Voids II+

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Effect of Dose Rate

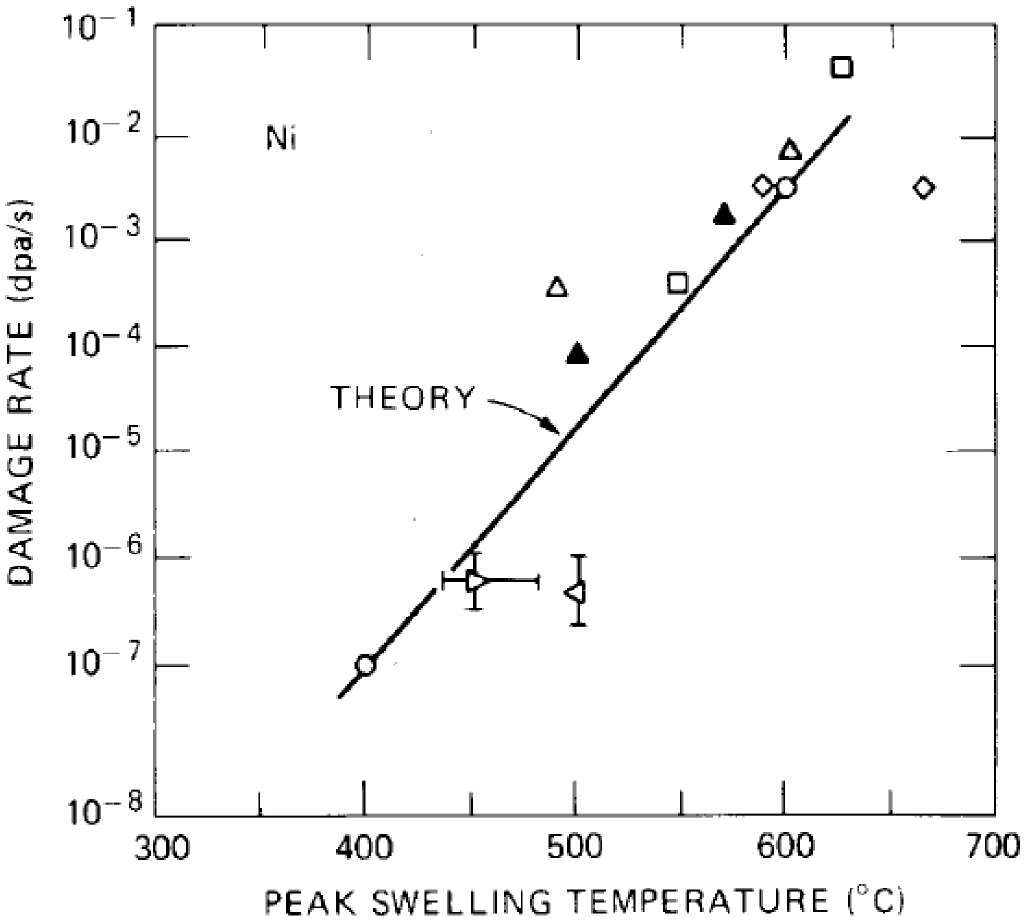

Figure 8.29. Compilation of experimental results for peak swelling temperature as a function of dose rate. Theoretically predicted trend is shown as the line. After Refs. 140 and 141.

Dose rate is captured in the **fourth term** where:

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

And:

$$\eta = \frac{4K_0K_{iv}}{D_iD_v(4\pi R\rho_v + z_v p_d)^2}$$

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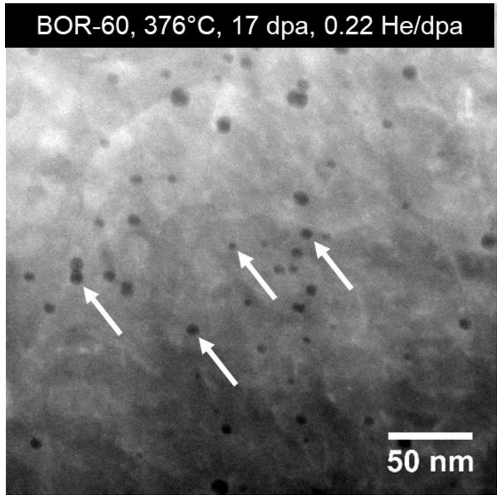
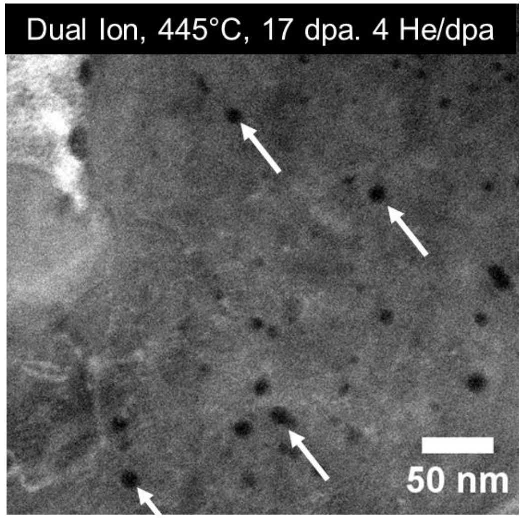
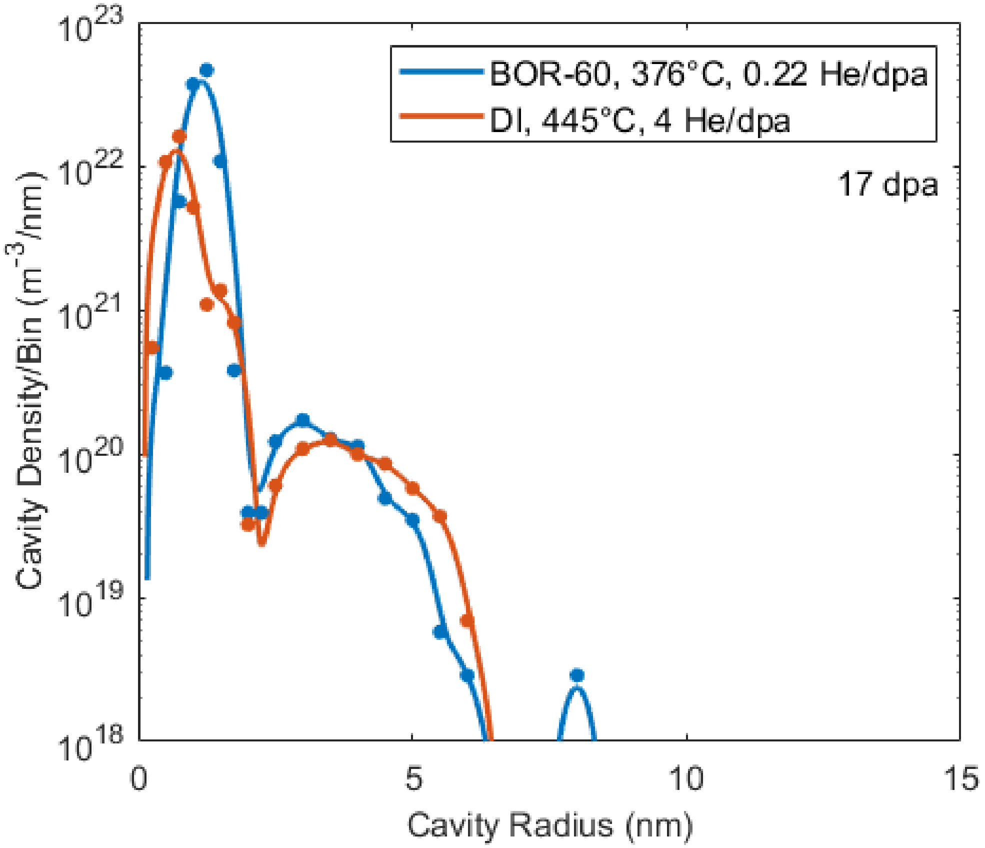
Effect of Dose Rate – Real World Example

