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Atoms for Peace and Development

Fundamentals of Radiation Damage

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Radiation Effects

The term *Radiation Effects* describes the response of materials to bombardment by energetic particles.

Materials science is a broad topic including:

- metals and alloys (conductors)
- electronic materials (semiconductors)
- ceramics and polymeric materials (insulators)

This introduction will focus on metals and alloys, which constitute the prime structural materials in reactor systems.

The primary objective of this lecture is to explain the *origin* of radiation damage and explore its *effects*

Outline

- Motivation
- The Radiation Damage Event
- Physical Effects of Radiation (basic introduction)
- Celine will deal with examples of macroscopic physical and mechanical effects
- Our talks on Thursday will deal in more detail with the effects of different particles and energies.

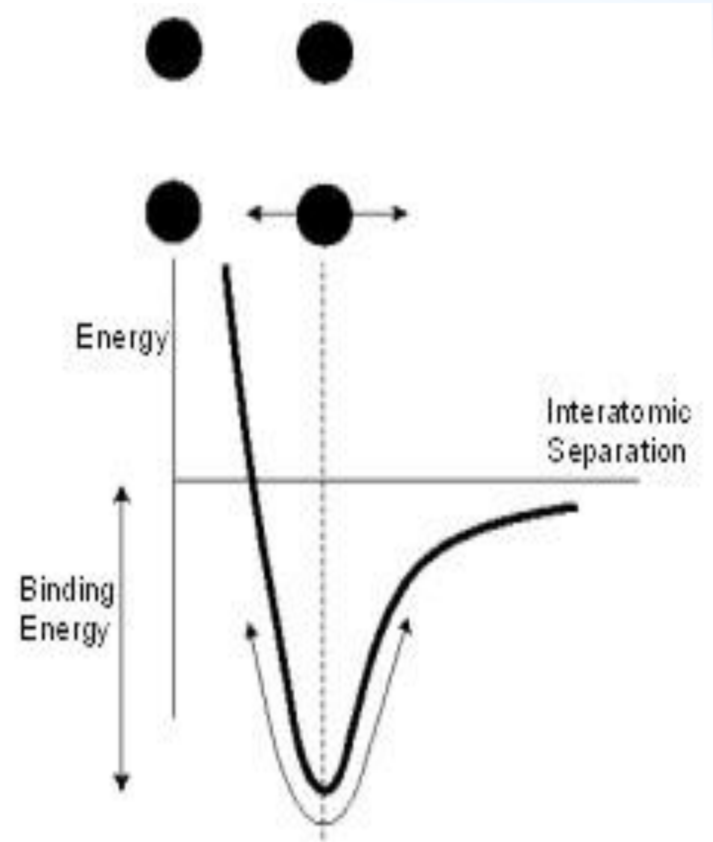
Interatomic potential

Atoms sit in a potential well.

The well can be asymmetric (symmetry)

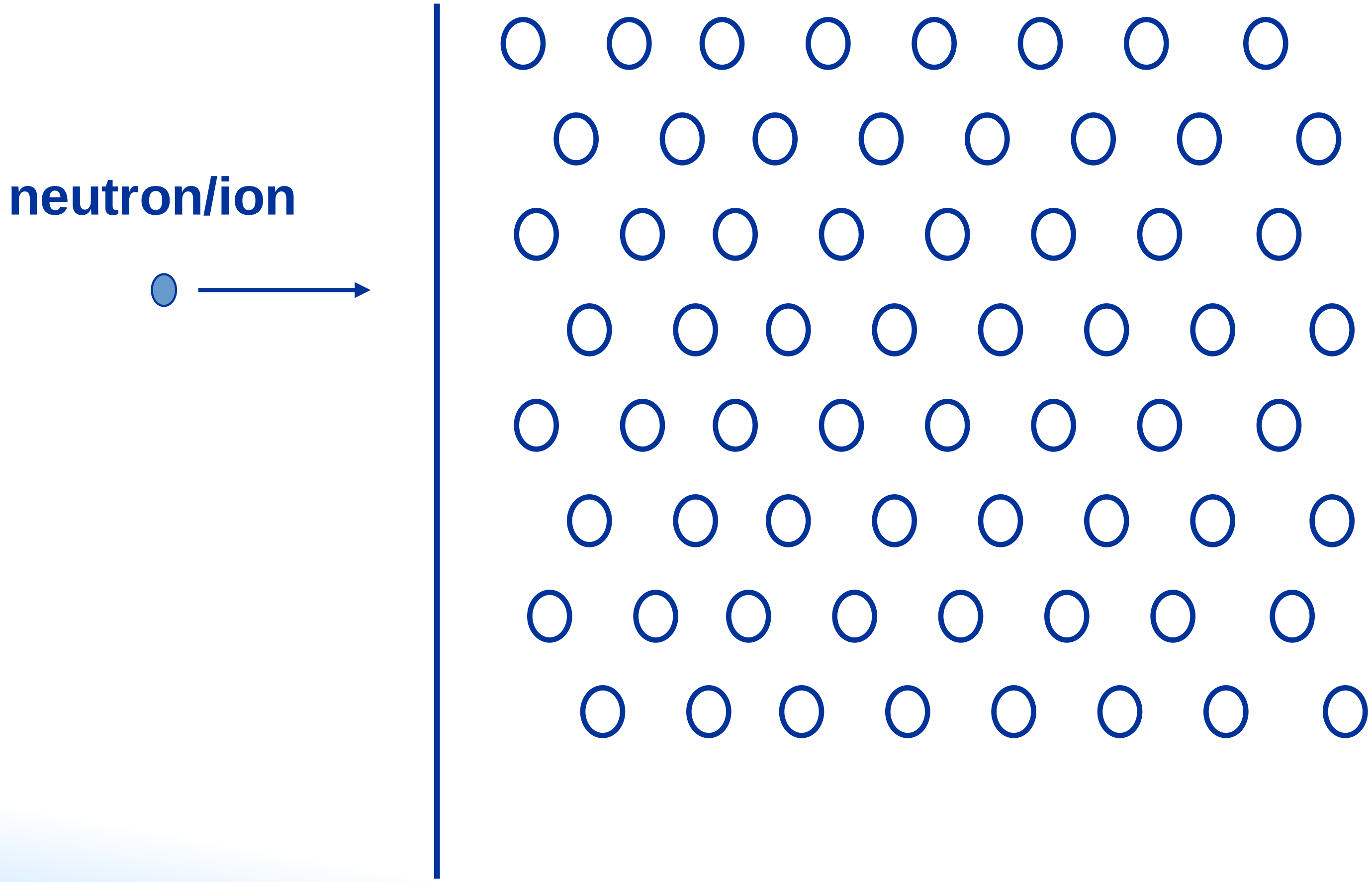
Atoms always moving - at different heights in potential (phonons)

In practice, there is a distribution of E_d depending on crystal direction, temperature.



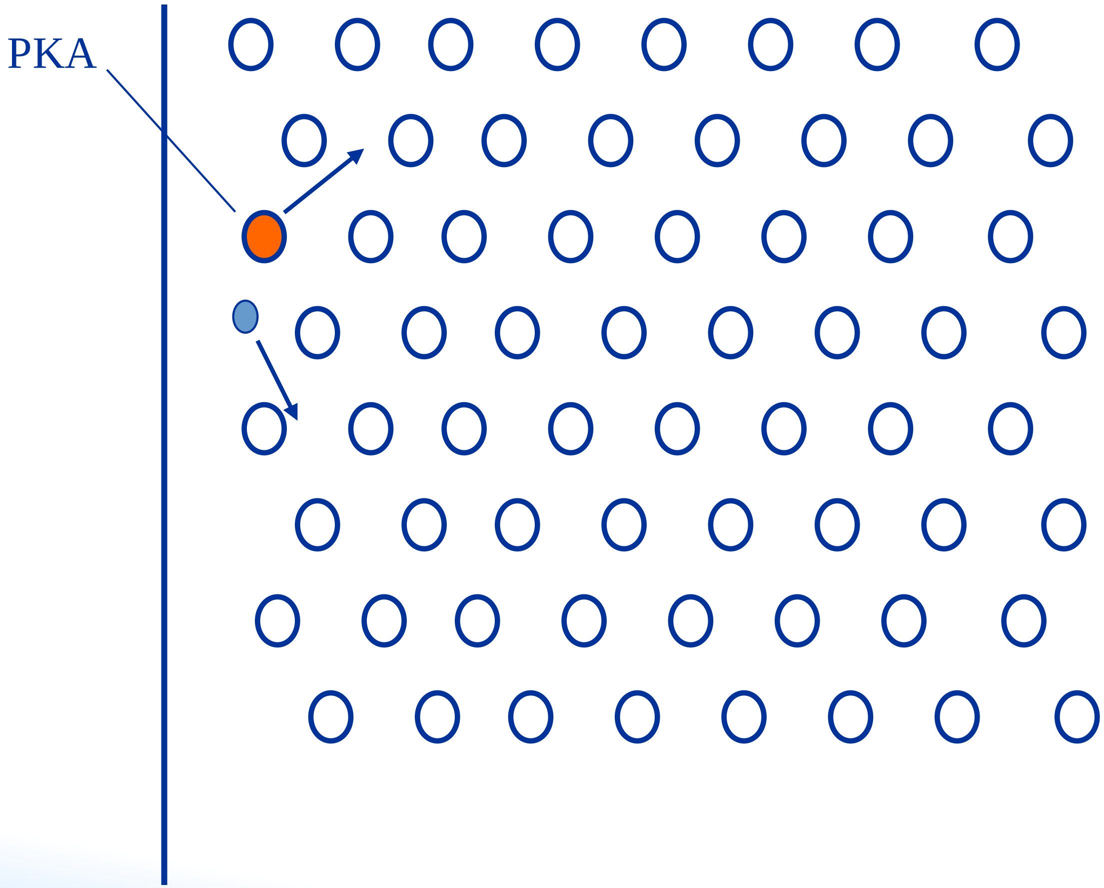
Displacement energy E_d: energy required to displace an atom from its lattice site.

