Materials in Nuclear Systems

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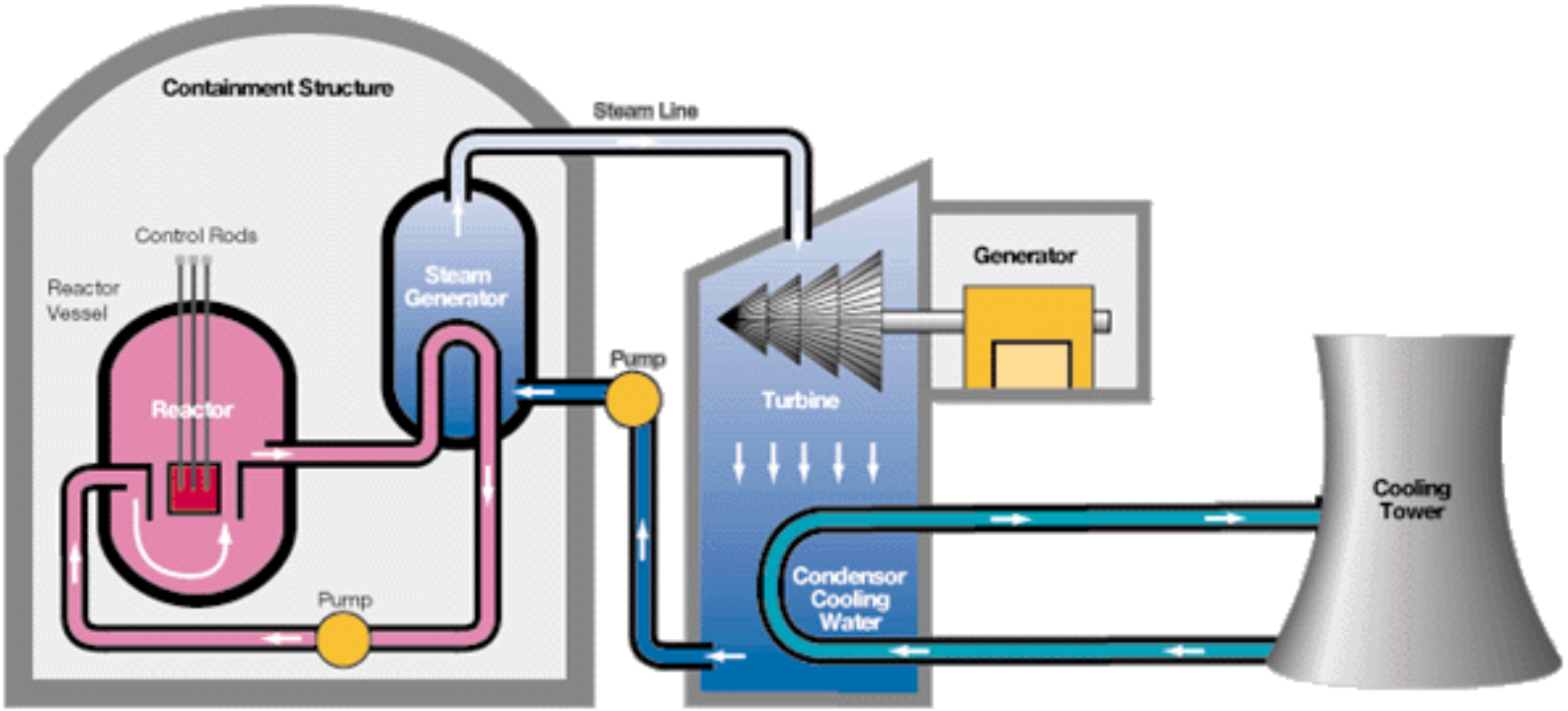
8 June 2010

