Nucleation & Growth

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Void Growth

$$R\dot{R} = K_o\Omega\left(\frac{z_i - z_v}{z_v}\right)\frac{z_v\rho_d}{(4\pi R\rho_v + z_v\rho_d)^2}F(\eta)$$

- The first term is the main dpa-rate effect on void growth
- The second term is the "bias" term: if $Z_I = Z_V$, *void growth is impossible*
- The third term is the sink-strength balance term. Void growth is eliminated if there are too many or too few dislocations. Optimum growth occurs when the void sink term $(4\pi R\rho_v)$ and the dislocation sink term $(z_v\rho_d)$ are equal.
- The fourth term contains the effect of point defect recombination:

$$F(\eta) = 2\left(\sqrt{1+\eta} - 1\right)/\eta$$

Since h decreases with increasing temperature and F decreases with increasing η:

- At high temperature, F $\rightarrow$ 1 and recombination does not effect void growth
- At low temperature, F $\rightarrow$ 0 and recombination prevents void growth.

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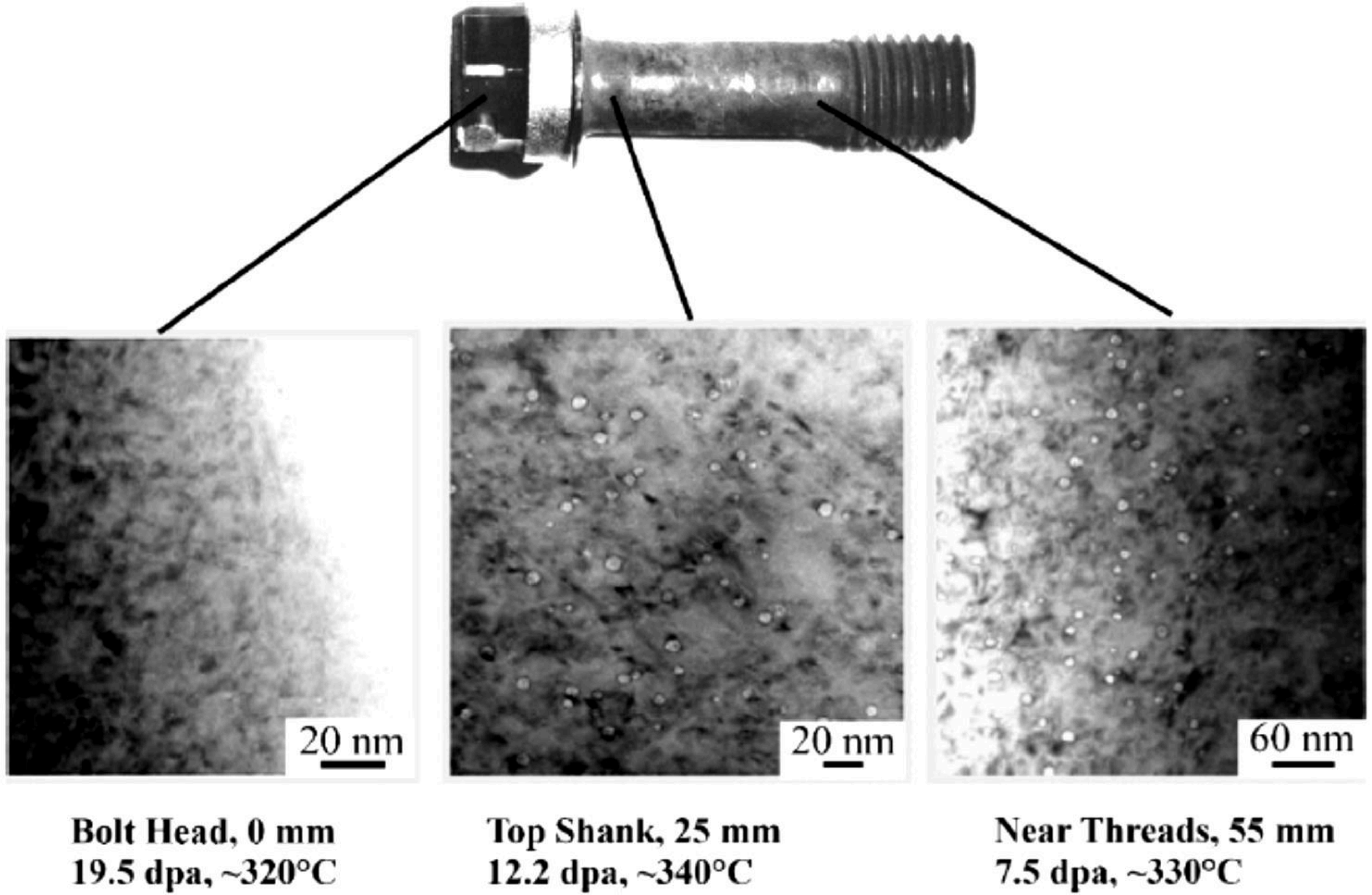

Swelling in a cold-worked 316 SS baffle bolt in a PWR as a function of position along the bolt length. (S.M. Bruemmerand Garner FA, PNNL)

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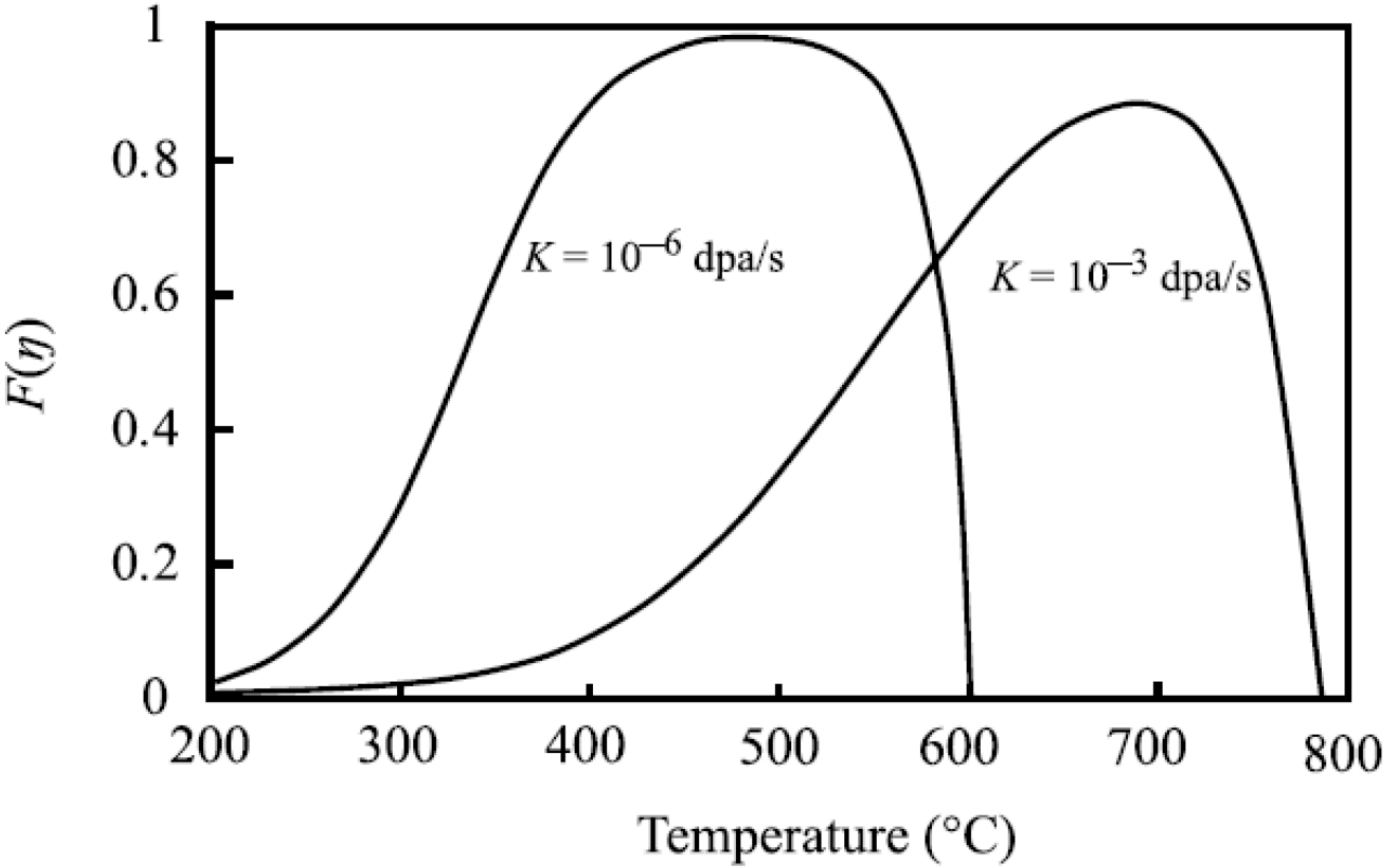
Effect of Dose Rate