Simple Picture



Source: T.R. Allen

Simple Picture



Source: T.R. Allen

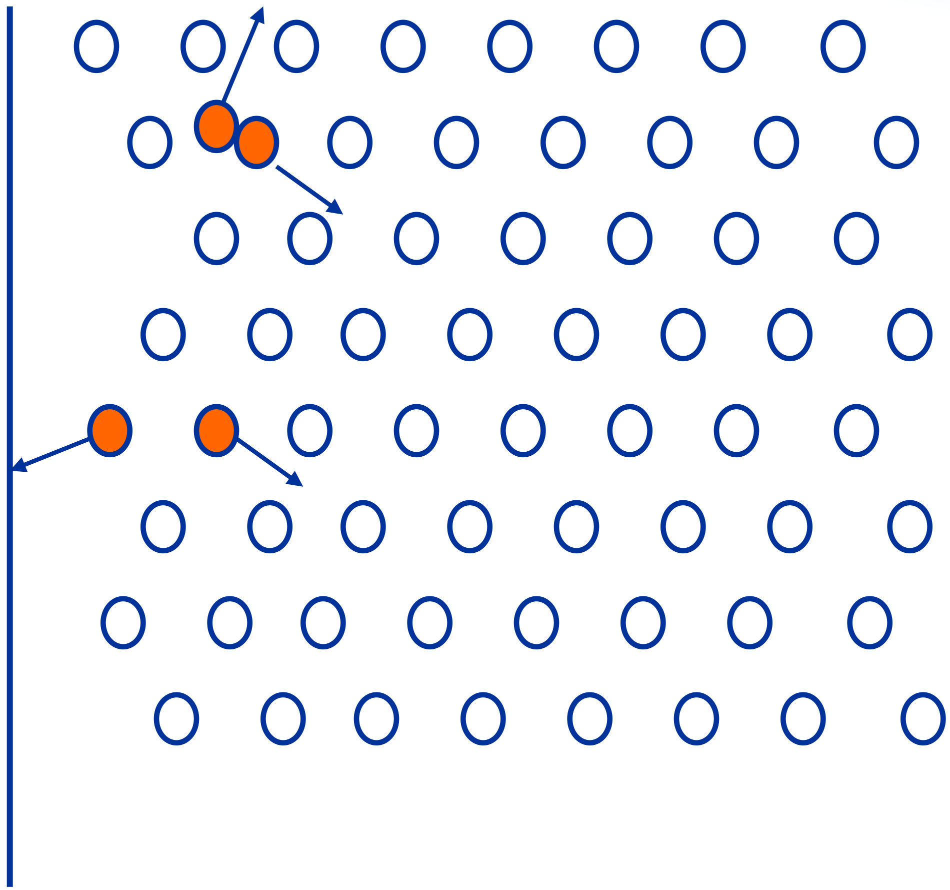
Primary knock-on atoms are an important part of the damage process

- Each neutron/atom collision transfers energy.

  For neutrons, average E_{PKA} varies:
  - in a fission reactor: ~20 keV
  - in a fusion reactor: ~50 keV

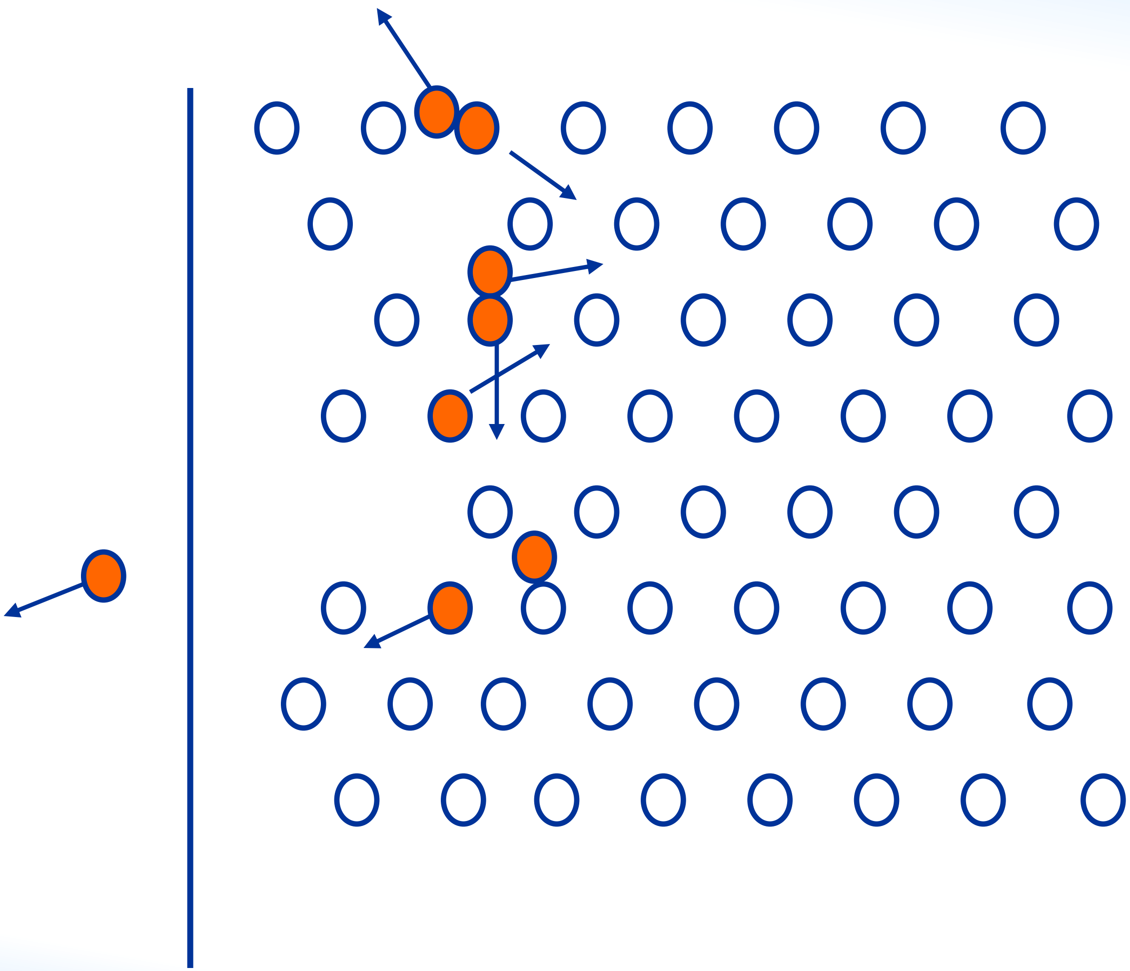
- If $E_{KA} > (E_d \sim 40$ eV), each subsequent KA will transfer energy to other atoms in the crystal.

Simple Picture



Source: T.R. Allen

Simple Picture



Source: T.R. Allen

The Displacement of Atoms

A 1 MeV neutron ⇒ PKA of energy ~35 keV ⇒ ~450 displacements.

The effect of neutron bombardment will depend on:

- **The flux of energetic particles (n/cm^2/s) and their energy E_i (distn)**
- **The probability of interaction – cross section σ(Ei, T)**
- **The energy partitioning per collision**

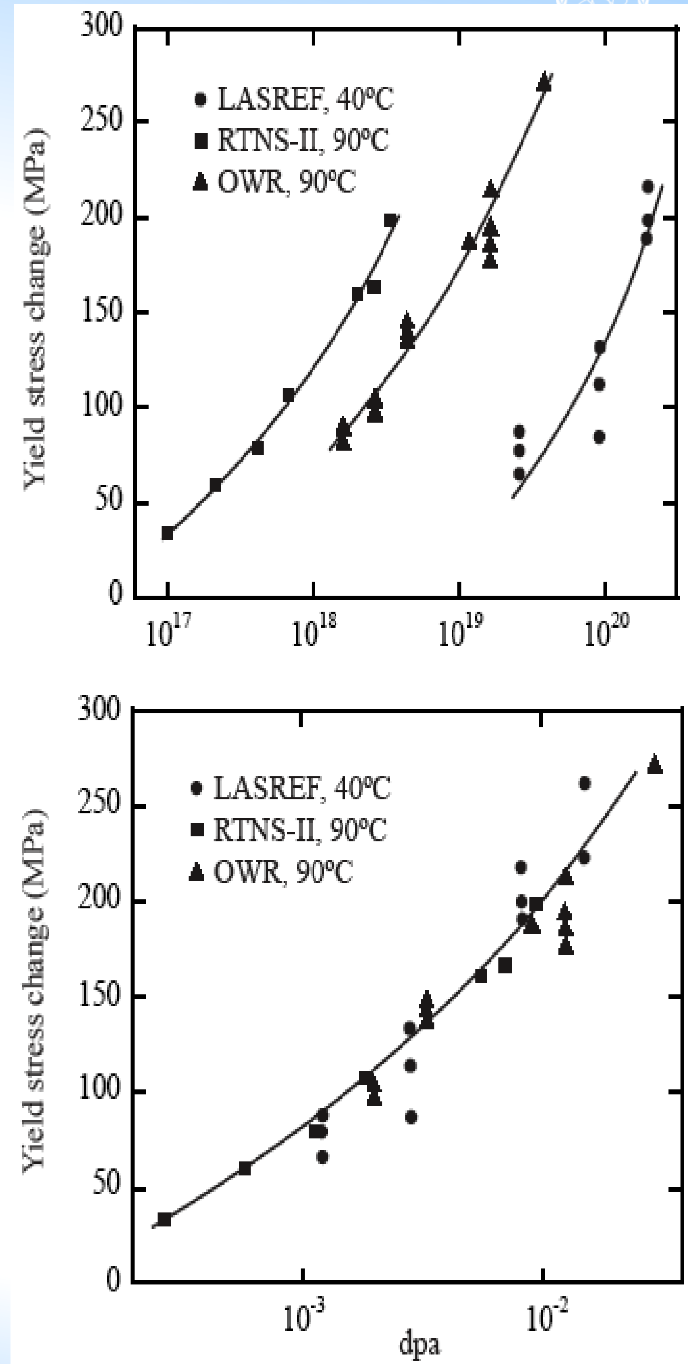
Typical displacement rates in reactors are:

10^{-11} dpa/s - LWR reactor pressure vessel
10^{-8} dpa/s - LWR core materials
10^{-6} dpa/s - Fast reactor core materials

There are 3e7 s in one year

Why displacement? - Why not fluence?

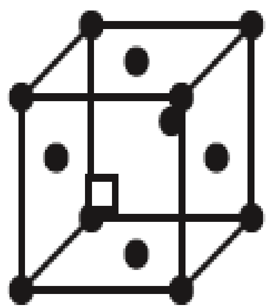
Comparison of yield stress change in 316 stainless steel irradiated in three facilities with very different neutron energy flux spectra. While there is no correlation in terms of neutron fluence, the yield stress changes correlate well against displacements per atom, dpa.



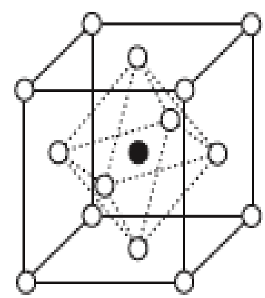
L. R. Greenwood, J. Nucl. Mater. 216 (1994) 29-44.

Point defects - Frenkel pair

The product of a displaced atom is a vacancy and an interstitial. The pair is known as a **Frenkel pair**.



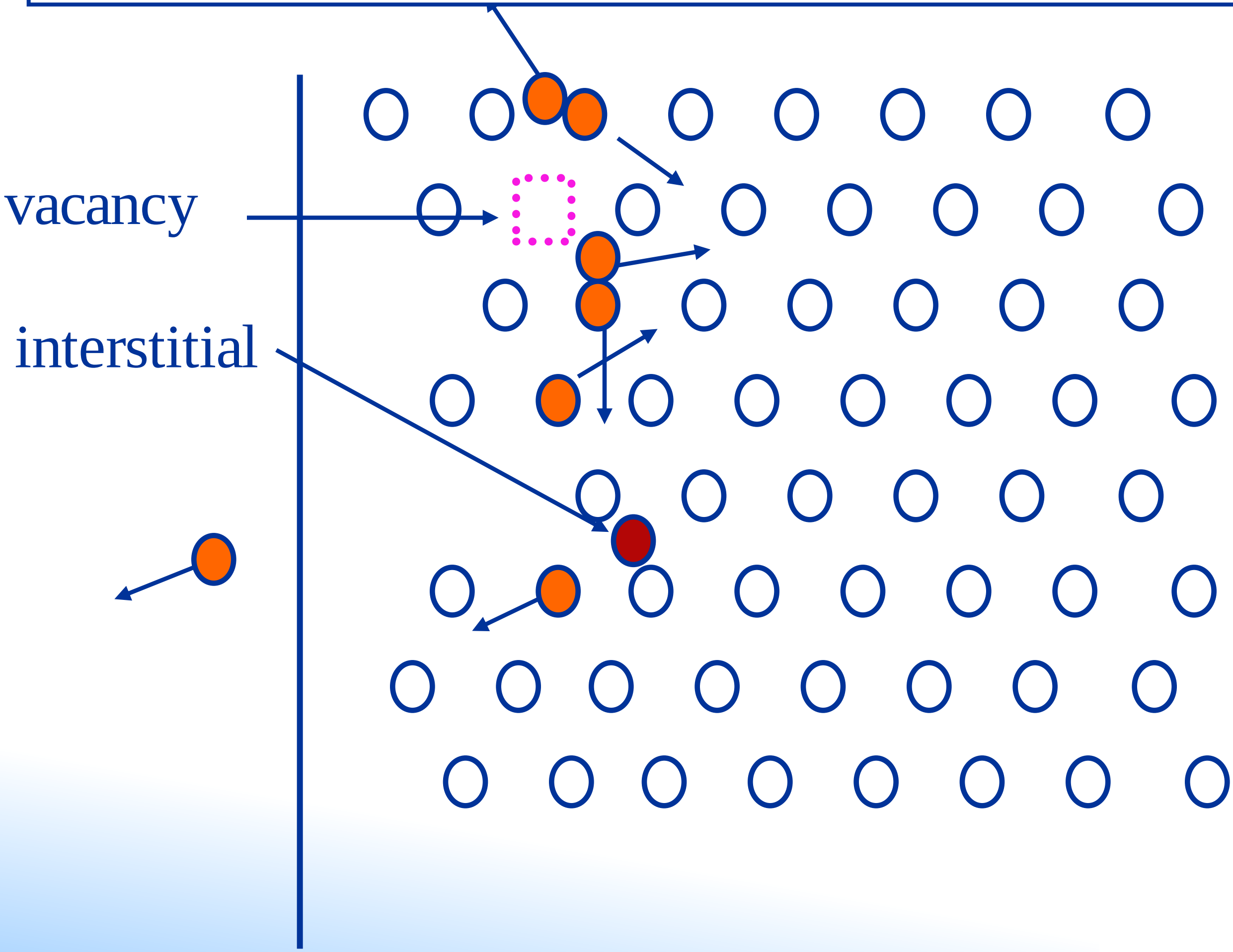
Vacancy in an fcc lattice



Interstitial in an fcc lattice

….Back to the simple picture

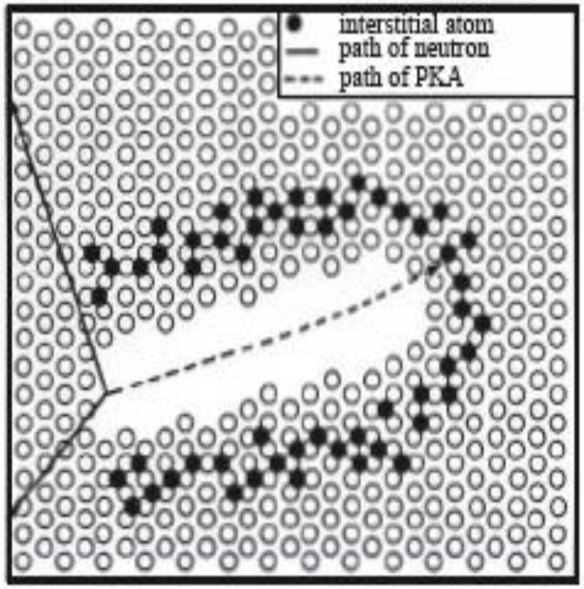
Vacancies and interstitials are the primary defects resulting from irradiation



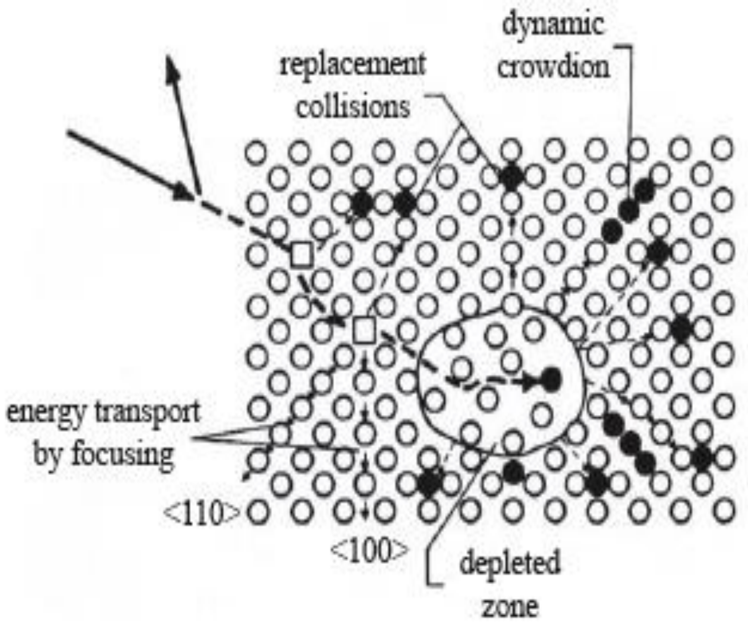
Source: T.R. Allen

The Damage Cascade

Early renditions of a displacement cascade.



J.A. Brinkman, Amer. J. Phys., 24, (1956) 251.