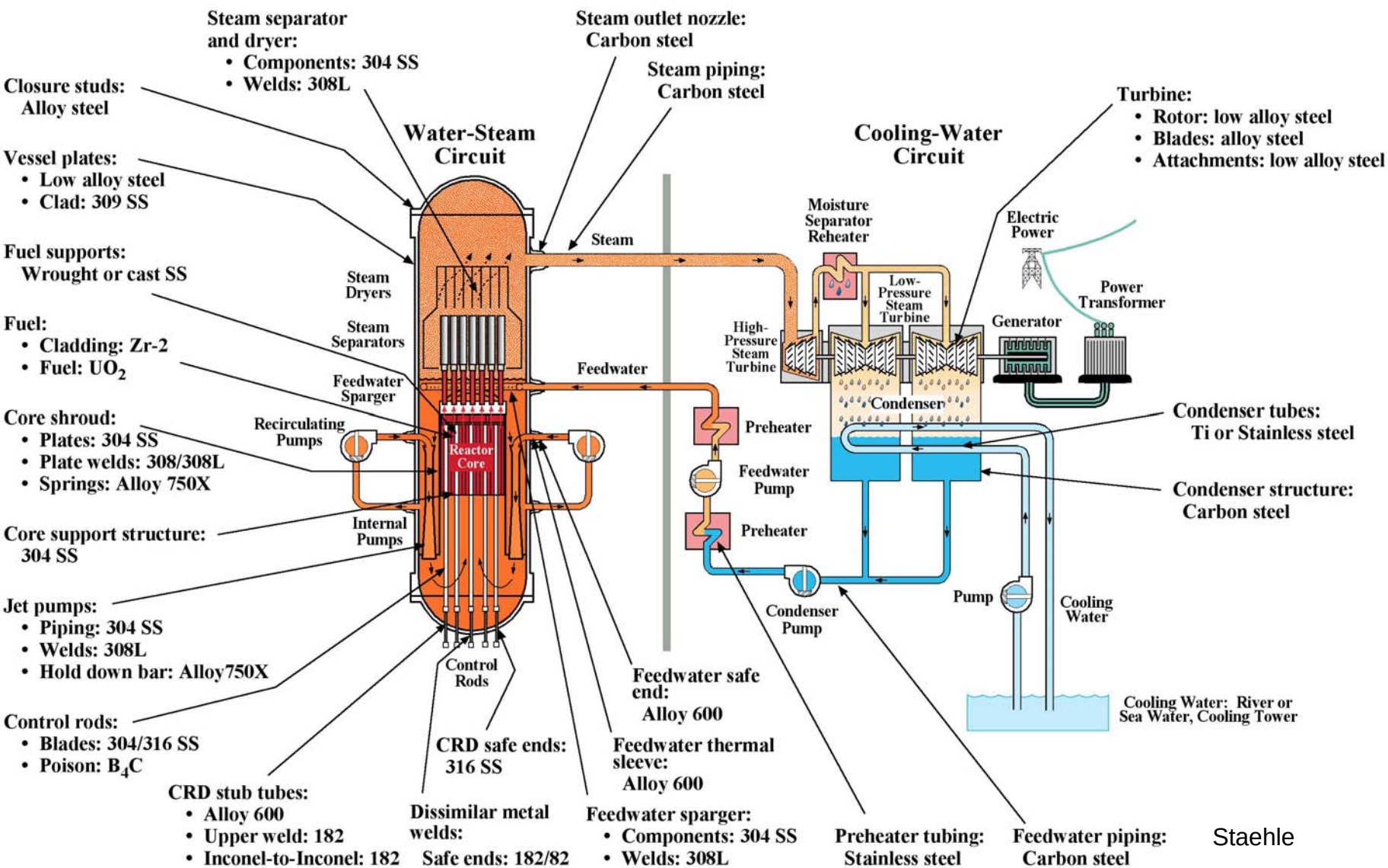
Idaho National Laboratory

ATR
National Scientific User Facility

Nuclear Reactor

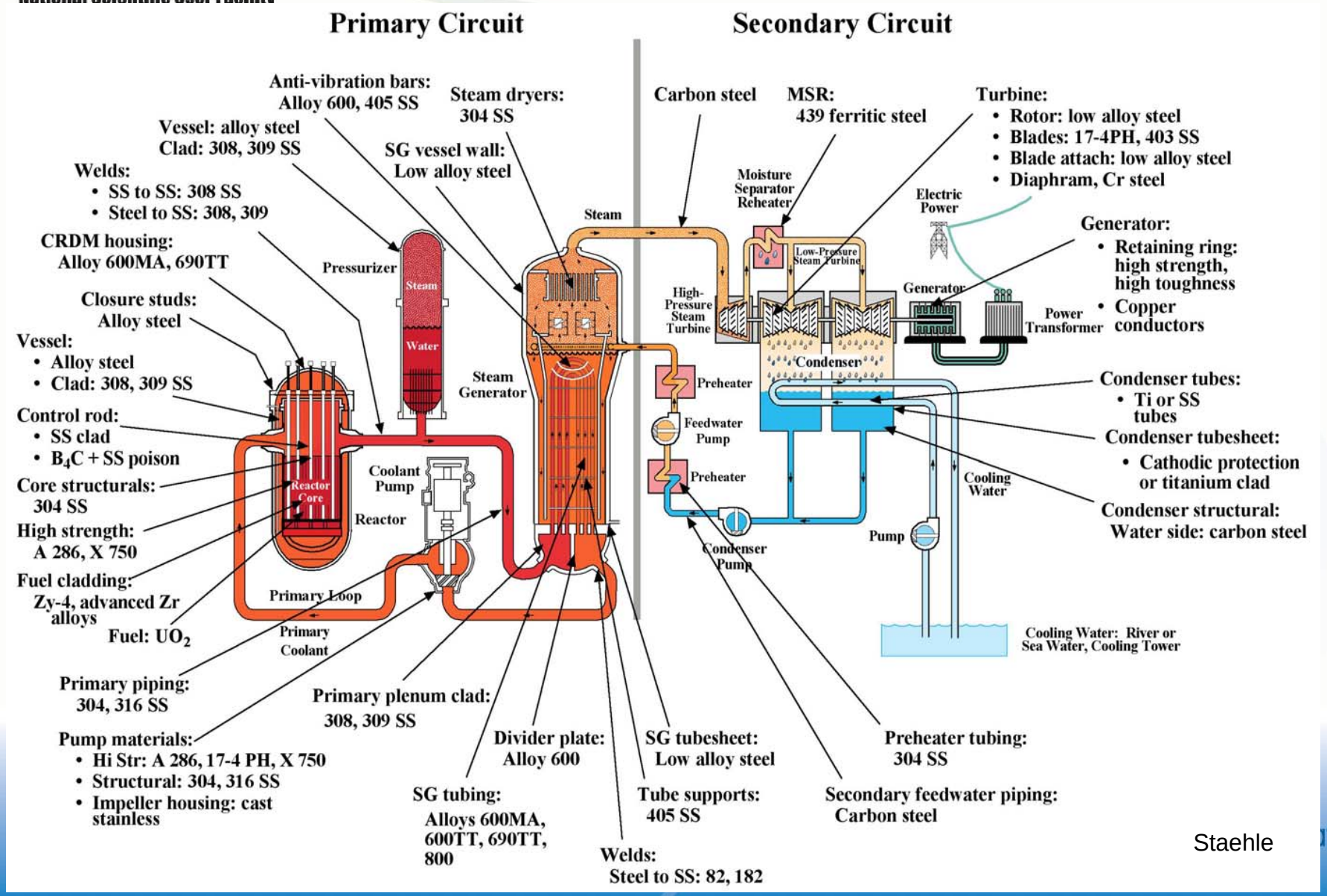


BWR Components and Materials