$$F(\eta) = 2\left(\sqrt{1+\eta} - 1\right)/\eta$$

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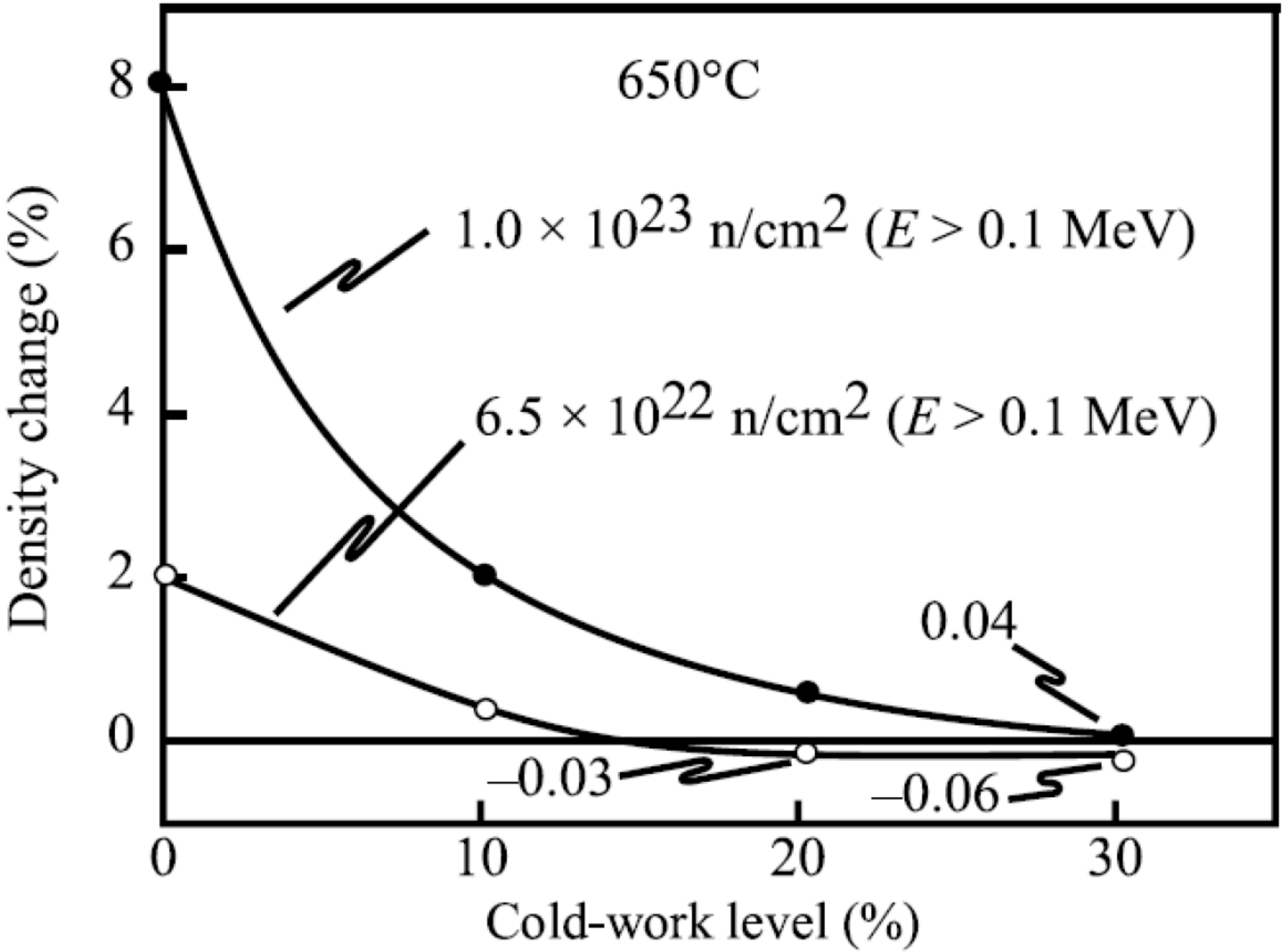
Effect of cold work on void swelling



$$Q_{i,v} = \frac{Z_{i,v}^{d}\rho_d}{4\pi r_c N_c Z_{i,v}^{c}}$$

- Growth rate is maximum when Q~1
- Growth decreases for Q != 1
- Observed experimentally
- CW reduces swelling because Q>>1

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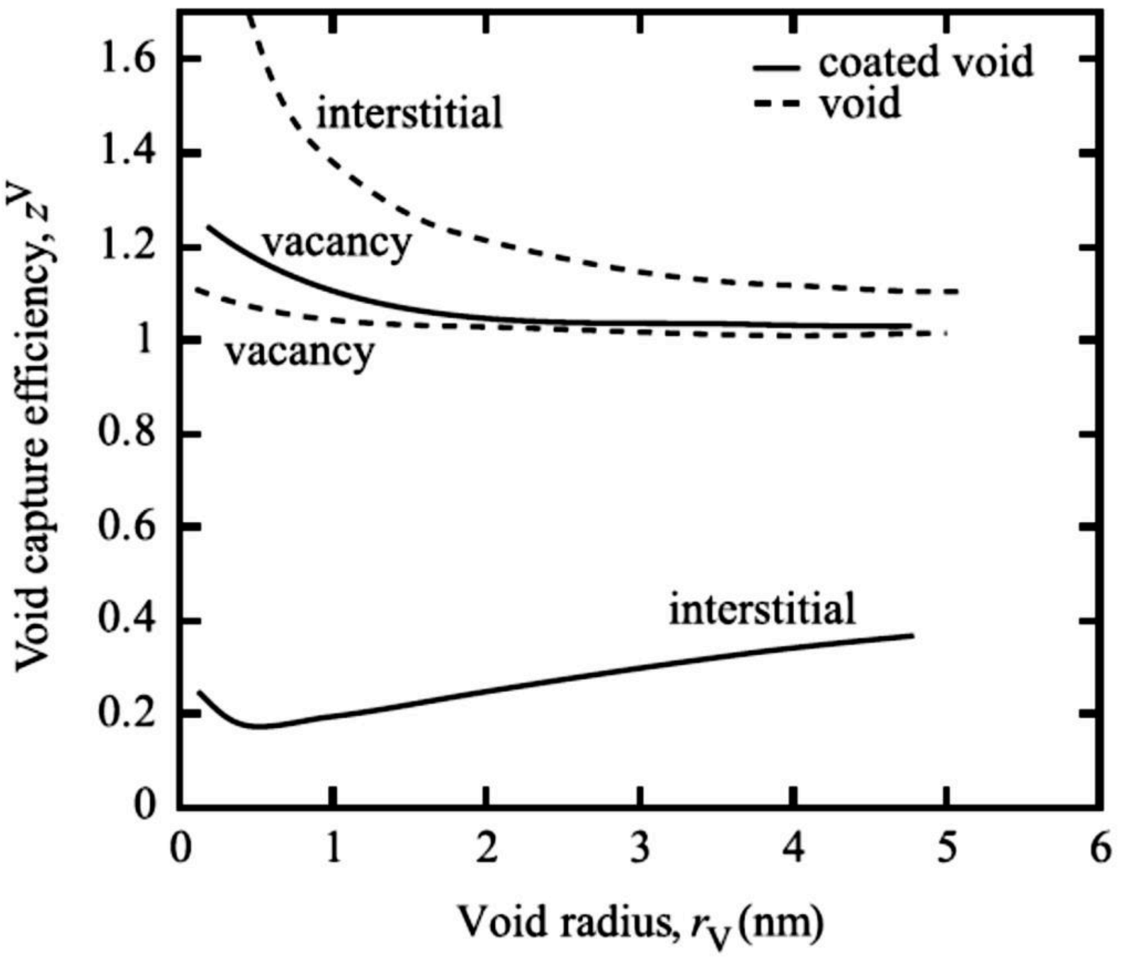
Effect of void surface segregation on defect bias