A. Seeger, in Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958, Vol. 6 p. 250, United Nations, N.Y. 1958.

Vacancy and interstitial concentrations under irradiation

$$\frac{\partial C_v}{\partial t} = K_0 - K_{iv}C_iC_v - K_{vs}C_vC_s + \nabla \cdot D_v \nabla C_v$$

$$\frac{\partial C_i}{\partial t} = K_0 - K_{iv}C_iC_v - K_{is}C_iC_s + \nabla \cdot D_i \nabla C_i.$$

production

recombination

loss to sinks

gradient

Our point defects (v, i) ⇒ linear, planar, 3d defects ⇒ more sessile

Fast neutrons, heavy ions ⇒ DENSE cascades.

High density of v, i ⇒ high probability of recombination

What is a sink?

Single defects (I,v) move to form or add to other non-point defects where they cease to be point defects.

A sink can be:

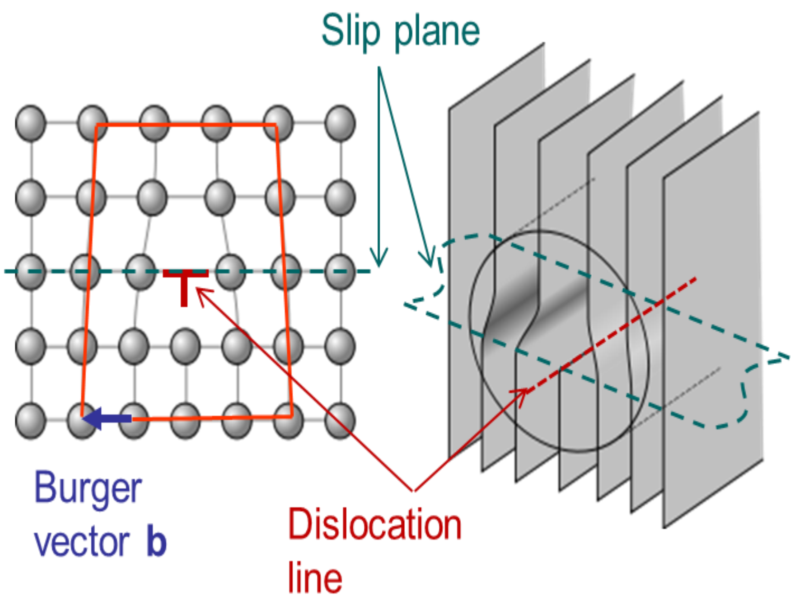
unbiased: accepts all defects

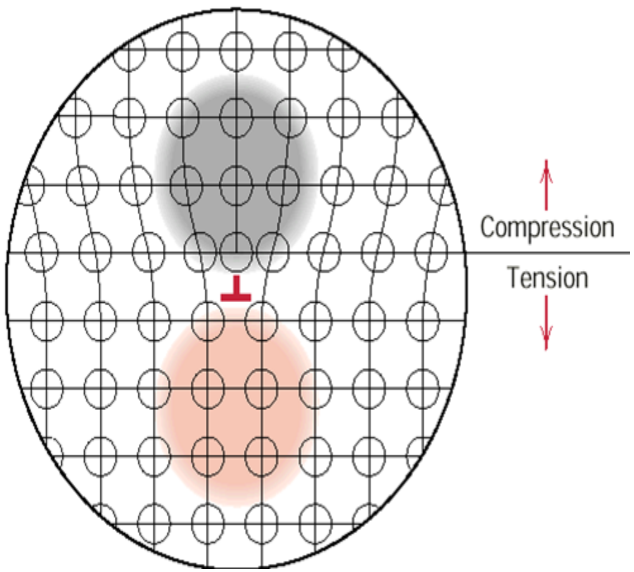
biased: preference for one type; e.g. ⊥s prefer interstitials due to the strain field

saturable or unsaturable: e.g. surface of a solid for v, i

Sink strength: affinity of a sink for a defect (equivalent of a nuclear cross-section: units cm^{-2})

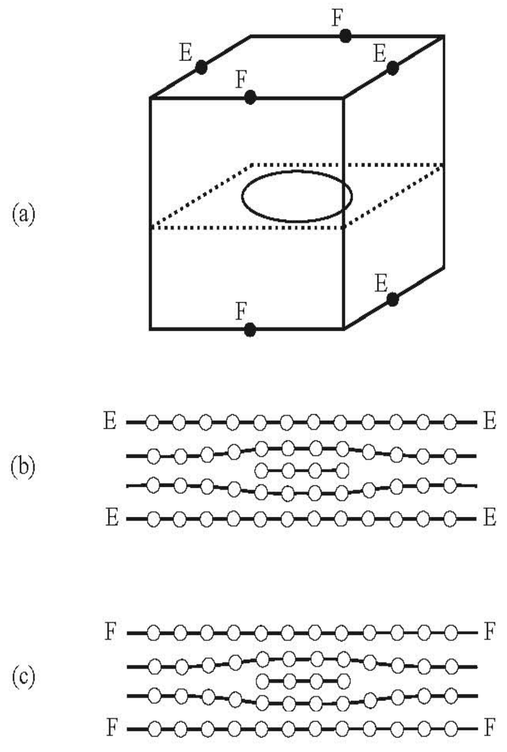
Linear defects

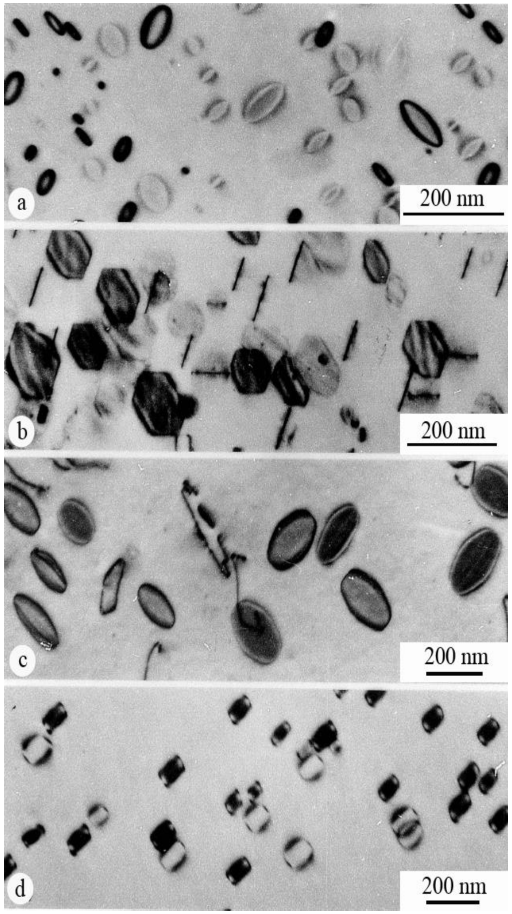




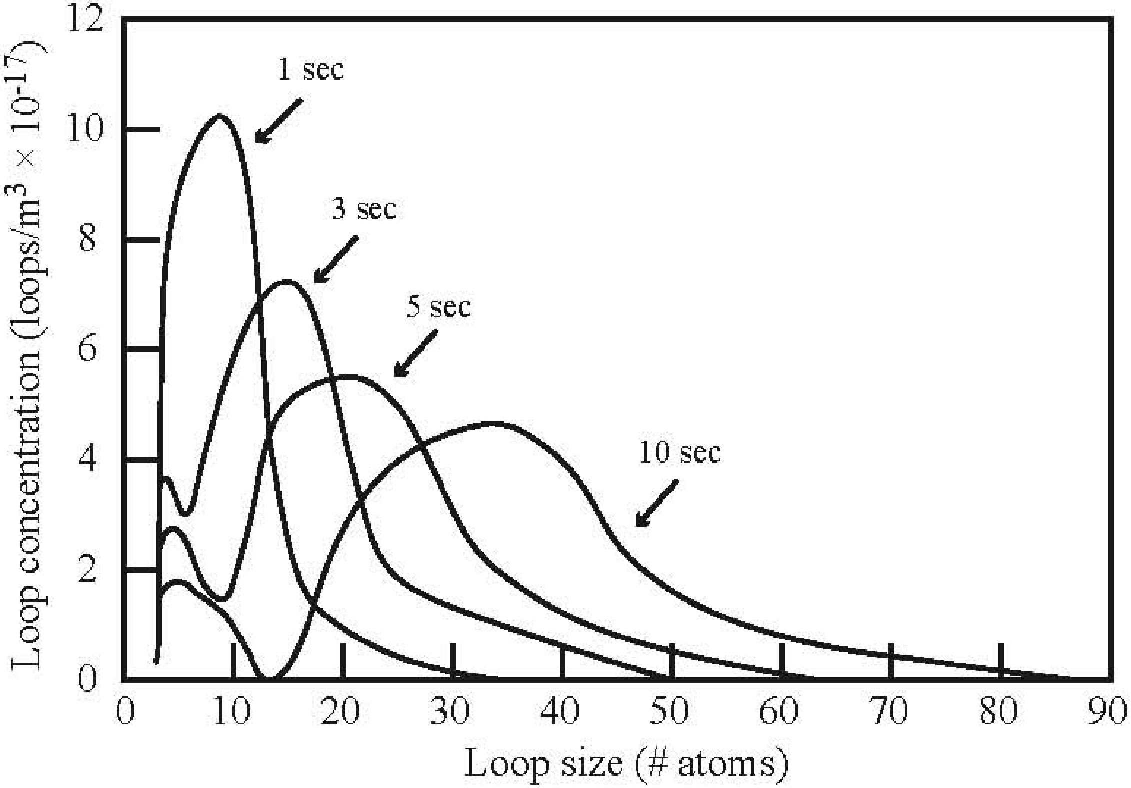
Planar Defects (I): Interstitials (or vacancies) can cluster into discs (loops)

