Bubbles

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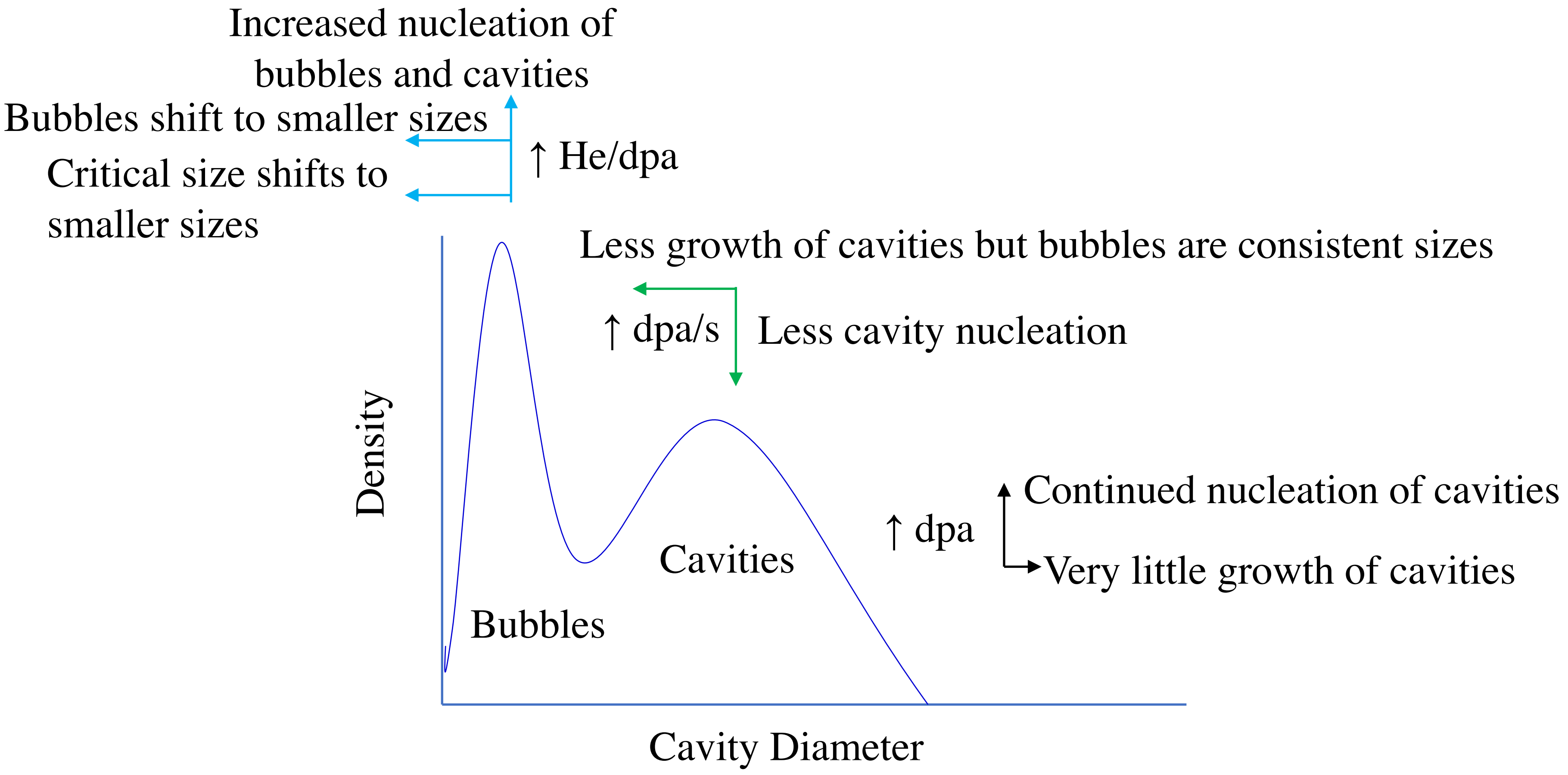
Experimental examples



Fixed dpa/s – Variable He/dpa

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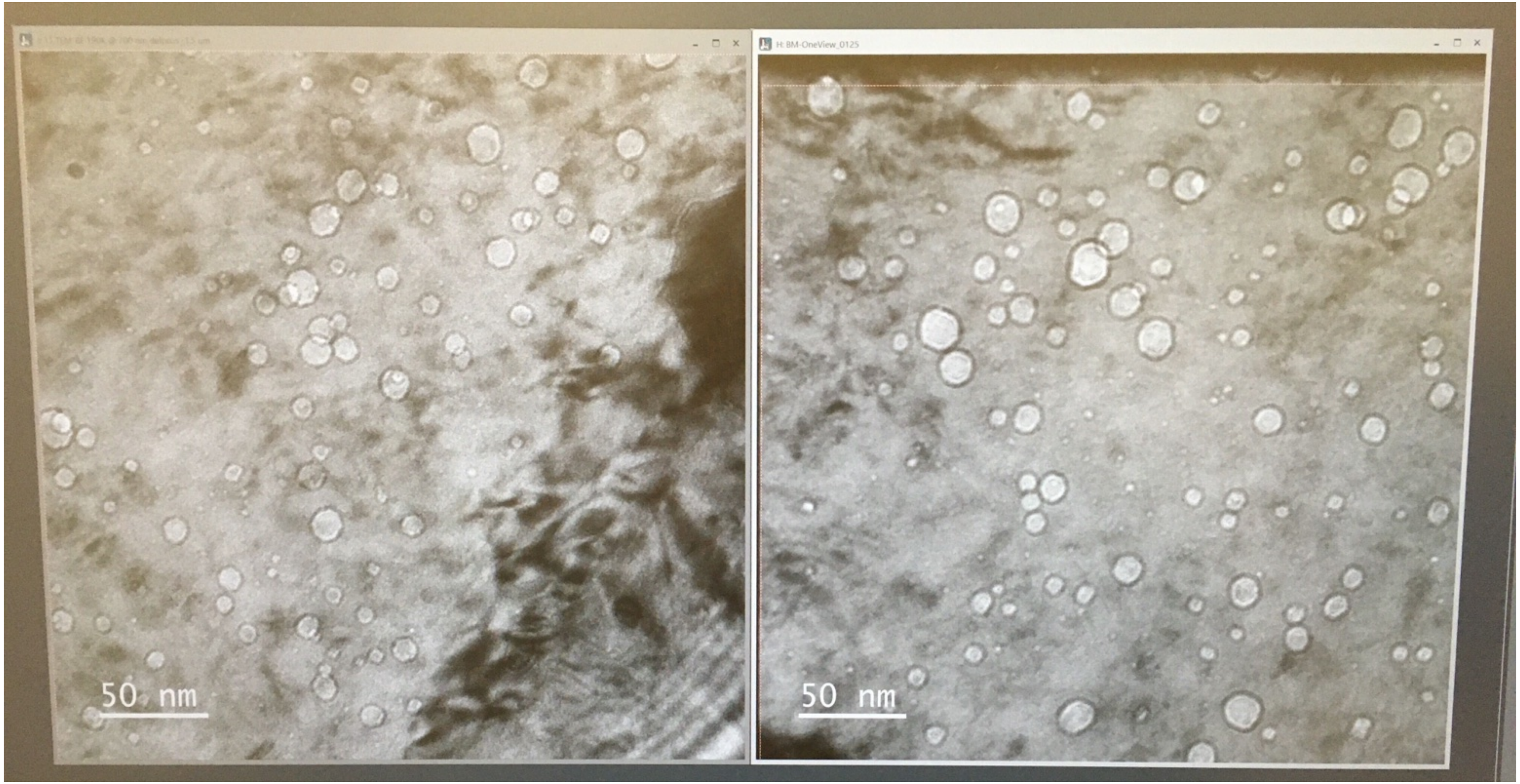
Increase in dpa for constant He/dpa and dpa/s

Taller (2019)

Hot off the press example (from MC2 last week)