STEM HAADF

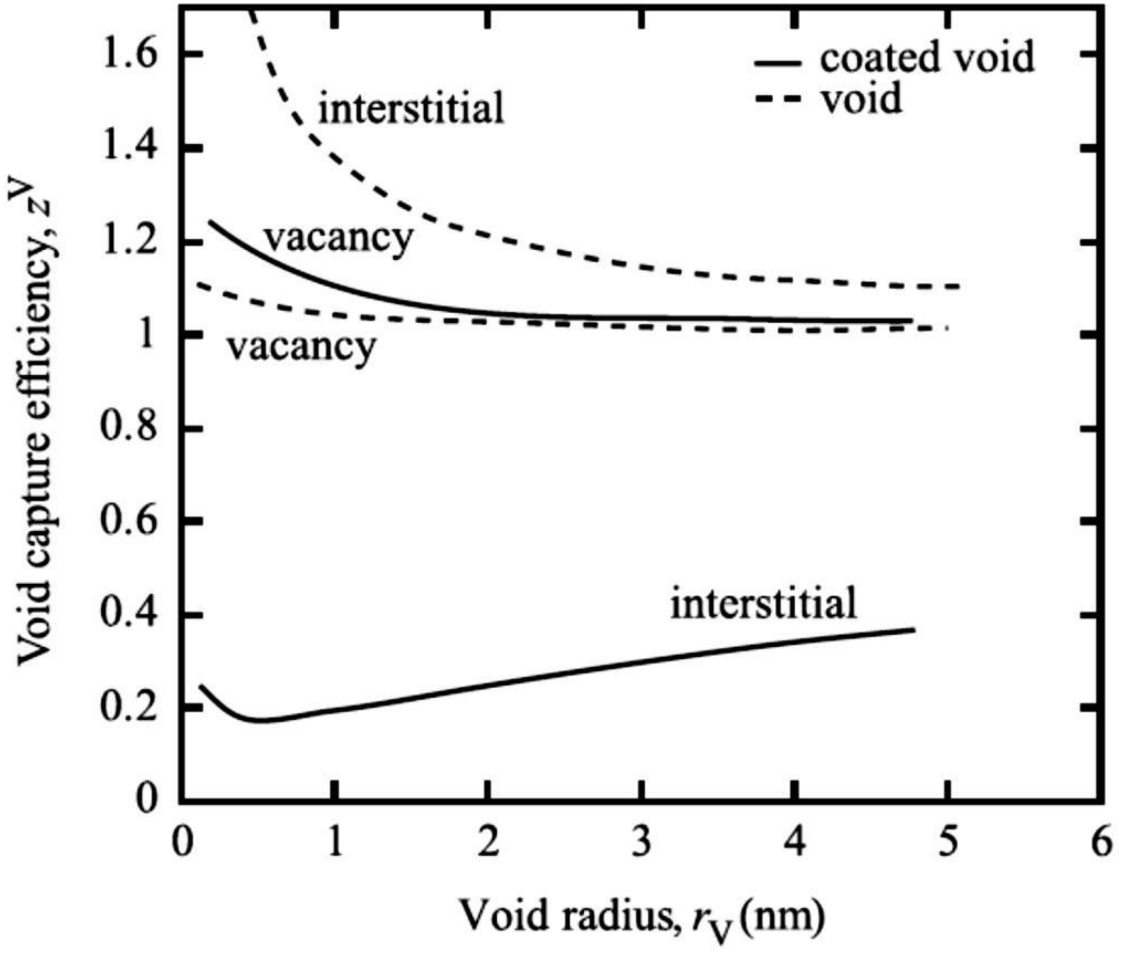






$$T_2 - T_1 = \frac{\dfrac{kT_1^2}{E_v^m + 2E_v^f} \ln\left(\dfrac{G_2}{G_1}\right)}{1 - \dfrac{kT_1}{E_v^m + 2E_v^f} \ln\left(\dfrac{G_2}{G_1}\right)}$$

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

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

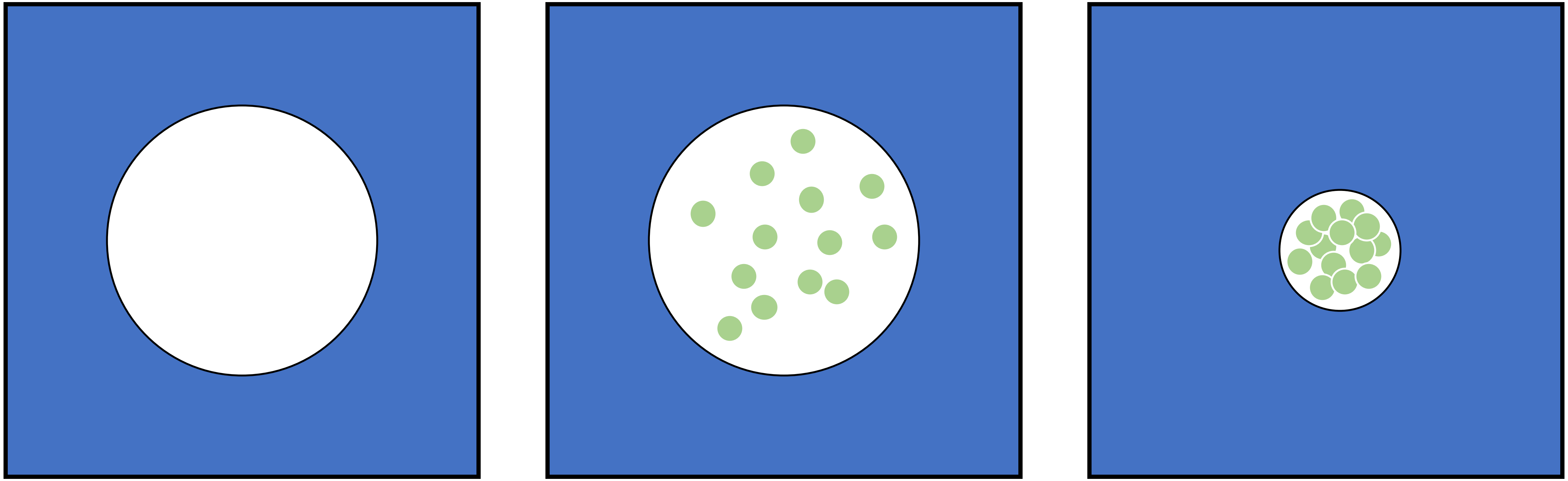
Side Note!
We generally define the following:

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

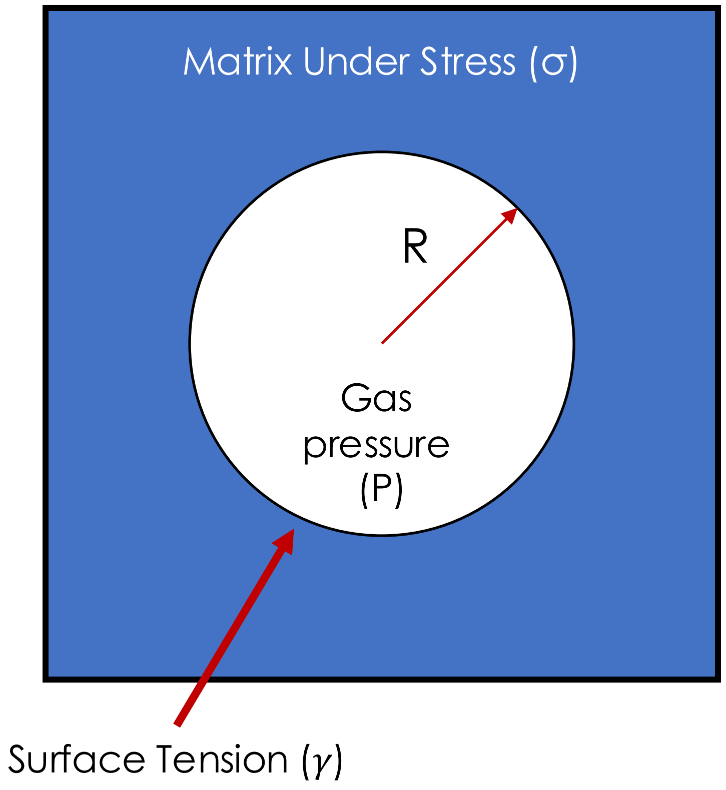
Bubble: open volume in a solid that is pressurized by inert gas