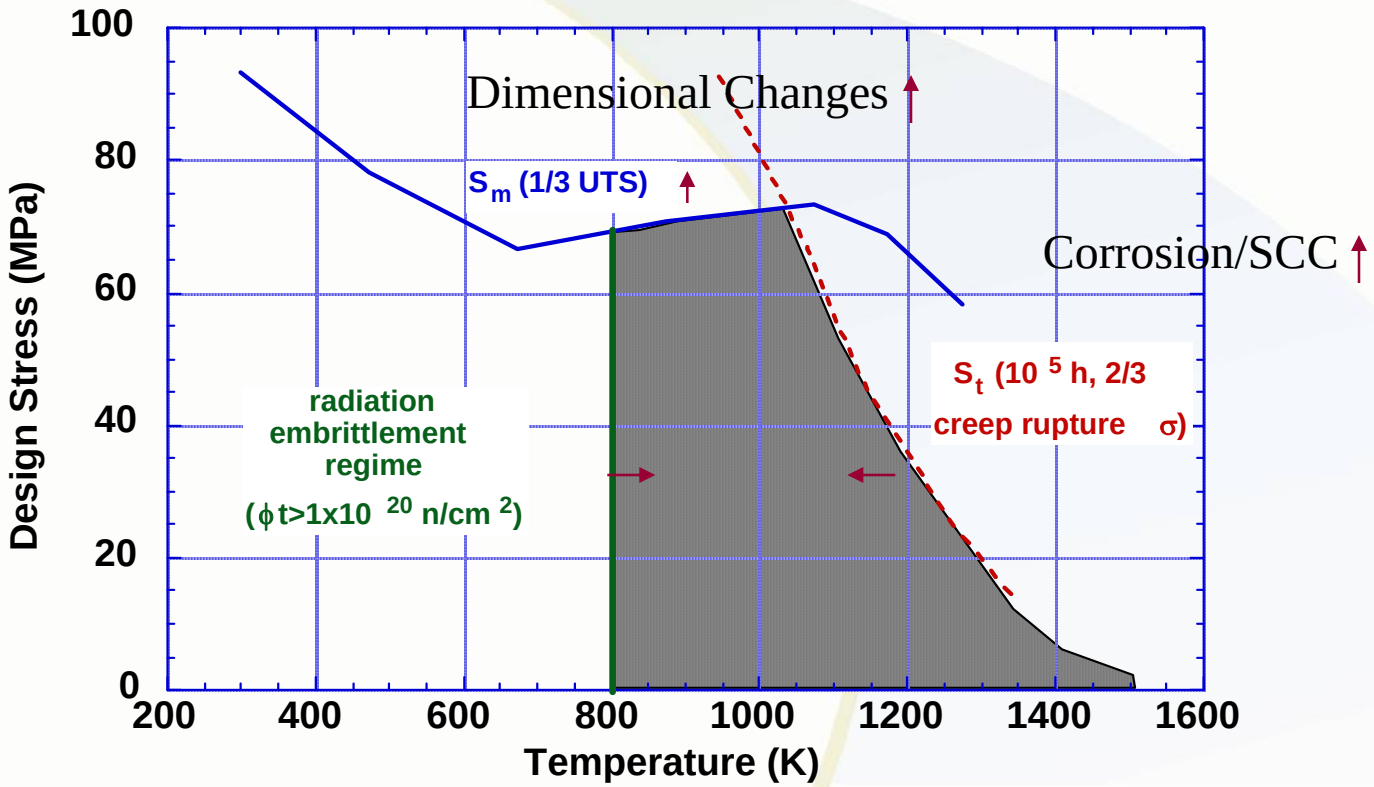
Staehle

PWR Components and Materials



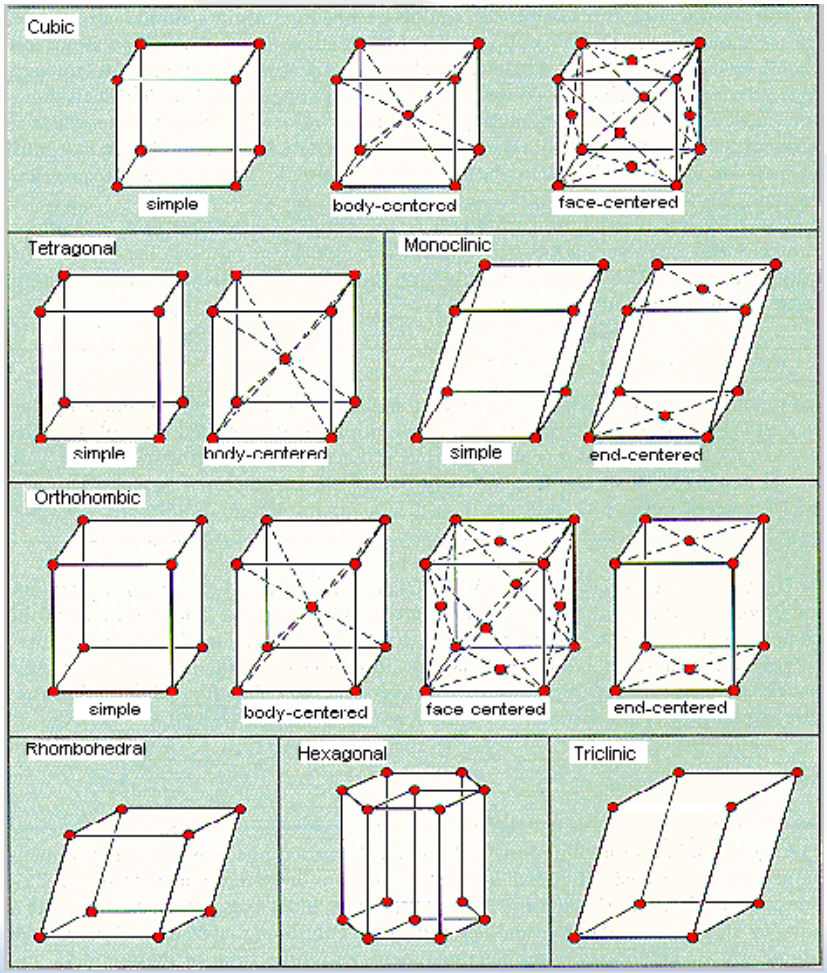
Staehle

Design Windows

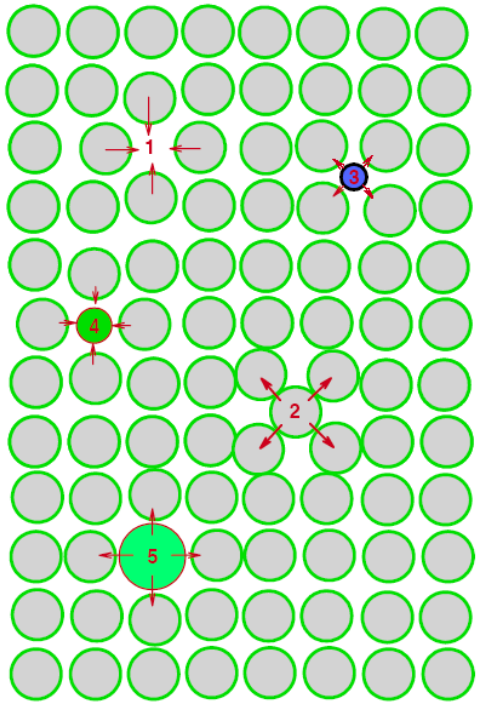


