Voids II+

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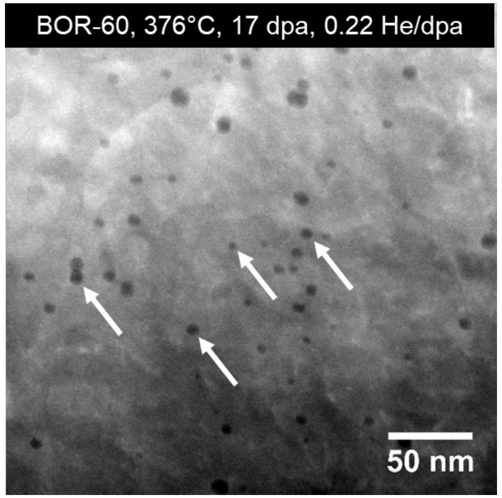
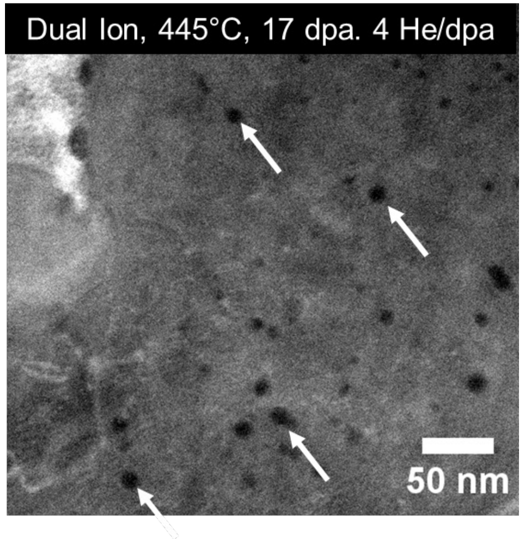
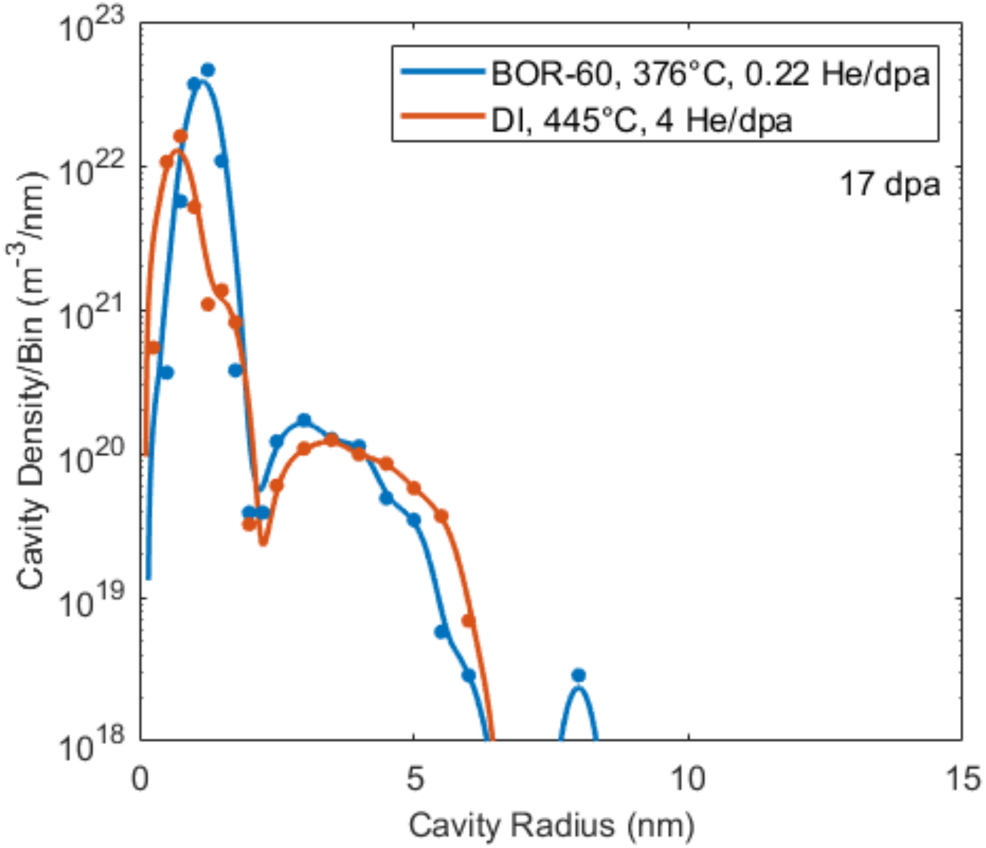
Effect of Dose Rate – Real World Example

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

STEM HAADF







$$T_2 - T_1 = \frac{\dfrac{kT_1^2}{E_v^m + 2E_v^f}\ln\left(\dfrac{G_2}{G_1}\right)}{1 - \dfrac{kT_1}{E_v^m + 2E_v^f}\ln\left(\dfrac{G_2}{G_1}\right)}$$

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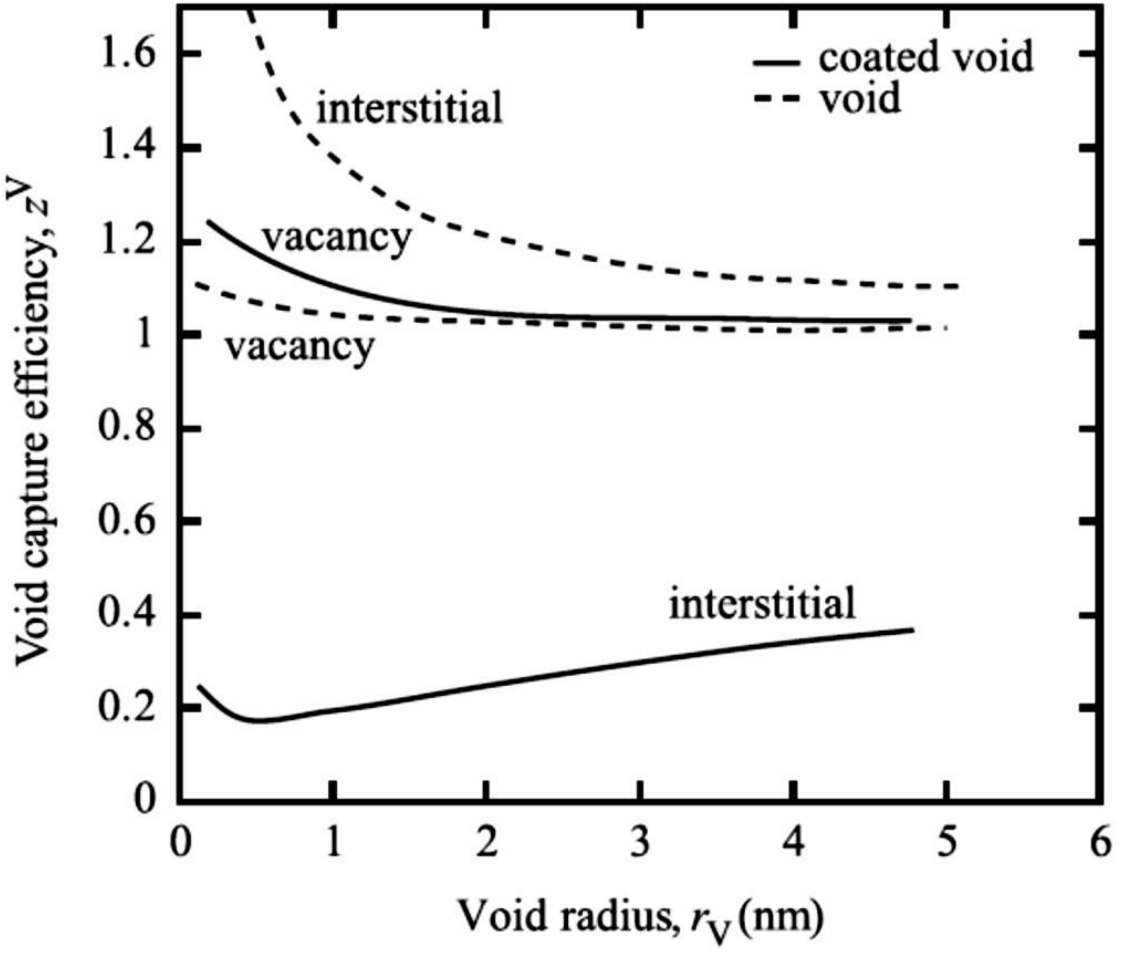
Effect of void surface segregation on defect bias



