High-Temperature Deformation Issues for Fusion Structural Metals

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Outline

- Key criteria for high performance systems
- Thermal creep
- Irradiation creep
- High-Temperature Helium Embrittlement

Suggested Performance Goals

Smith, Billone,Majumdar, Mattas & Sze, 1998

Criteria	Minimum Values	Goal Values
Average neutron wall load (MW/m^2)	2-3	5-10
Peak heat flux (MW/m^2)		
High heat flux components	5-7	50
First wall	1-1.5	2-4
First wall lifetime (dpa)	~100	~200
Average cost of core materials ($/kg)	~100	~50
Net cycle efficiency (%)	~40	>50

Surface Heat Flux Limits

Smith, Billone,Majumdar, Mattas & Sze, 1998

Structural Material	Martensitic Steel	Vanadium Alloy	SiC/SiC
Max. temperature (°C)	550	750	950
Max. coolant ΔT (°C)	250	350	450
Max. first wall ΔT (°C)[a]	200	300	400
Heat flux limit (MW/m^2)[b]			
5 mm thick wall	1.2	2.0	4.0(uirr.) 0.4(irr.)
3 mm thick wall	1.9	3.2	6.4(unirr.) 0.6(irr.)

[a]Assumed maximum wall ΔT
[b]Value based on data for existing materials

Diffusion-Controlled Creep Mechanisms

Murty, Mohamed and Dorn, 1972

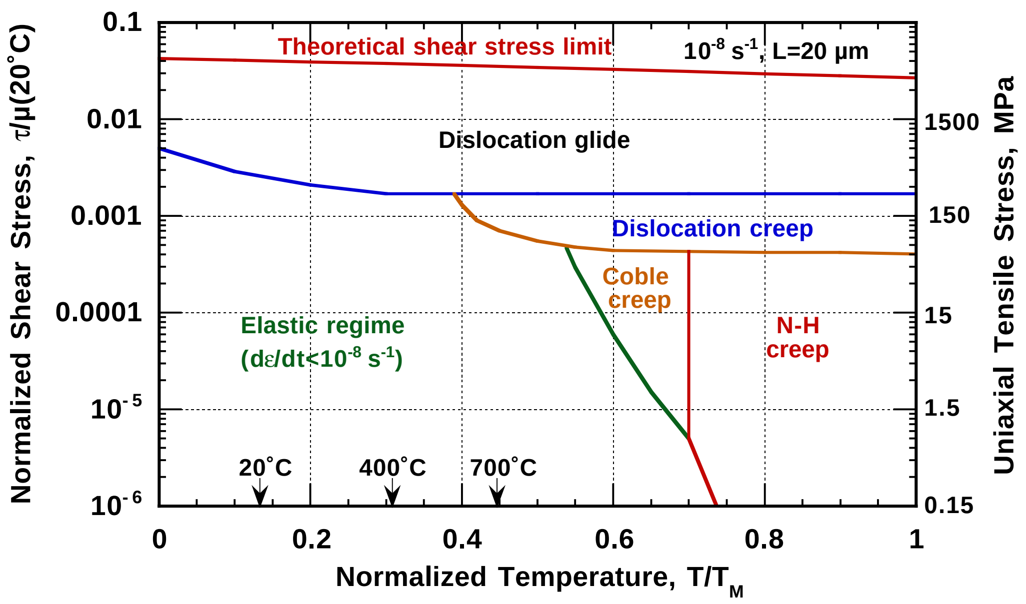
$$\frac{\dot{\varepsilon} kT}{DGb} = A\left(\frac{b}{d}\right)^m \left(\frac{\sigma}{G}\right)^n$$

Mechanism	D	n	A	m
Climb of Edge Dislocations	D_L	5	6×10^7	0
Viscous Glide (Microcreep)	D_S	3	6	0
Low-Temperature Climb	D_d	7	2×10^8	0
Harper-Dorn	D_L	1	3×10^{-10}	0
Nabarro-Herring	D_L	1	12	2
Coble	D_b	1	100	3
GBS (Superplasticity)	D_b	2	200	2
Nabarro-Subgrain	D_L	1	12	2
Nabarro-Bardeen-Herring	D_L	3	10	0

Deformation Mechanism Map for V-4Cr-4Ti

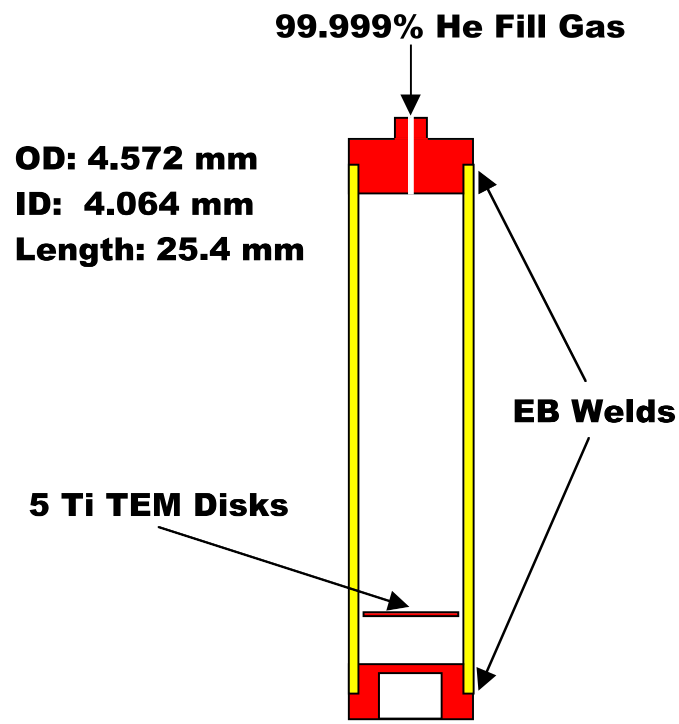
Zinkle and Lucas

$$\dot{\varepsilon} = 10^{-8} s^{-1},\ \mathrm{L} = 20\mu m$$



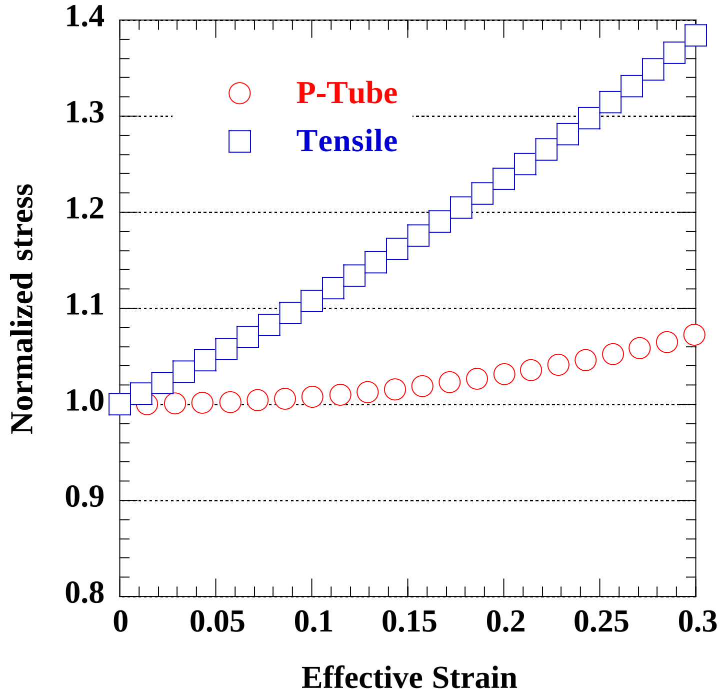
Creep Tube Specimens - Example of SSTT

- Materials: V-4Cr-4Ti (Heat #832665) and V-3Fe-4Ti
- Double wall radiographed
- Vacuum annealed 1h at 1000°C following end cap welding
- Sheathed with Ti foil while in furnace



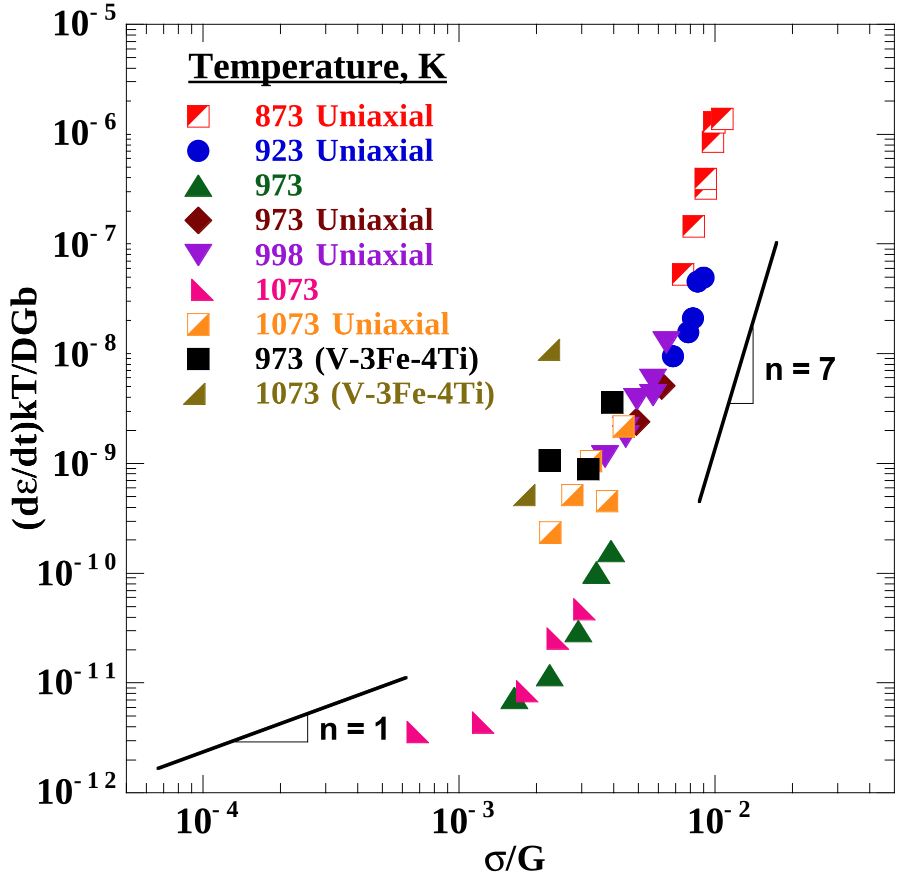
Comparison of P-Tube & Tensile Specimen Stresses