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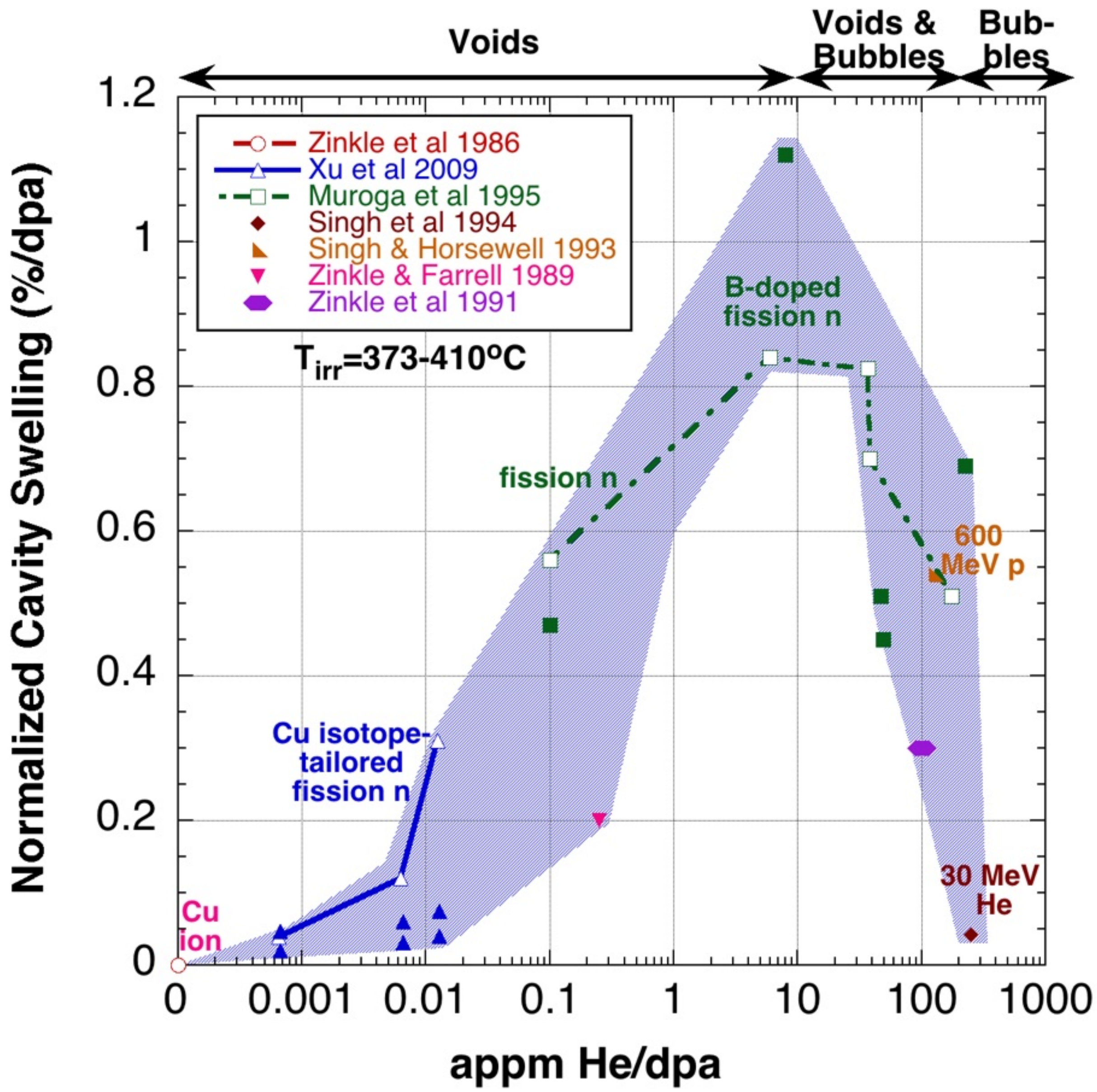
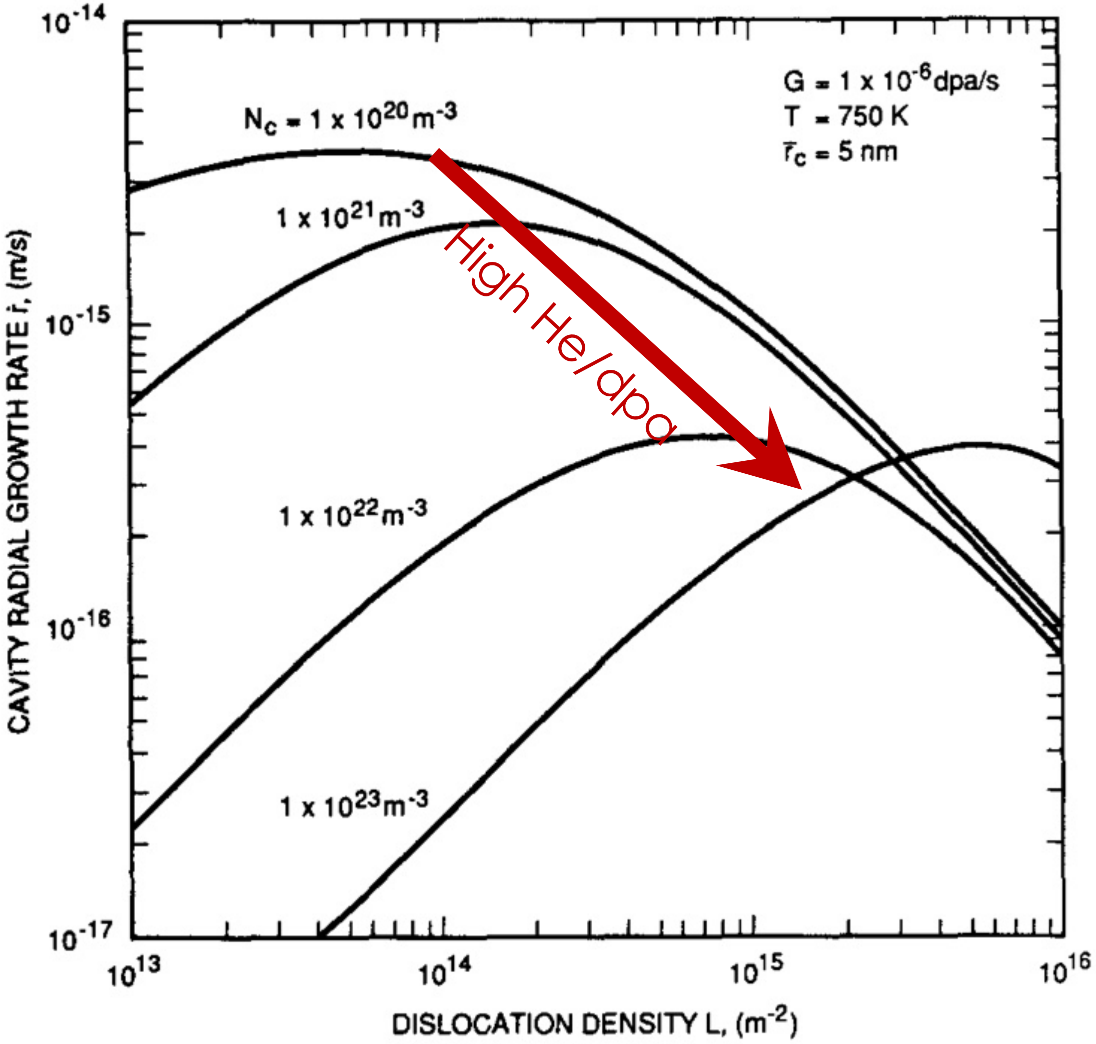
Cavity swelling vs. He/dpa ratio in irradiated copper



~1-10 dpa

Calculated void growth rate is typically reduced for high cavity and dislocation sink strengths