Capture efficiency for point defects diffusion to a void and a coated void as a function of void radius RV. (W.G. Wolfer, L.K. Mansur, The capture efficiency of coated voids, Journal of Nuclear Materials, Volume 91, Issue 2, 1980, Pages 265-276)

- Voids prefer interstitials, especially at small void sizes
- The preference is reversed for the coated void
- For a bare unpressurized void, interstitial bias is greater than vacancy bias. Voids will shrink
- If "shell" shear modulus or lattice parameter is greater than matrix shear modulus, vacancy bias becomes greater than interstitial bias
- Thicker shells have a greater effect

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Effect of materials variables on void growth

Effect of Inert Gas: Bubbles & Voids

- Inert gas atoms (H, He, etc.) are created by transmutation and interact with vacancies
  - Must be accounted for on bubble/void growth as:
    - Insoluble gas atoms can act as immobile nucleation sites to which vacancies and interstitials migrate to form voids
    - Inert gas atoms can stabilize a cavity and assist the nuclei during nucleation
- First, let's assume the following:

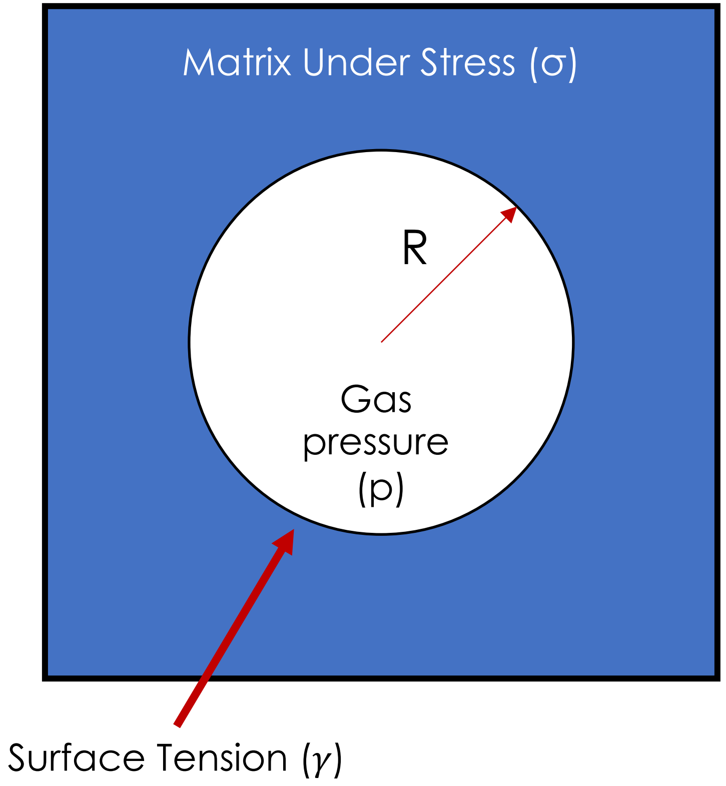
Side Note!
We generally define the following:

Void: open volume in a solid not pressurized by inert gas

Bubble: open volume in a solid that is pressurized by inert gas

Cavity: Generalization for open volume in a solid – can be a bubble or void

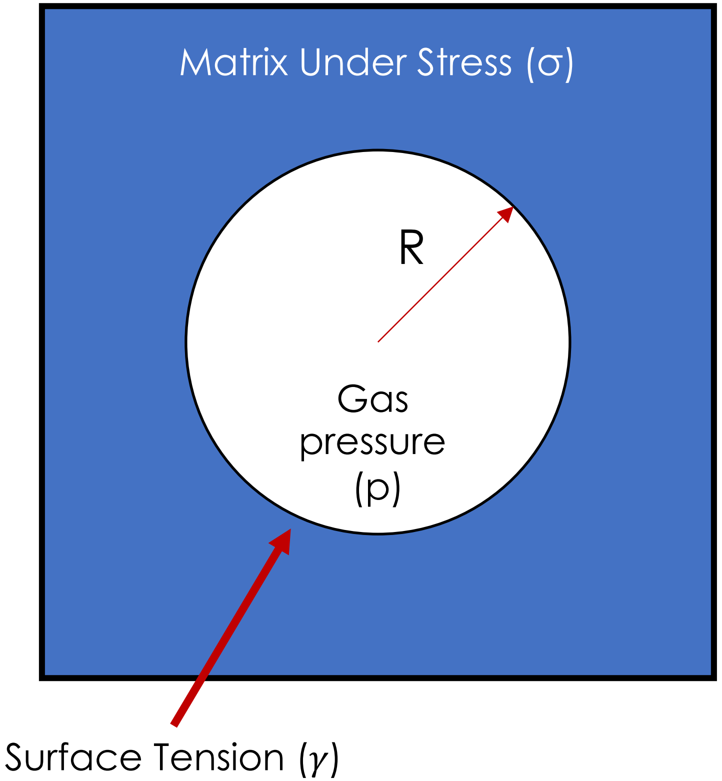
Effect of Inert Gas: Bubbles & Voids



- At equilibrium, the force balance is:

- At non-equilibrium, the force balance is:

Effect of Inert Gas: Bubbles & Voids



- Let's now calculate the number of gas atoms present in the bubble:

Effect of Inert Gas: Bubbles & Voids

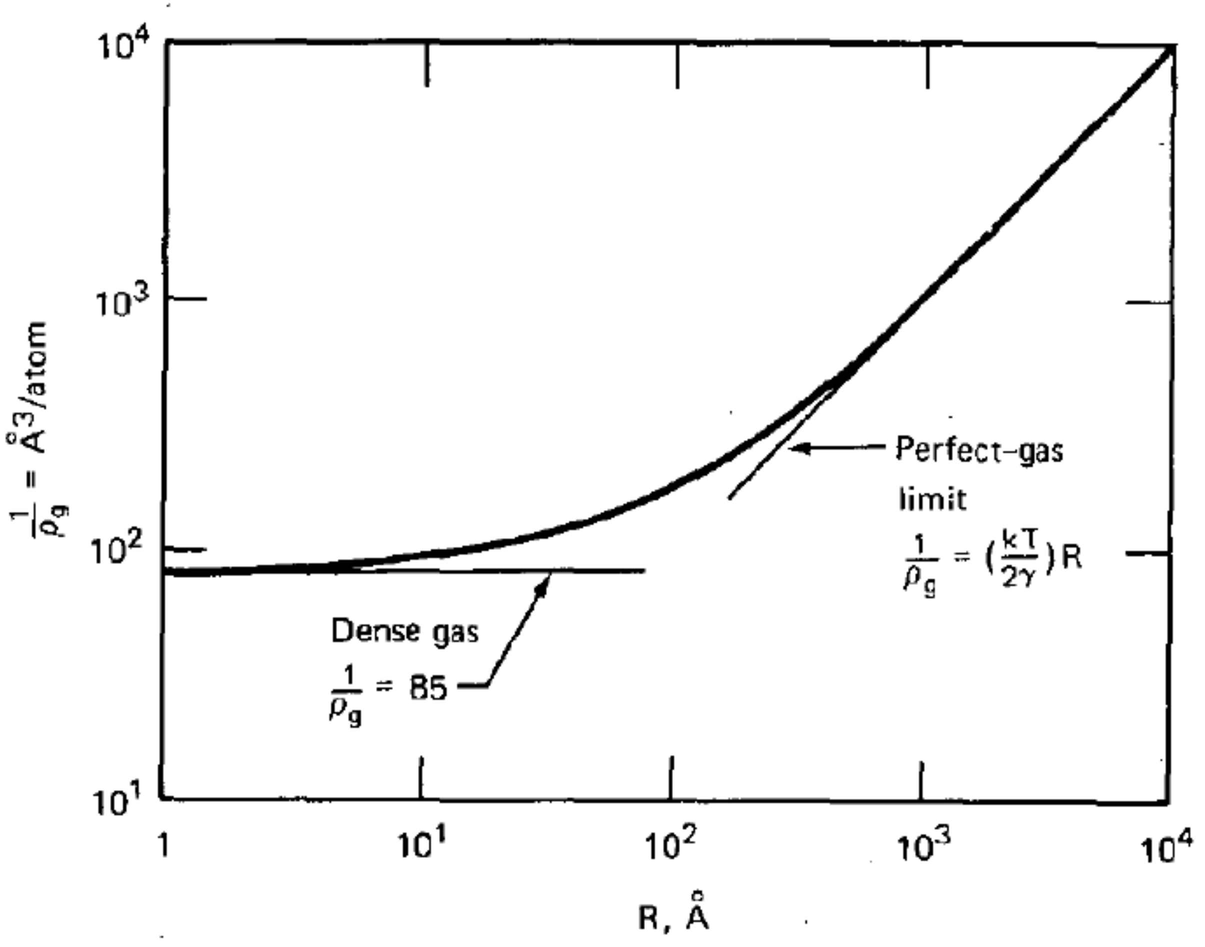
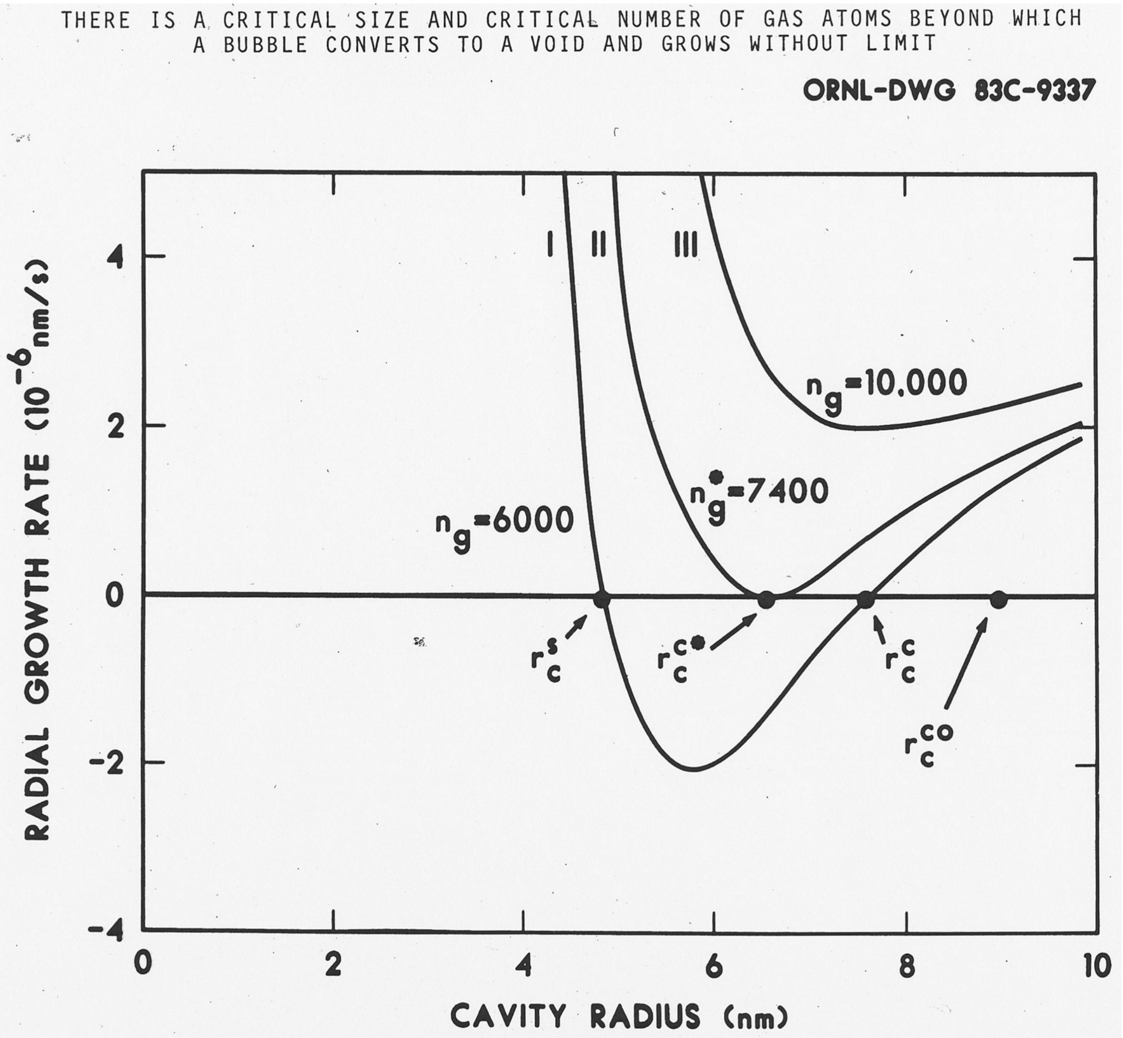


Fig. 13.3 Density of xenon gas in a spherical bubble imbedded in a stress-free solid of surface tension of 1000 dynes/cm.

Now that we have an expression for n_x and P, we can add these into the terms for the growth rate law including thermal emission, we then get:

$$R\dot{R} = K_o\Omega\left(\frac{z_i - z_v}{z_v}\right)\frac{z_v\rho_d}{(4\pi R\rho_v + z_v\rho_d)^2}F(\eta) - \frac{D_v C_v^0 \Omega^2 z_v \rho_d}{kT(4\pi RN + z_v\rho_d)}\left(\frac{2\gamma}{R} - \frac{n_x kT}{{}^4/_3\,\pi R^3 - n_x B}\right)$$



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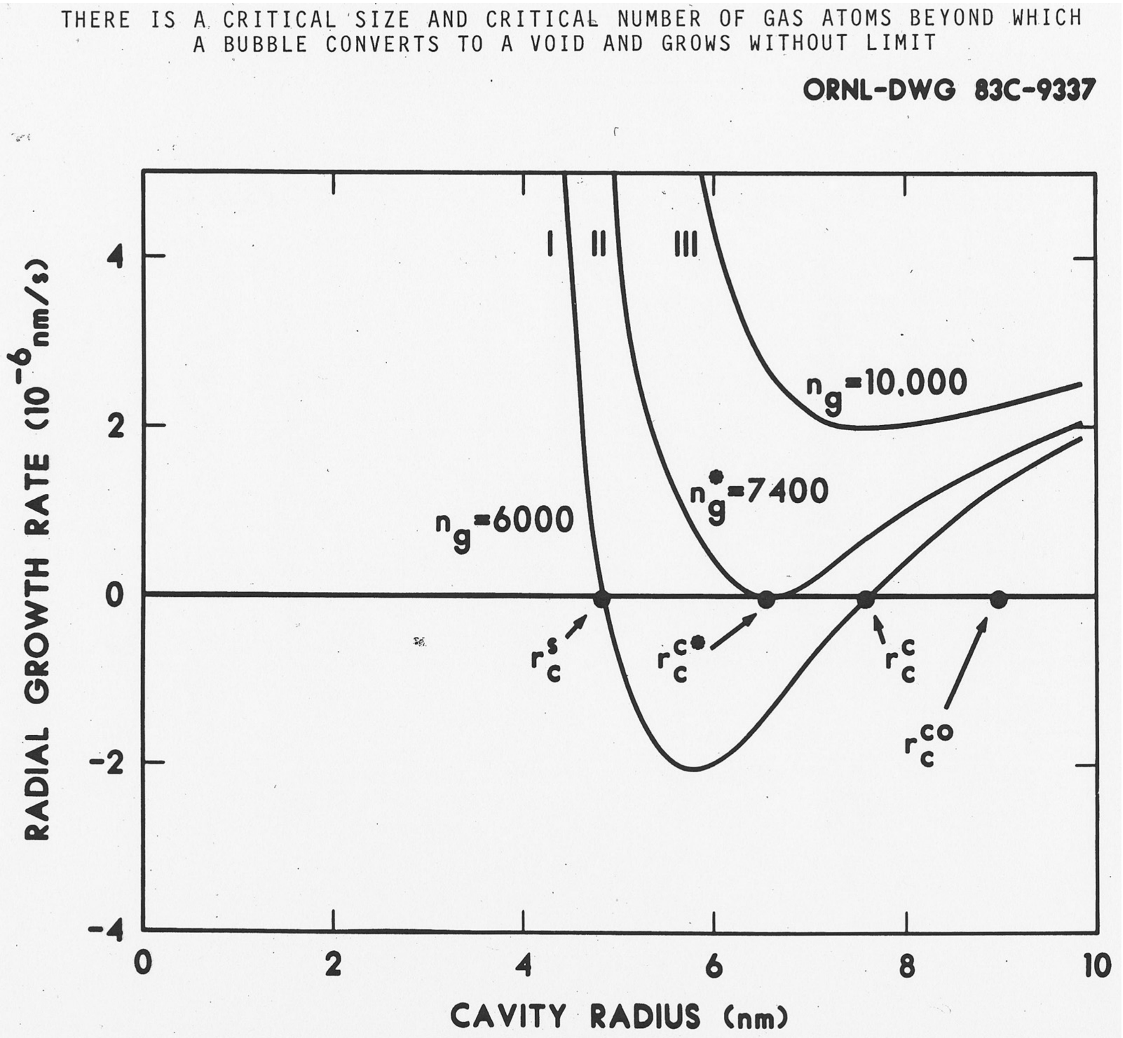
When gas is present, the current models predicts that cavities containing less than n_g* gas atoms remain at or below r_c*, but those with more than n_g*, this creates a bimodal distribution