Faulted (Frank) Loop

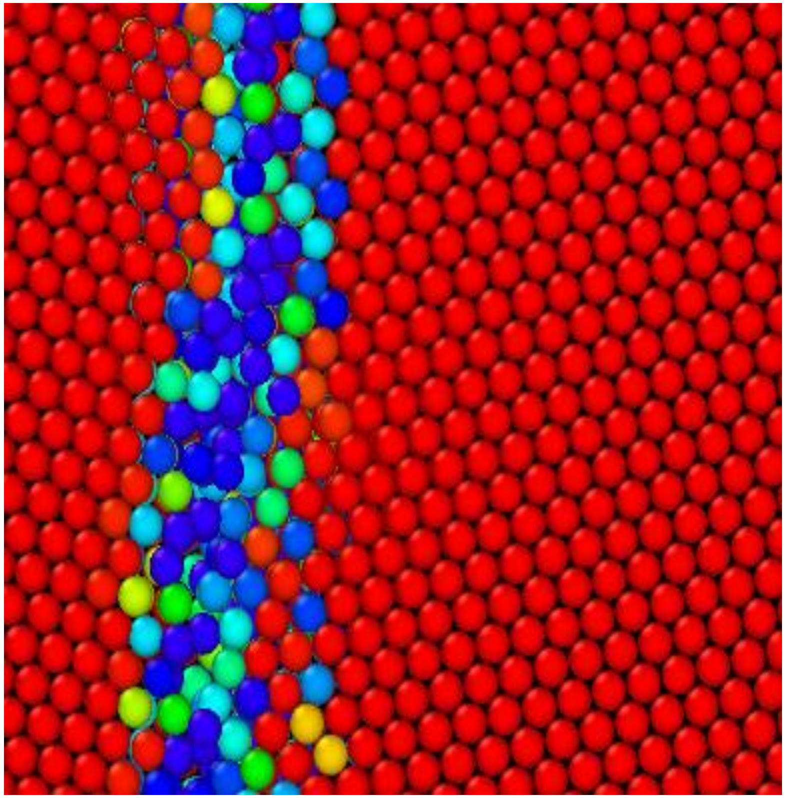




Evolution of loop size distribution in 316 SS irradiated at 10^{-6} dpa/s at 550° C with $\rho_d = 10^{13}$ m^{-2}



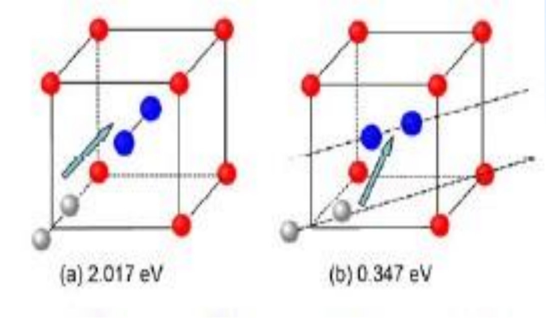
Planar defects (II): grain boundary



v,I can migrate to grain boundaries.

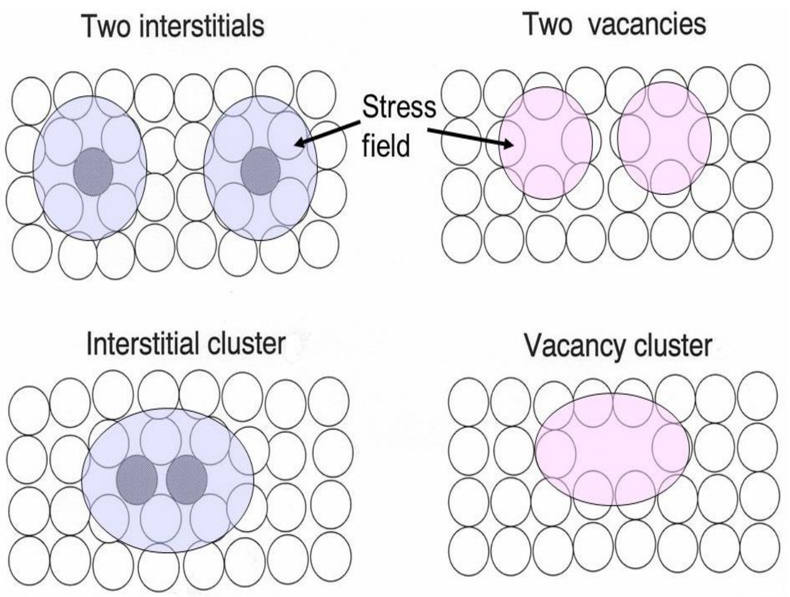
3d (volume) defects I: Interstitial and Vacancy clusters

- interstitials can cluster:
  - interstitials and lattice atoms pair and share lattice sites: dumbbells interstitials: lower energy, and preferred lattice orientation



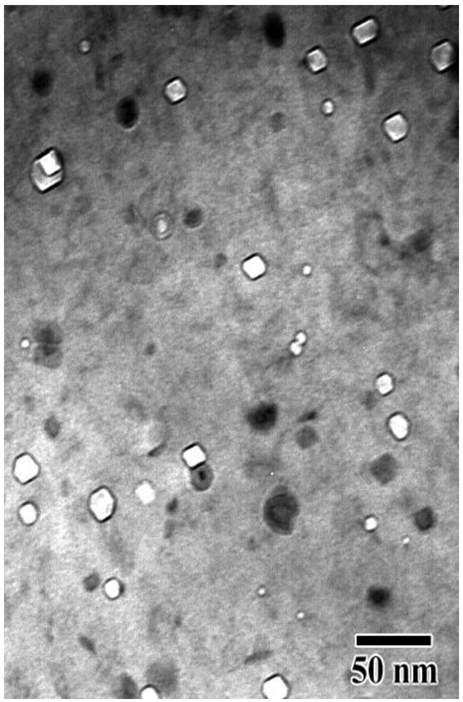
Long et al.: doi: 10.1007/s11433-012-4679-8

- Vacancies can cluster and can form voids inside the materials

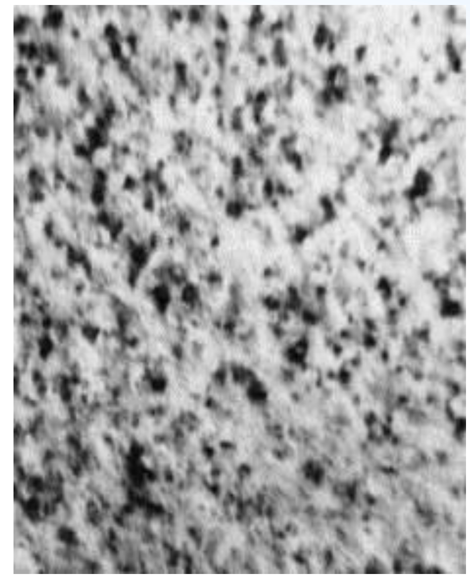


T Yoshiie.

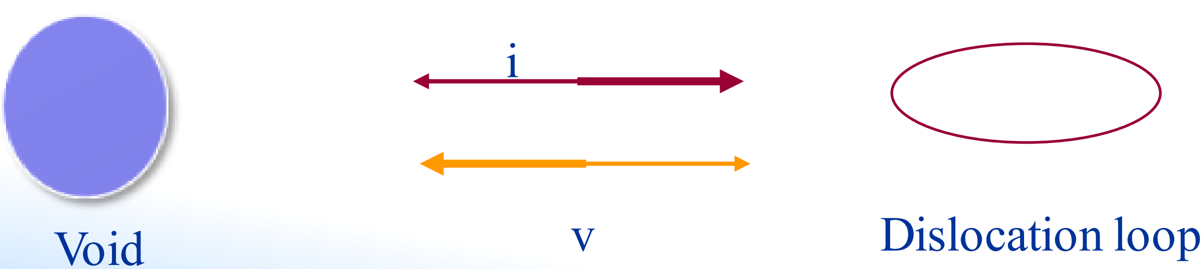
Clusters: voids and dislocation loops



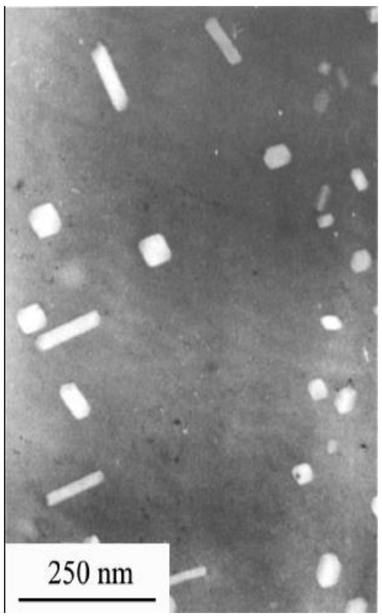
- Process
  - Radiation produces point defects
  - Interstitials migrate preferentially to dislocations leaving excess vacancies to form voids
  - Both grow as they absorb more defects



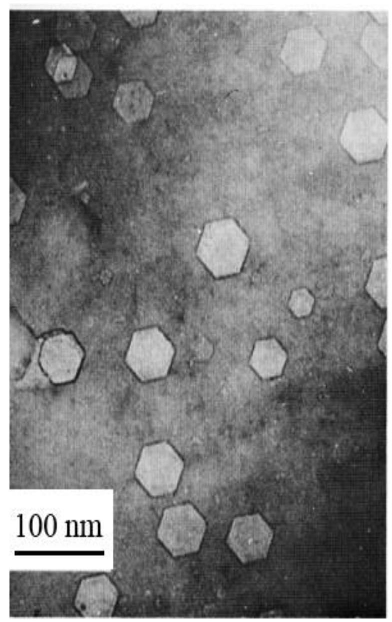
$\rho_d = 17.0 \times 10^{21}\ m^{-3}$
d = 4.9 nm 50 nm