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)

- 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
  - This effect can occur because of radiation induced segregation
- Thicker shells have a greater effect

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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 and growth
- First, let's assume the following:
  - No account taken of cascades or lattice imperfections
  - Gas atom association is stable and mobile

<u>Side Note!</u>

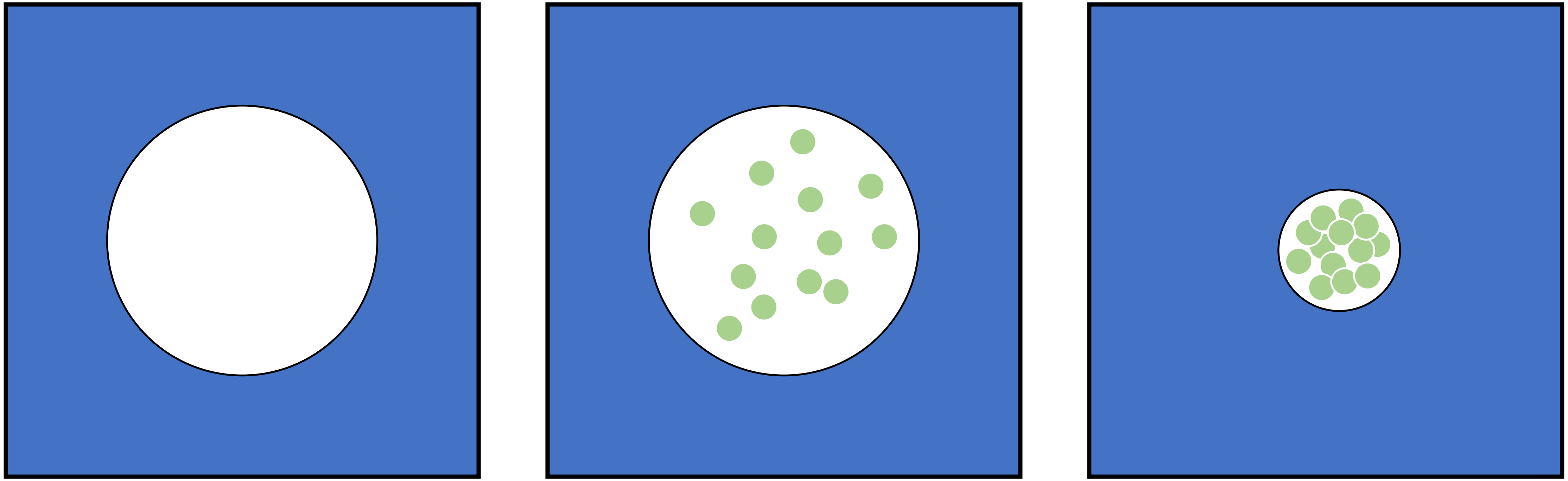
We generally define the following:

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

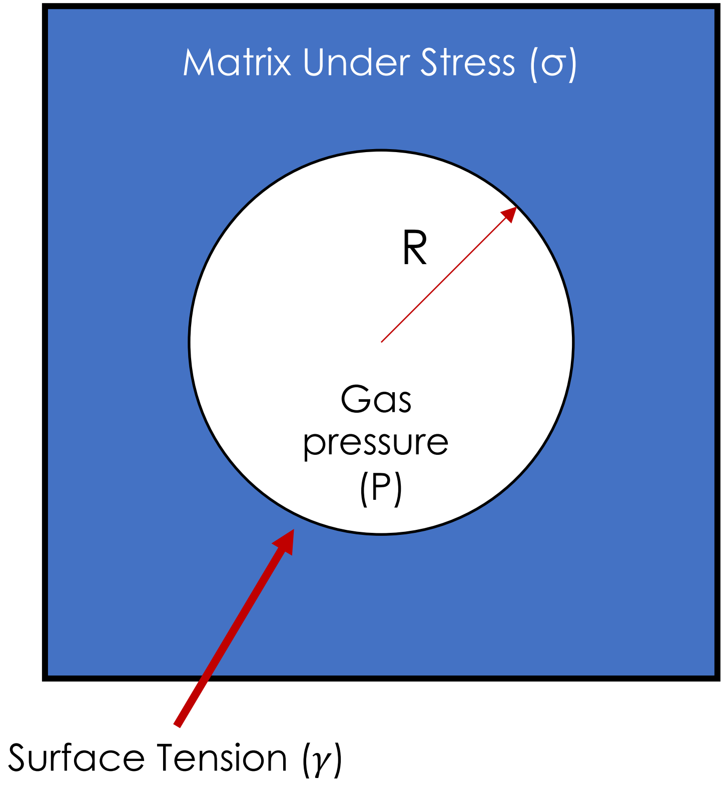
Bubble: open volume in a solid that is pressurized by inert gas

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

Effect of Inert Gas: Bubbles & Voids

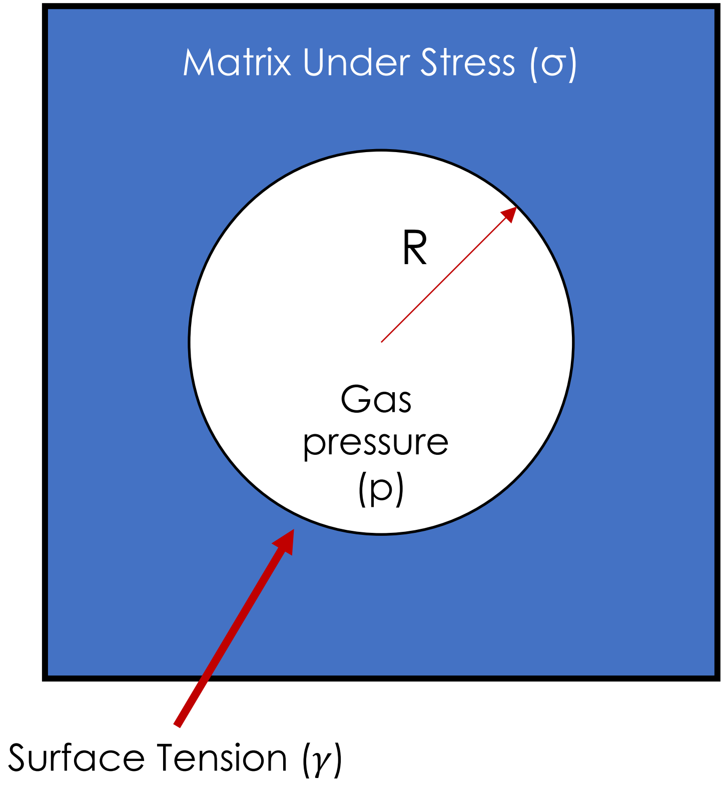


Effect of Inert Gas: Bubbles & Voids



- For a spherical cavity, the change in volume and surface area is:
- Under expansion (cavity growth) the pressure does work on $P\ dV$ and the surface energy increase by $\gamma\ dA$, or simply,
- If not at mechanical equilibrium, then:

Effect of Inert Gas: Bubbles & Voids



- Let's now calculate the number of gas atoms present in the bubble, using the ideal gas law:

- Remembering that $P = \frac{2\gamma}{r}$ and plugging in we get:

Effect of Inert Gas: Bubbles & Voids

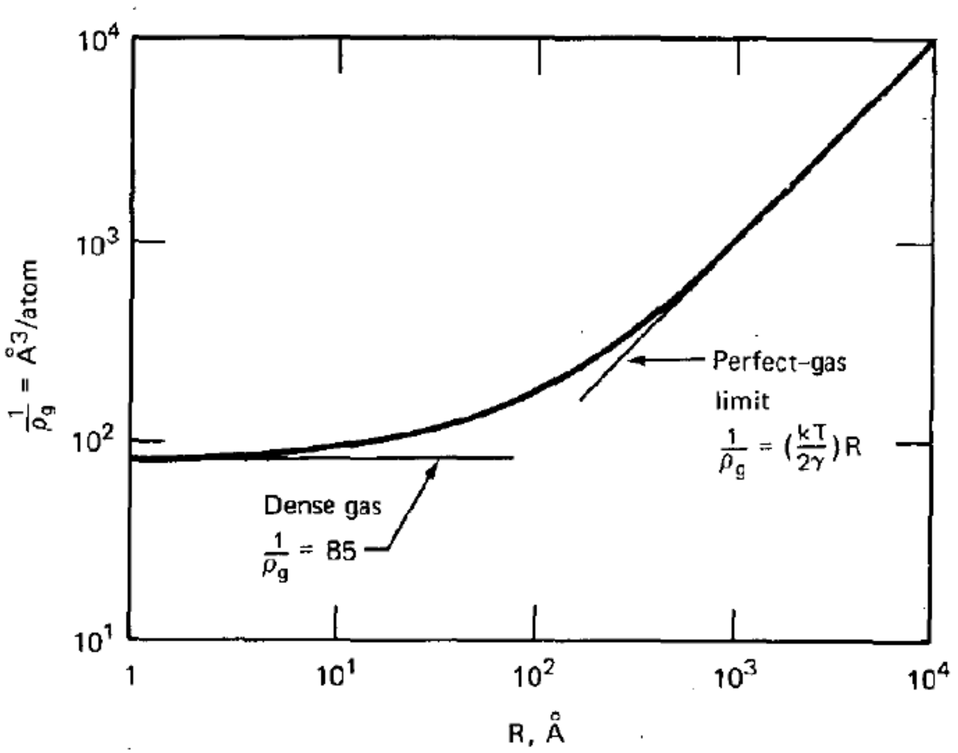


Fig. 13.3 Density of xenon gas in a spherical bubble imbedded in a stress-free solid of surface tension of 1000 dynes/cm.

For most applications we assume an ideal gas in mechanical equilibrium

- To account for non-ideal gas (e.g. high pressure in small bubbles) we need a different eq'n of state:

- We can then solve for n_x again using this relationship to get the number of gas atoms in the **dense gas limit:**