- Stress in pressurized tube is approximately constant as the tube deforms
- Stress in constant-load tensile specimen increases as cross-section decreases
- Small-strain deformation behavior should be similar but times-to-failure might be different



Stress Dependence and Activation Energy for Creep in Vacuum

Kurtz and Matsui, 2000; Natesan et al, 2000



Activation Energy

$$Q = \frac{R * Ln(\dot{\varepsilon}_1 / \dot{\varepsilon}_2)}{1/T_1 - 1/T_2}$$

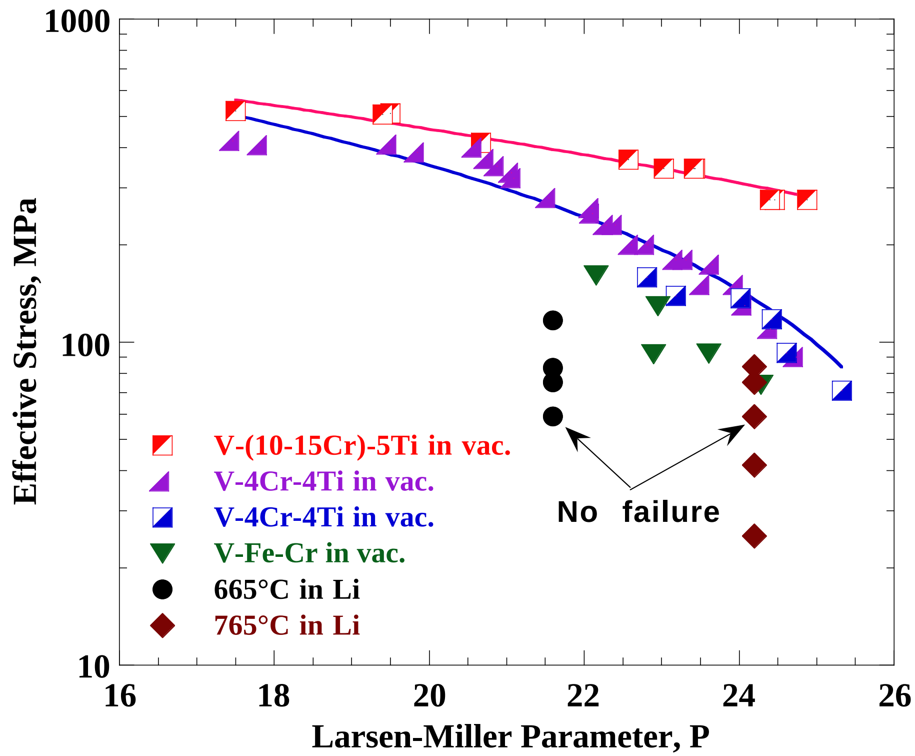
Stress, MPa	Activation Energy, kJ/mole
70	272
90	326
120	300

Q_{SD} ~ 270 kJ/mole (Pure V)