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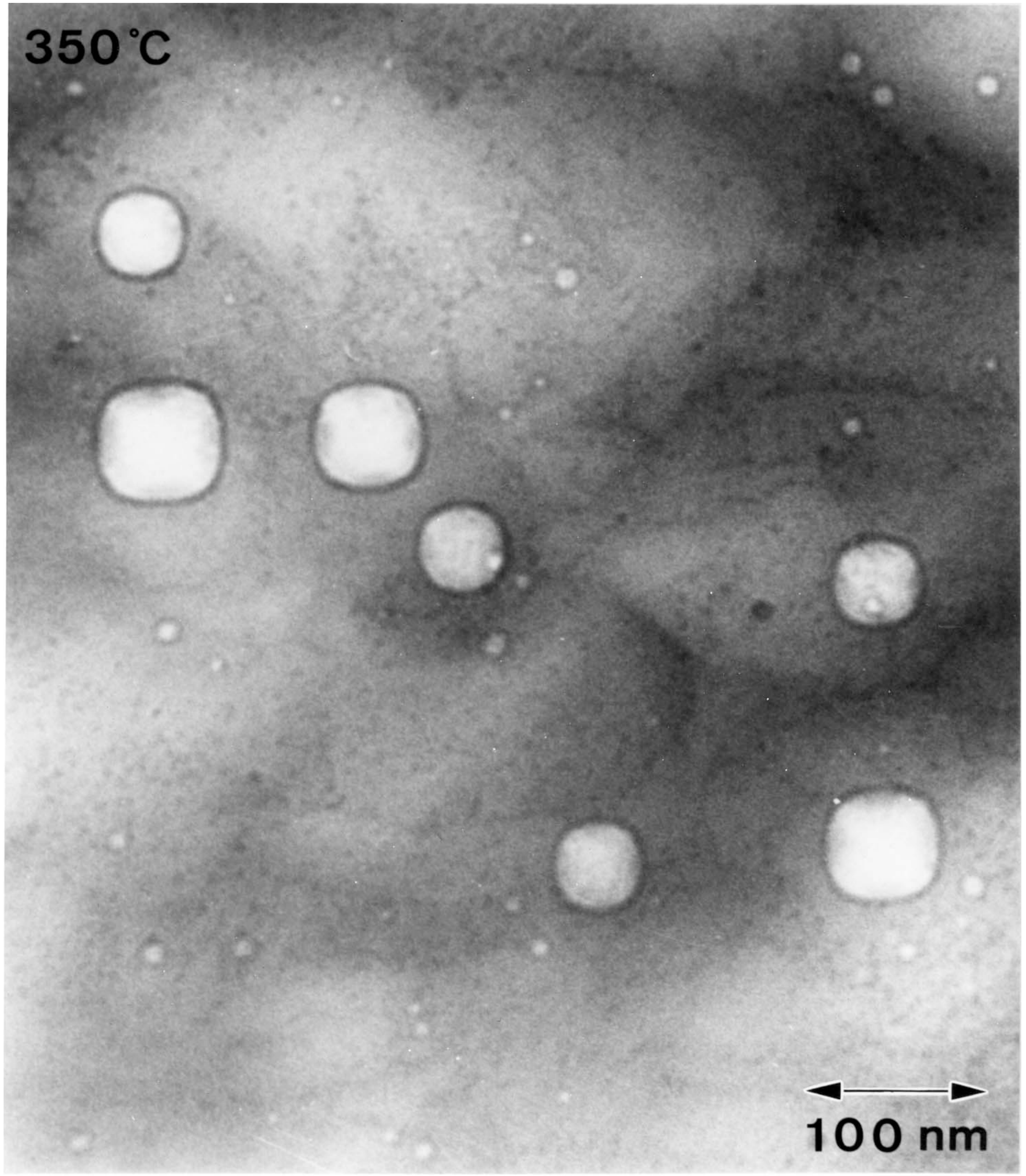
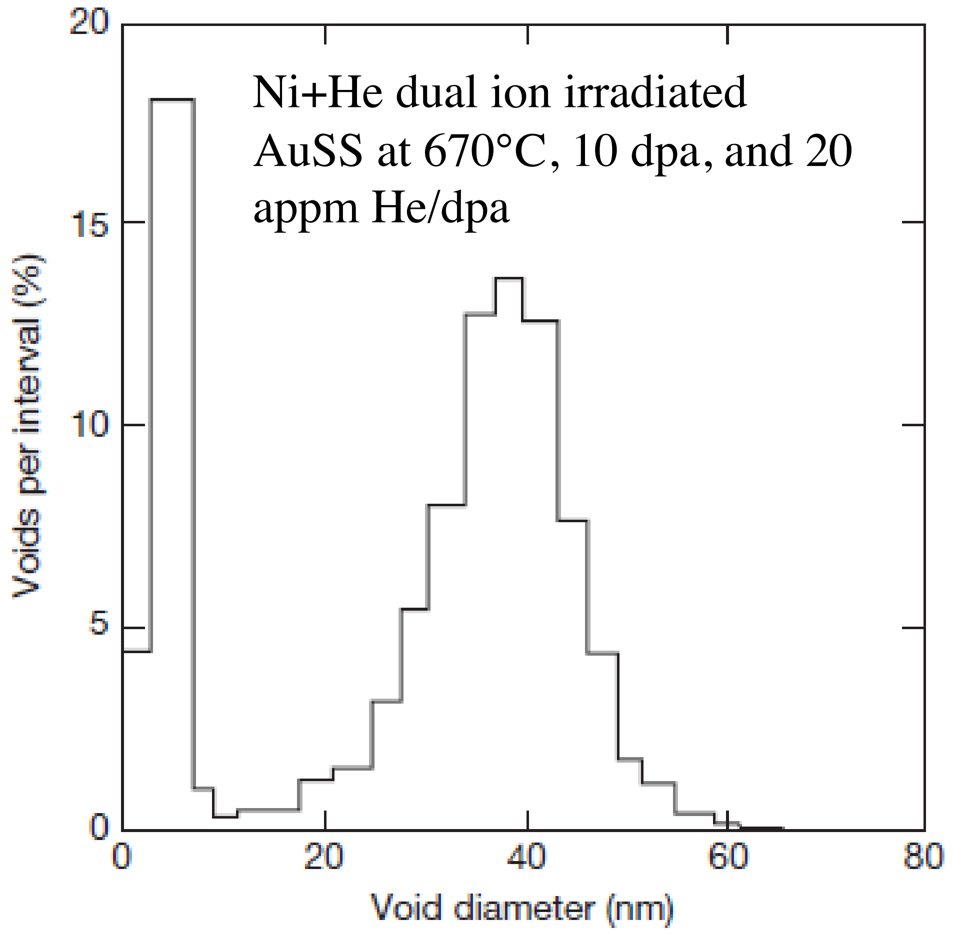
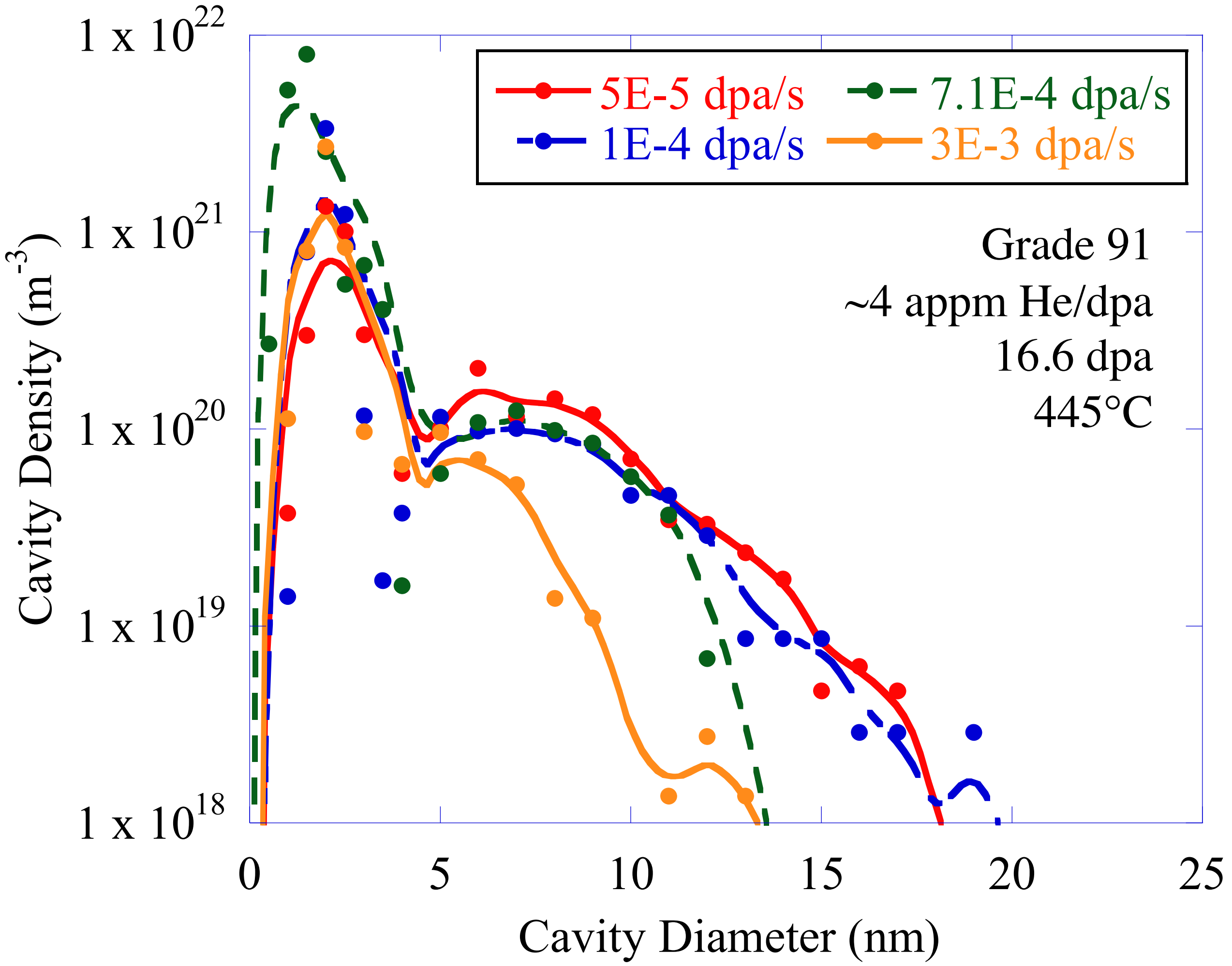