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

Effect of Inert Gas: Bubbles & Voids

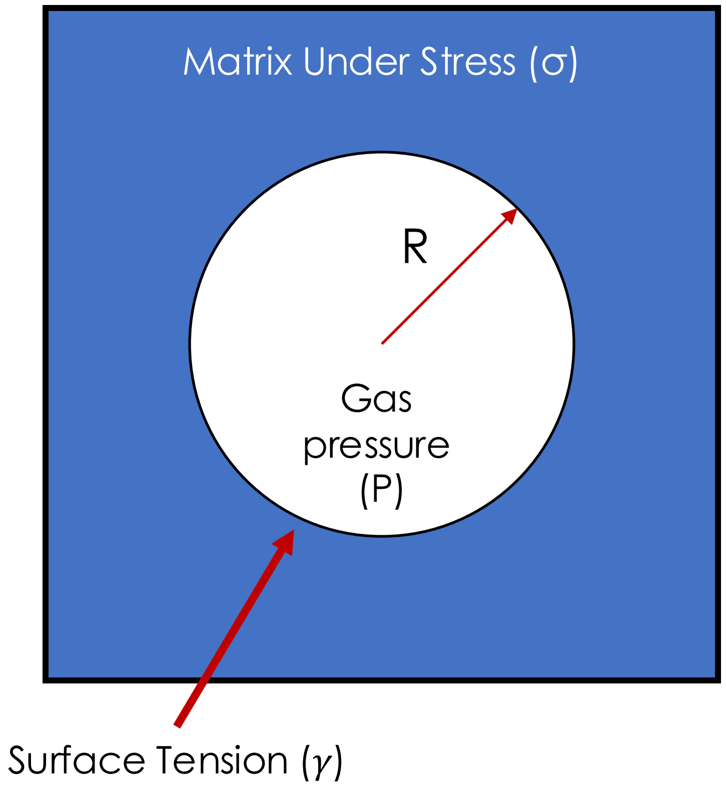


Effect of Inert Gas: Bubbles & Voids



- 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

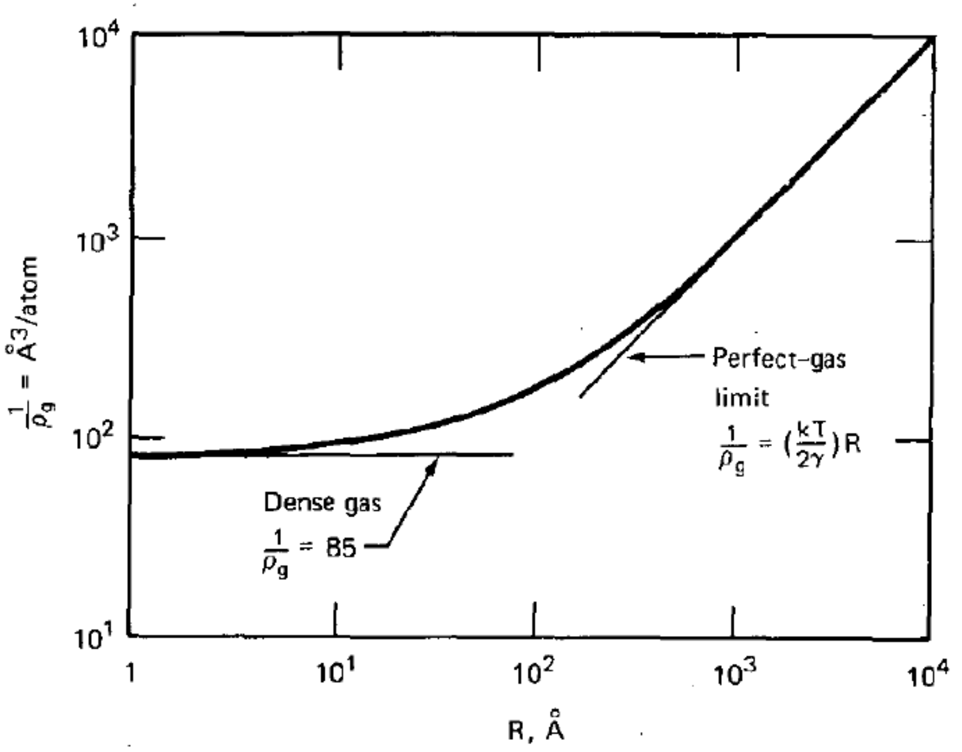


Fig. 13.3 Density of xenon gas in a spherical bubble imbedded in a stress-free solid of surface tension of 1000 dynes/cm.

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:**

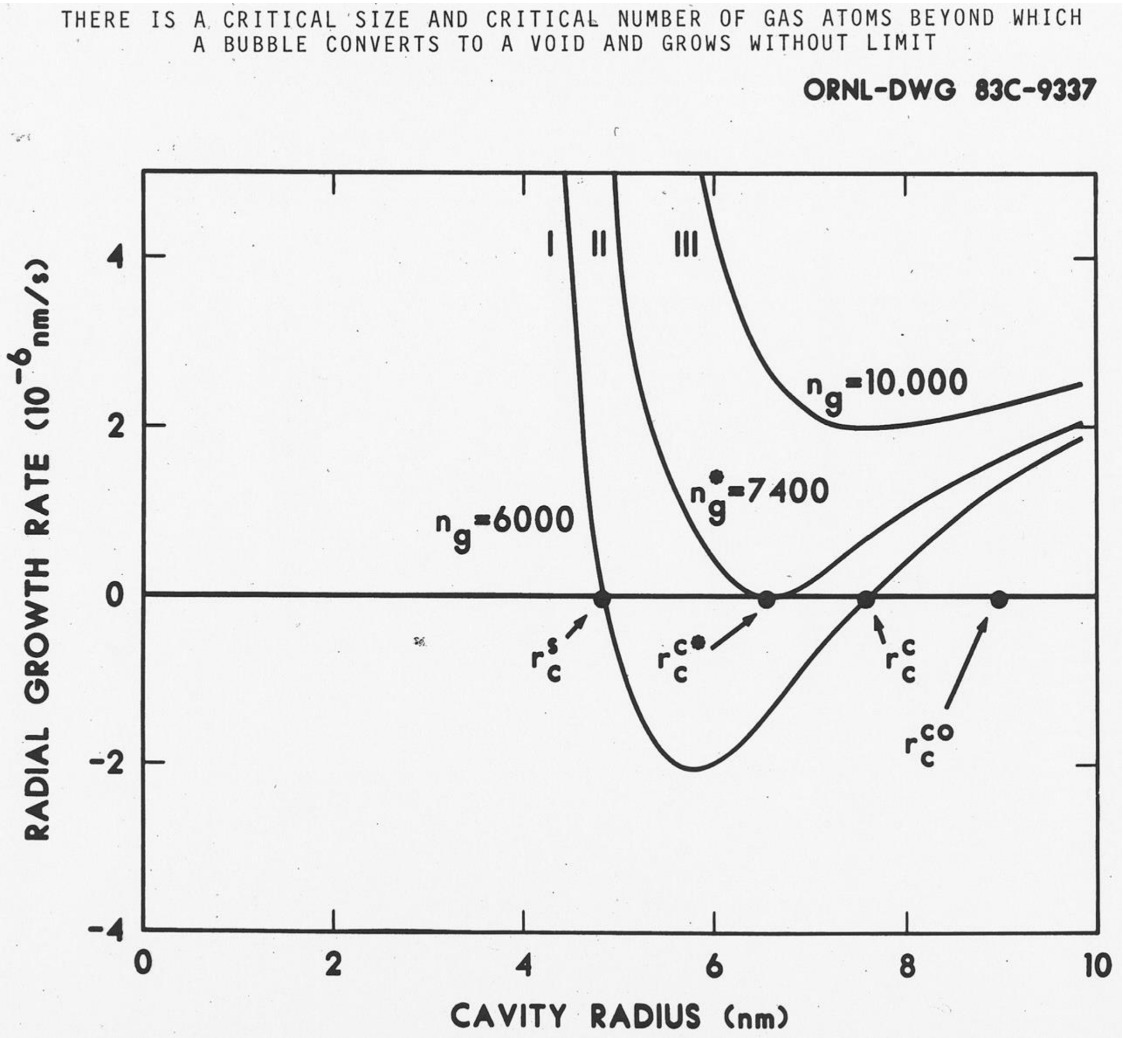
$$n_x = \frac{{}^4/_3\,\pi r^3}{B + \left({}^{k_b T}/_{2\gamma}\right) r}$$

And for non-equilibrium bubbles:

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

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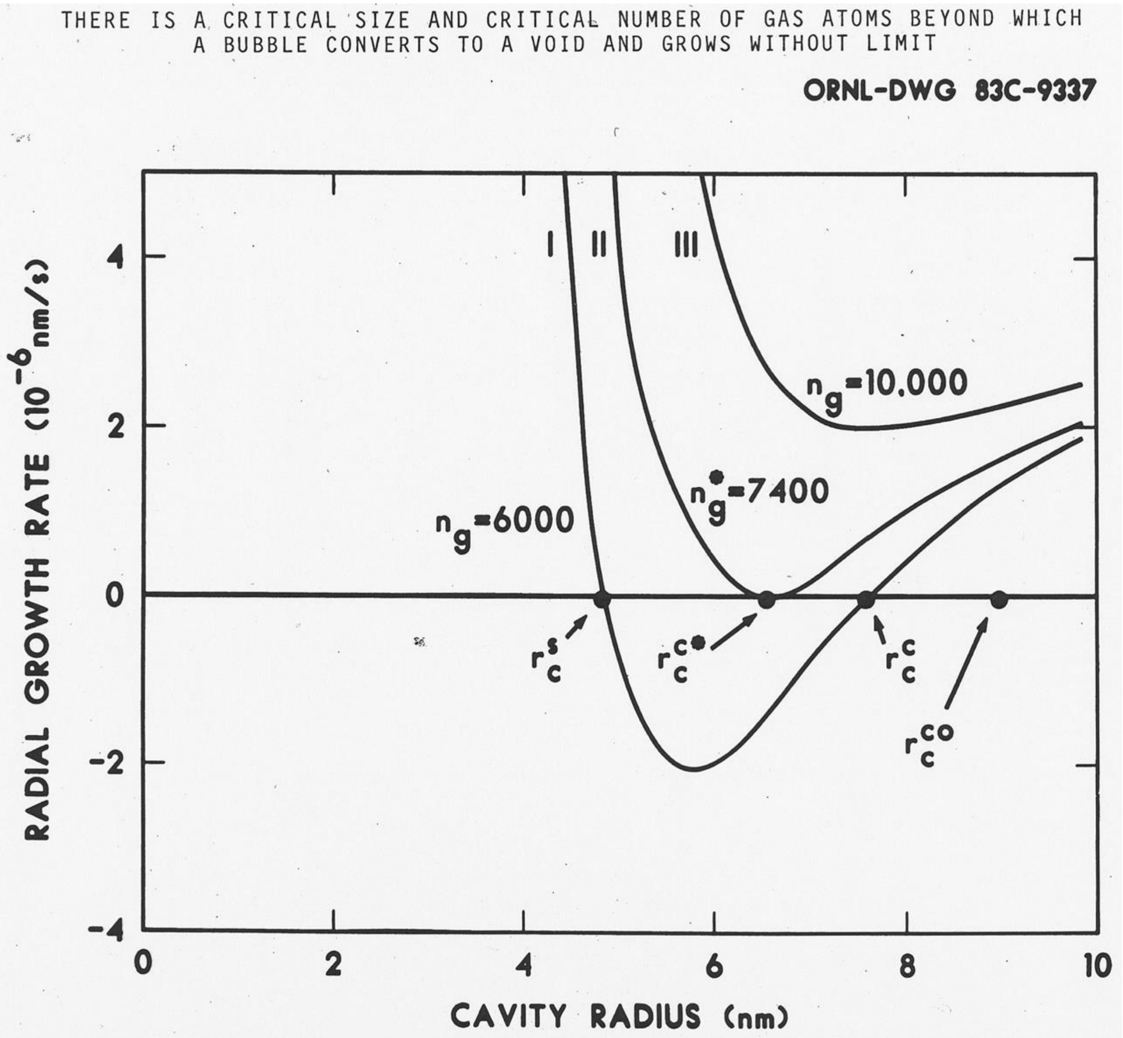
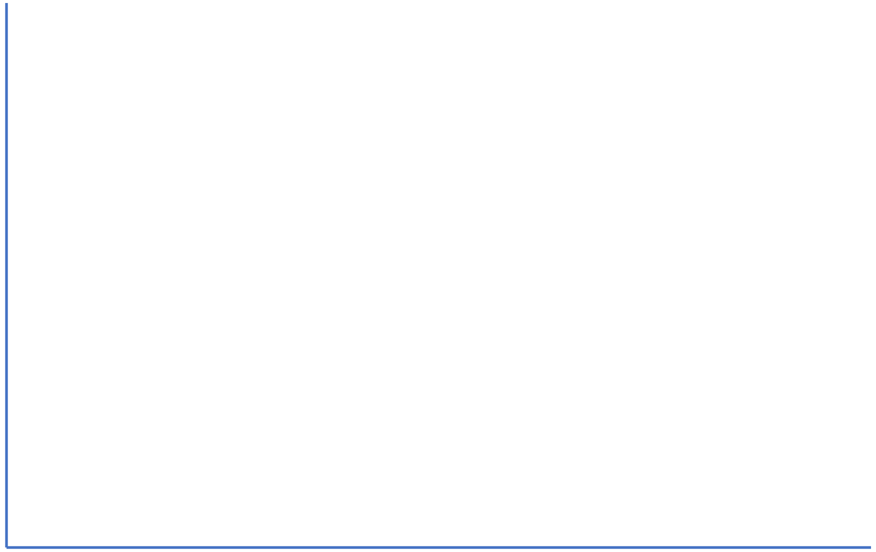
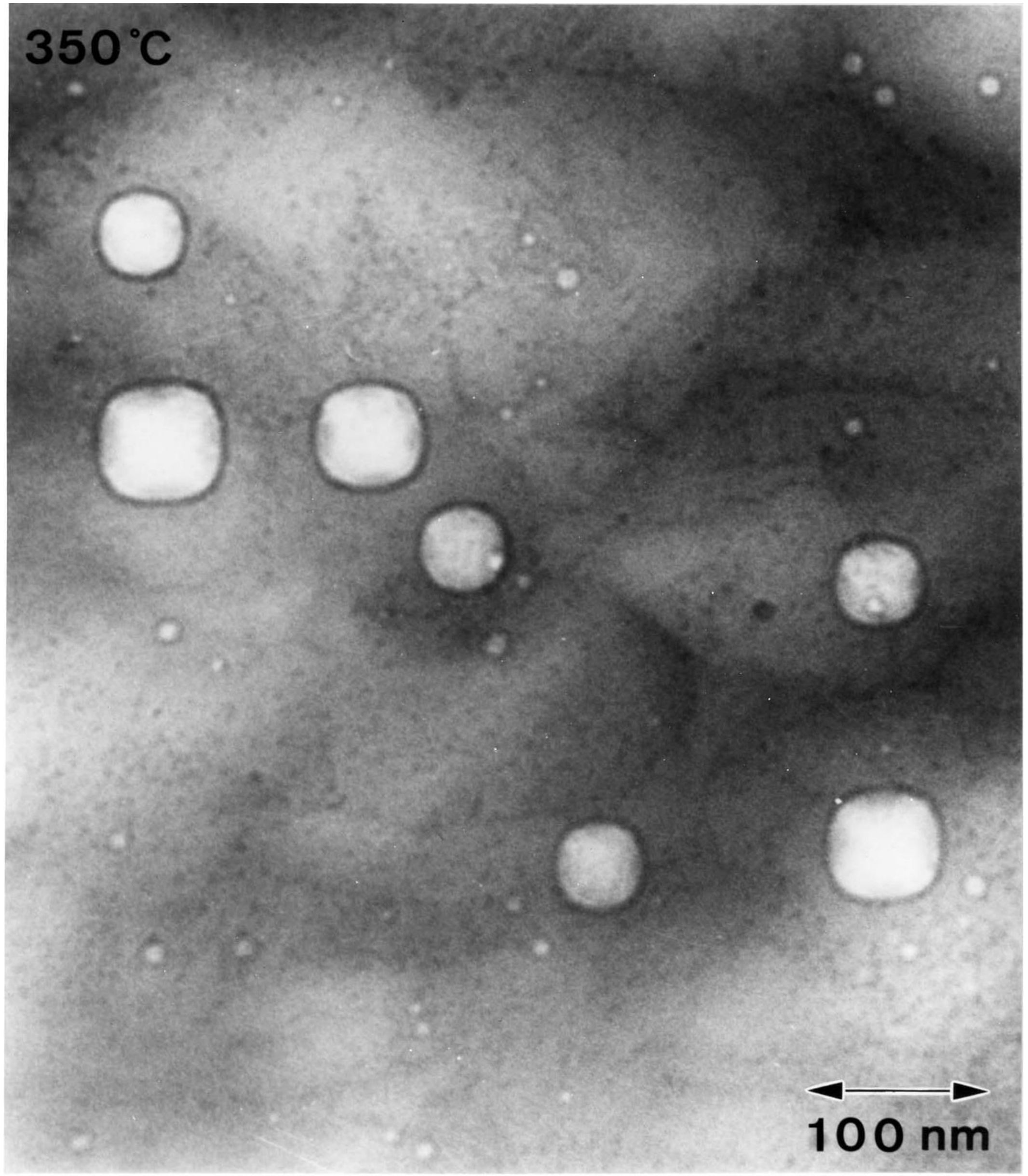
When gas is present, the current models predicts that cavities containing less than n_g* gas atoms remain at or below r_c*, but those with more than n_g*, this creates a bimodal distribution