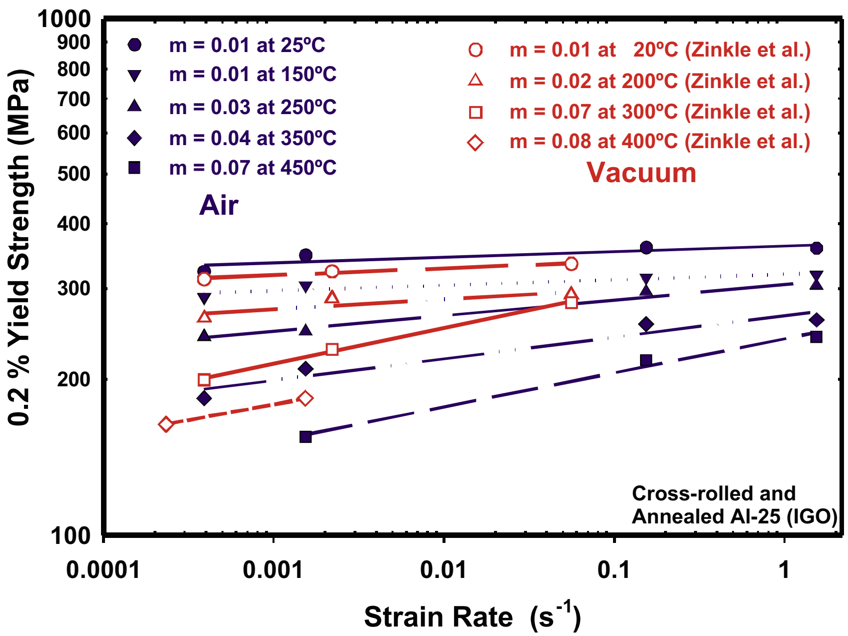
Creep-Rupture of Vanadium Alloys

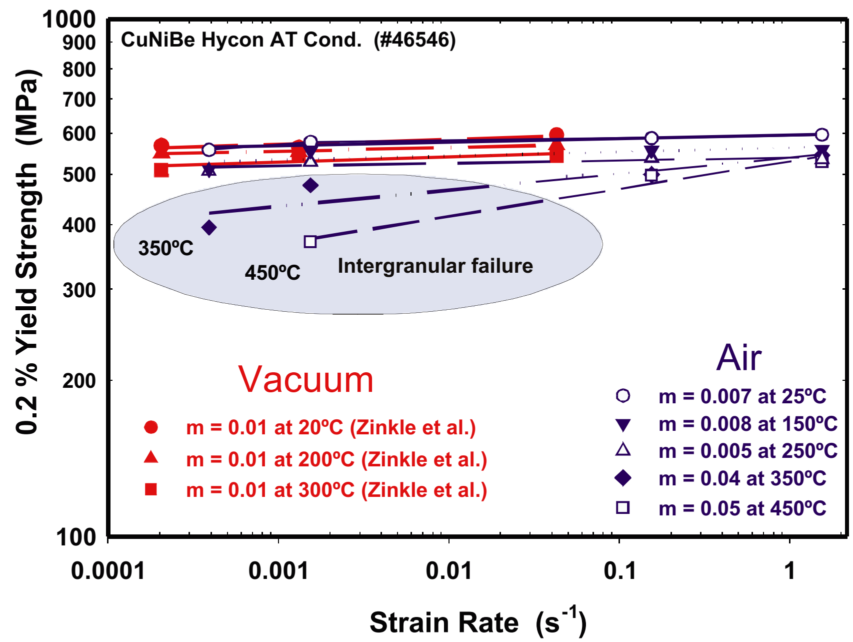
$$P = \frac{T(\log t_r + 20)}{1000}$$

Kurtz and Matsui, 2000; Natesan et al, 2000; Grossbeck, 2001



Strain Rate and Temperature Dependence of the Yield Strength of Copper Alloys

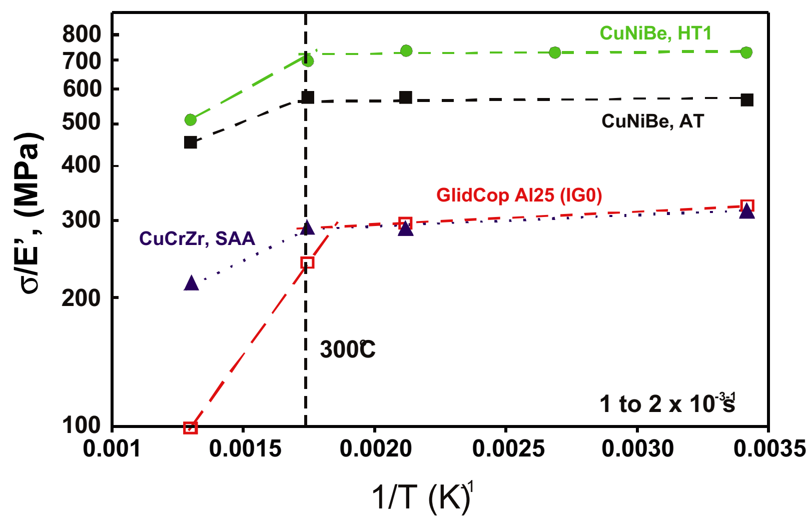




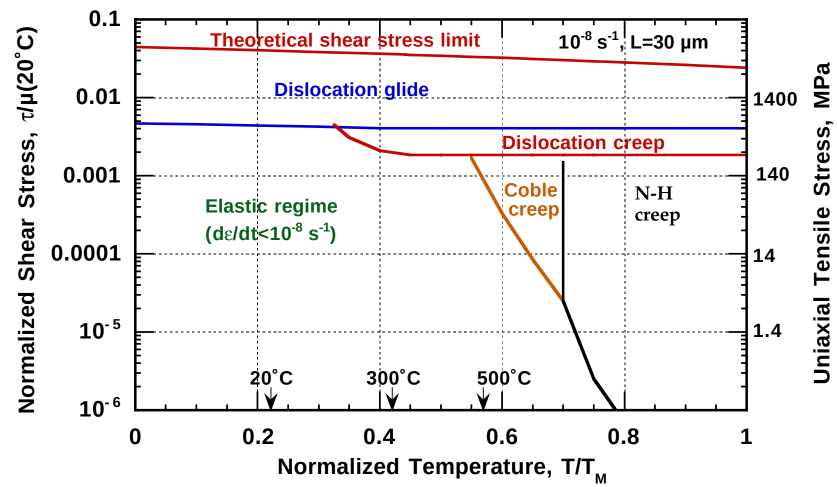
- CuNiBe has superior properties below 100˚C; CuCrZr and Cu-Al_2O_3 have best properties at intermediate temperatures
- High temperature limits (~300°C) in CuNiBe and Cu-Al_2O_3 alloys are associated with grain boundary phenomena (embrittlement and sliding, respectively)
- Each alloy exhibits a different response to testing environment (air vs. vacuum) at temperatures >300°C, indicating different mechanisms controlling behavior

Deformation Mechanism Maps Rationalize Mechanical Behavior of Copper Alloys

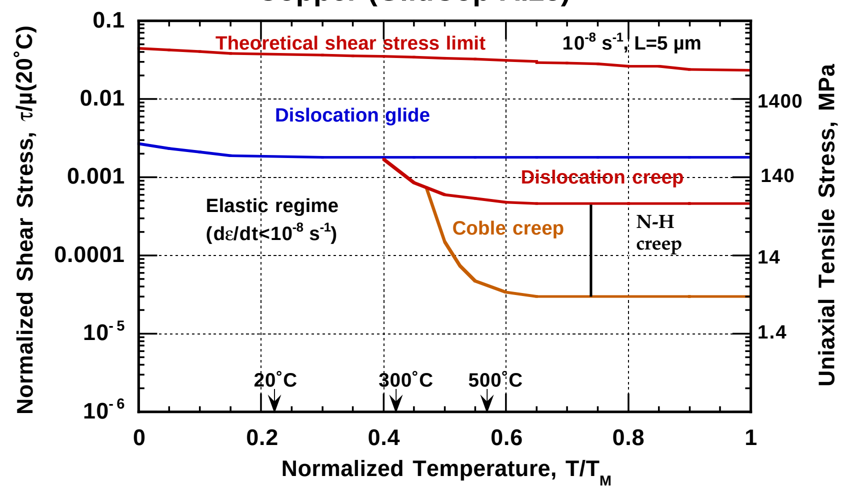
Onset of Creep in in High Strength Copper Alloys



Deformation Map for CuNiBe (Brush-Wellman Hycon 3HP)



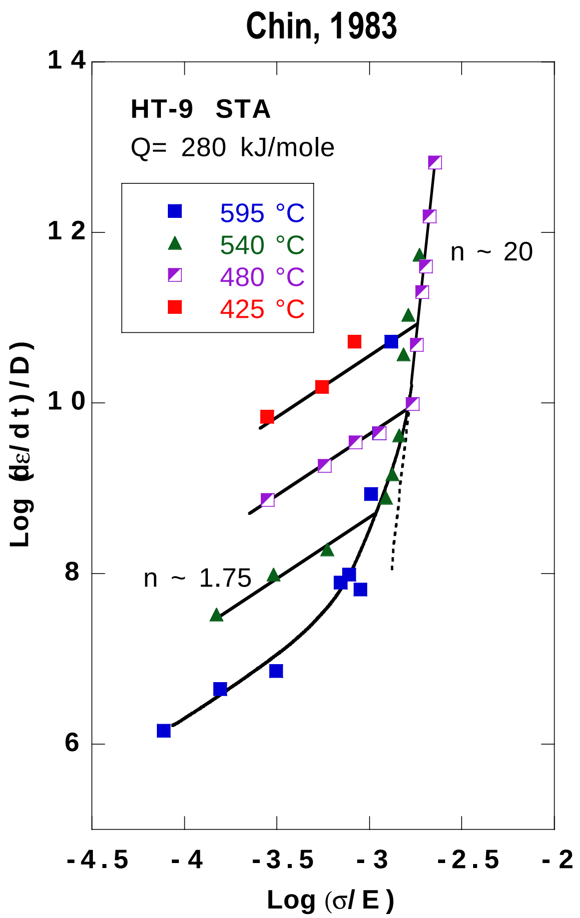
Deformation Map for Oxide Dispersion-strengthened Copper (GlidCop Al25)



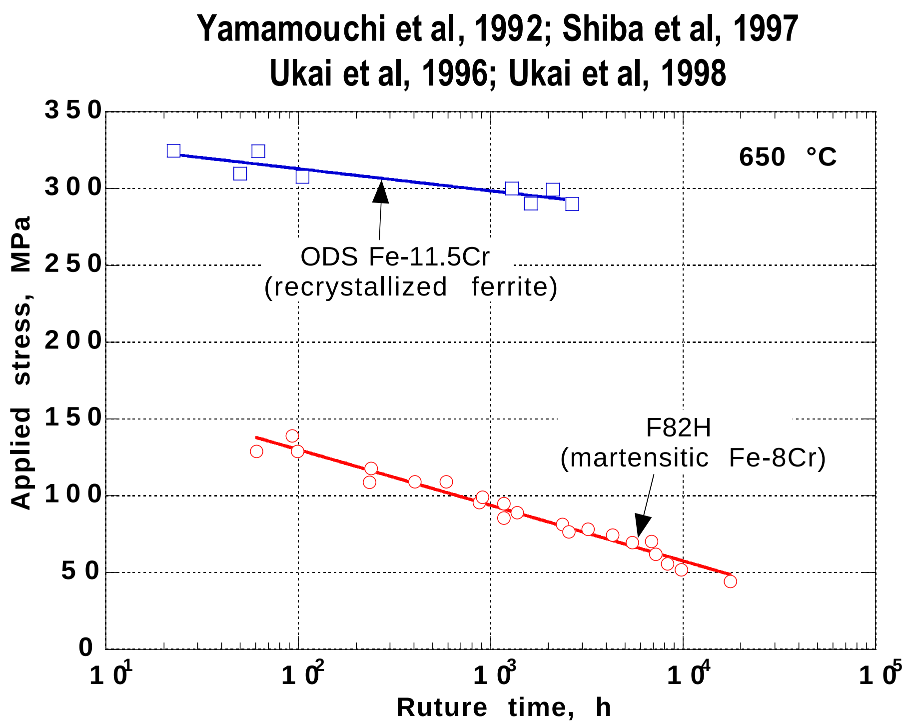
- Creep begins to dominate deformation above 300°C
- Grain boundary embrittlement and sliding limit high temperature applicability

Applications to US industry (e.g., USCAR) as well as fusion energy sciences program

Thermal Creep of Tempered Martensitic Steels



Nano-composited steels offer potential route to significantly improved creep resistance