Zinkle, Farrell and Kanazawa, J. Nucl. Mater. 179-191 (1991) 994

Void and He bubble formation in Cu-100 ppm B following fission neutron irradiation to 1.2 dpa at 350°C

Experimental examples





Mansur, Coghlan JNM 119 (1983)

Taller (2019)

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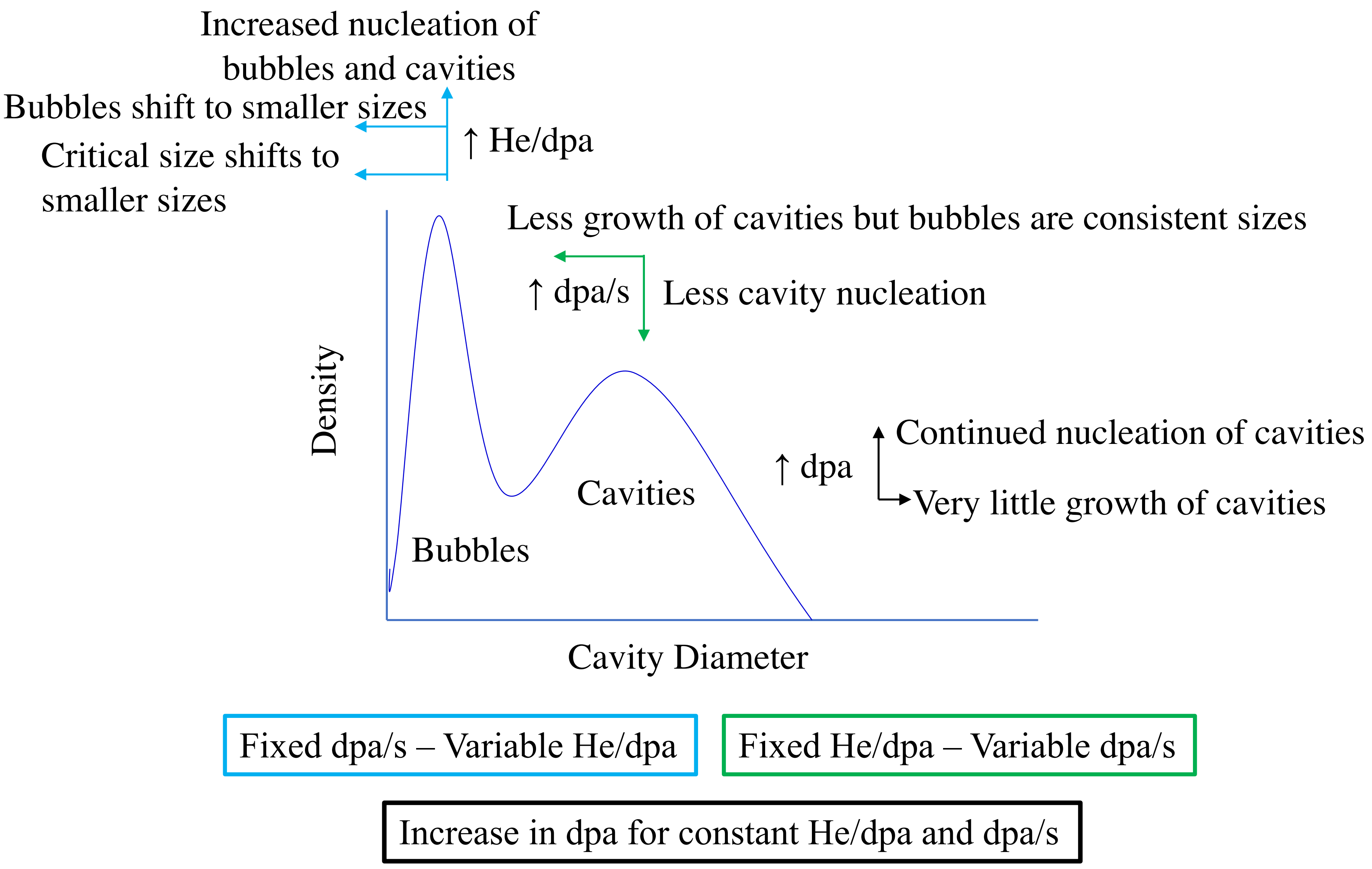
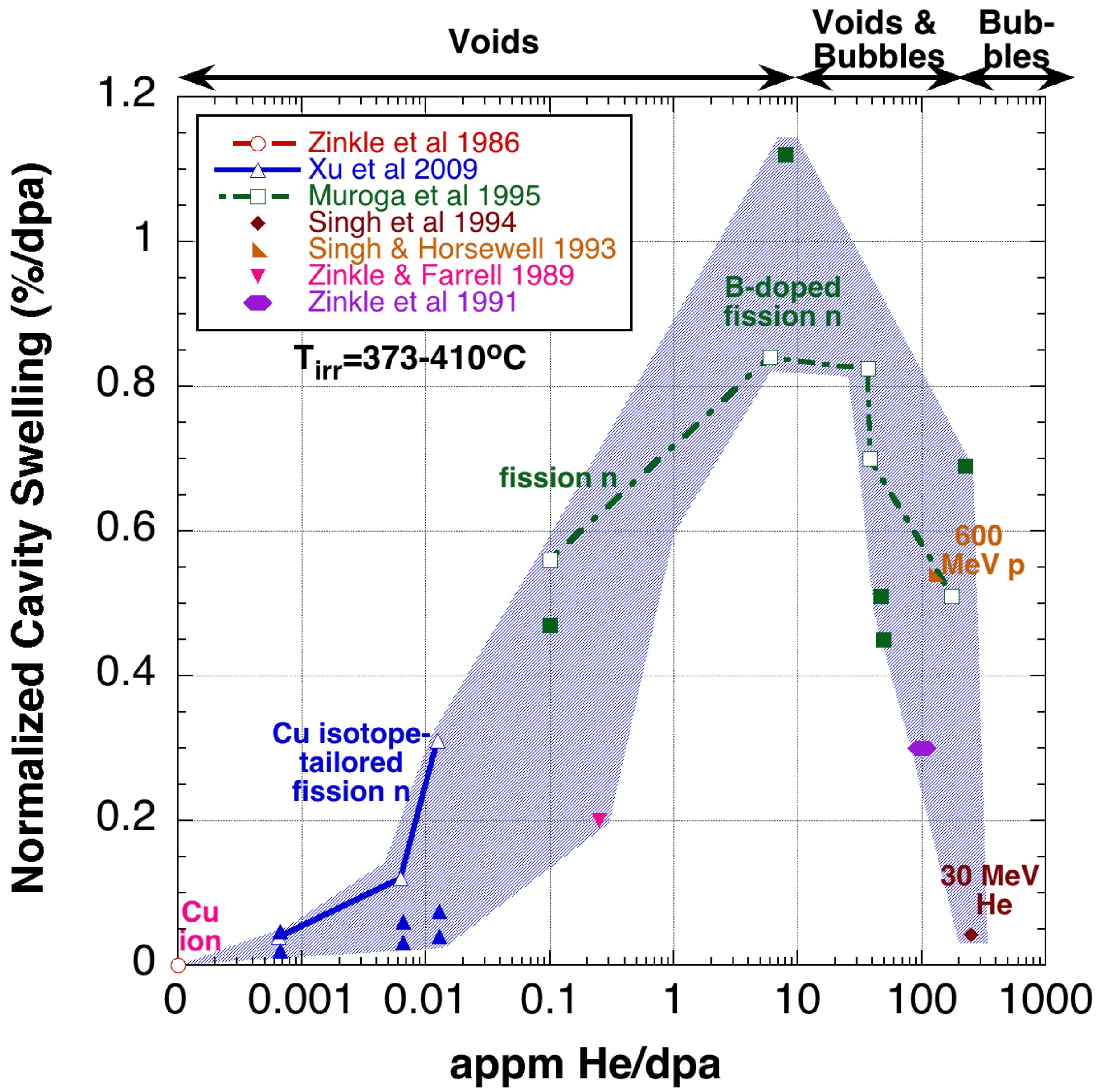
Experimental examples