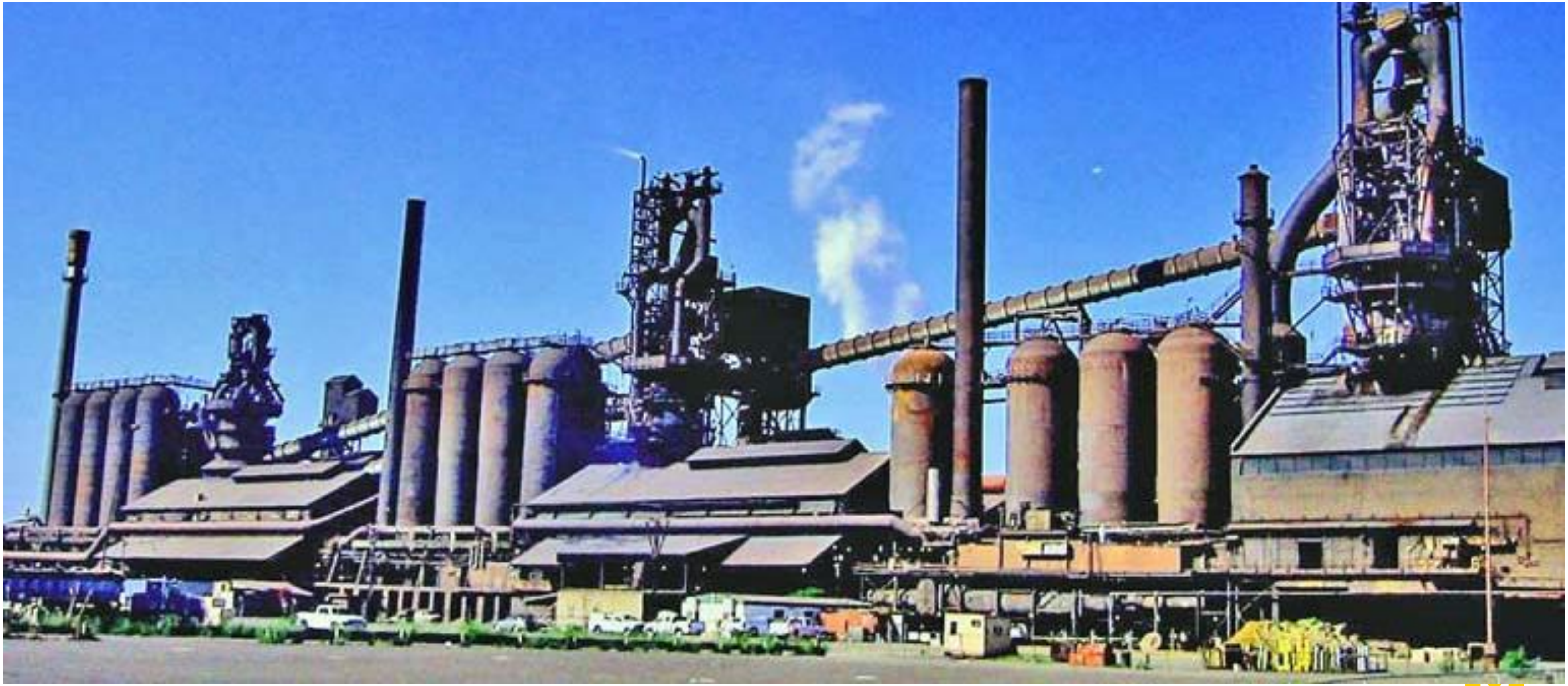




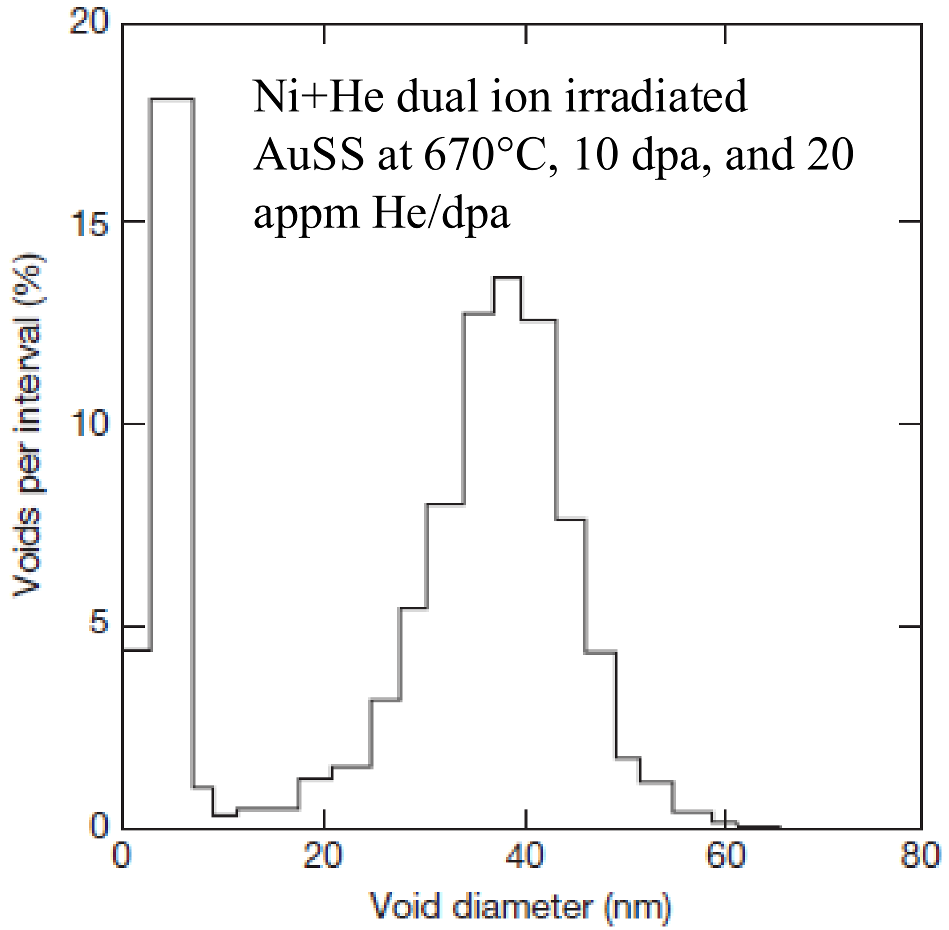
Zinkle, Farrell and Kanazawa, J. Nucl. Mater. 179-191 (1991) 994