Over nucleation of cavities due to too high He/dpa can suppress void swelling

E.H. Lee & L.K. Mansur, Met. Trans. A 21 (1990) 1021

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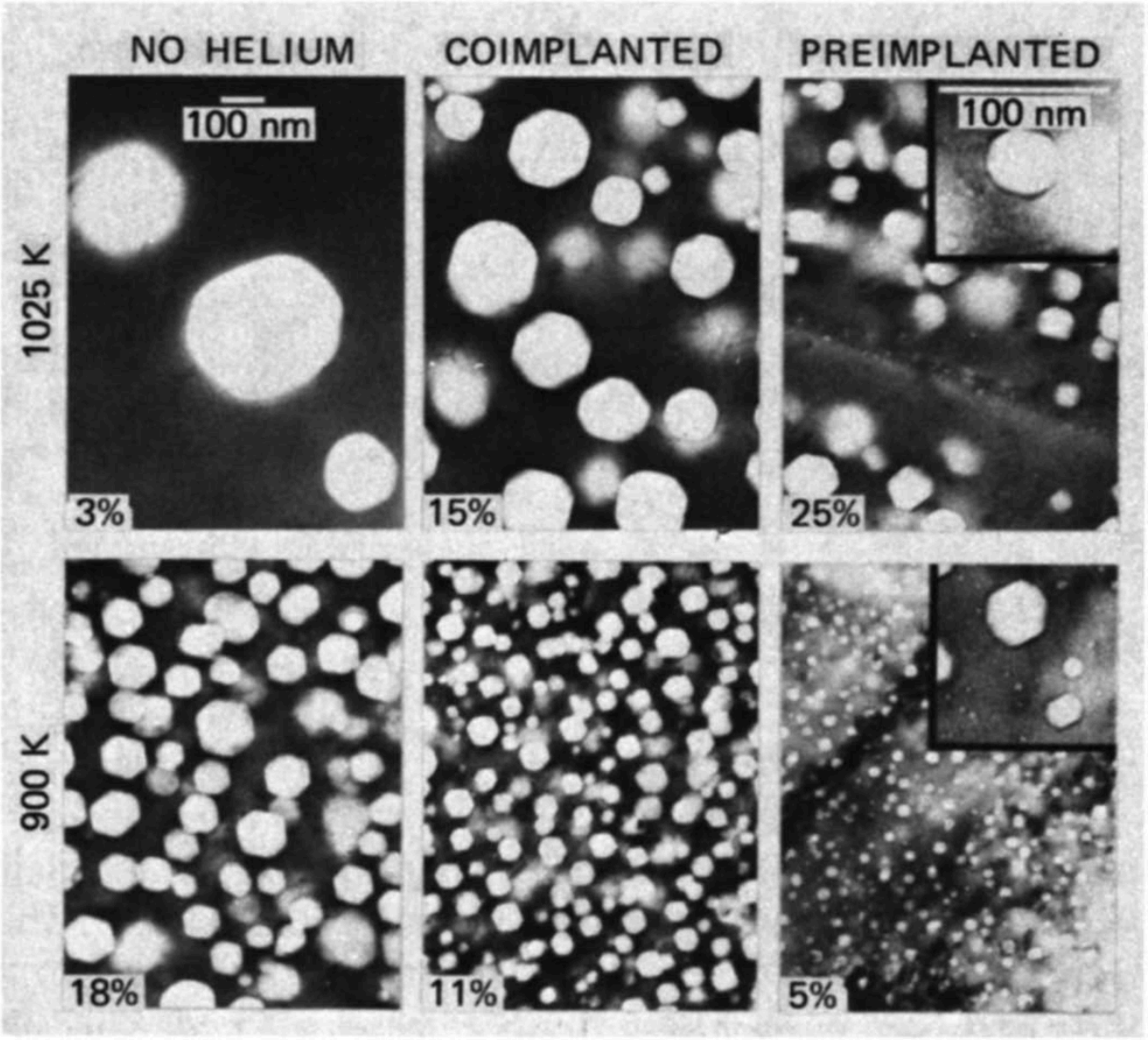
Effect of He in ion irradiations



Implantation method of He can drastically effect swelling in ion irradiated materials

Image of Fe-17Cr-16.7Ni-2.5Mo

Packan & Farrell, NT-Fusion, 1983

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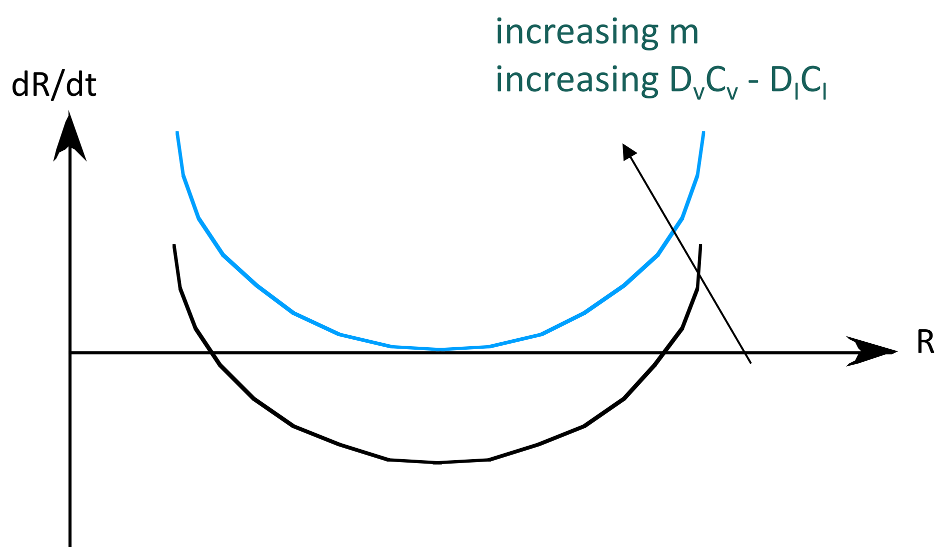
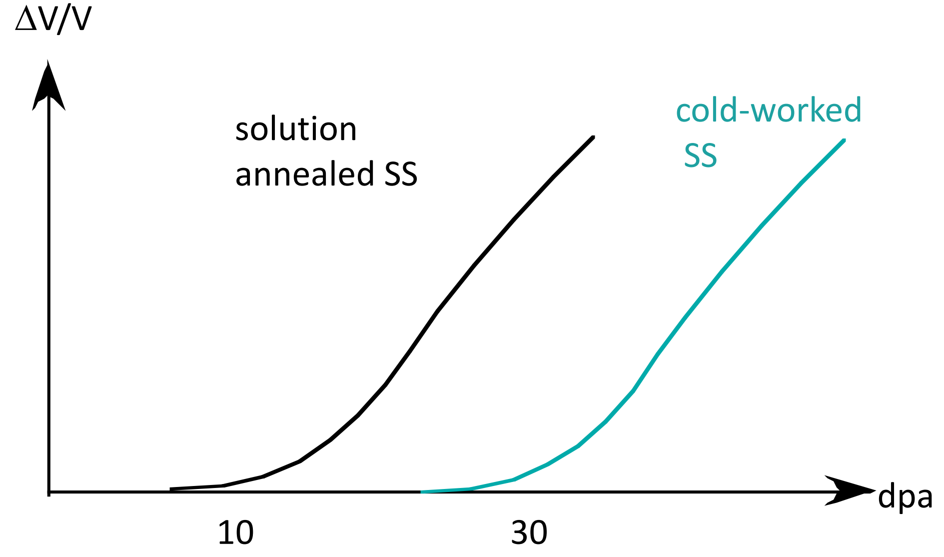
Remedies for void swelling?

Remedies for void swelling?

- Decrease D_vC_v - D_IC_I arriving at cavity;
- Eliminate He gas production (expensive or impractical)

- Reduce C_v, C_I:
  - increase recombination
    - add precipitates or dispersoids (TiC/TiO_2) to act as recombination sink, trap He and stabilize dislocations
  - increase other sink strengths
    - add dislocations (cold-work); generally only effective for low to moderate doses
    - introduce nanoscale grain boundaries