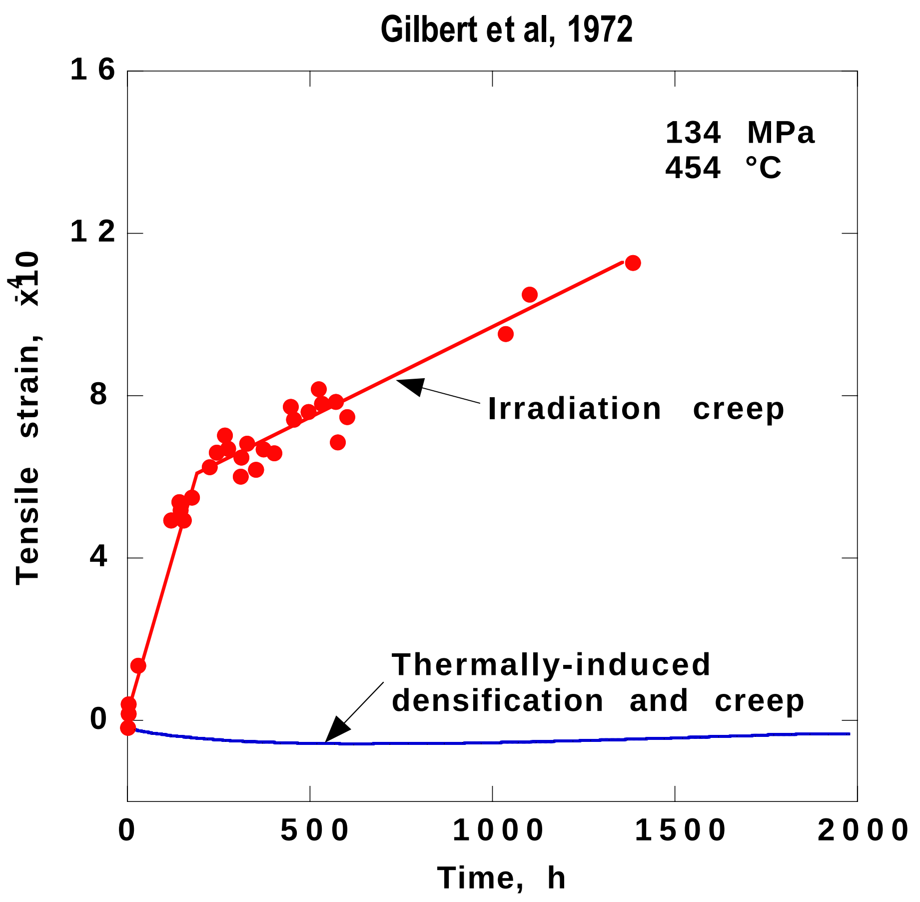


Irradiation Creep - Phenomenological Description

- Orders of magnitude increase in creep strain during relatively low-temperature irradiation
- Degree of creep enhancement is greatest at low temperature, decreasing as the thermal creep regime is approached
- Constitutive equation:

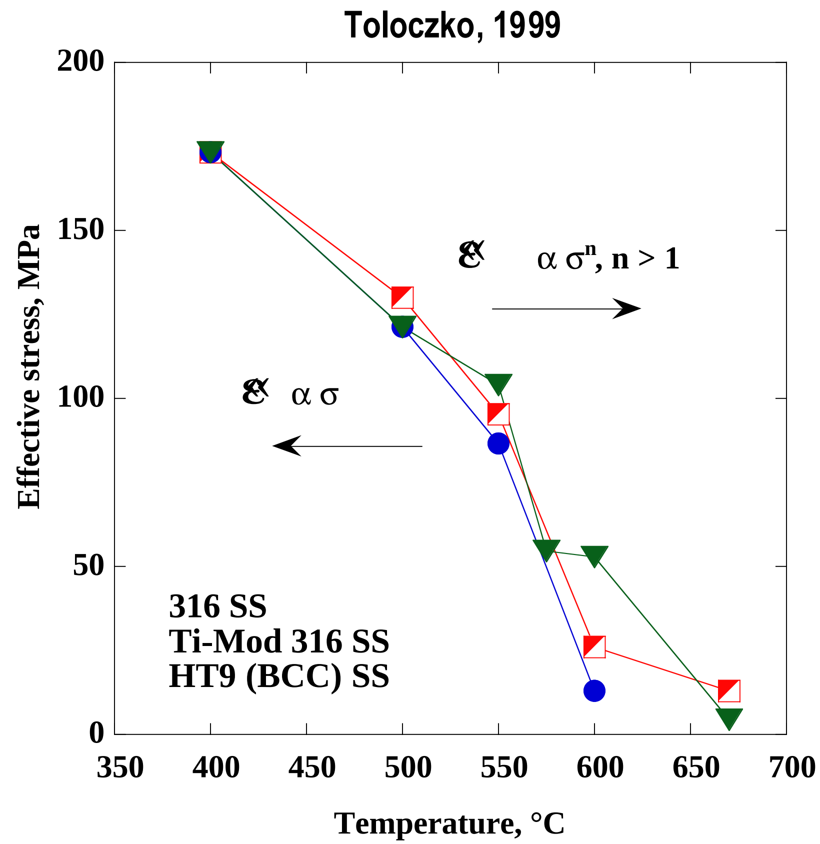
$$\frac{\partial \varepsilon_c}{\partial \phi} = B(\phi,T)\sigma^n, n \approx 1$$

$$B(\phi,T) = B_o + D\frac{\partial S(\phi,T)}{\partial \phi}$$



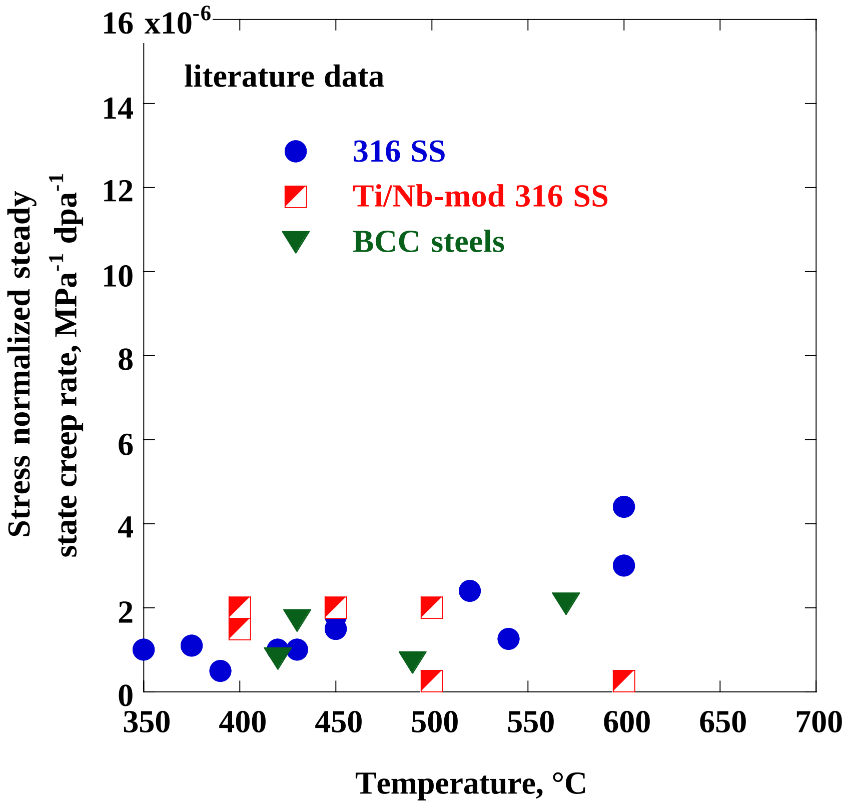
Stress Dependence of Irradiation Creep in the Absence of Swelling

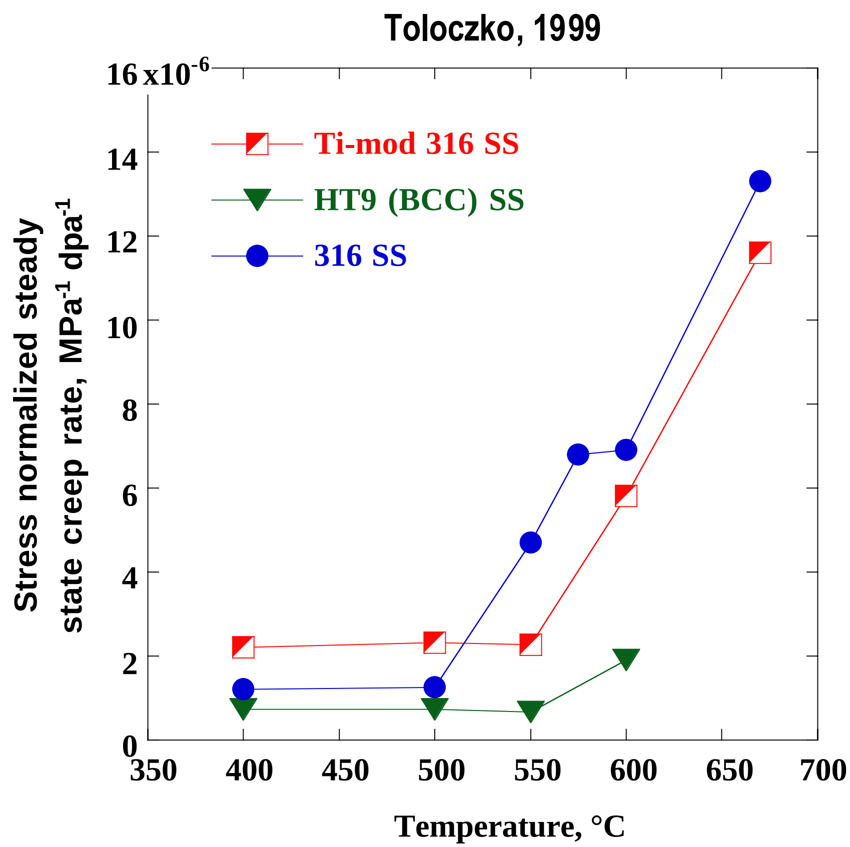
- Irradiation creep exhibits a linear stress dependence over a limited stress range that is temperature dependent
- Similar behavior for FCC and BCC stainless steels