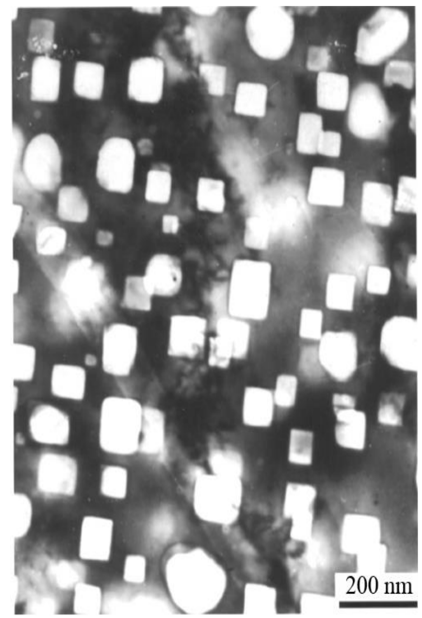
Voids



stainless steel



aluminum

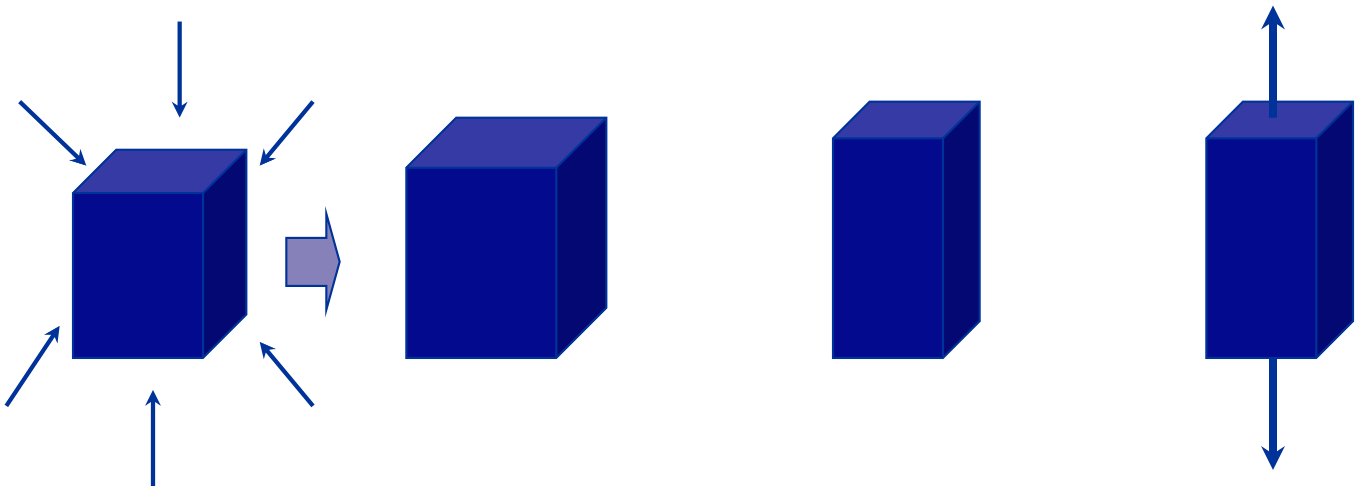


magnesium

M. L. Jenkins, M. A. Kirk, Characterization of Radiation Damage by Transmission Electron Microscopy, Institute of Physics Publishing, Philadelphia, 2001.

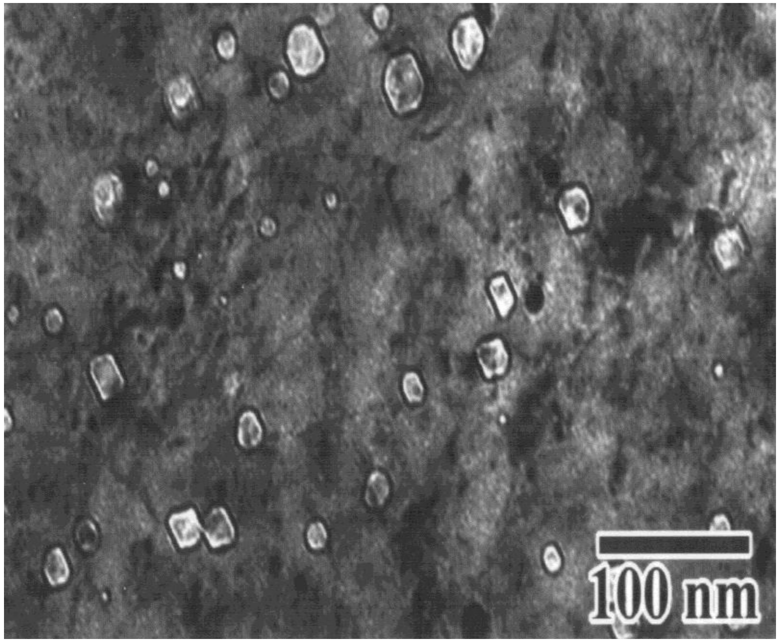
U. Adda, Proc. International Conference on Radiation Induced Voids in Metals, CONF-710601, National Technical Information Service, 1972, p. 31.

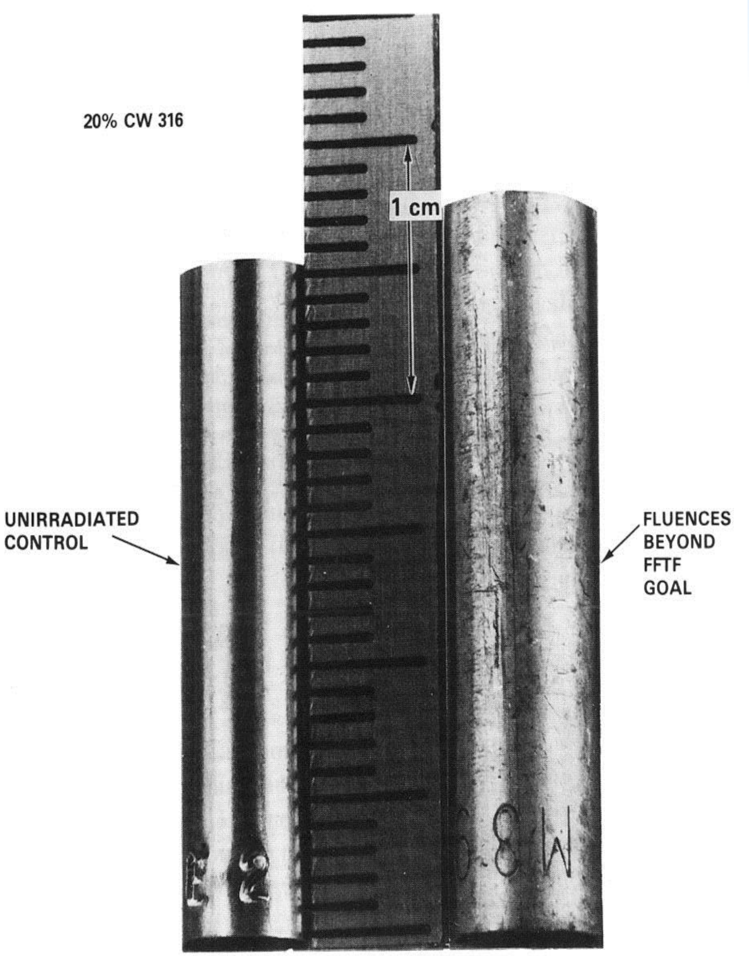
Macroscopic Effects: swelling, growth and creep



swelling	growth	creep
unstressed	unstressed	stressed
$\Delta V/V > 0$	$\Delta V/V = 0$	$\Delta V/V = 0$
undistorted	distorted	distorted

Swelling is readily observed in many steels under various reactor conditions





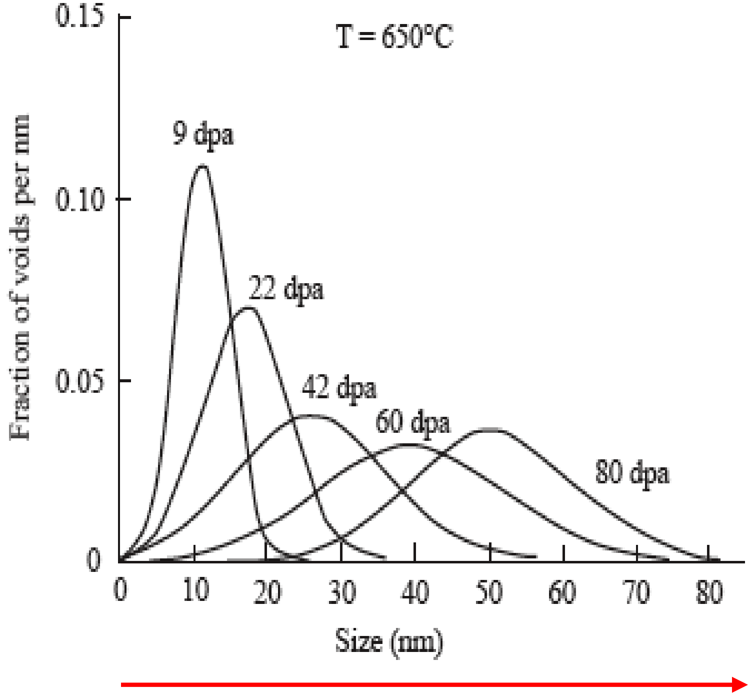
Straalsund, 1982, and F. Garner

Swelling

Swelling depends on:

- Temperature (peaks at intermediate T)
- Dose (increases with dose after "incubation" period)
- Dose rate (increases with decreasing dose rate for same dose)
- Stress state (hydrostatic tensile stress enhances swelling)
- Composition (very complicated)
- Presence of He (helps nucleate voids and bubbles)

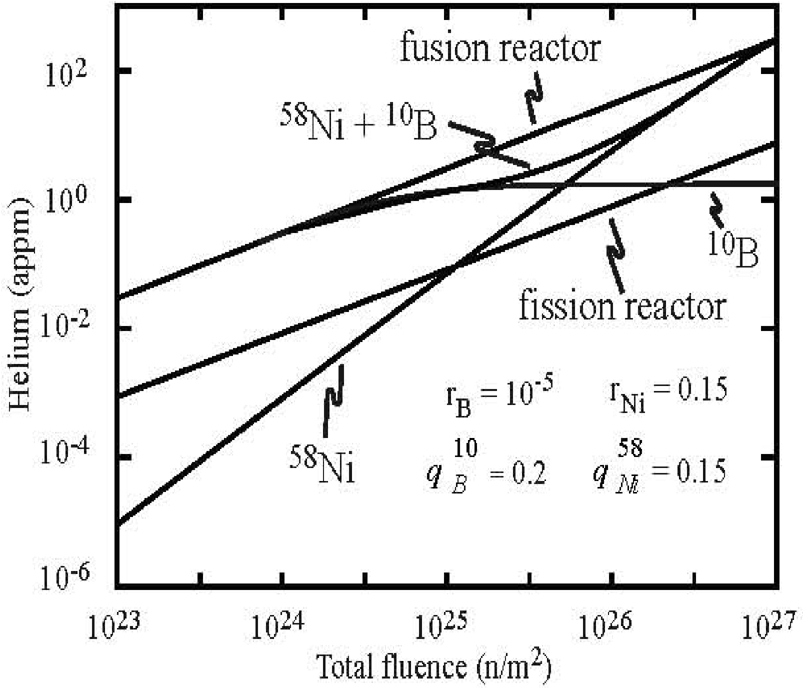
Voids and Bubbles



dpa = dose

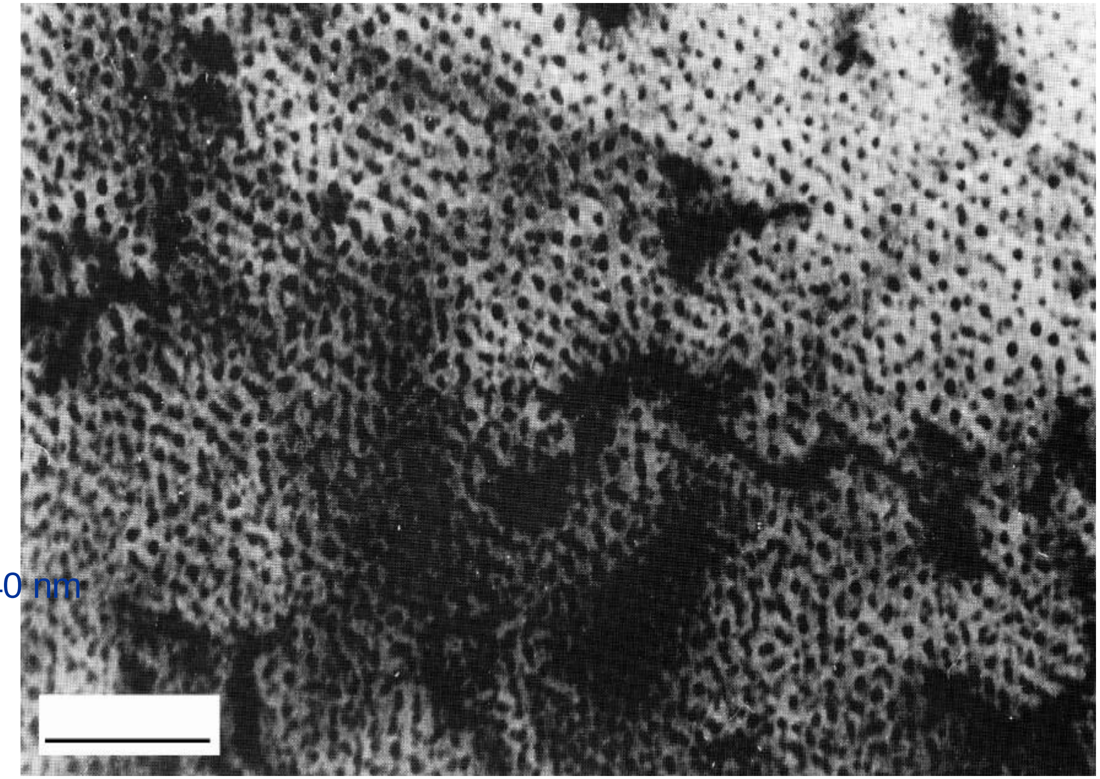
C. Abromeit, J. Nucl. Mater. 216 (1994) 78-96.

He production



$$^{58}Ni + n \rightarrow {}^{59}Ni + \gamma$$
$$^{59}Ni + n \rightarrow {}^{56}Fe + {}^{4}He$$
$$^{59}Ni + n \rightarrow {}^{59}Co + H$$
$$^{59}Ni + n \rightarrow {}^{60}Ni + \gamma$$