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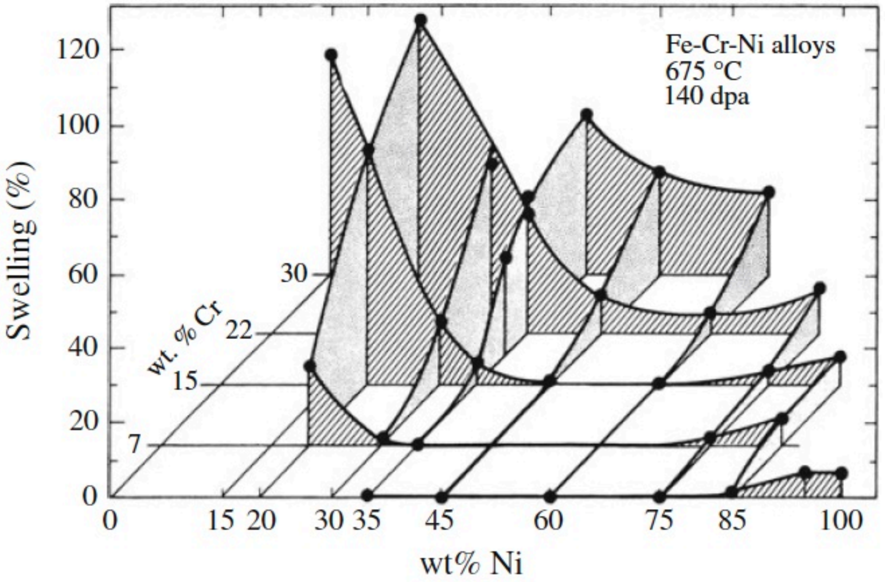
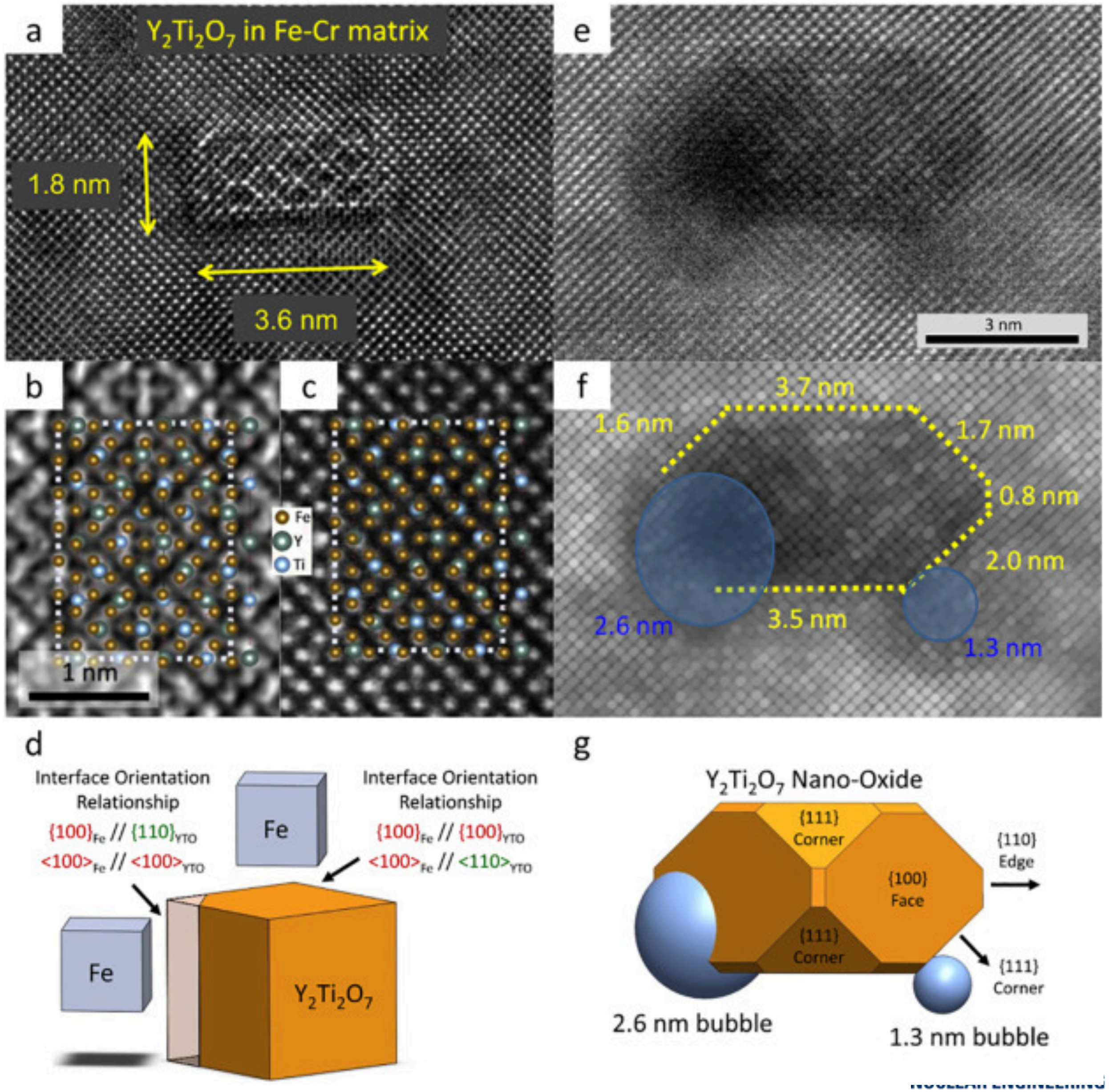


Fig. 8.45 Two-dimensional plot of the nickel and chromium dependence of swelling in Fe–Cr–Ni alloys irradiated with 5 MeV Ni$^+$ ions at 675 °C to a dose of 140 dpa. Swelling was measured by the step-height technique (after [19])



Phase Transformations Under Irradiation

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Why are we interested in phase transformations under irradiation?

Radiation tolerance of FeCrAl alloys is linked to precipitation under irradiation

Number Density

Burgers Vector

Size

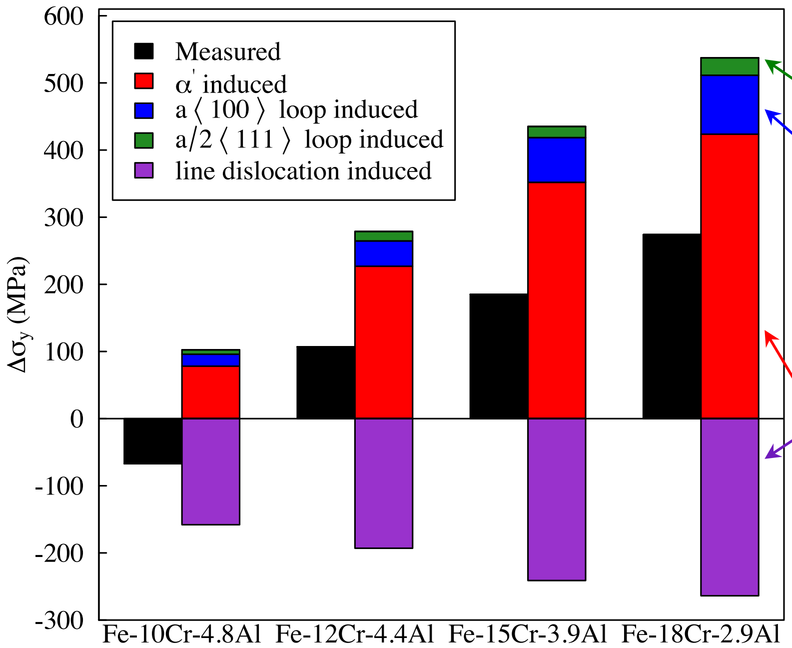
Change in Yield Strength

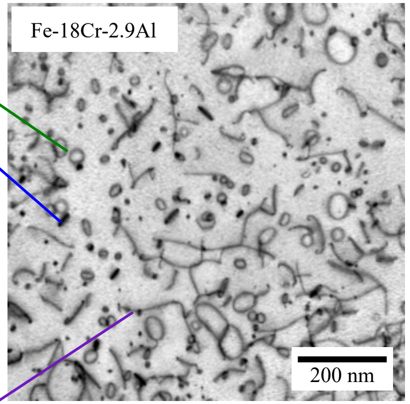
$$\Delta\sigma_y = M\alpha\mu b\sqrt{\rho \cdot d}$$

Taylor Factor

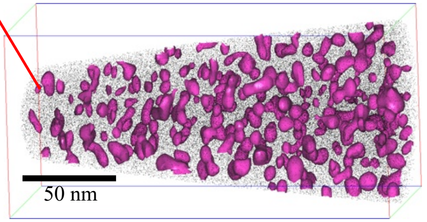
Shear Modulus

Super. rule	Barrier strength of visible defects (α)			
	Cr-rich α'	⟨100⟩	½⟨111⟩	Line
Linear	0.04	0.31	0.05	0.68
SRS	0.06	0.33	0.17	0.56





STEM image showing dislocation loops and line dislocations in 1.8 dpa, 382°C irradiated Fe-18Cr-2.9Al alloy



APT reconstruction showing α' in 1.8 dpa, 382°C irradiated Fe-18Cr-2.9Al alloy

- Dispersed barrier hardening (DBH) has linked radiation-hardening in FeCrAl alloys to formation of Cr-rich α' and dislocation loops after neutron irradiation to 1.8 dpa at 382°C

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[1] K. G. Field, X. Hu, K. C. Littrell, Y. Yamamoto, L. L. Snead, Radiation tolerance of neutron- irradiated model Fe-Cr-Al alloys, *Journal of Nuclear Materials*, **465**, pgs. 746-755, 2015.