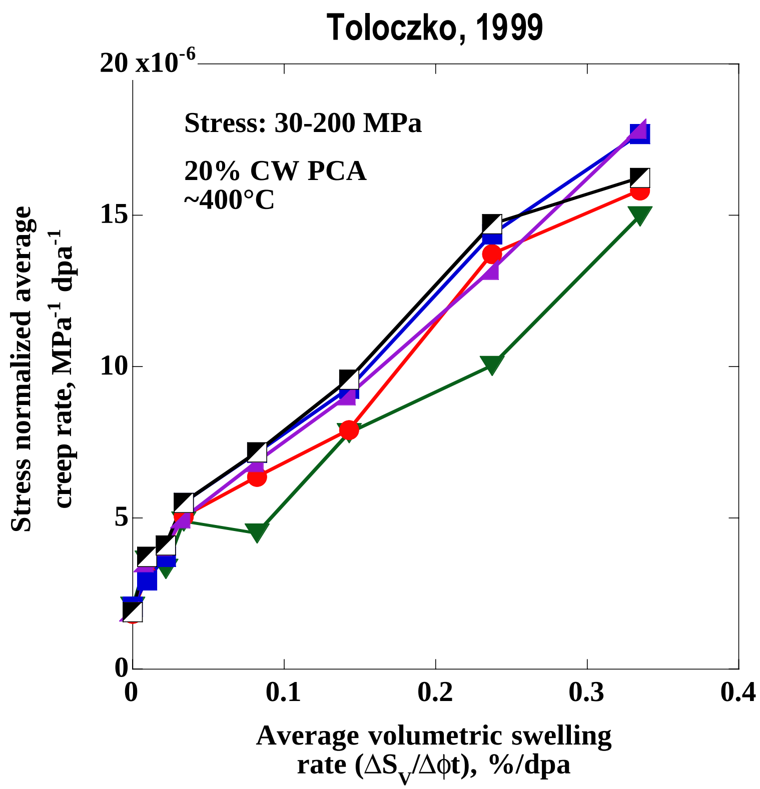
Temperature Dependence of Irradiation Creep in the Absence of Swelling

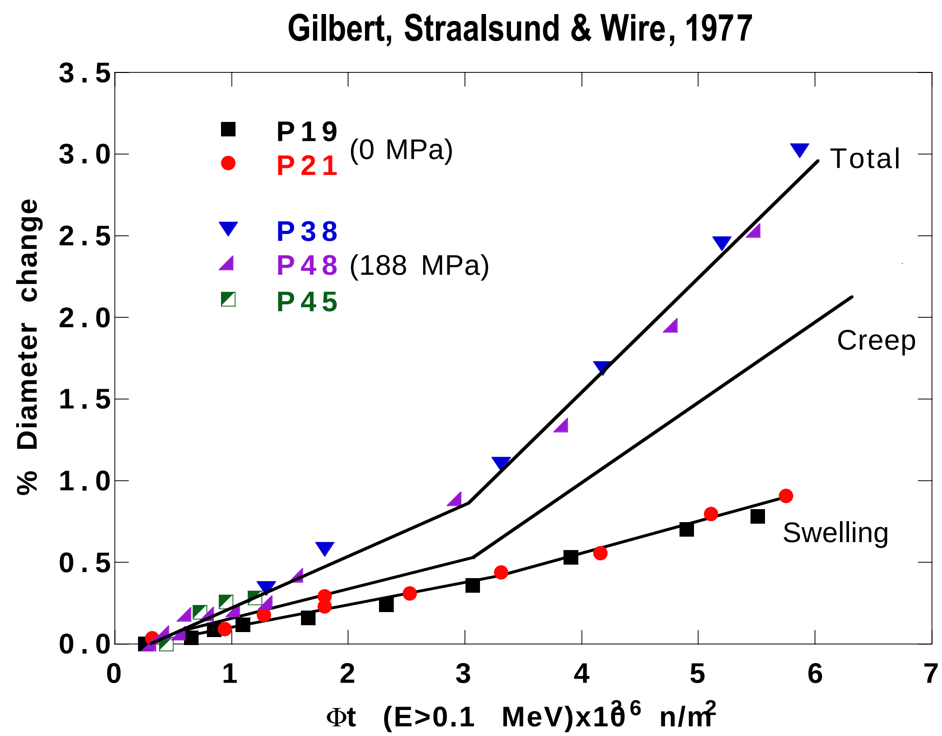
- In the regime of linear stress dependence, contributions from thermal creep become significant at 500°C-600°C





Creep-Swelling Coupling



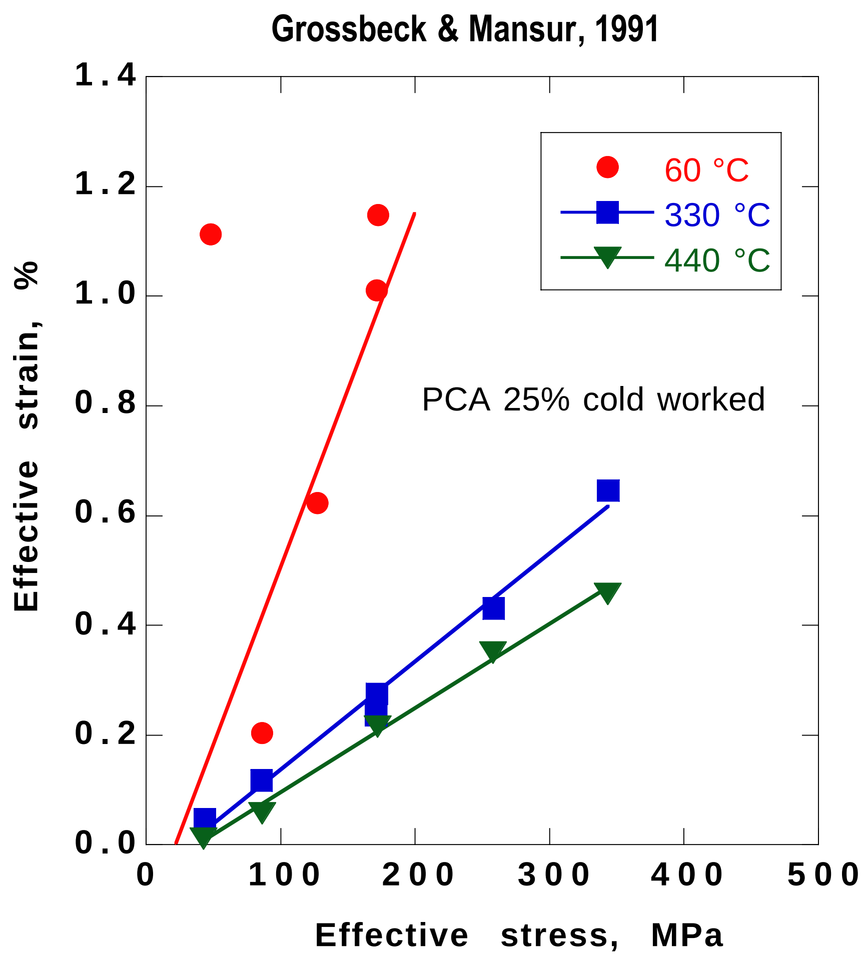


Low-Temperature Transient Irradiation Creep

- High levels of irradiation creep observed in austenitic and ferritic steels at low temperatures
- Transient interstitial absorption mechanism proposed
- Rate equations for point defect accumulation:

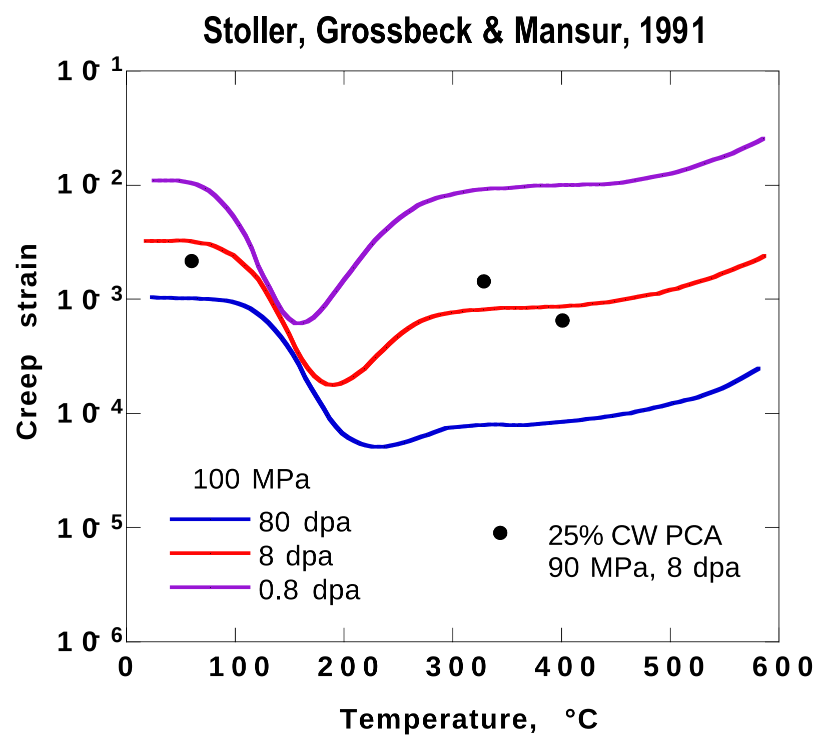
$$\frac{\partial C_v}{\partial t} = G - RC_vC_i - K_vC_v$$