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

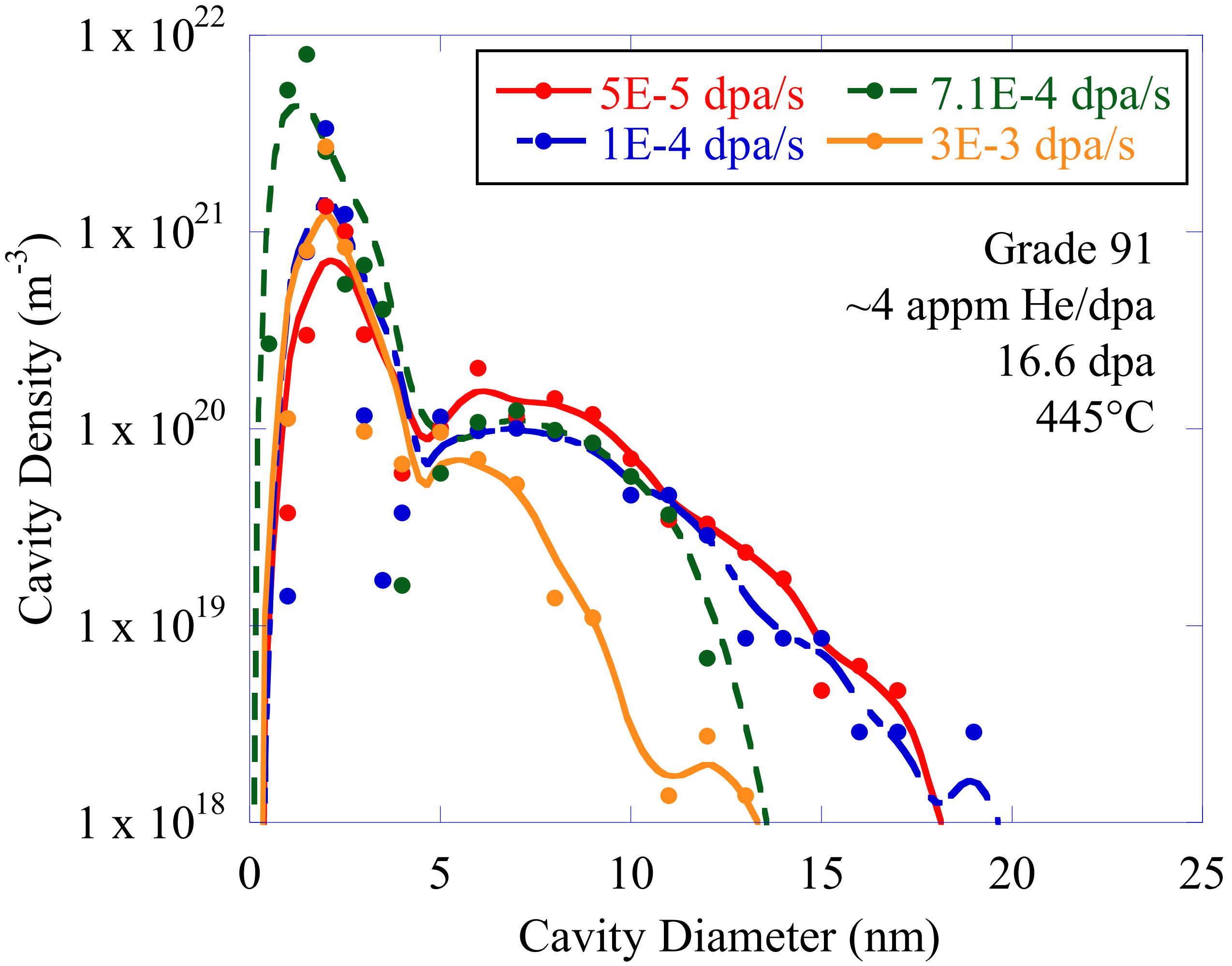
Completed in 1928, Henry Ford’s Rouge Complex in Dearborn, Michigan, was a massive feat of industrial architecture designed by Albert Kahn. At the time of its completion, how large was the complex's infrastructure in terms of buildings and railway tracks?



Experimental examples

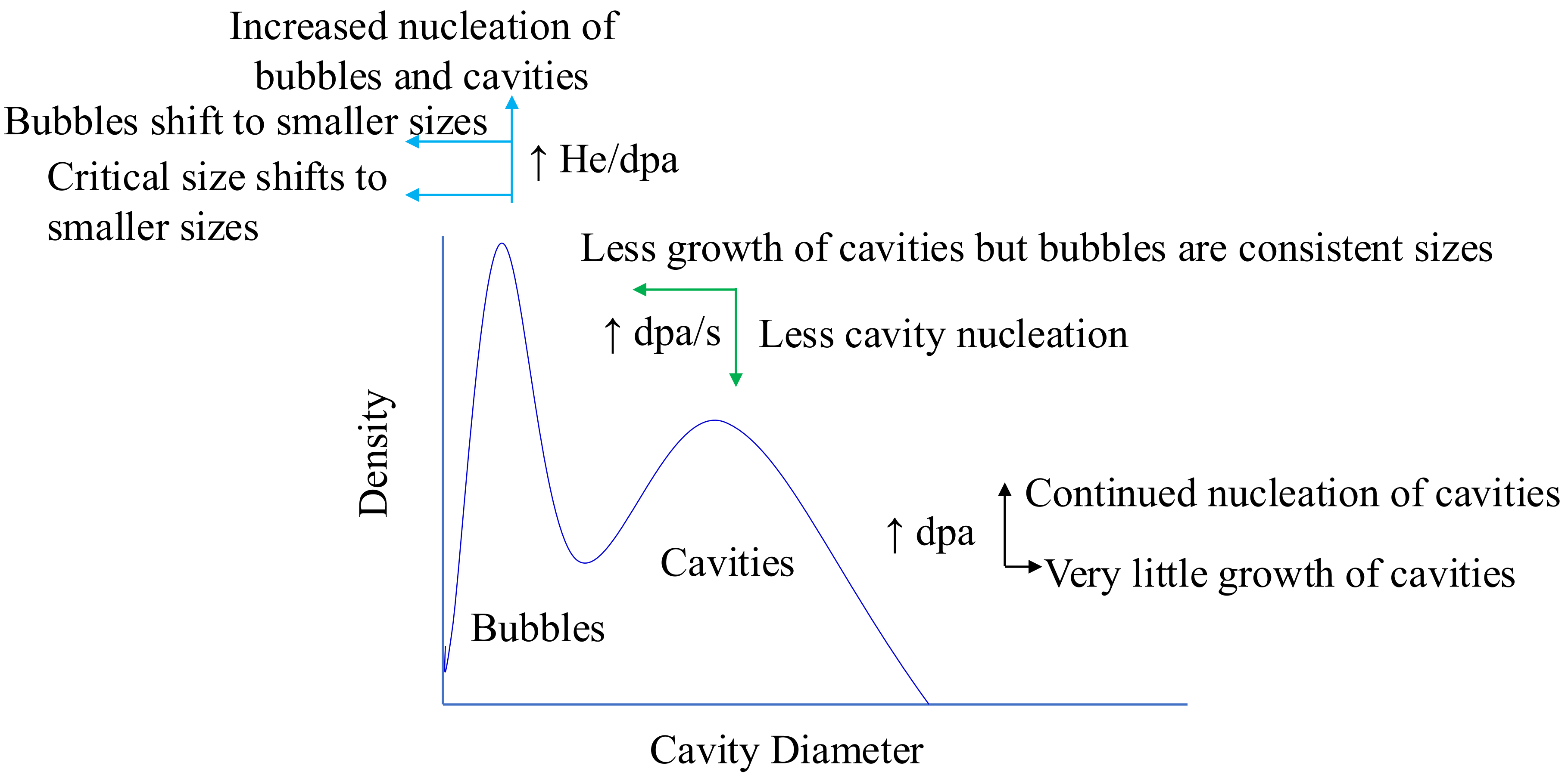


Mansur, Coghlan JNM 119 (1983)



Taller (2019)