Phase transformations under irradiation

- Experience has shown anything is possible with phase transformations under irradiation:
  - Stable phases can be destabilized
  - Approach to thermal equilibrium can be enhanced or retarded
  - Irradiation-induced precipitation or dissolution can occur

Depends on irradiation conditions, material composition and microstructure!

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Two primary irradiation induced phase transformation types:

Background on models for phase transformations

- Irradiation limits the use of thermodynamics because the persistent input of energy and mass means the system can not be considered closed -> causes a ”forced” system
- The complexity of a forced system means no generalized model exists for phase transformations under the presence of irradiation
  - 3 general methods have been used:
    1. Modify the free energy construct to take into account the effects of irradiation such as the increased point defect concentration
    2. Assume that equilibrium free energy is the same and describe the kinetics of atomic transport accounting for irradiation including the modified chemical potentials
    3. Derive new Gibbs free energy functions and perform minimization of the functions to predict phase transformations

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Phase transformations with changes in composition

Radiation-enhanced effects on kinetics

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Radiation-enhanced effects on kinetics

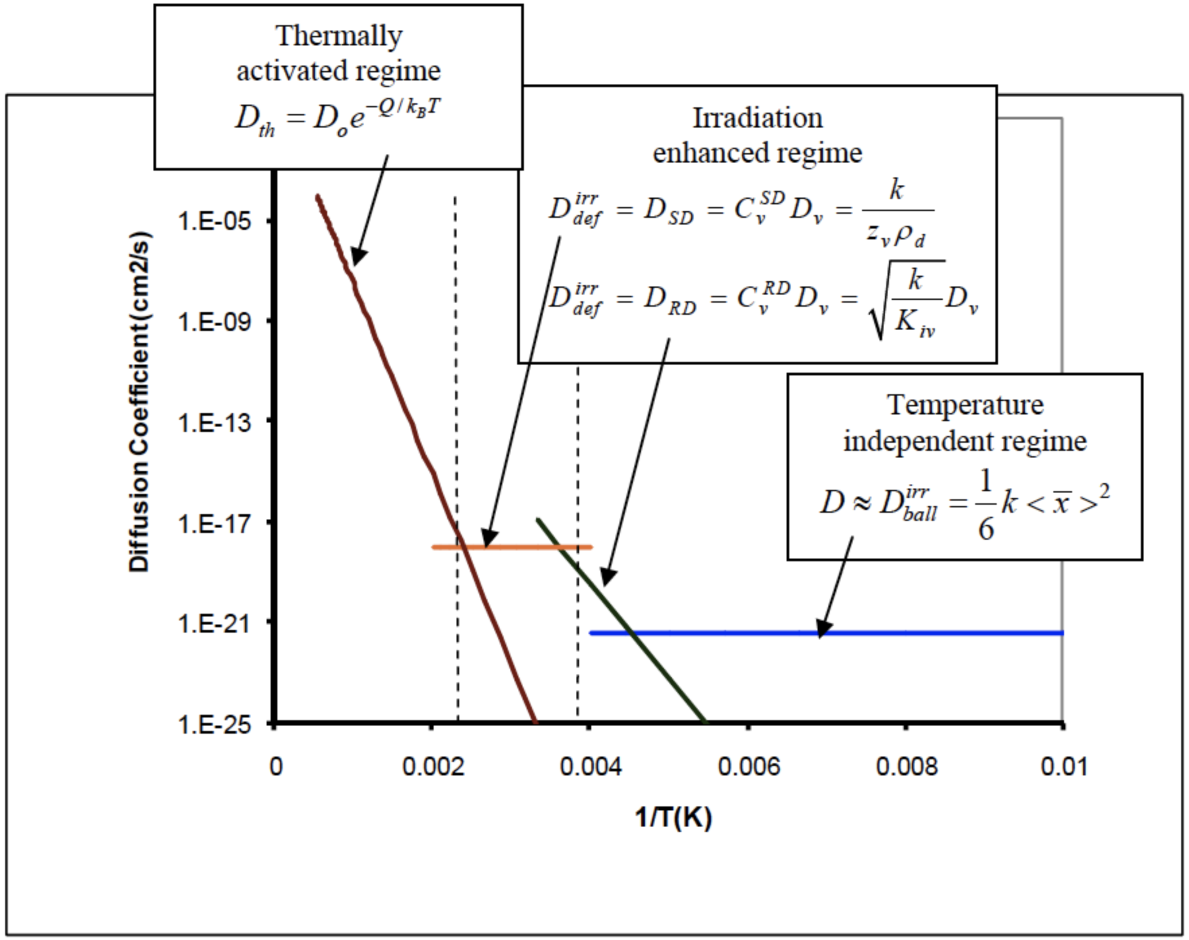
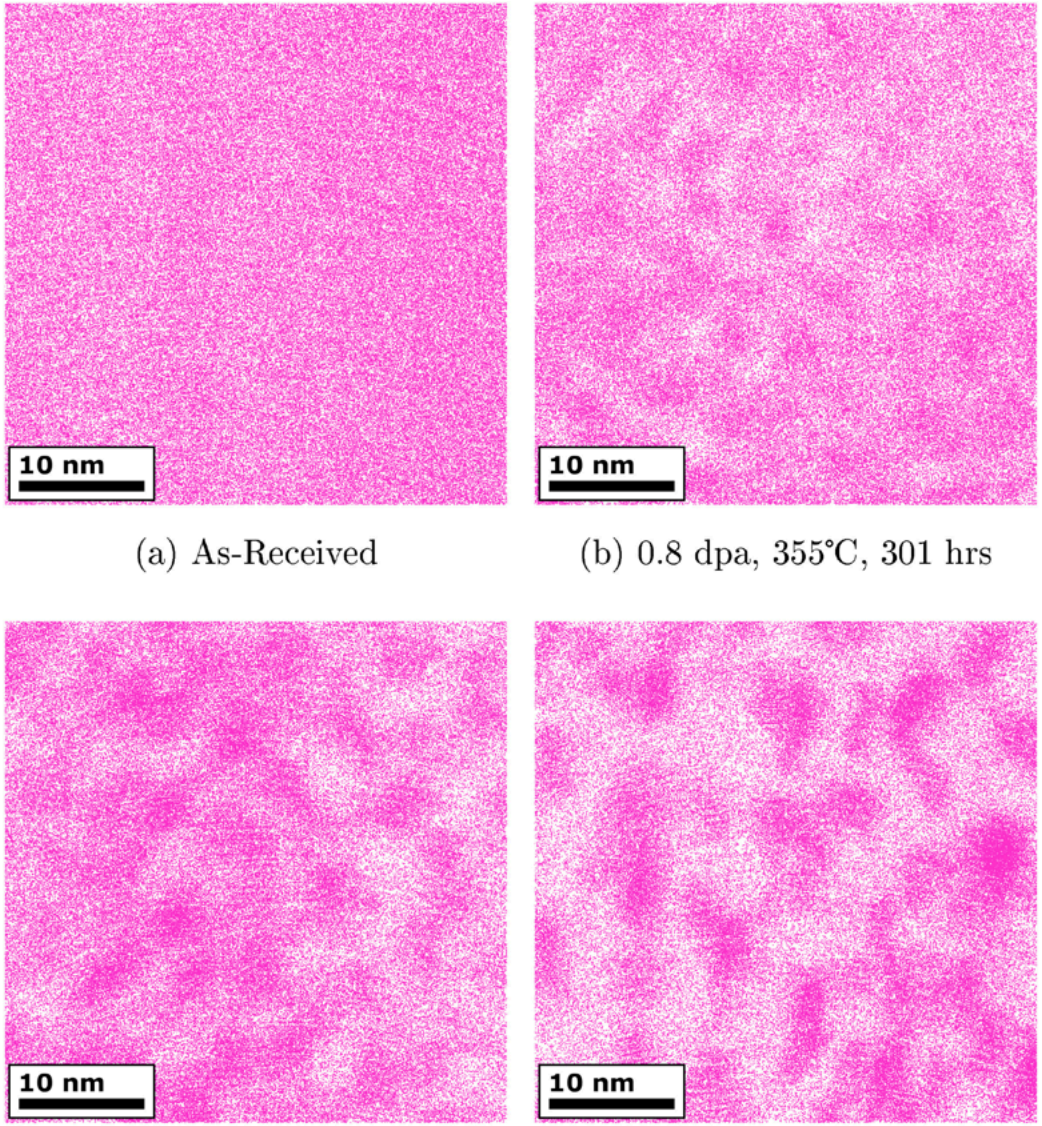