Taller (2019)

Cavity swelling vs. He/dpa ratio in irradiated copper



~1-10 dpa

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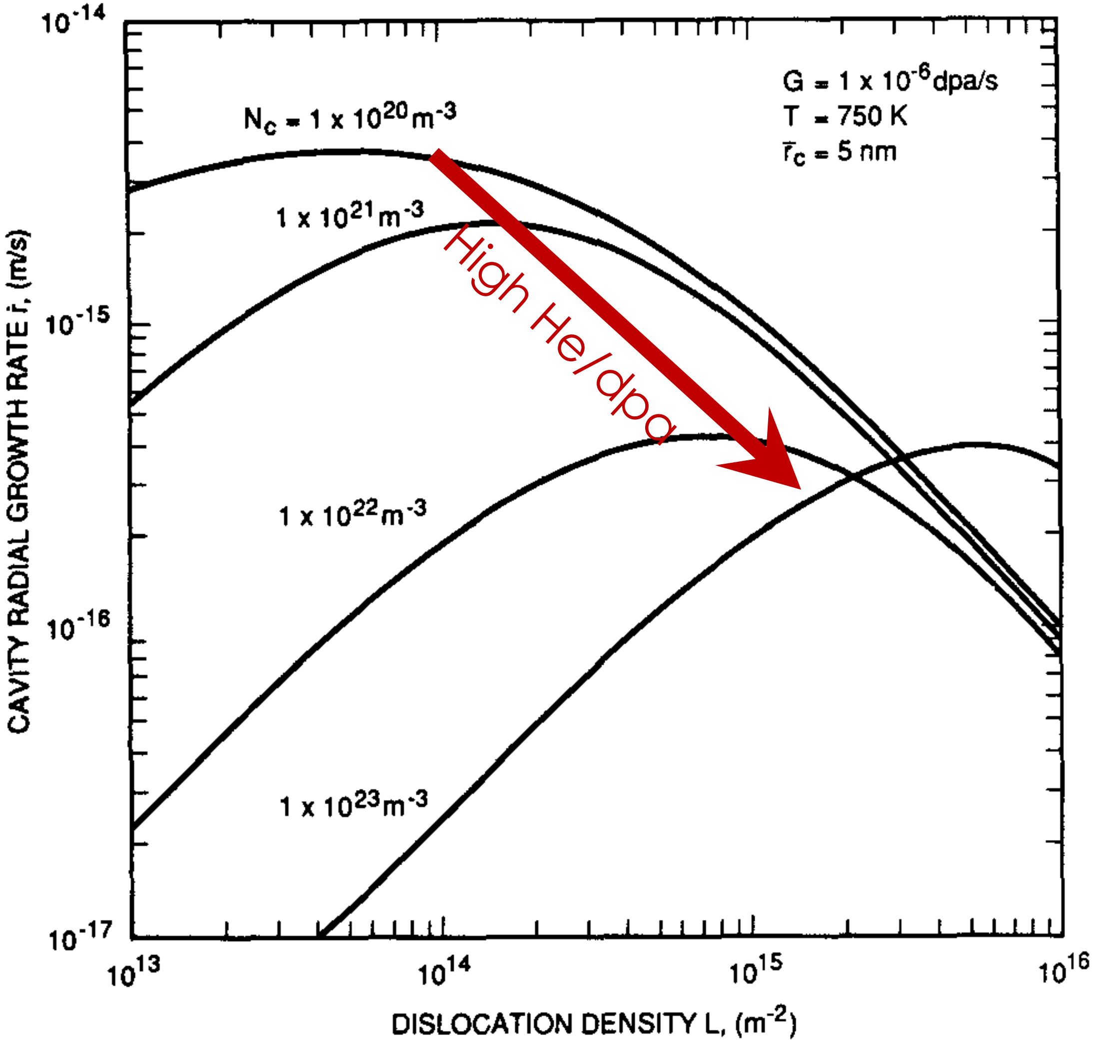
Calculated void growth rate is typically reduced for high cavity and dislocation sink strengths