$$n_x = \frac{{}^4/_3\,\pi r^3}{B + \left({}^{k_b T}/_{2\gamma}\right) r}$$

And for non-equilibrium bubbles:

$$n_x = \frac{128\pi\gamma^3}{81\sigma_c^2 k_b T}$$

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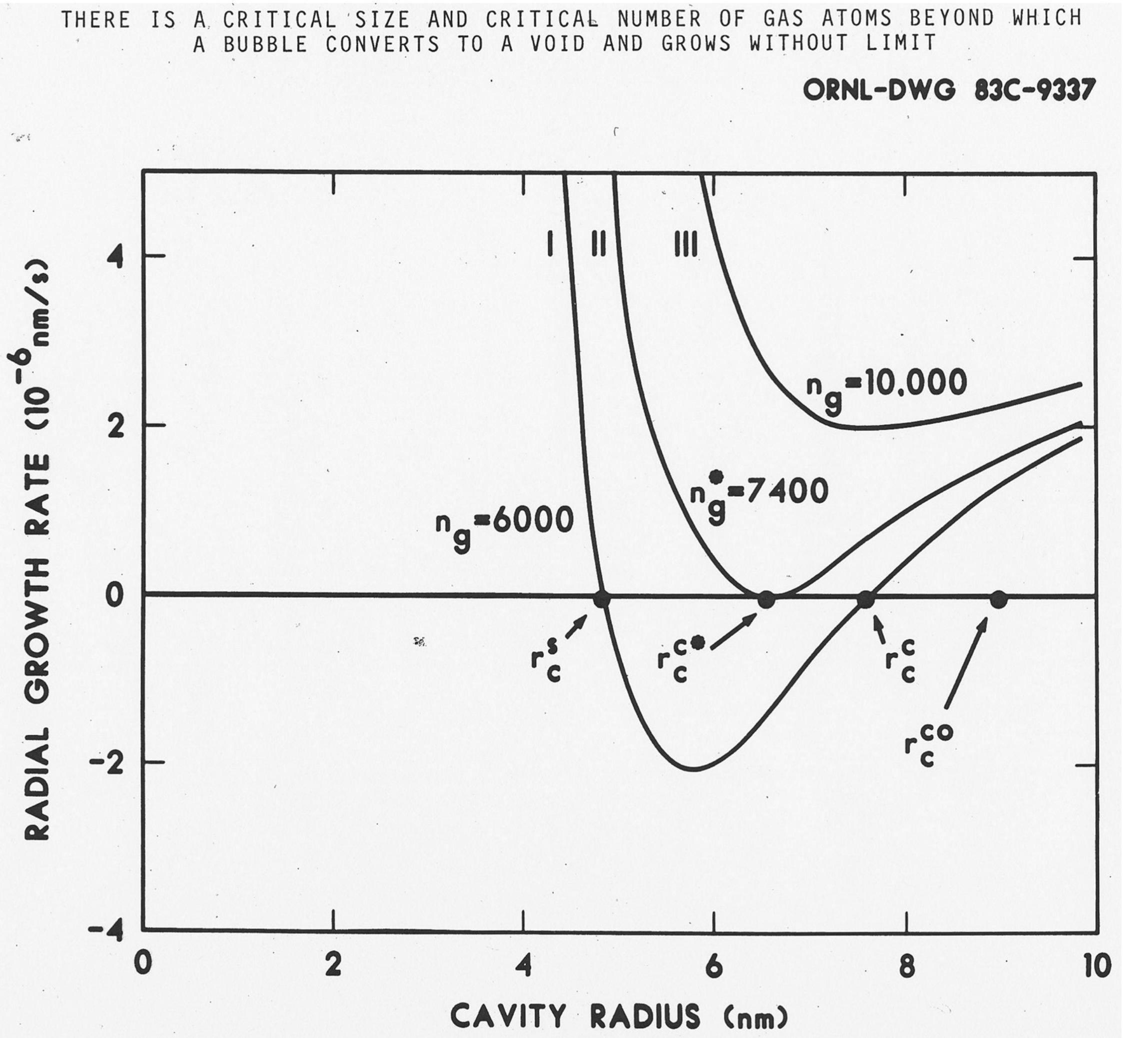
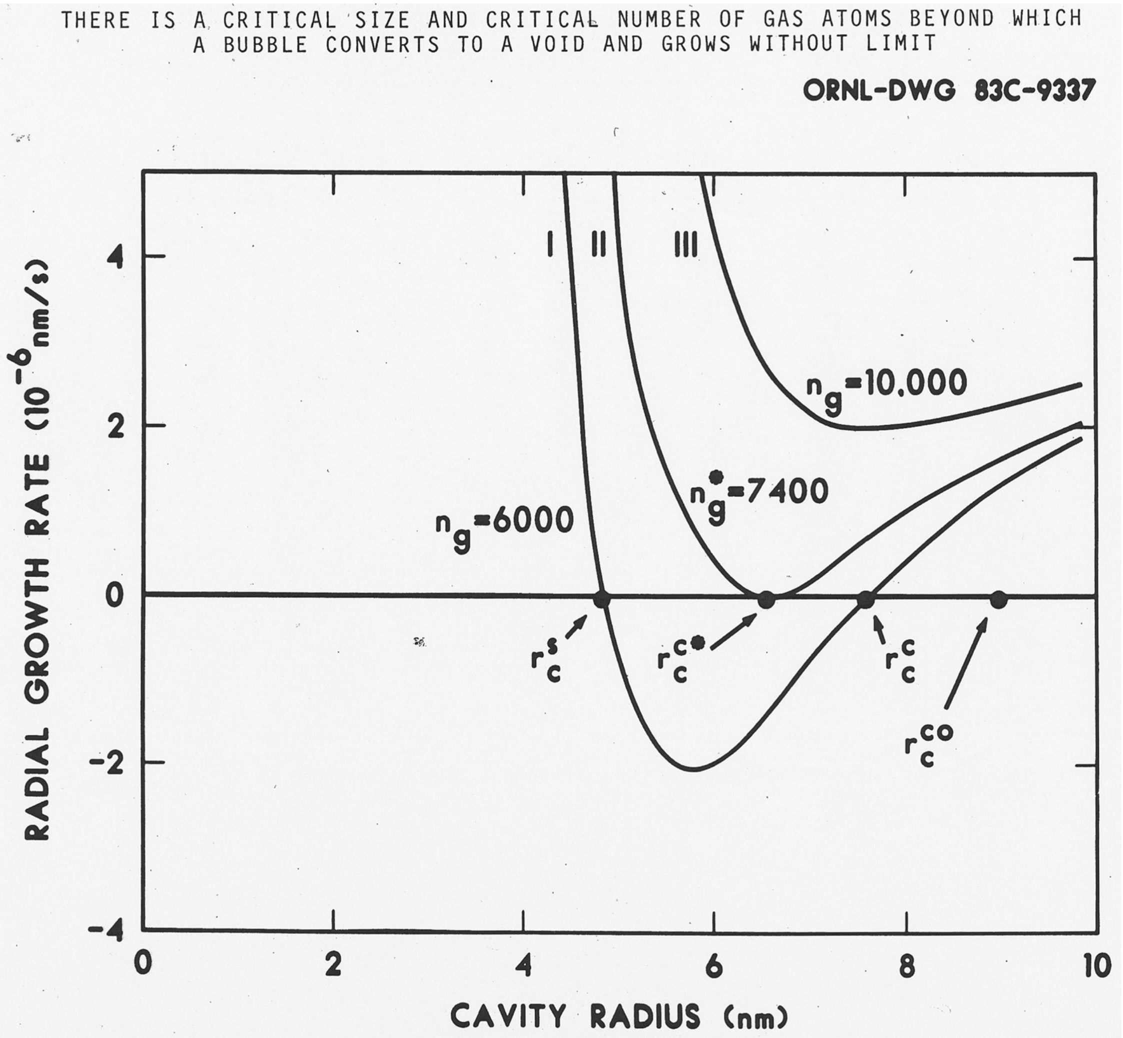
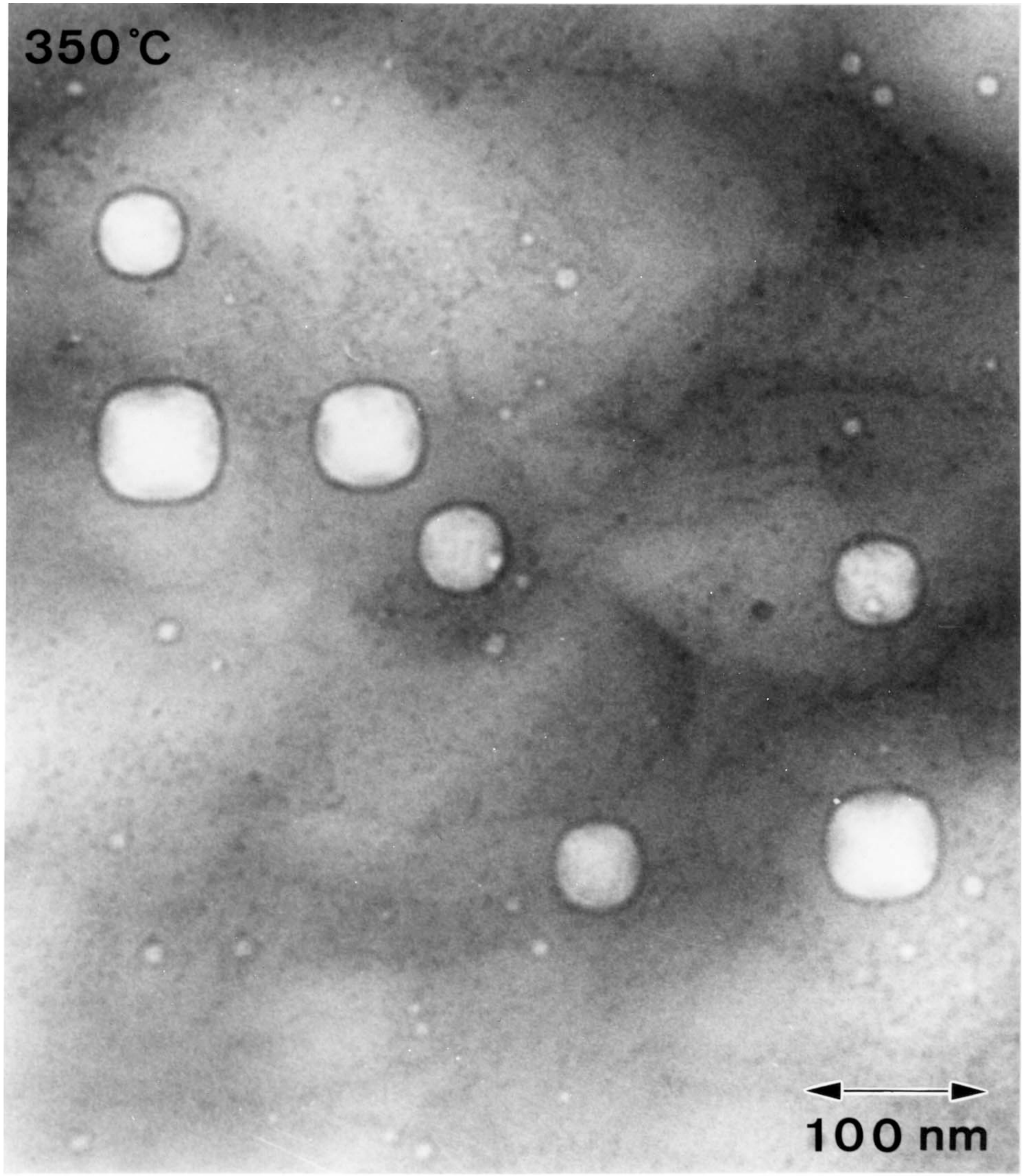
Now that we have an expression for n_x and P, we can add these into the terms for the growth rate law including thermal emission, we then get:

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



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

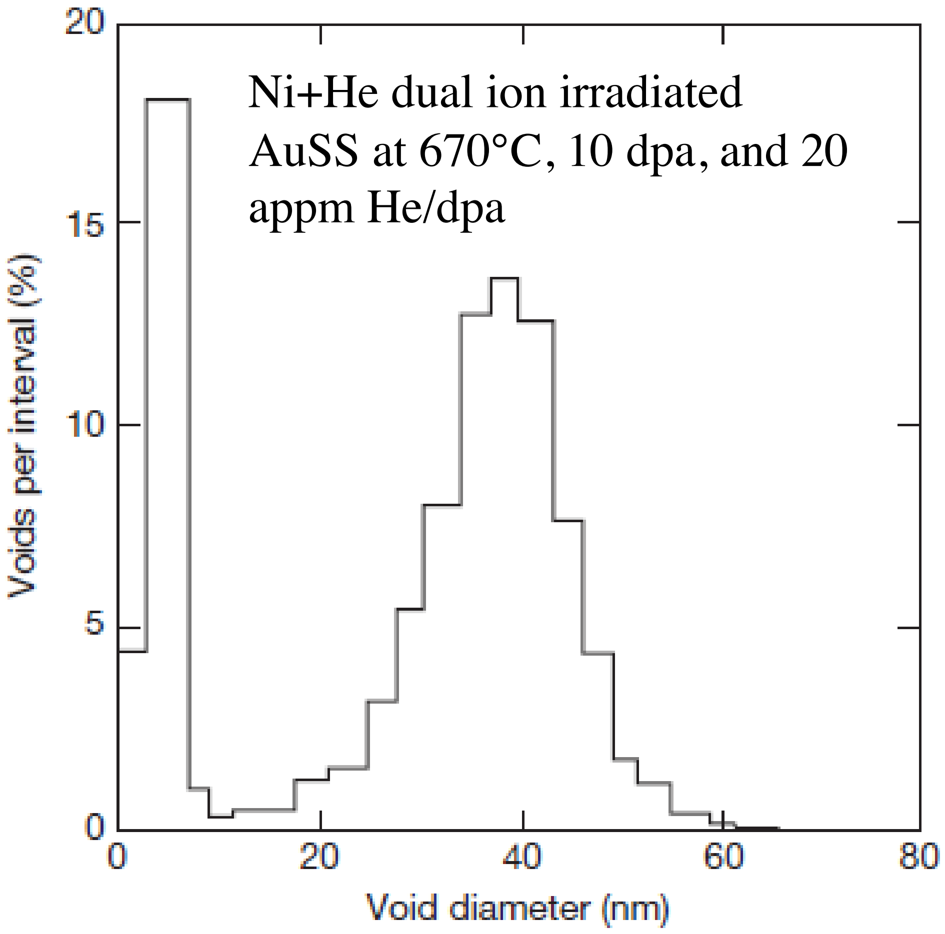




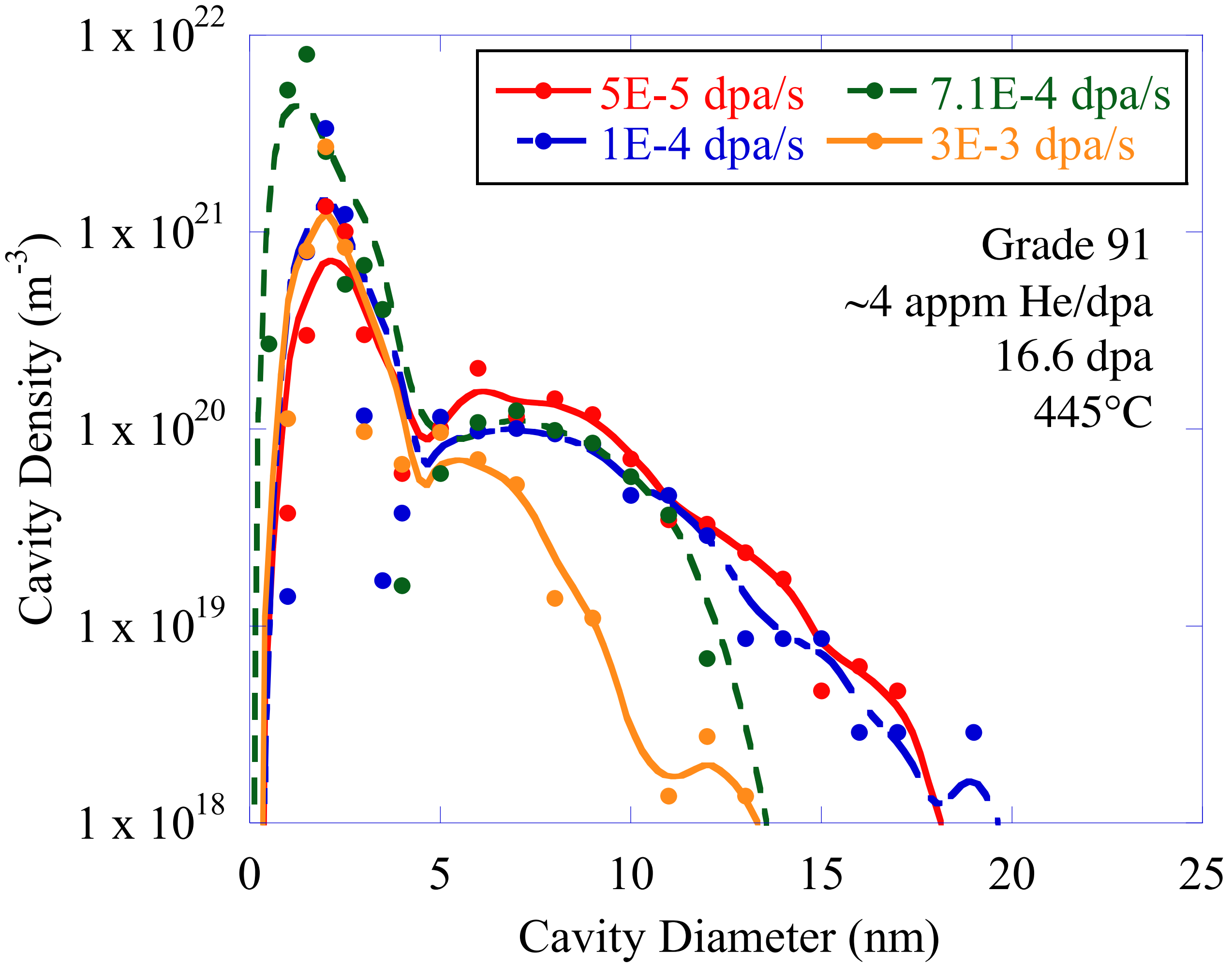
Zinkle, Farrell and Kanazawa, J. Nucl. Mater. 179-191 (1991) 994

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

Experimental examples

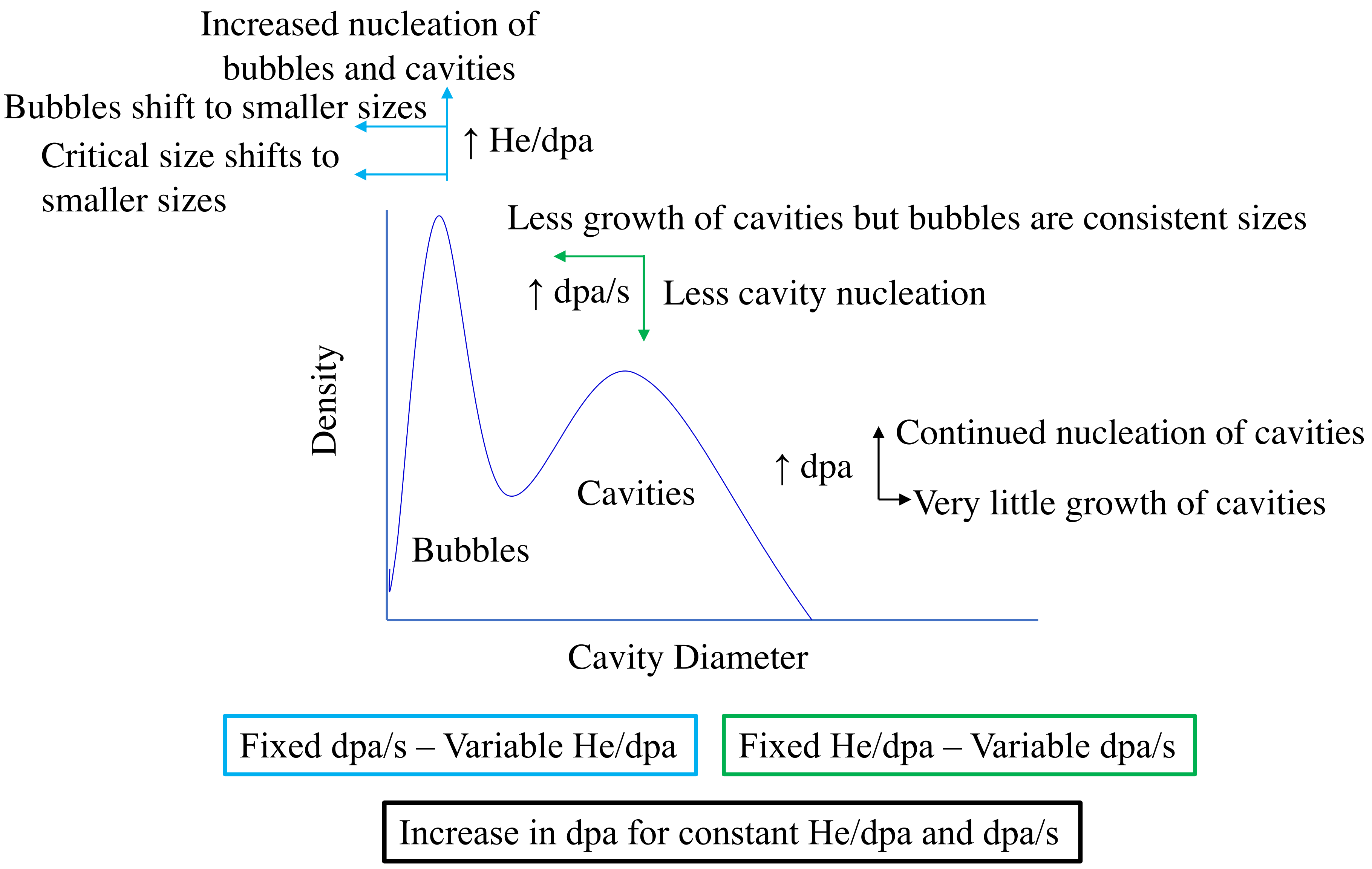


Mansur, Coghlan JNM 119 (1983)