Properties change with radiation →

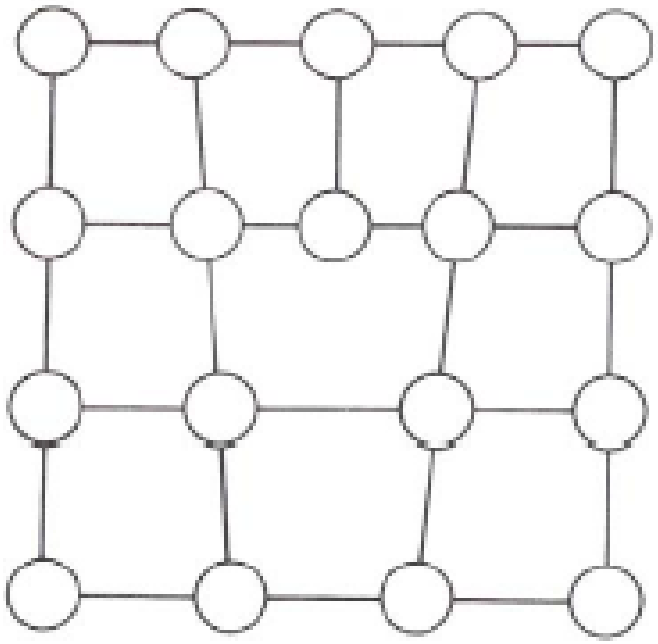
Lattice Configurations



Point Defects & Dislocations



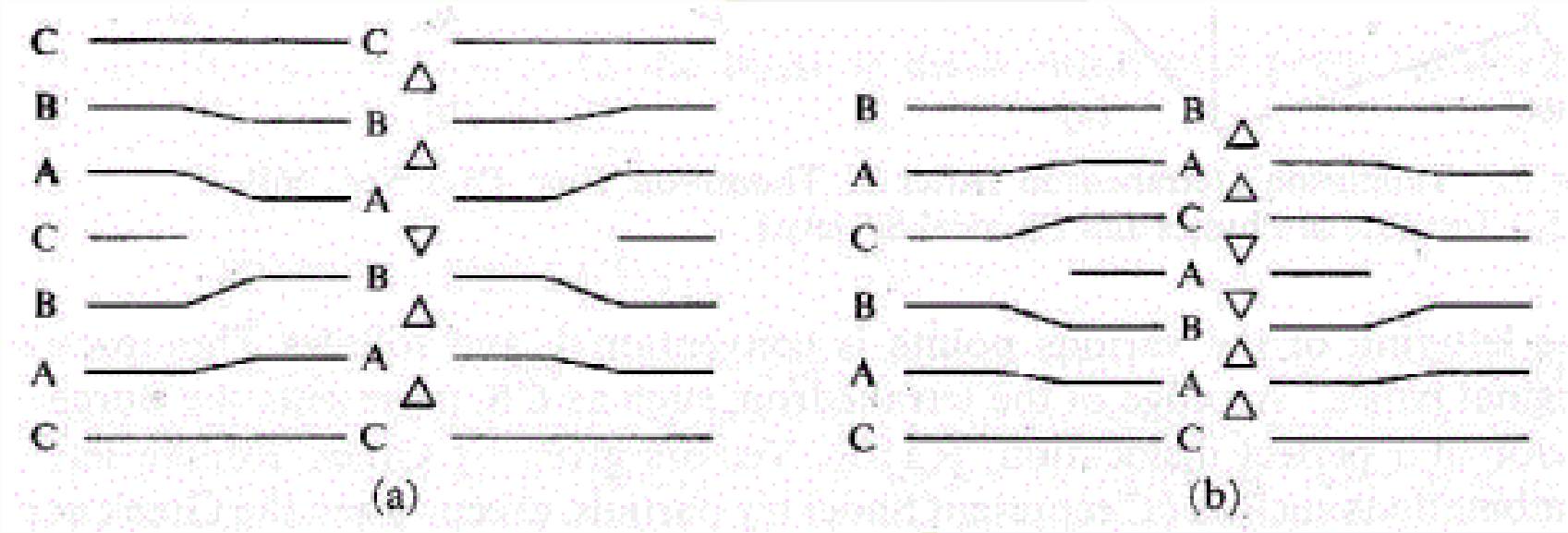
Schematic representation of different point defects in a crystal. (1) vacancy; (2) self-interstitial; (3) interstitial impurity; (4), (5) substitutional impurities. The arrows show the local stresses introduced by the point defects.