Experimental examples



Fixed dpa/s – Variable He/dpa

Fixed He/dpa – Variable dpa/s

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

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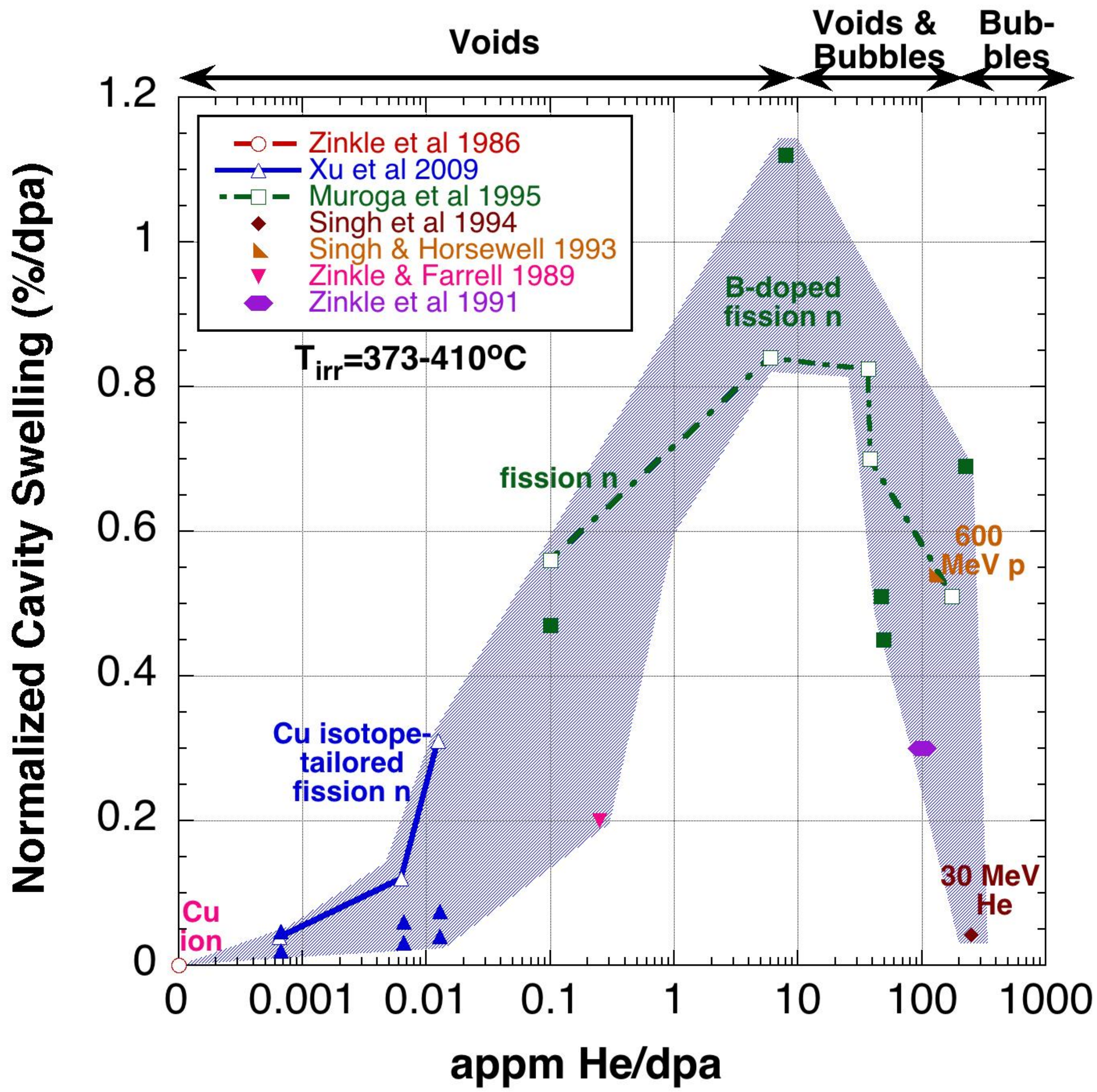
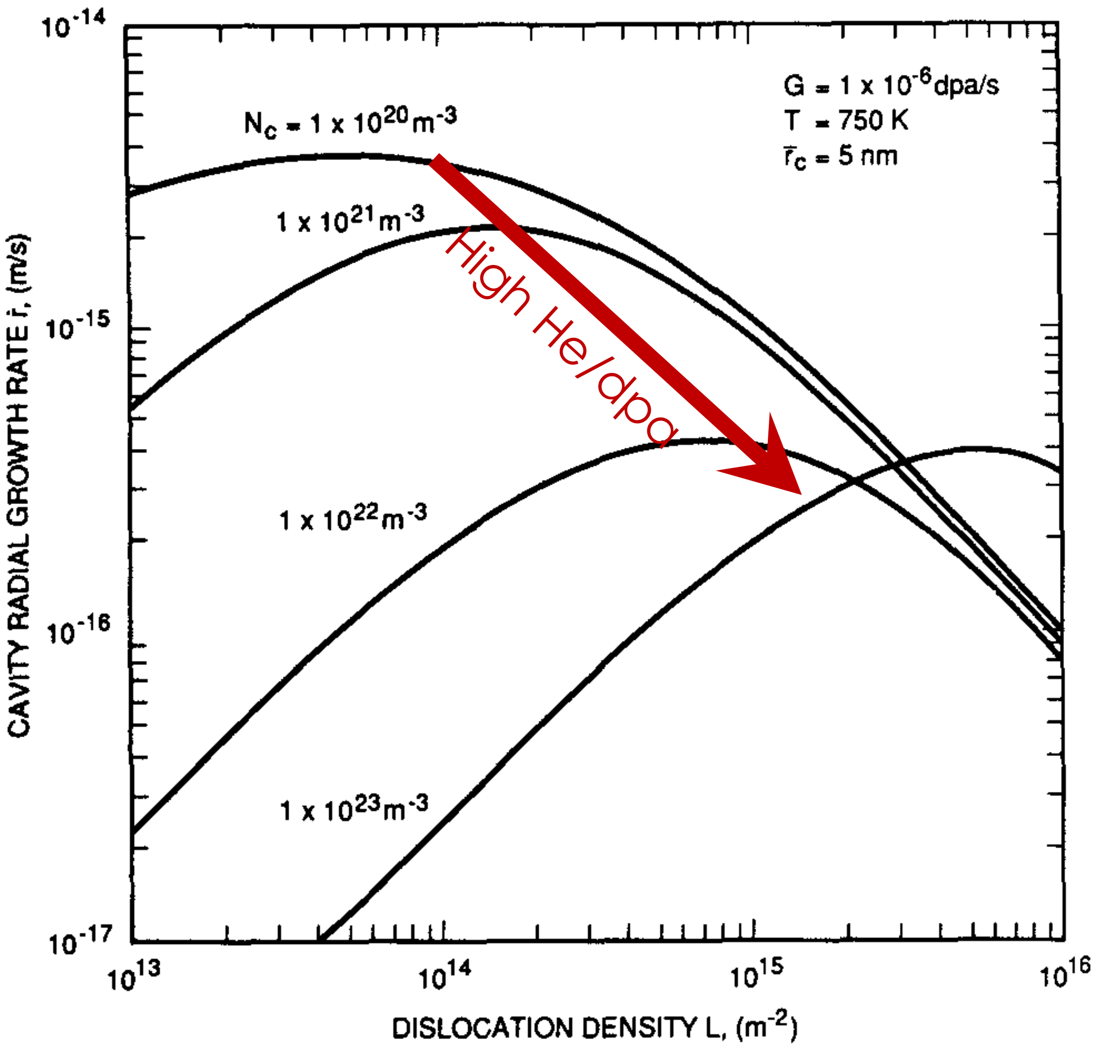
Cavity swelling vs. He/dpa ratio in irradiated copper



~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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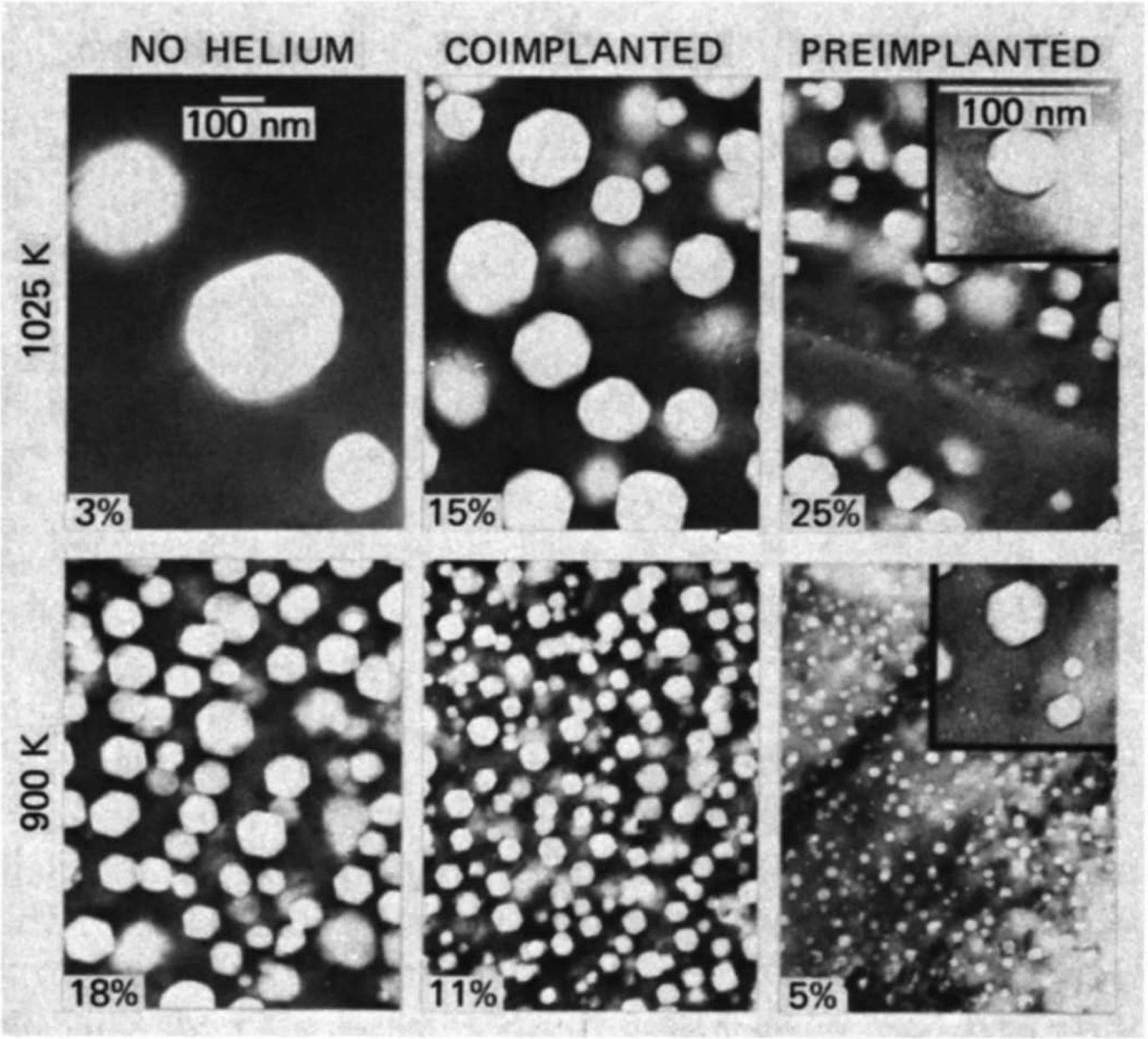
Effect of He in ion irradiations