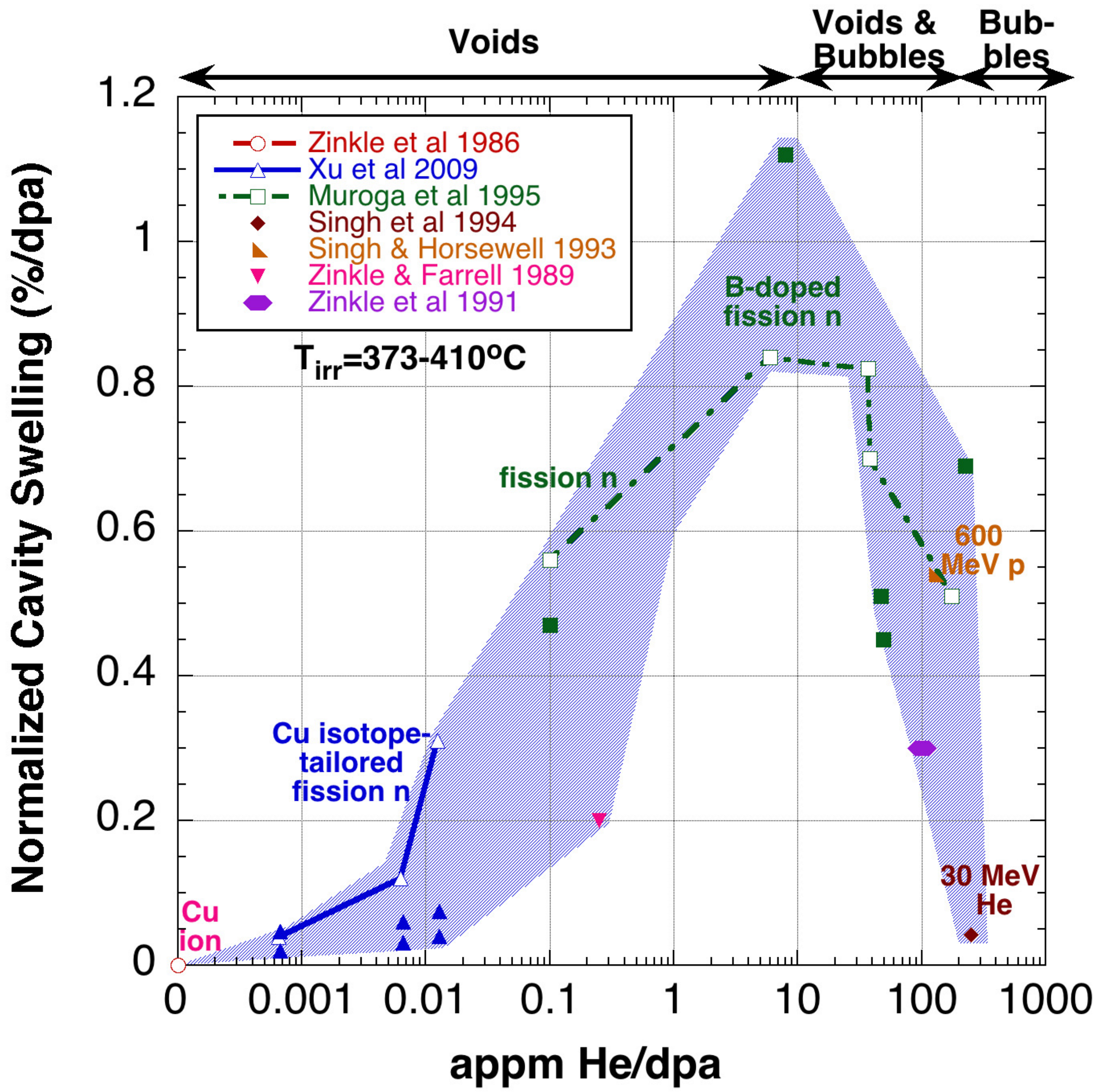
Taller (2019)

Experimental examples



Taller (2019)

Cavity swelling vs. He/dpa ratio in irradiated copper



~1-10 dpa

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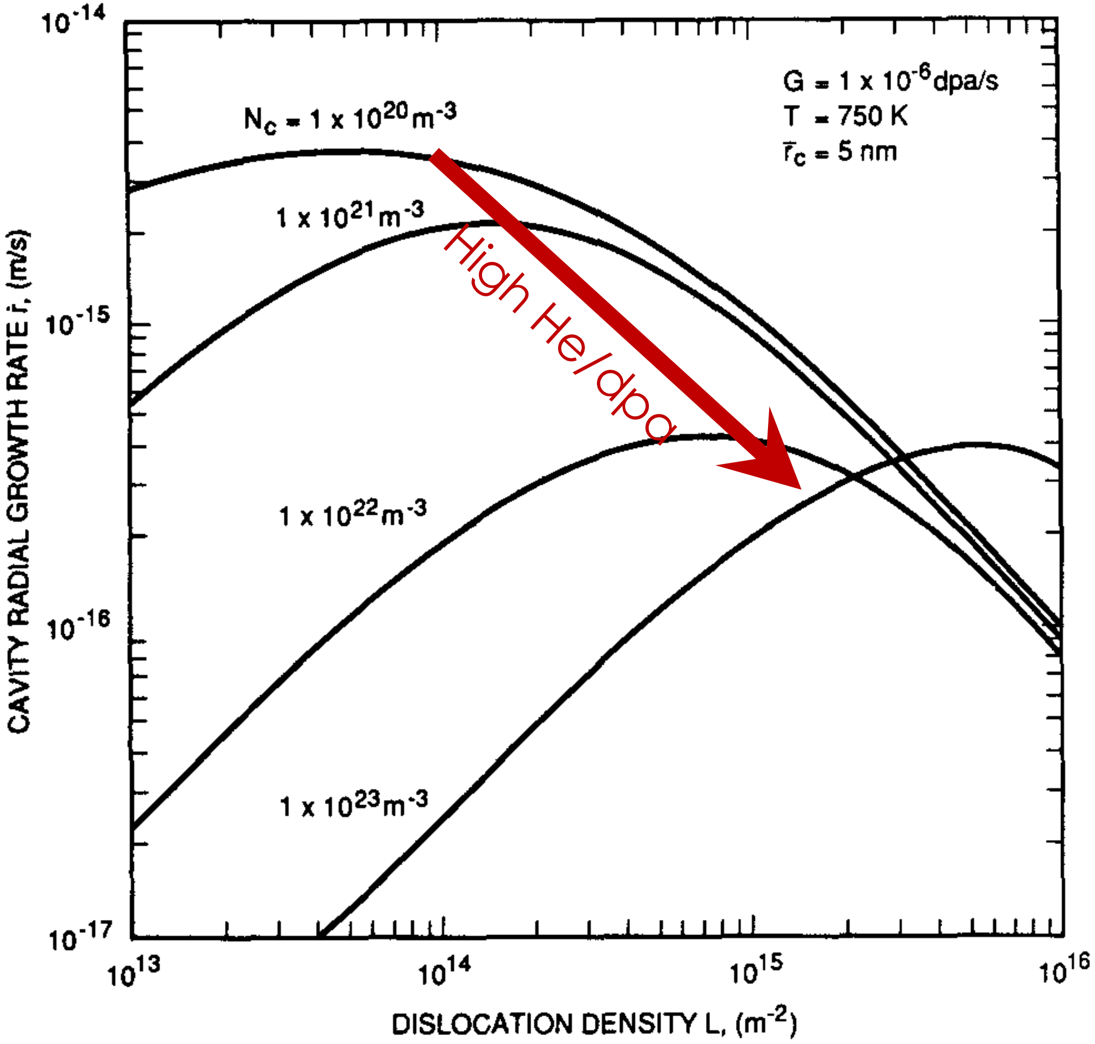
Calculated void growth rate is typically reduced for high cavity and dislocation sink strengths



