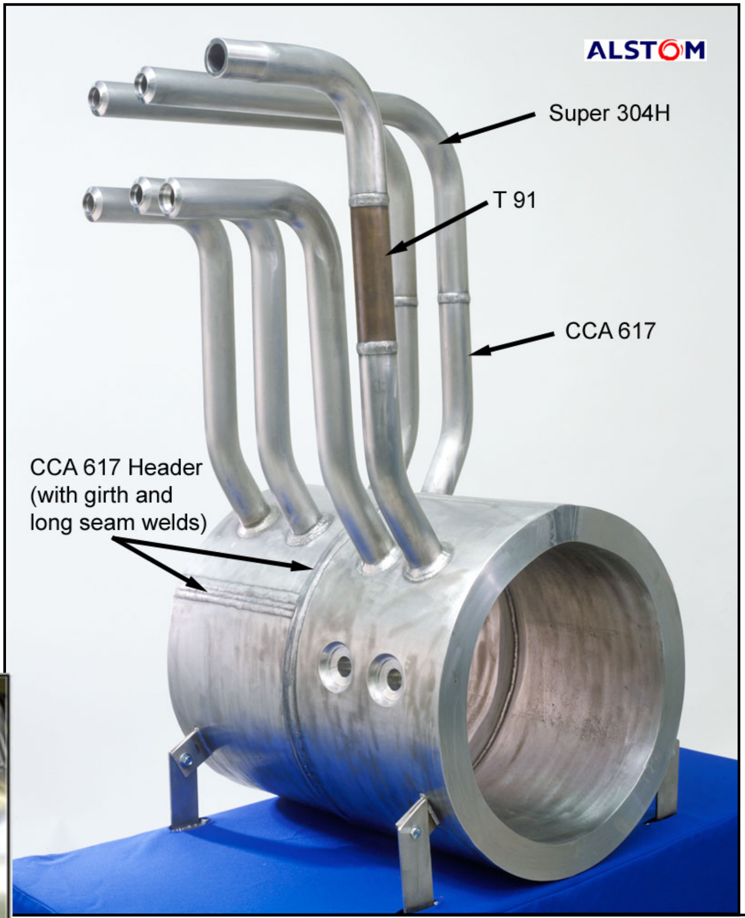


Cost-Effective Materials Are Key

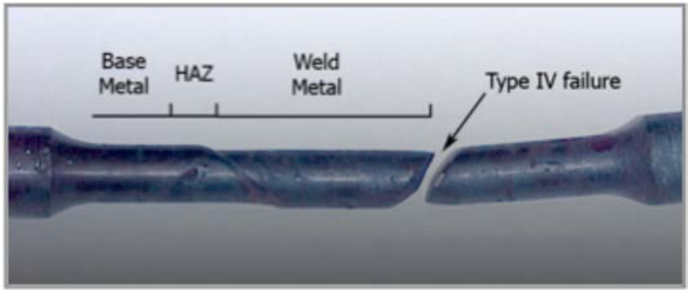
Illustration: EPRI
Data: Alstom

Tubing/piping materials for advanced ultra-supercritical (A-USC) steam (760ºC, 350 bar)

- **Objective: qualify/develop advanced alloys to enable reliable, high efficiency operation of A-USC plants**
- **Key Deliverables:**
  - **Generate alloy properties database for U.S. boiler manufacturers to enable component design and fabrication**
  - **Qualification of fabrication/welding techniques for use with specific alloys**
  - **ASME Boiler and Pressure Vessel Code case for Inconel 740**
  - **Evaluate environmental compatibility**



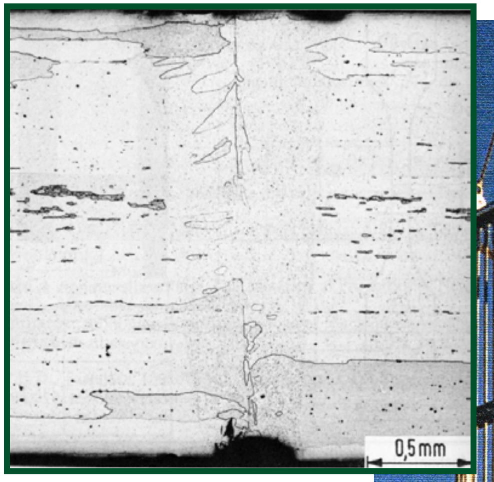
Demonstration header fabricated from advanced alloys qualified by the U.S. A-USC Consortium

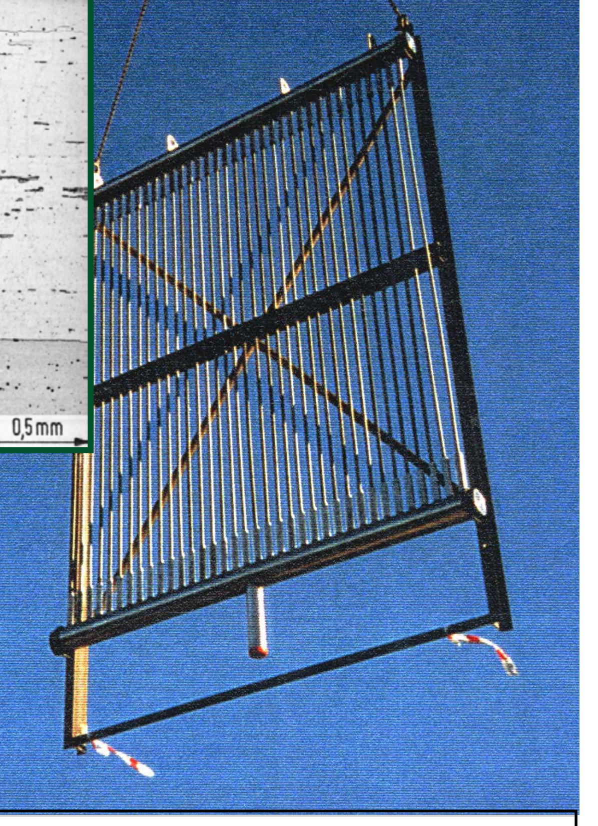


Cast nickel-base alloys for steam turbine casings

Qualification of new, commercial ODS alloys for use in advanced FE processes

- Objective: Determine capabilities of new commercially-produced ODS alloys for application at temperatures up to 1200C in advanced fossil combustion and conversion processes





25 mm diam x 4 m long ODS FeCrAl tubes used in British Gas/COST 501 1100°C air heater demonstrator

- Key Deliverables
  - Data on the full range of properties required to qualify the alloy for fossil applications
  - Evaluate joining technologies
  - Feasibility of employing a less costly route for producing ODS alloy powders

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

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