$$\frac{\partial C_i}{\partial t} = G - RC_vC_i - K_iC_i$$

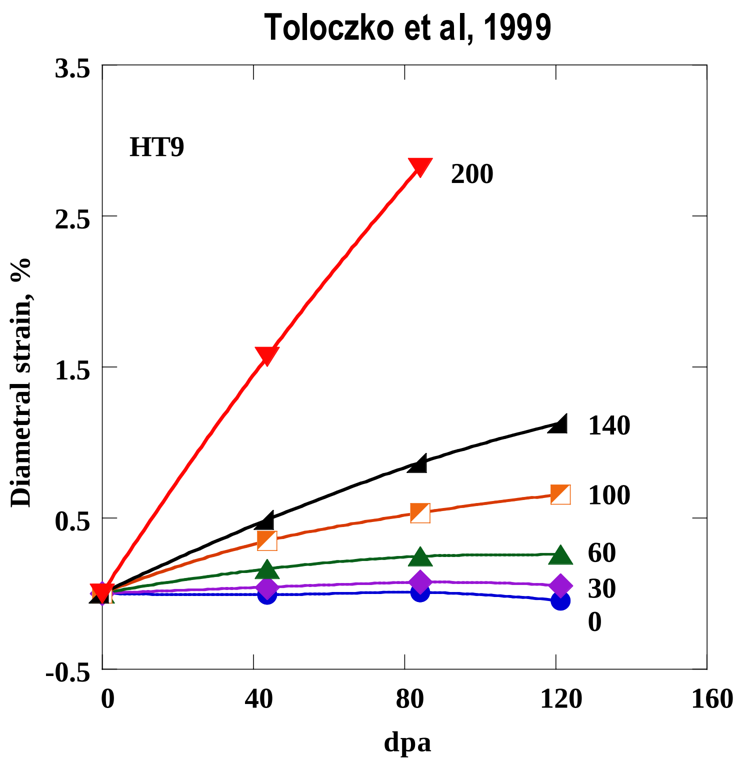


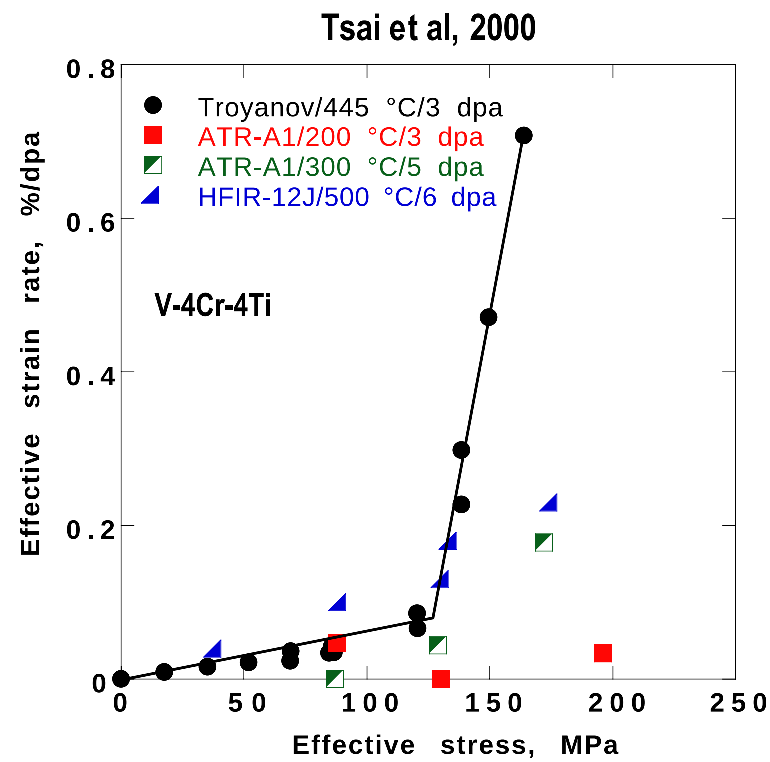
Model Calculations

- Numerical solution of rate equations gives point defect concentrations as a function of time
- At low-temperatures vacancies are essentially immobile resulting in enhanced irradiation creep due to adsorption of interstitials at dislocations



Limited Irradiation Creep Data on Tempered Martensitic Steels and Vanadium Alloys





Neutronic Responses of First-Wall/Blanket Structural Materials

Smith, Majumdar, Billone & Mattas, 2000

Alloy	dpa[a]	He Trans.[a], appm	H Trans.[a], appm	Dose Rate[b], Sv/h	Decay Heat[b], W/kg
Austenitic steel (316)	170	2400	8550	4000	3
Ferritic steel (9Cr-1Mo)	170	1800	7350	1000	1
Vanadium alloy (V-4Cr-4Ti)	170	855	4050	0.3	.0005
SiC/SiC	135	19500	13350	0.0001	.00003

[a]Approximate values at first wall after 15 Mwy/m^2

[b]Approximate values one month after 3 y at 5 MW/m^2

Basic Properties of Helium in Metals-1

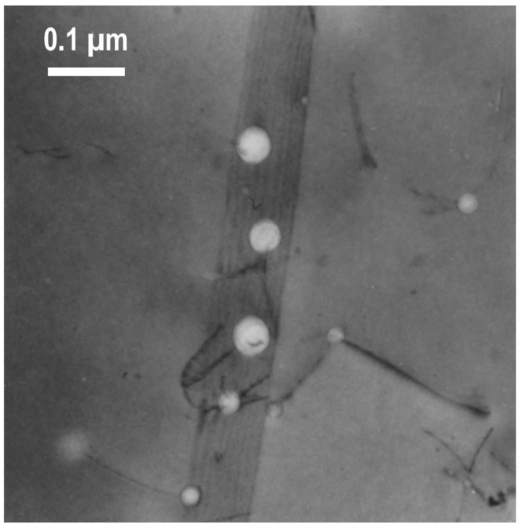
- Helium has essentially no solubility in metals
- Diffusion of interstitial He through the crystal lattice is fast and occurs in most metals even below room temperature
- Between 0.2 and 0.5 T_m & under irradiation, substitutional He is replaced by SIA and diffuses interstitially to other vacancies
- Migration may also occur by conventional He-vacancy exchange
- At low T, collision cascades displace helium from He-vacancy clusters and contribute to transport

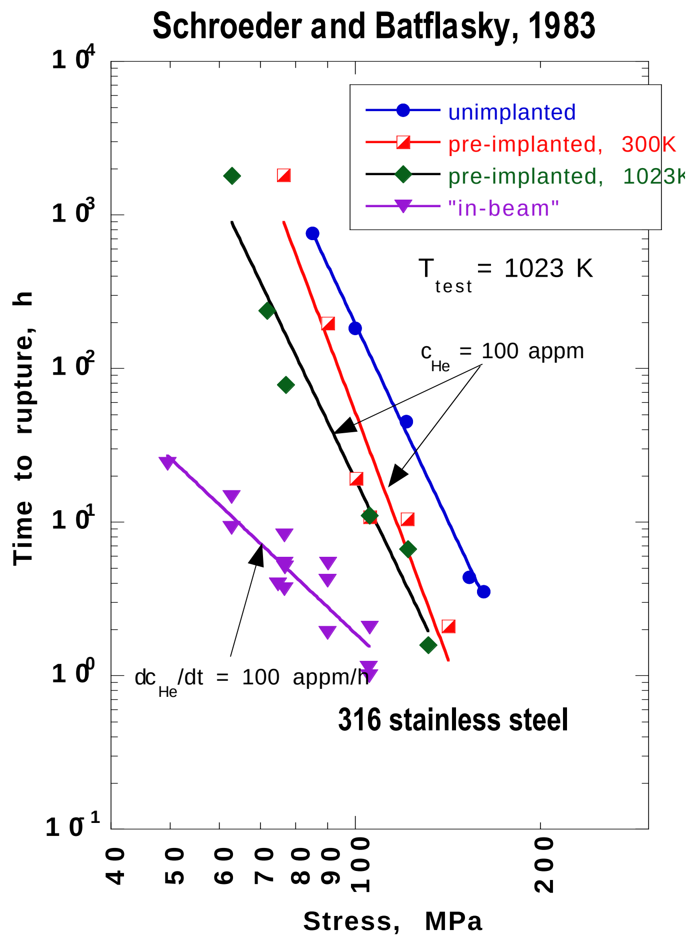
Basic Properties of Helium in Metals-2

- At higher T, He atoms dissociate from vacancy clusters by thermal activation and diffuse interstitially until trapped
- Since He is strongly bound to vacancies, migration of He-vacancy complexes is also a possibility
- Helium atoms trapped at dislocations or grain boundaries are able to migrate rapidly along these diffusion paths
- Because of He-vacancy clustering, He transport is coupled with nucleation