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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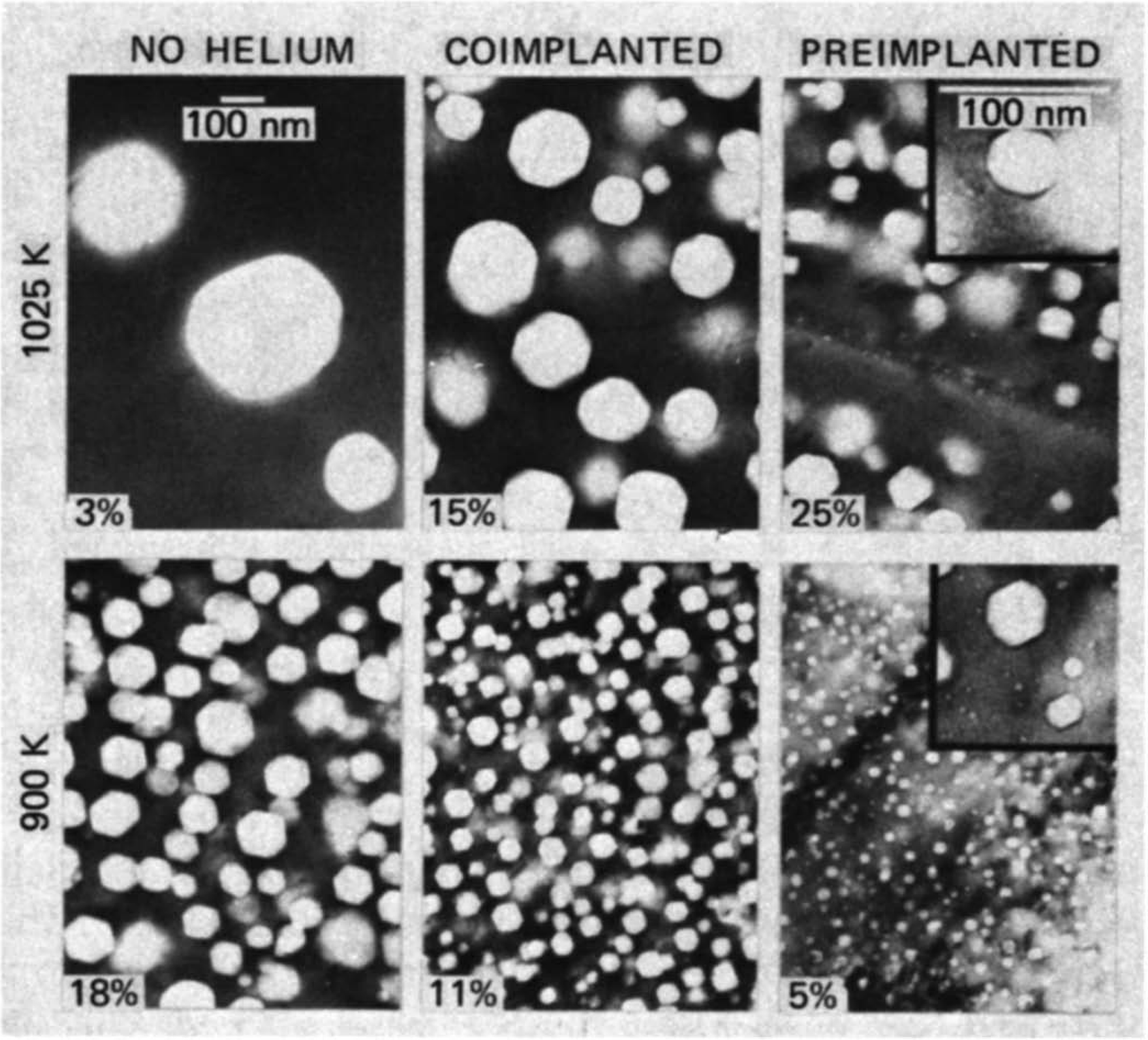
Effect of He in ion irradiations



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

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

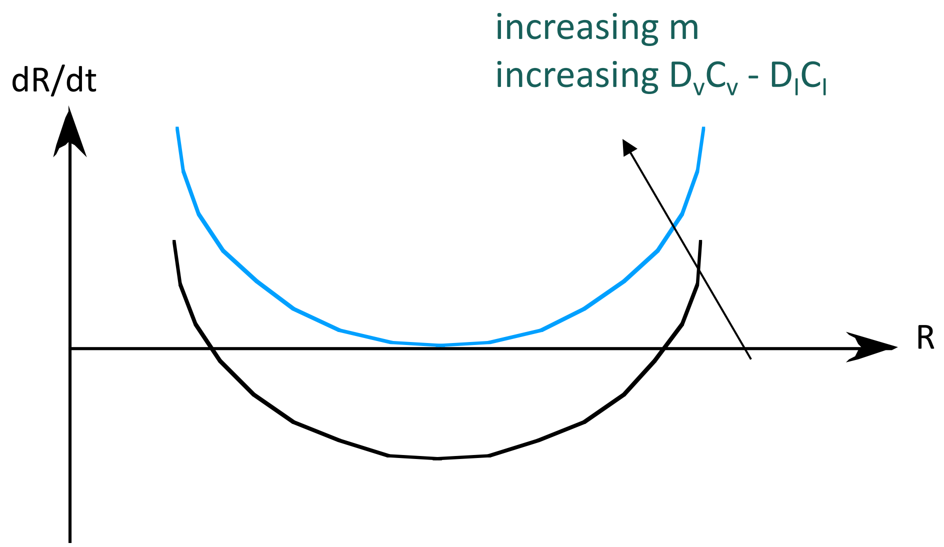
Packan & Farrell, NT-Fusion, 1983

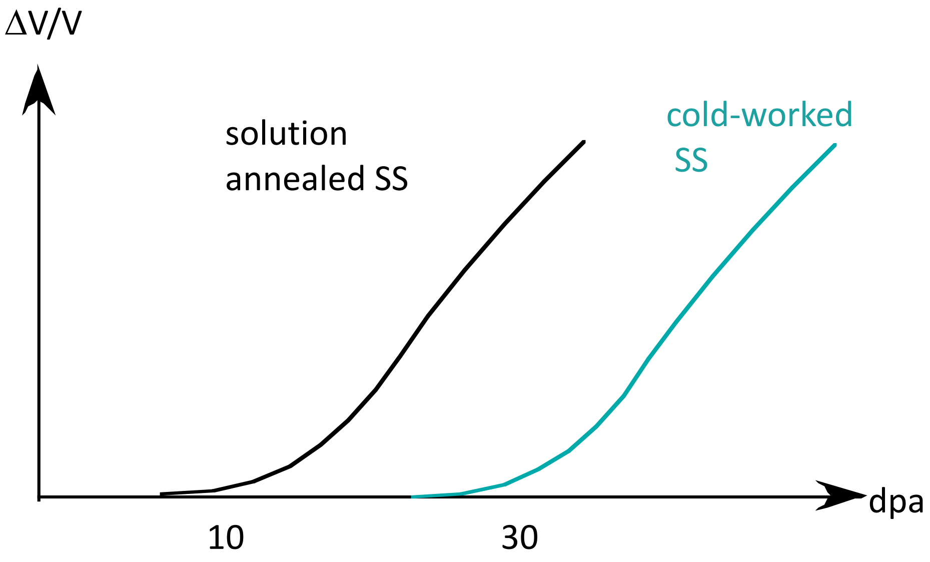
Remedies for void swelling?

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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Why are we interested in phase transformations under irradiation?

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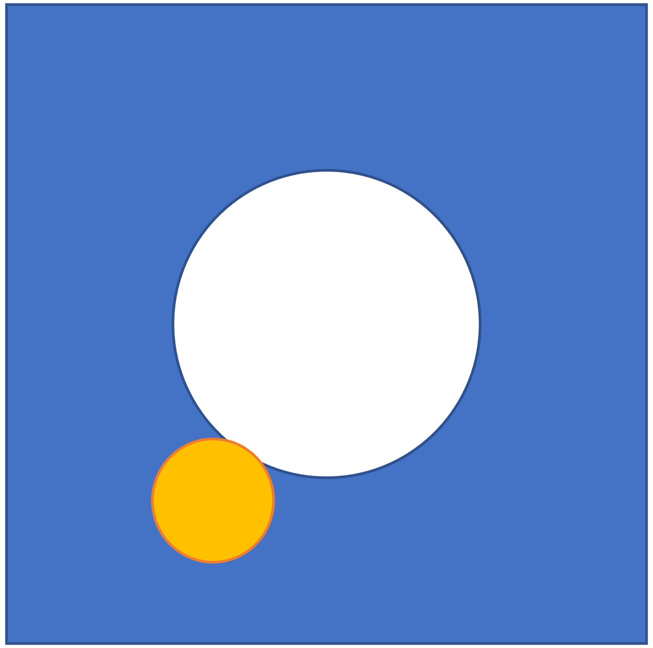
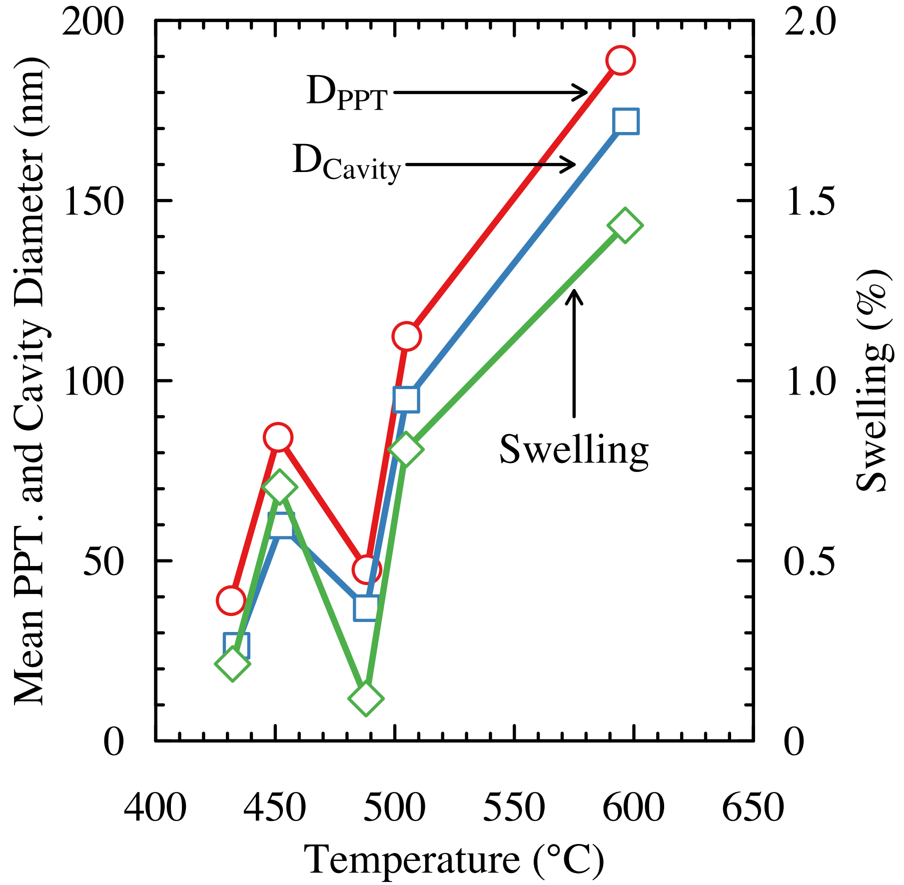
Influence of phase stability and cavity growth