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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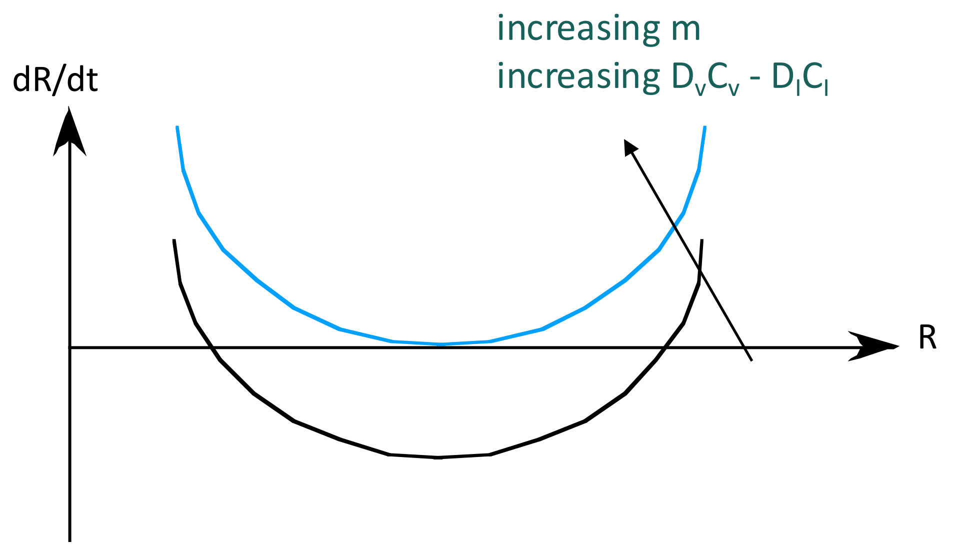
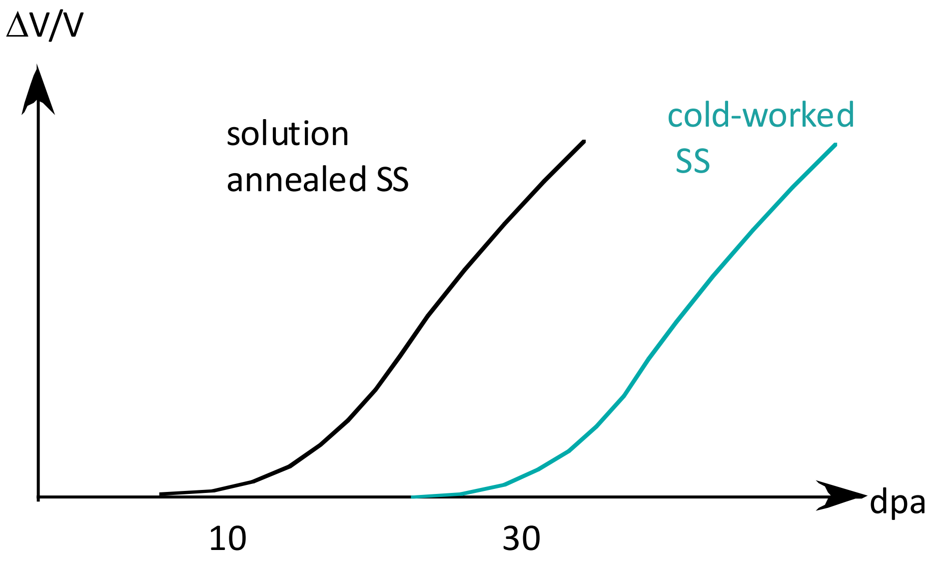
Remedies for void swelling?

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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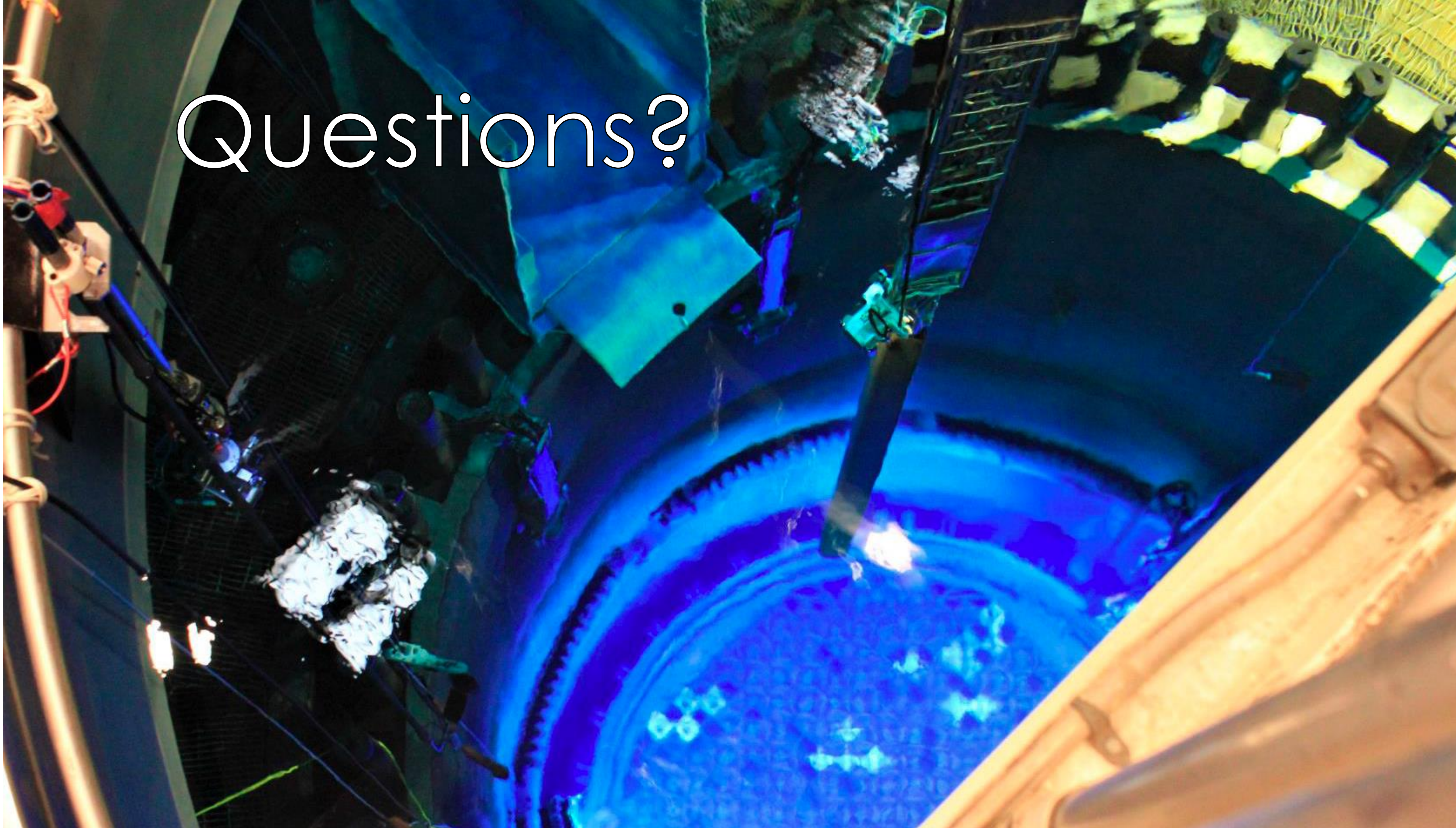
Questions?