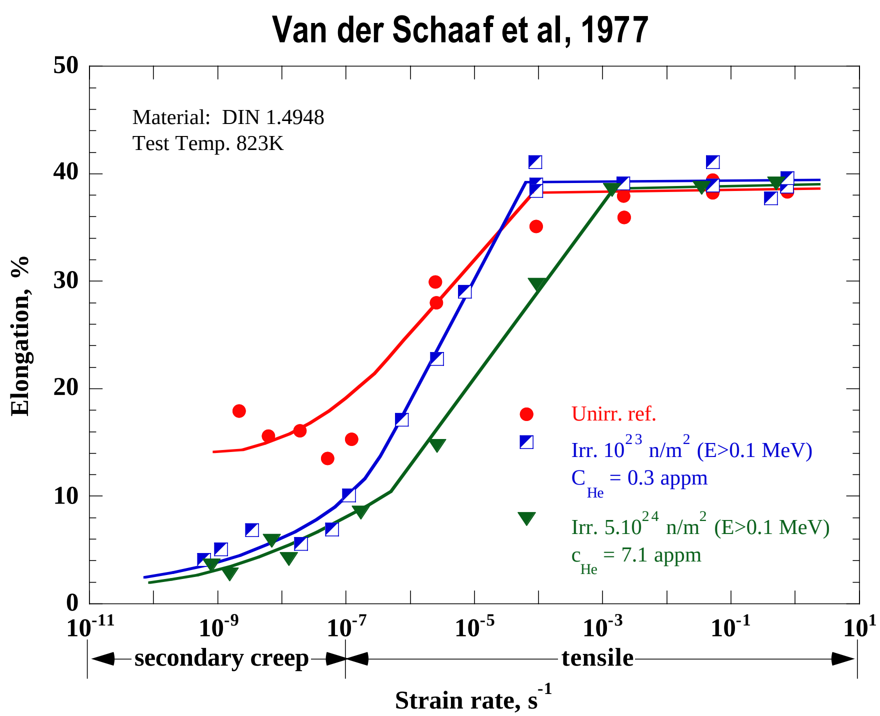
Mechanical Property Degradation Due to Helium

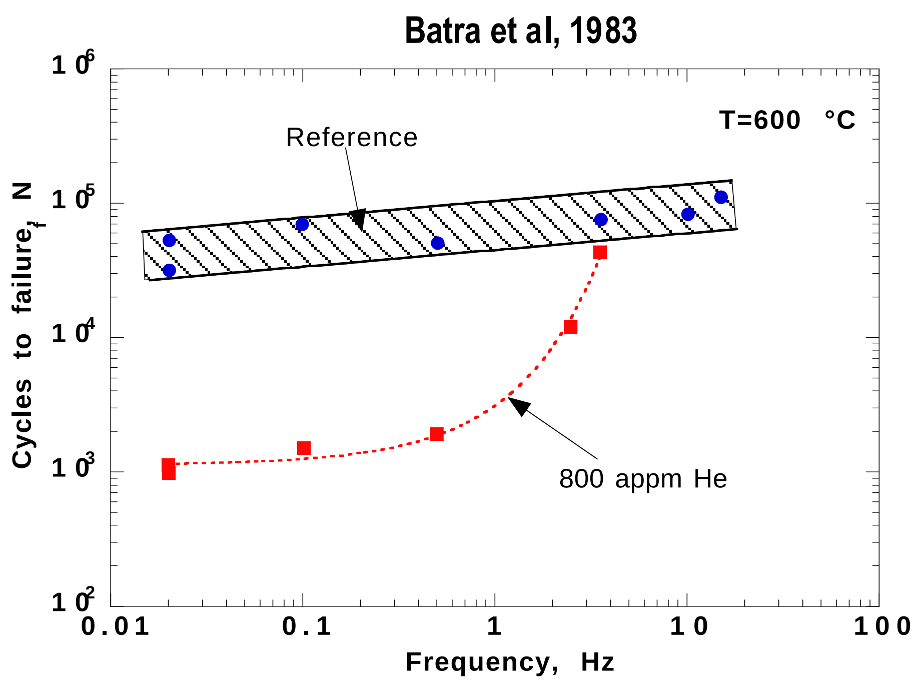
- Above 0.5 T_m , the coalescence of cavities at GBs can result in intergranular fracture
- The life time under creep and creep fatigue conditions is dominated by the time of stable gas driven growth of bubbles on GBs (rather than by gas driven growth of intergranular cracks





Effect of Strain Rate



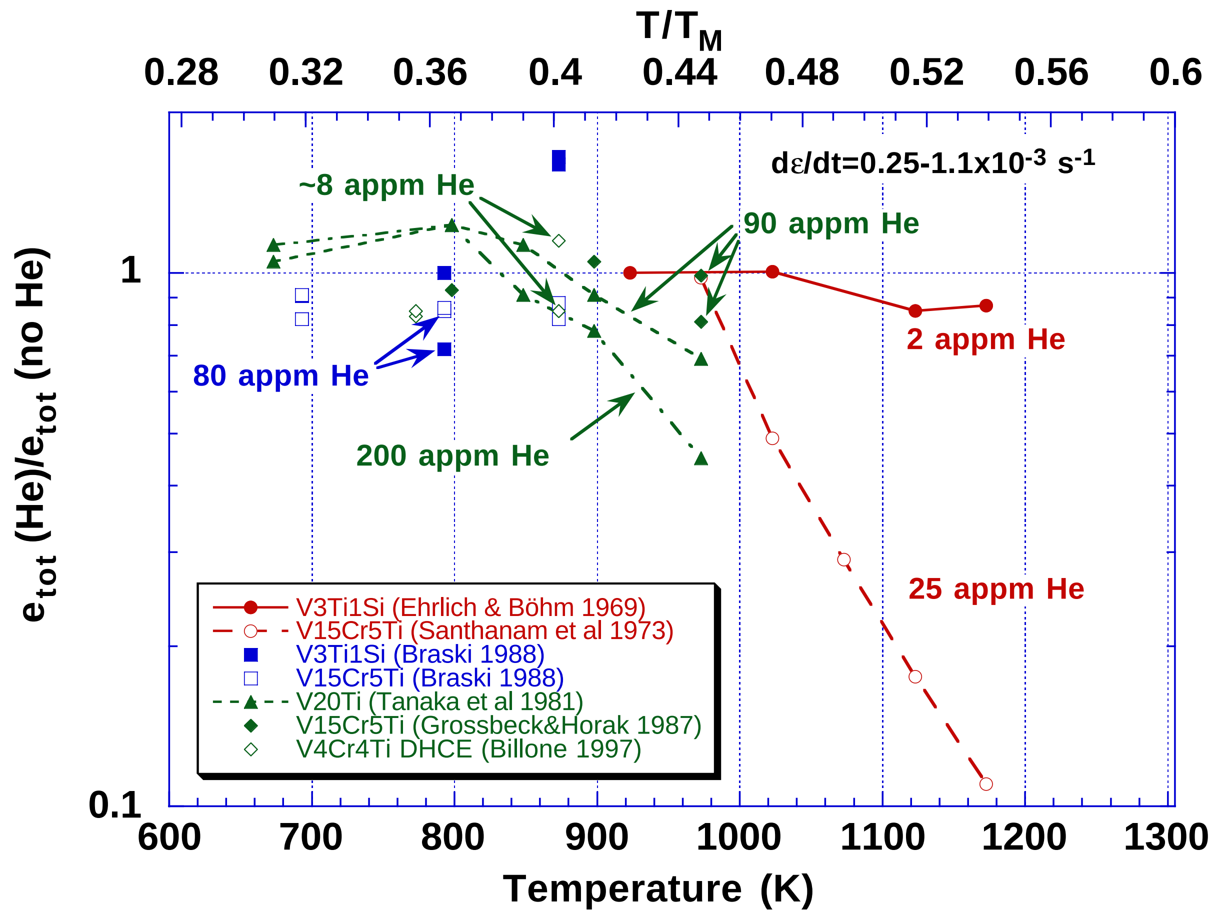


Effect of He on Tensile Properties of Vanadium Alloys

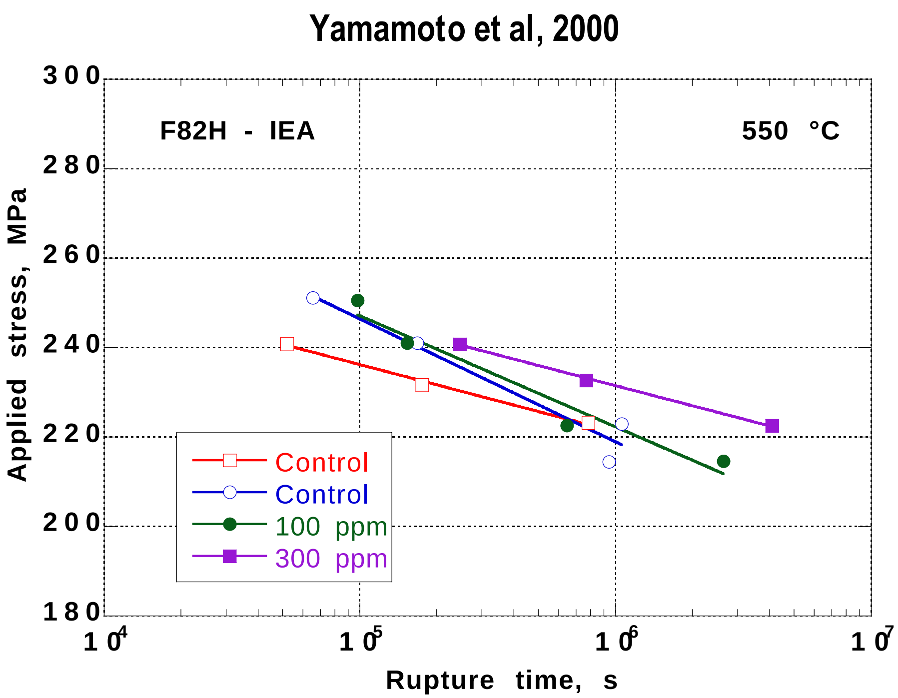
He embrittlement in V alloys becomes evident in tensile tests for:

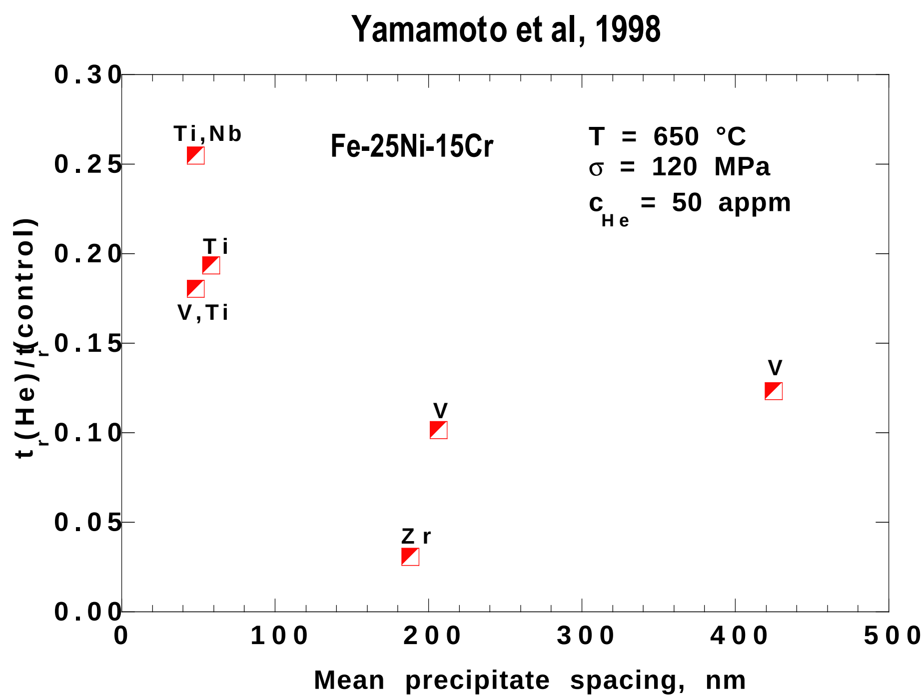
T > 700°C

C_{he} > 100 appm



Design of Appropriate Microstructures Improves Resistance to He Embrittlement

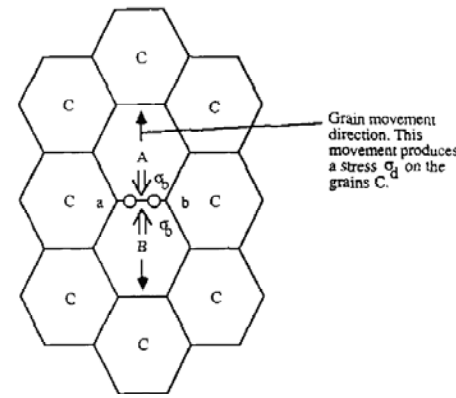




Micromechanics of Creep-Rupture and Helium Embrittlement

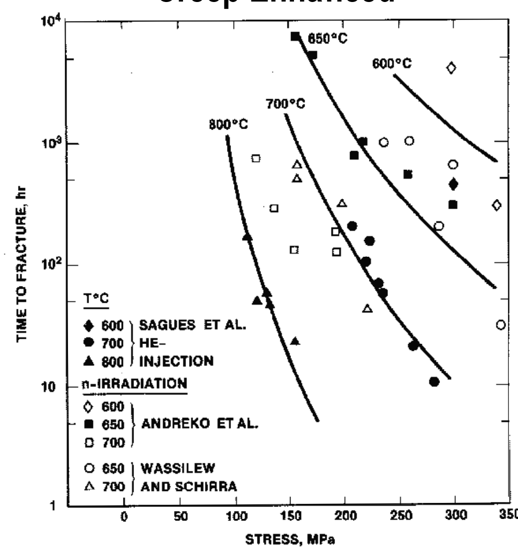
- Flow of He to grain boundaries, bubble nucleation-growth and σ-induced unstable cavity conversion only part of creep-rupture physics
- Need coupling of diffusional growth with various creep related processes that enhance (e.g., localize diffusion) or retard (creep accommodation of dilation) cavity growth. Rationalize Monkman-Grant relation: $t_r\varepsilon_{min} \approx C \approx$ 'weak' $f(T,\sigma)$
- Build on large 1970-80's creep-rupture literature, and related phenomena like hydrogen attack, computational advances - when/how does high grain boundary He change the creep-rupture process?
- Key issues include in-situ versus post irradiation testing, is irradiation creep damaging?

Creep Constrained



Odette 1981

Creep Enhanced

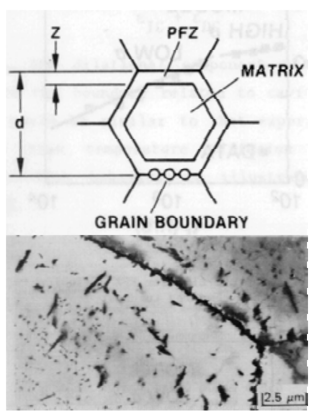


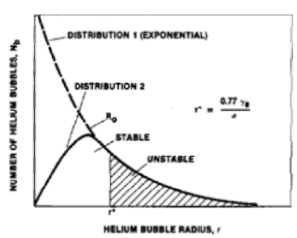
Example Creep-Cavity Growth Coupling

- In-situ creep-rupture: Nabarro-Herring flow of vacancies from PFZ plus irradiation creep (B) leads to simple scaling laws:

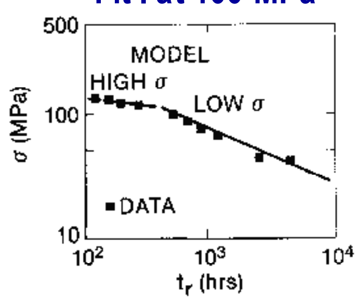
  @ low σ: $t_r \approx I/[(He/dpaB)^{1/2}\sigma^2]$ and $\varepsilon_r \approx I\sqrt{B}/[(He/dpaB)^{1/2}\sigma^2]$

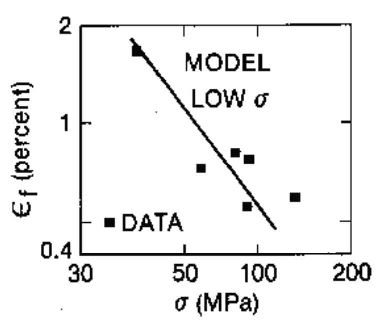
Odette 1984



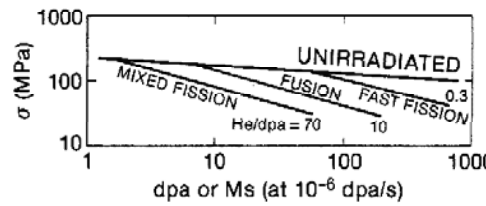


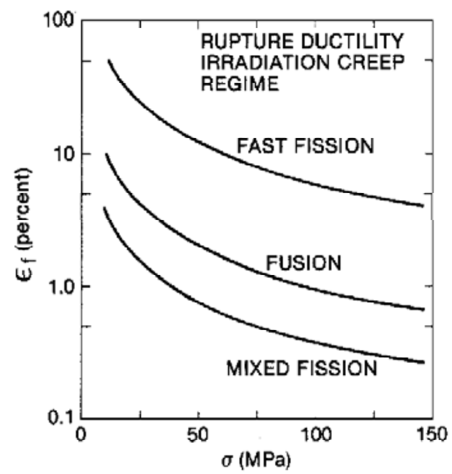
Fit I at 100 MPa





Predicted Implications





Unresolved Questions & Needed Research-1

- Kinetic Monte Carlo & molecular dynamics modeling of helium diffusion to confirm/ modify/ negate rate theory conclusions
- Ab-initio/ MD calculations are required for He-V cluster binding energies. At what size will continuum theory be adequate?
- Cascade effects on helium re-solution from bubbles
- Under which conditions do migration and coalescence of bubbles play a role at low T?
- Effect of grain boundary type on He bubble density and size
- High T bubble nucleation/ growth are challenging to model by KMC and even by detailed rate equations

Unresolved Questions & Needed Research-2

- Bubble-to-void transitions as function of helium/dpa ratio
- Transition from equilibrium bubbles (matrix & GB bubbles) during transients and under stress need to be identified
- Mechanisms of grain boundary cavity growth in BCC versus FCC are not well established
- Need well-characterized, model-driven, single-variable experiments to resolve remaining He effects questions
- Proposed US/Japan collaborative experiments with possible He effects studies
  - DOE/JAERI (F82H and model ferritic alloys; He effects study would concentrate on 300 & 400˚C tensile, fracture behavior)
  - DOE/MEXT Jupiter-II (V alloys; experimental matrix for 1st irradiation to be decided this fall)