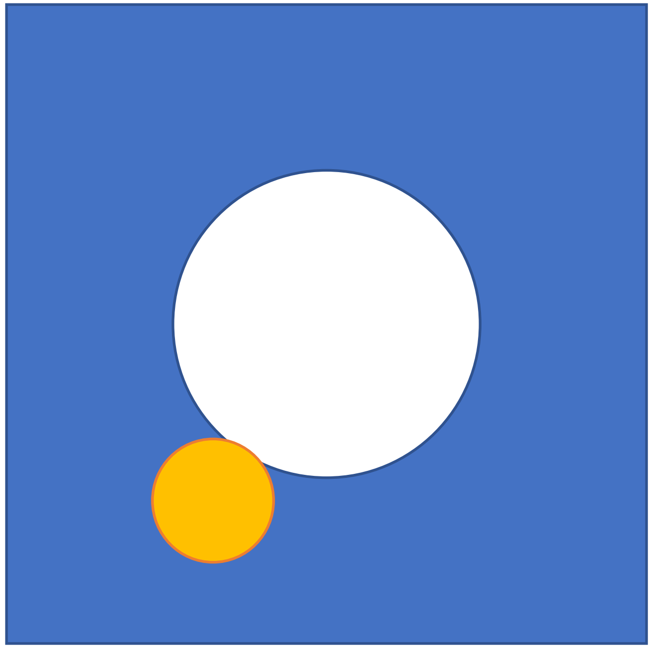
If we account for cavity growth on a precipitate-matrix interface, then we can relate the **cavity growth to precipitate size** by:

$$\frac{dr_{cp}}{dr_c} = \frac{\left(r_{cp}^2 + r_p^2\right)^{1/2}}{r_{cp}^2} r_c$$



E.H. Lee et al. / Precipitation and cavity formation in austenitic stainless steels

Influence of phase stability and cavity growth



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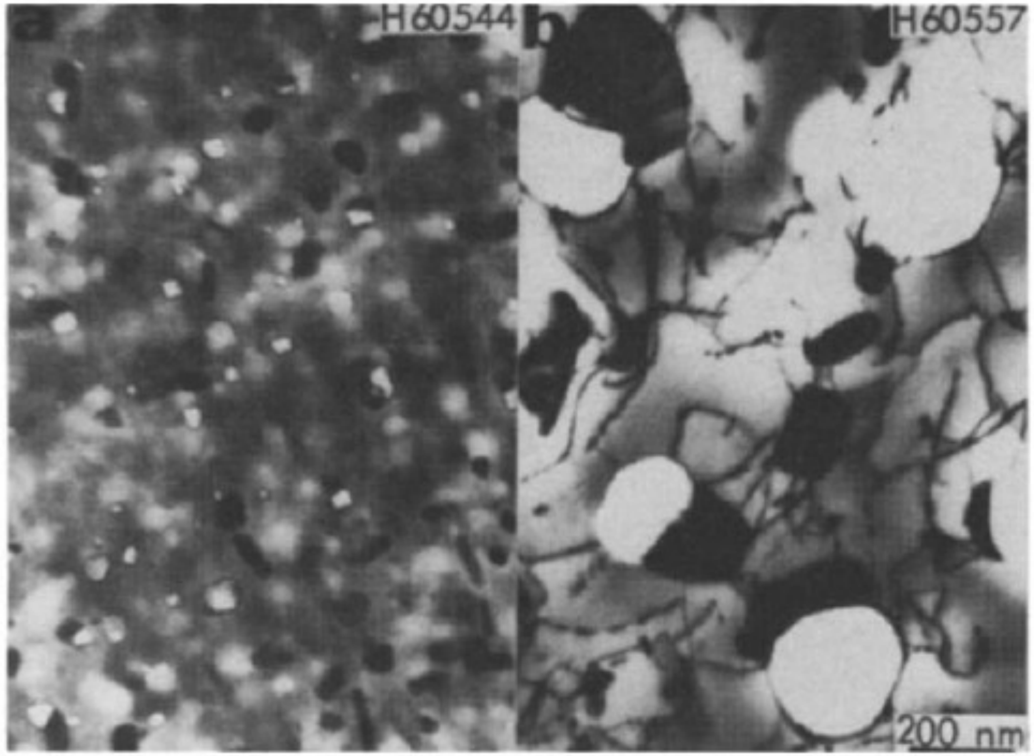

Fig. 2. Cavity-particle association in LS1C irradiated to ~35 dpa in EBR-II at (a) 425°C, (b) 600°C.

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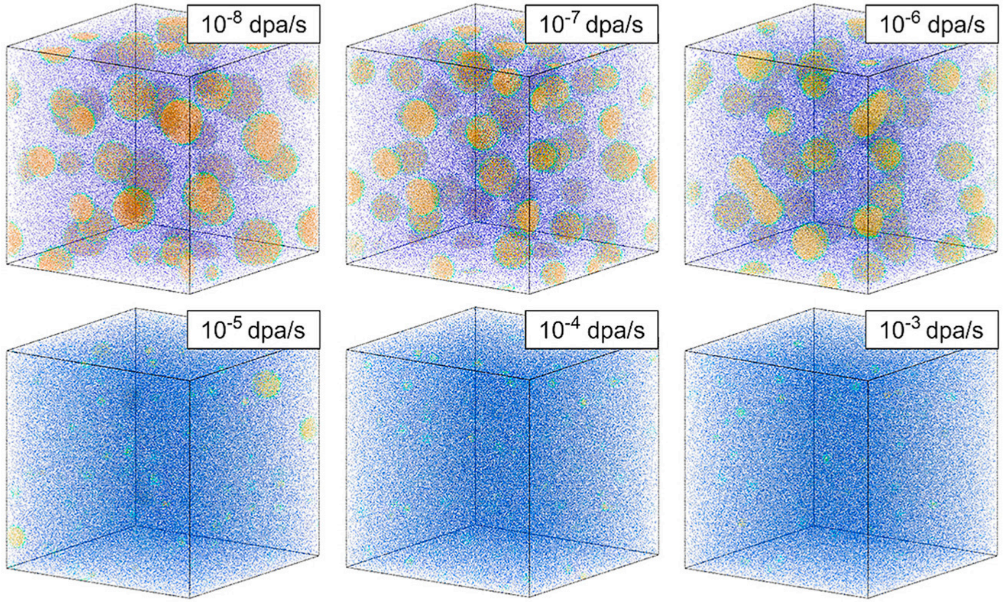
Two primary irradiation induced phase transformation types:

1. Requires compositional changes
    1. Induced precipitation from solid solution
    2. Dissolution of precipitates
2. Constant composition
    - Allotropic or Polymorphic
        - Allotropic: change in the crystal structure of a single element
        - Polymorphic: change in the structure of an alloy or compound
    - Ordering/disordering
        - Loss of chemical order (disordering)
        - Loss of crystal structure, e.g. amorphization

Irradiation flux effect on α' precipitation in Fe-Cr



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Questions?