Figure 24.1 Diffusion coefficient versus inverse temperature. The curves are plotted using $k=10^{-6}$ dpa/s, $E_m^v = 1\,eV$; $E_f^v = 1\,eV$; $E_m^i = 0.5\,eV$ $D_o = 0.01\,cm^2/s$, recombination number =500, $<\bar{x}>$=5 x 10^{-7} cm, and $\rho_d = 10^{10}\ cm^{-2}$.



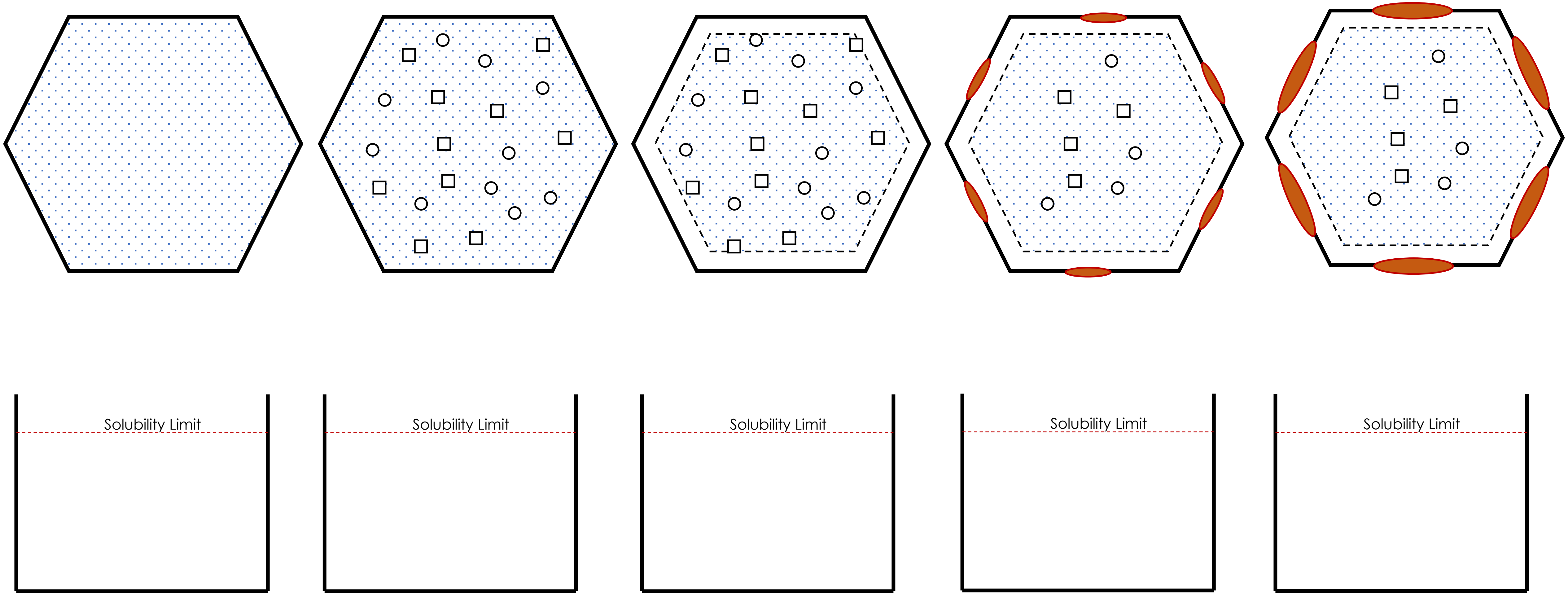
(a) As-Received

(b) 0.8 dpa, 355°C, 301 hrs

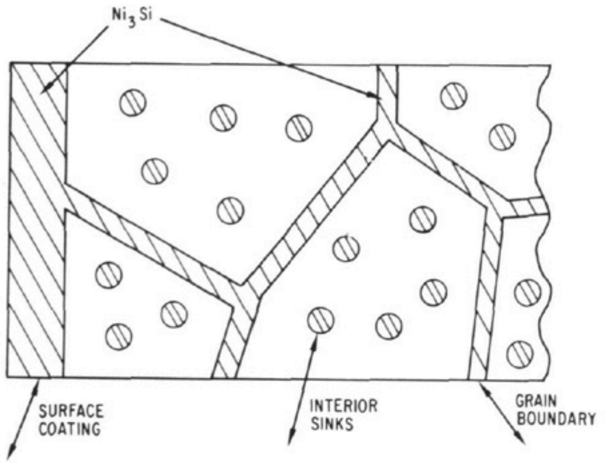
(c) 1.8 dpa, 380°C, 614 hrs

(d) 7.0 dpa, 320°C, 2456 hrs

RIS and Radiation-induced precipitation



RIS and Radiation-induced precipitation



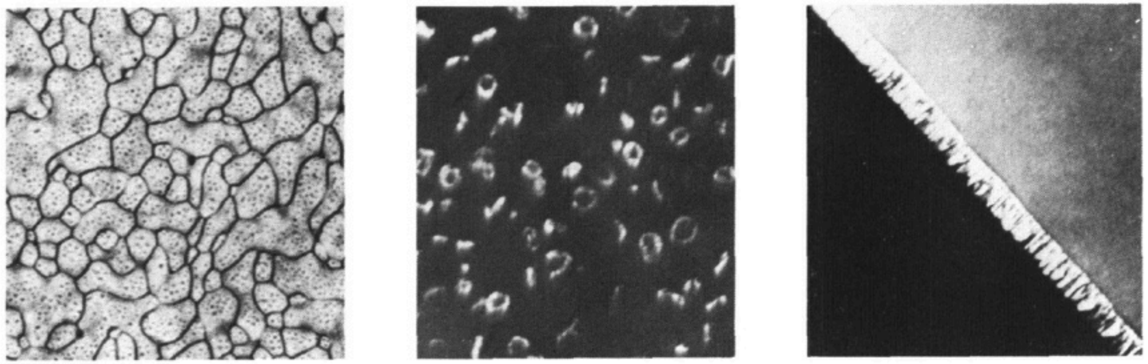


Fig. 1. Formation of γ'-Ni_3Si on defect sinks in a solid solution Ni-Si alloy because of RIS. The dark-field micrographs from the work of K.-H. Robrock and P. R. Okamoto show: (a) the anti-phase domain structure in a contiguous surface coating; (b) toroidal γ'-precipitates on interstitial loops; and (c) a grain boundary coated with γ'.