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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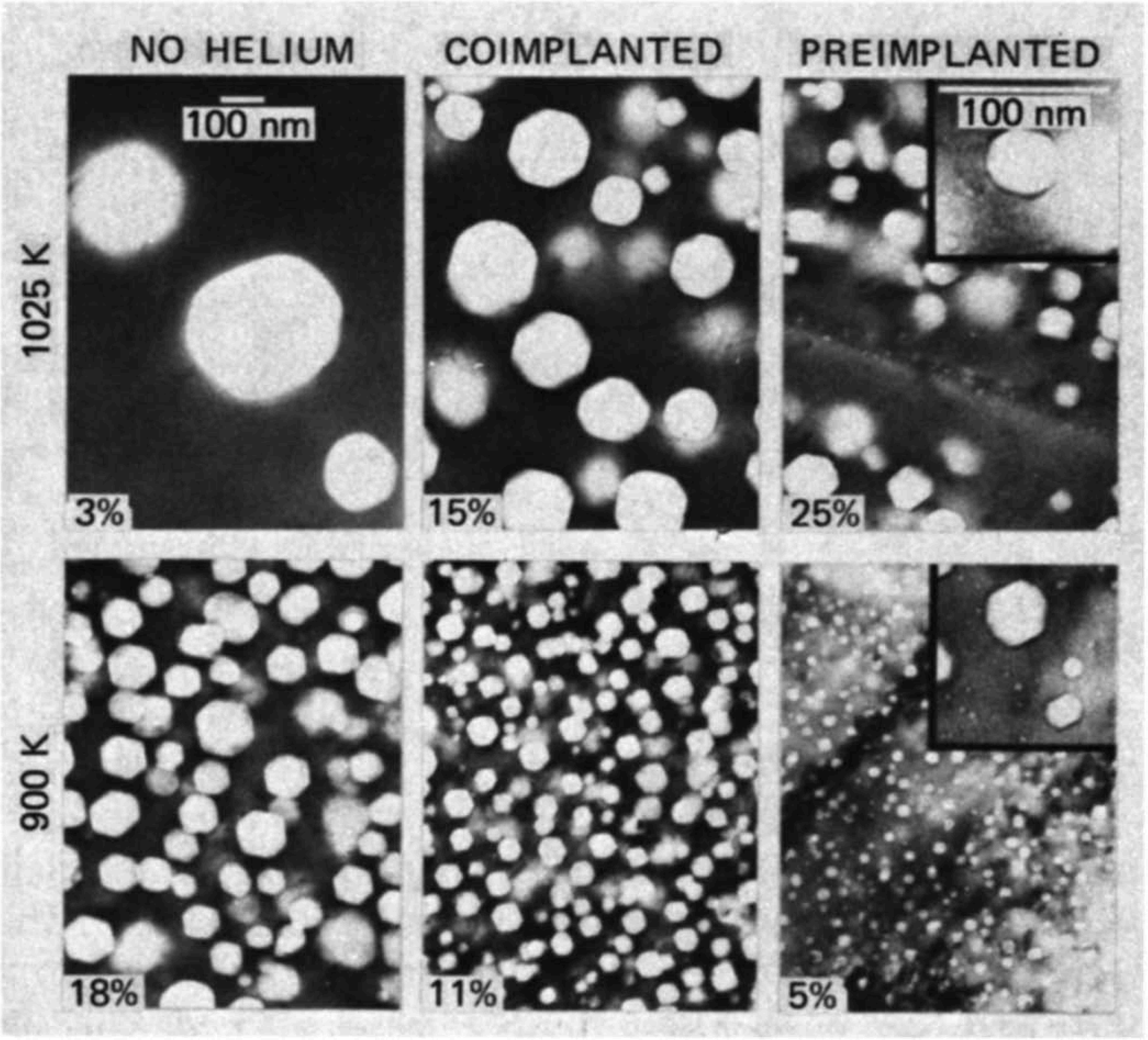
Effect of He in ion irradiations



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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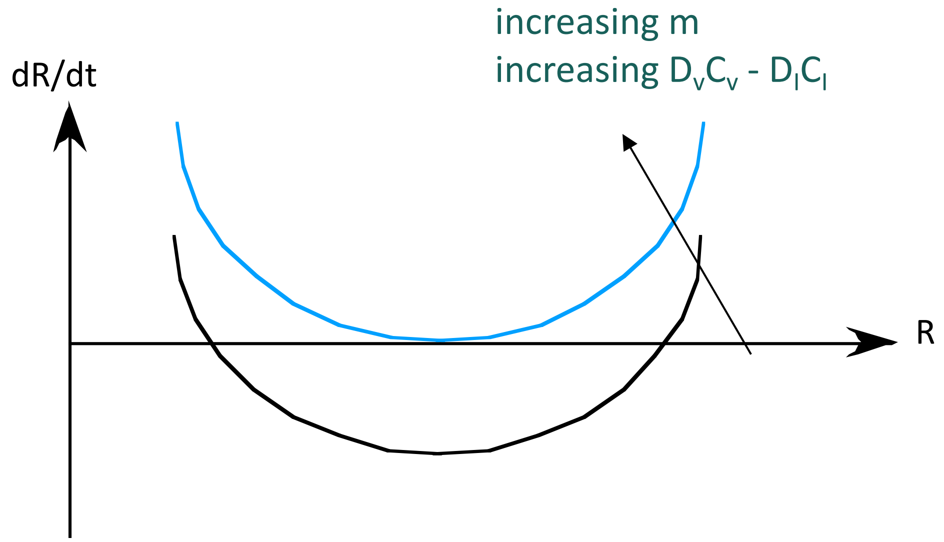
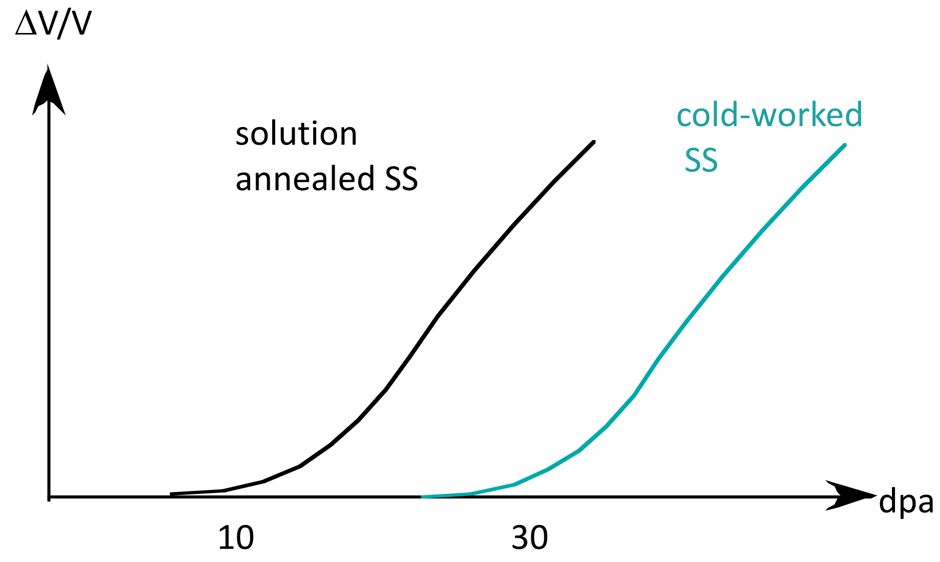
Remedies for void swelling?

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





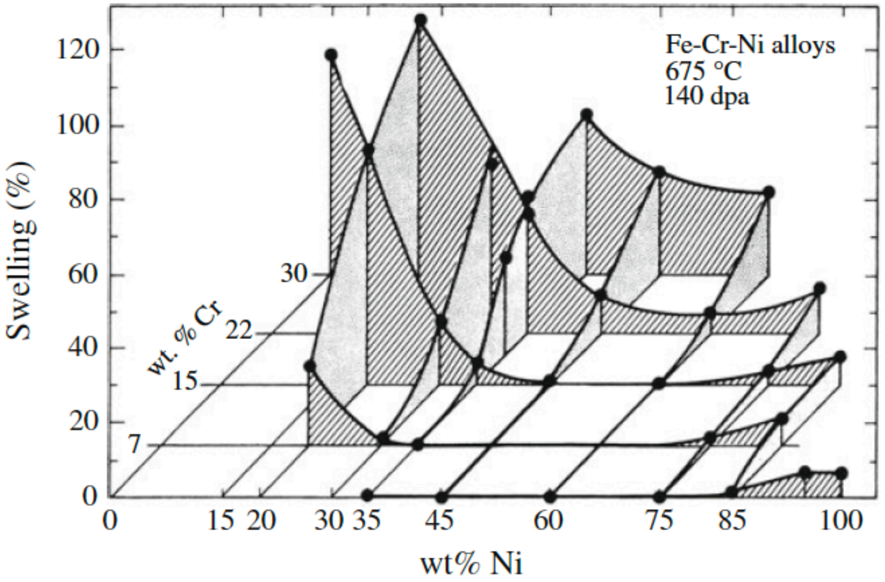


Fig. 8.45 Two-dimensional plot of the nickel and chromium dependence of swelling in Fe–Cr–Ni alloys irradiated with 5 MeV Ni$^+$ ions at 675 °C to a dose of 140 dpa. Swelling was measured by the step-height technique (after [19])