Bubbles - clusters of vacancies with He gas atoms

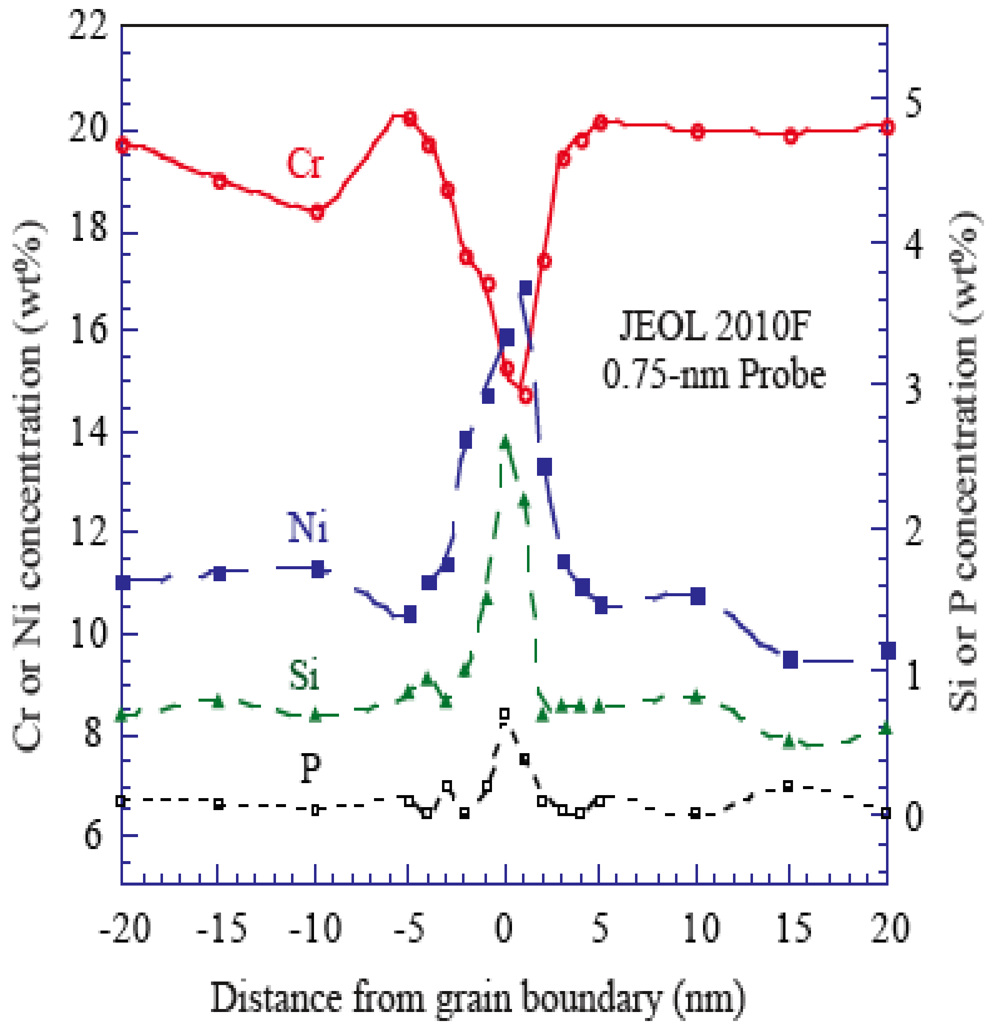


N.M. Ghoniem, et al, 2002

Physical Effects of Radiation Damage

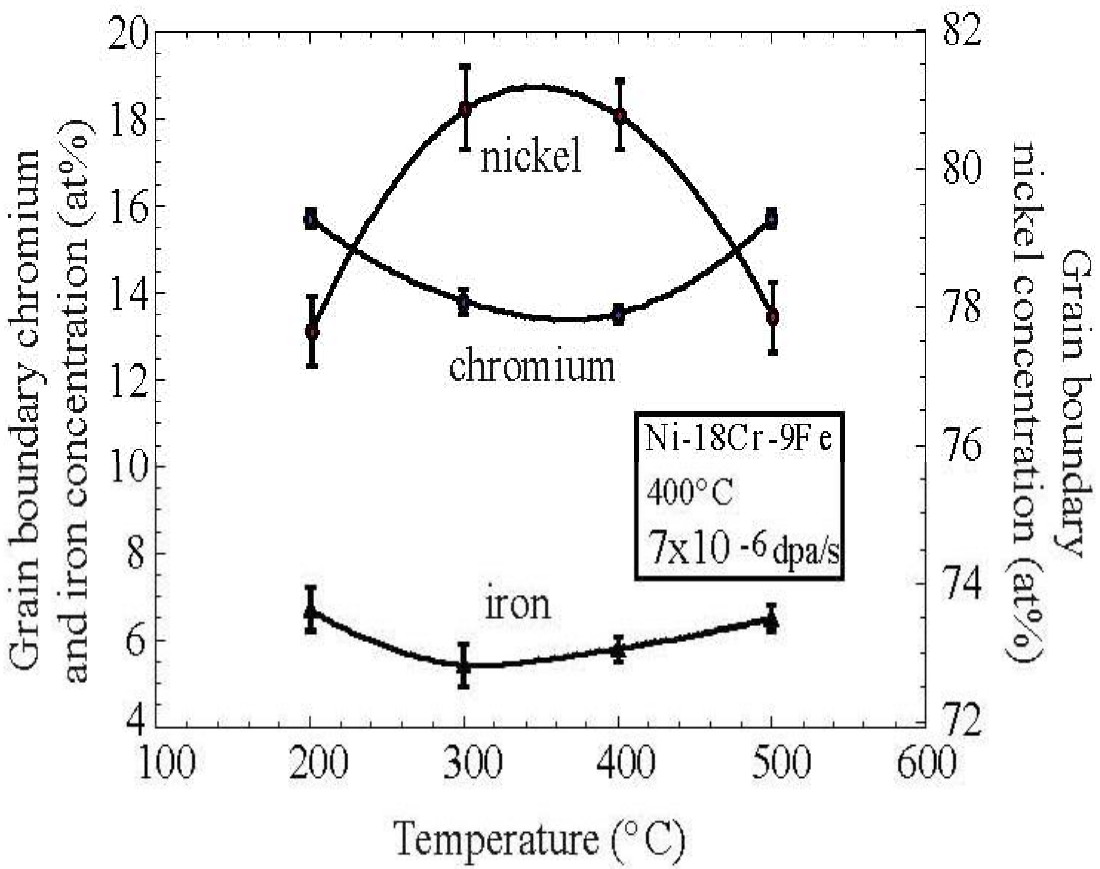
- Diffusion Driven Processes
  - Radiation-induced segregation (RIS)
  - Radiation-induced growth

RIS stainless steel

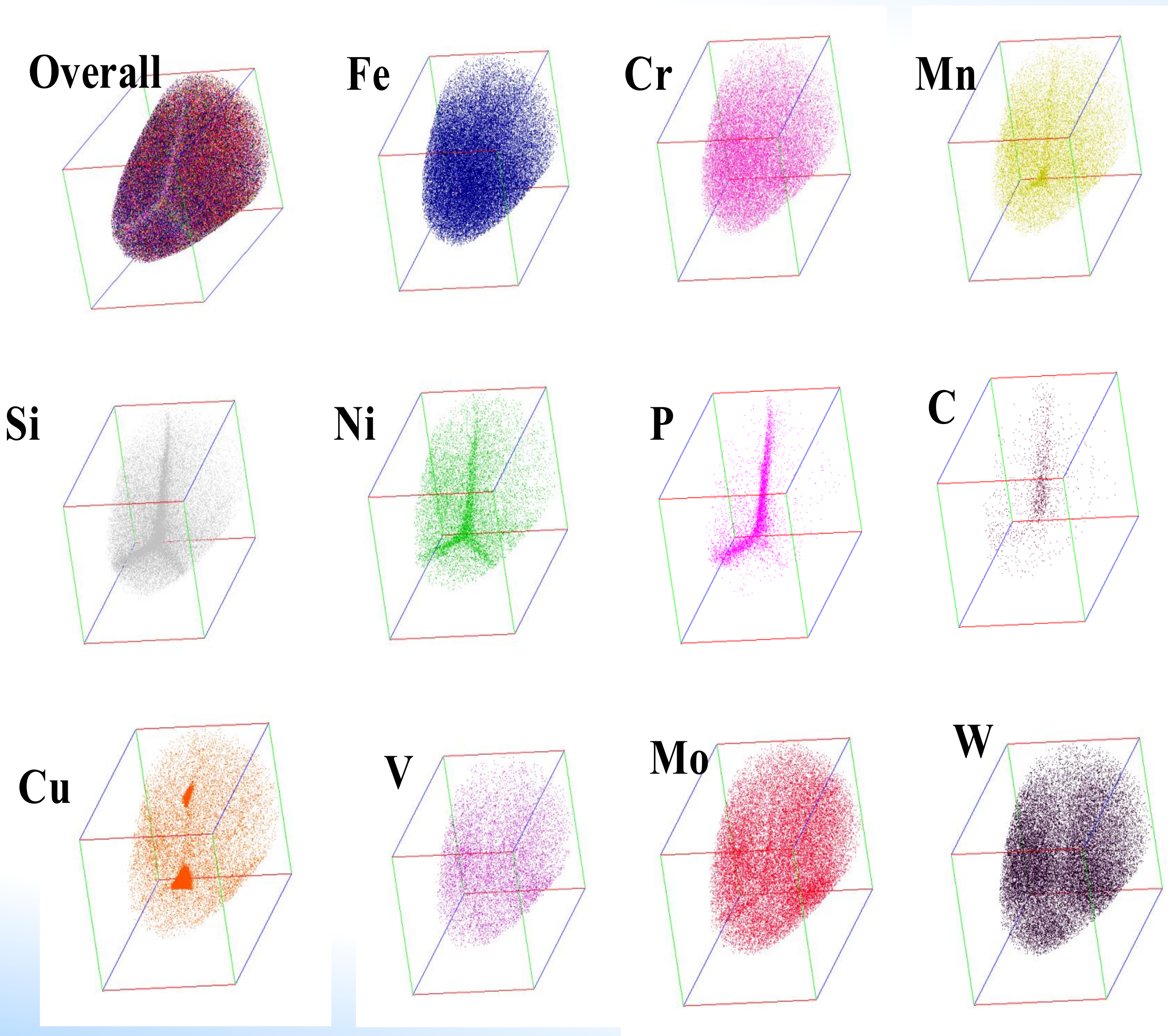


S. M. Bruemmer, E. P. Simonen, P. M. Scott, P. L. Andresen, G. S. Was and L. J. Nelson, J. Nucl. Mater. 274 (1999) 299

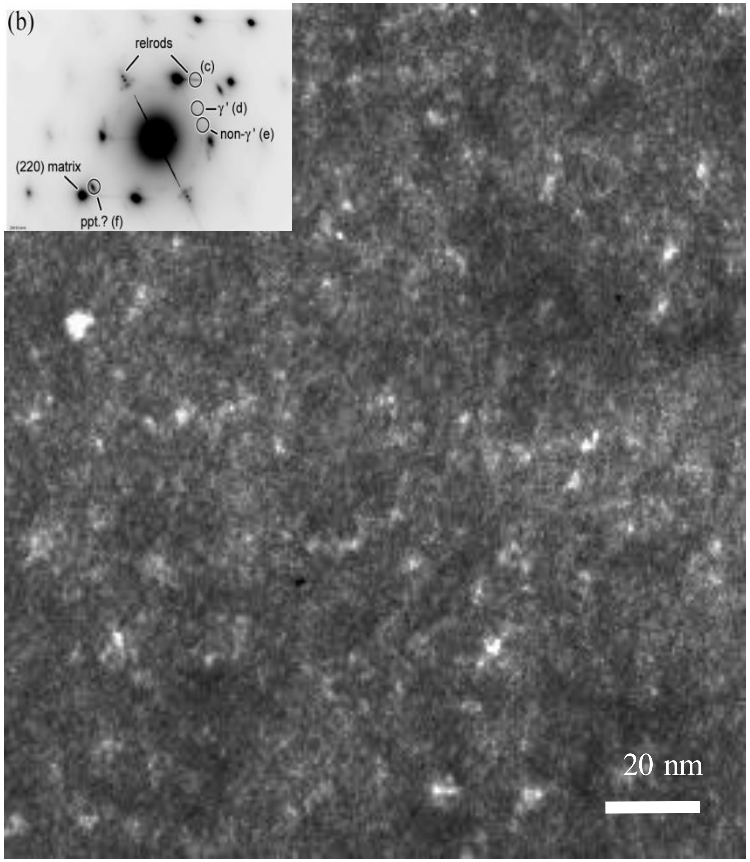
Temperature Dependence



RIS at *Grain Boundaries* in HCM12A following irradiation to 100 dpa at 500° C



Precipitation of γ’ in neutron-irradiated stainless steel baffle bolt



Tihange baffle bolt:
neutron-irradiated to ~7 dpa at 299° C.

ATEM Characterization of Stress-Corrosion Cracks in LWR-Irradiated Austenitic Stainless Steel Core Components, PNNL EPRI Report, 11/2001.

Resume

- PKA
- Frenkel Pairs
- Cascades
- Athermal Recombination
- Sinks
- Preferential flow
- Radiation induced segregation
- Coalescence and Swelling

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Thank you!