Radiation-induced precipitate dissolution

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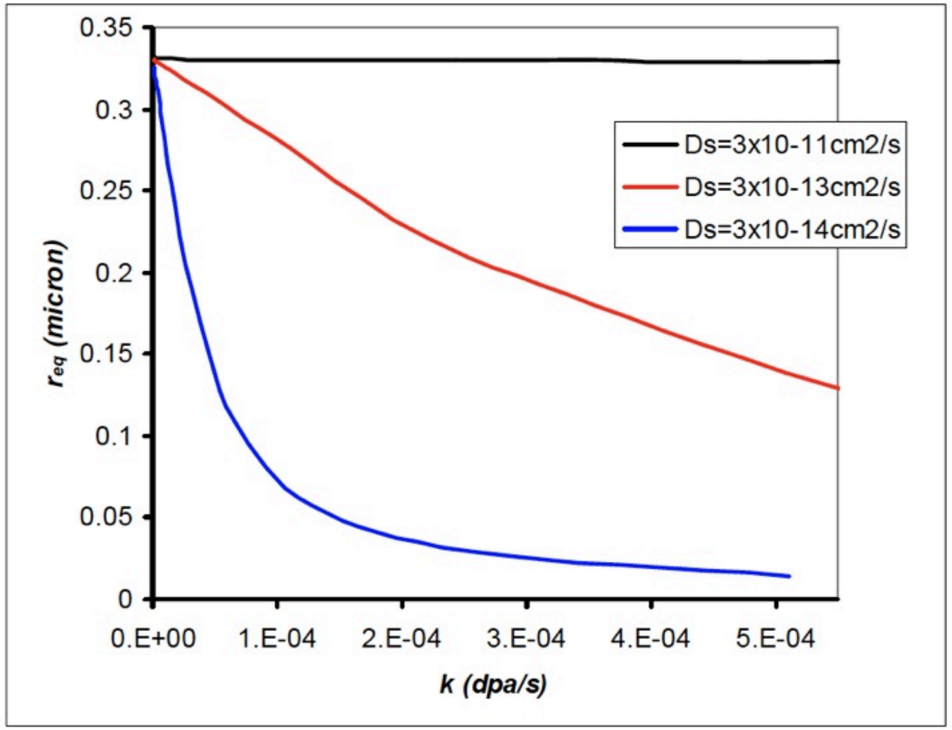


Figure 24.13: Equilibrium radius for a precipitate subjected to recoil dissolution as a function of displacement rate for three values of the solute diffusion coefficient. x_S=1% and C_p=66%.

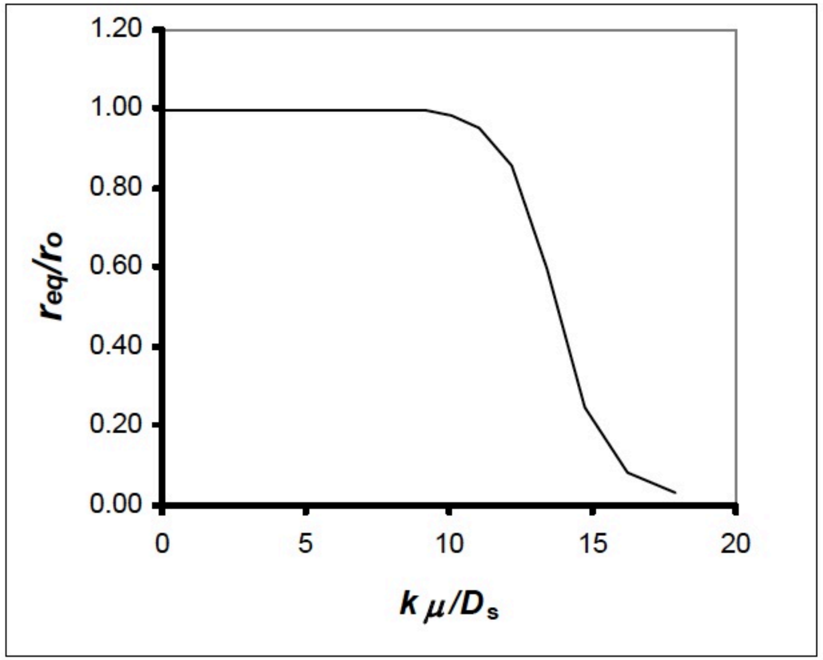
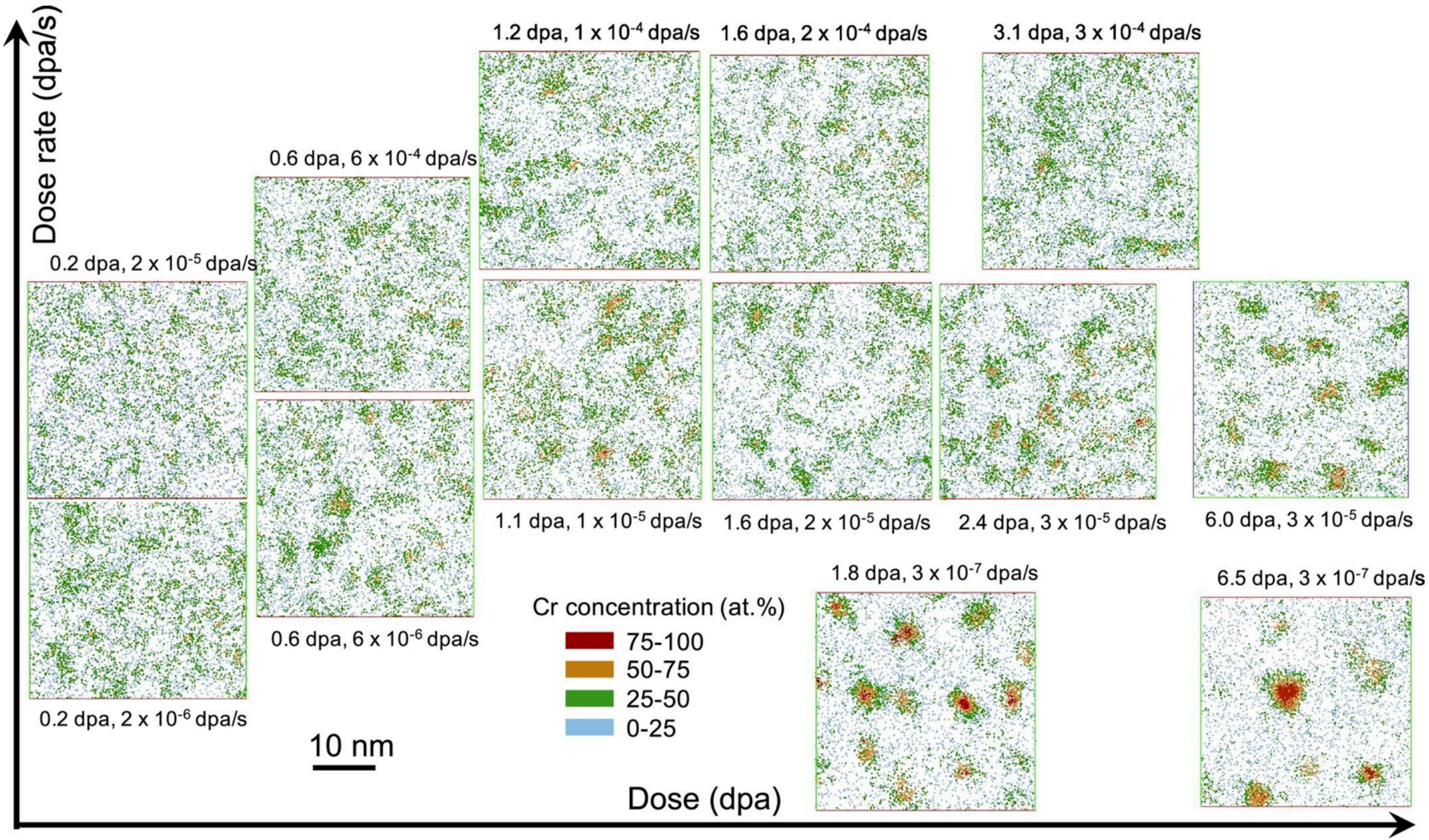


Figure 24.14: Ratio of equilibrium precipitate radius to radius in the absence of recoil dissolution, versus parameter $\frac{k\mu}{D_s}$.



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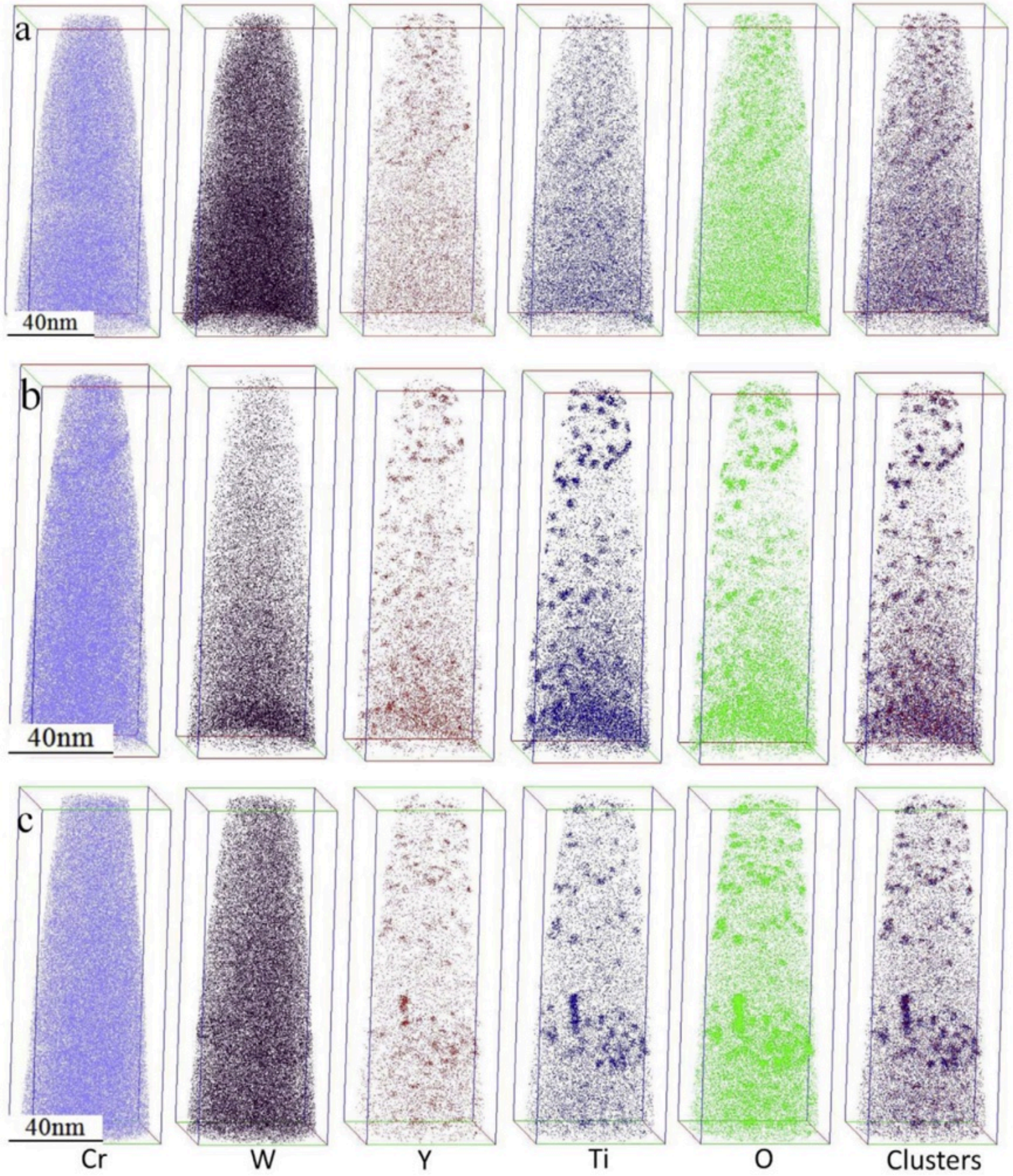

Fig. 4. APT 3D reconstruction of 14YWT samples irradiation with 5 MeV Ni ions to a damage level of 100 dpa at temperatures of: (a) 300 °C, (b) 450 °C, and (c) 600 °C.

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Radiation-induced precipitate dissolution

Radiation-induced precipitate dissolution

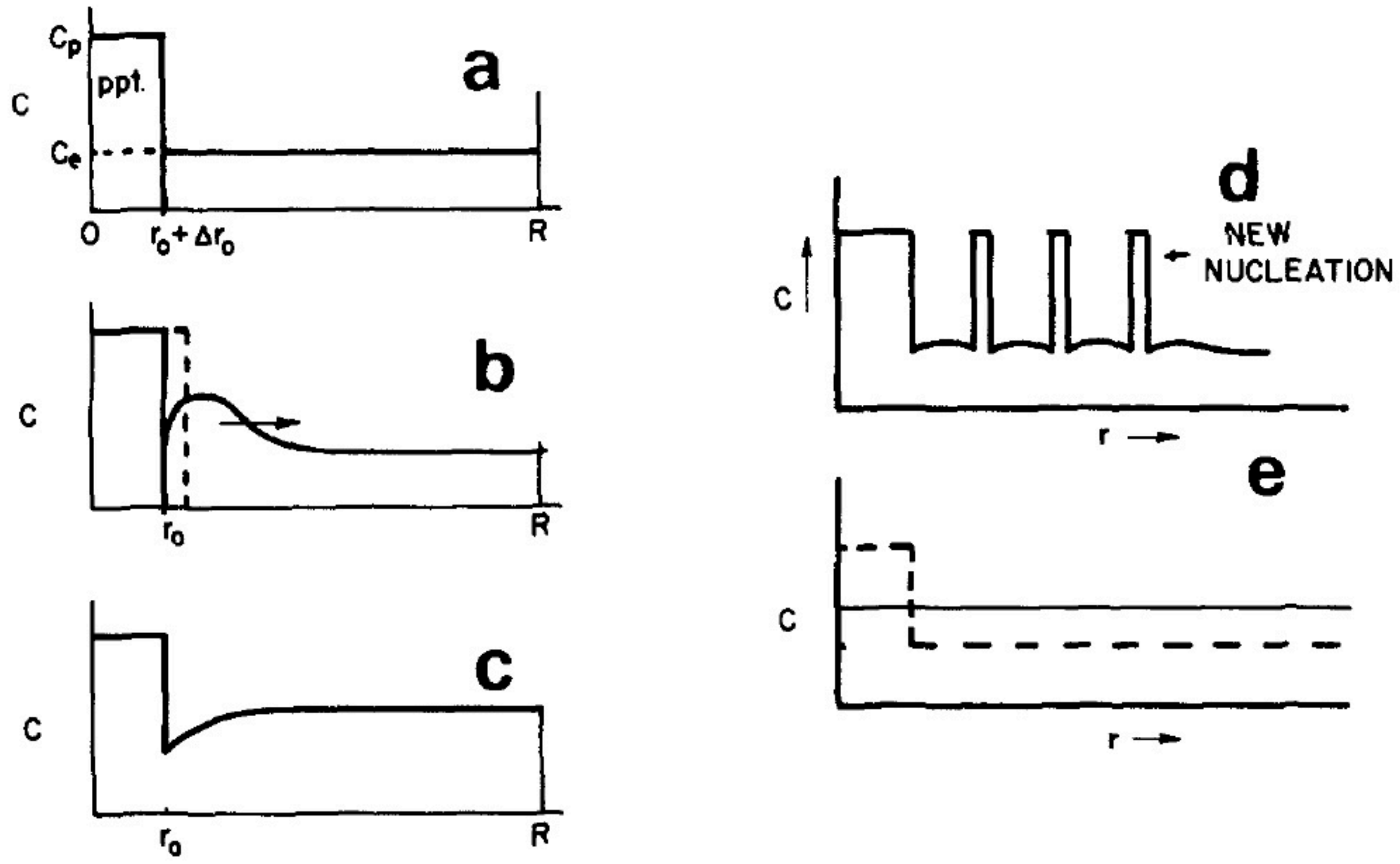

Fig. 3. A schematic diagram of concentration variations in a precipitate cell: (a) before irradiation with a precipitate of radius $r_0 + \Delta r$ in equilibrium with a uniform matrix concentration c_e; (b) when irradiation begins surface disssolution causes a local solute supersaturation some of which diffuses outwards down the gradient; (c) at steady-state, the matrix is now uniformly supersaturated and the precipitate dissolution is matched by the back diffusion into the precipitate; (d) if the local supersaturation around the precipitate exceeds that required for nucleation, new precipitates may nucleate; (e) if the precipitates are widely spaced, the matrix may not reach the steady-state value and all precipitates will then dissolve.

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Radiation-induced precipitate dissolution

In reality, modeling recoil distribution is inherently complex. Models that try to take this into account:

- Nelson model (NHM) – pg. 488-489 in Was: Simplest. Similar to that derived in class and uses rate theory. Proposed inverse Ostwald ripening:
- Wilkes model – pg. 489-492 in Was: Uses a cell model and add in a source term that is uniform in cell:
- Frost and Russell – pg. 492-493 in Was: Provides for a source term for redeposited solute as a function of radius:

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