Edge Dislocation

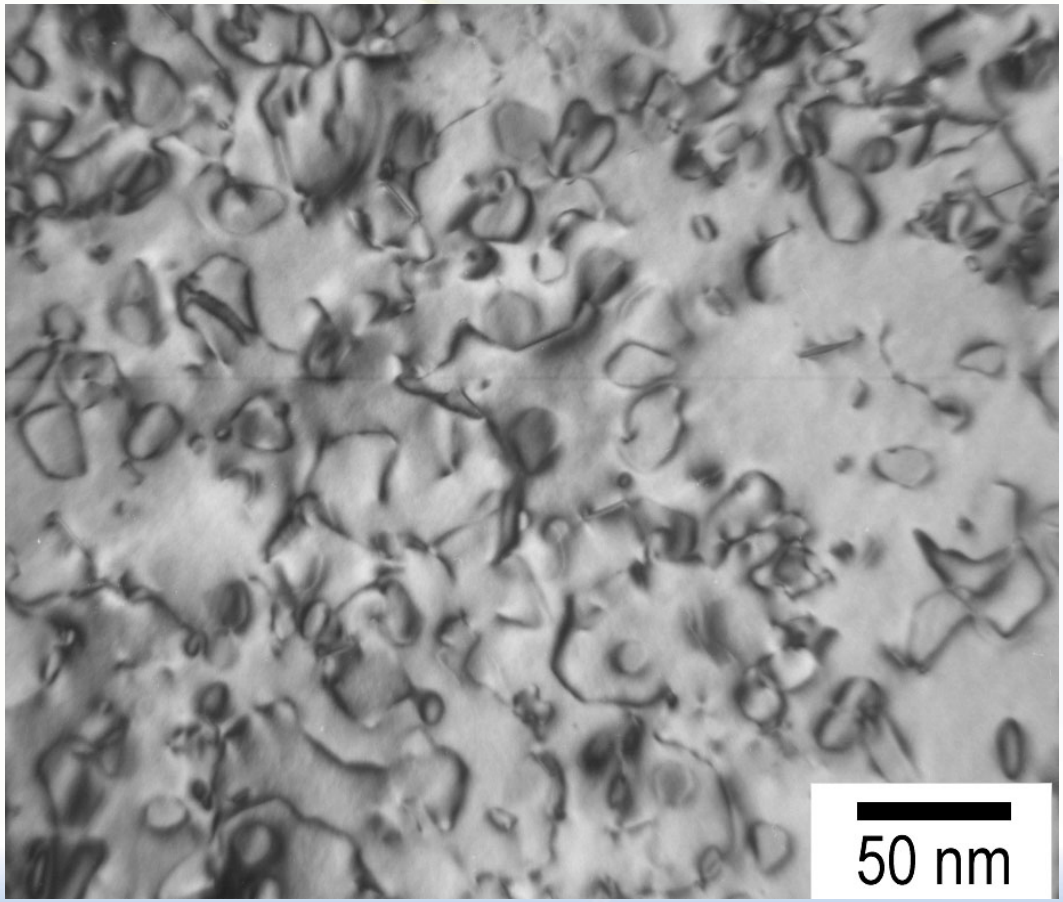
www.people.virginia.edu/~lz2n/ mse201/mse201-defects.pdf

Vacancy & Interstitial Loops

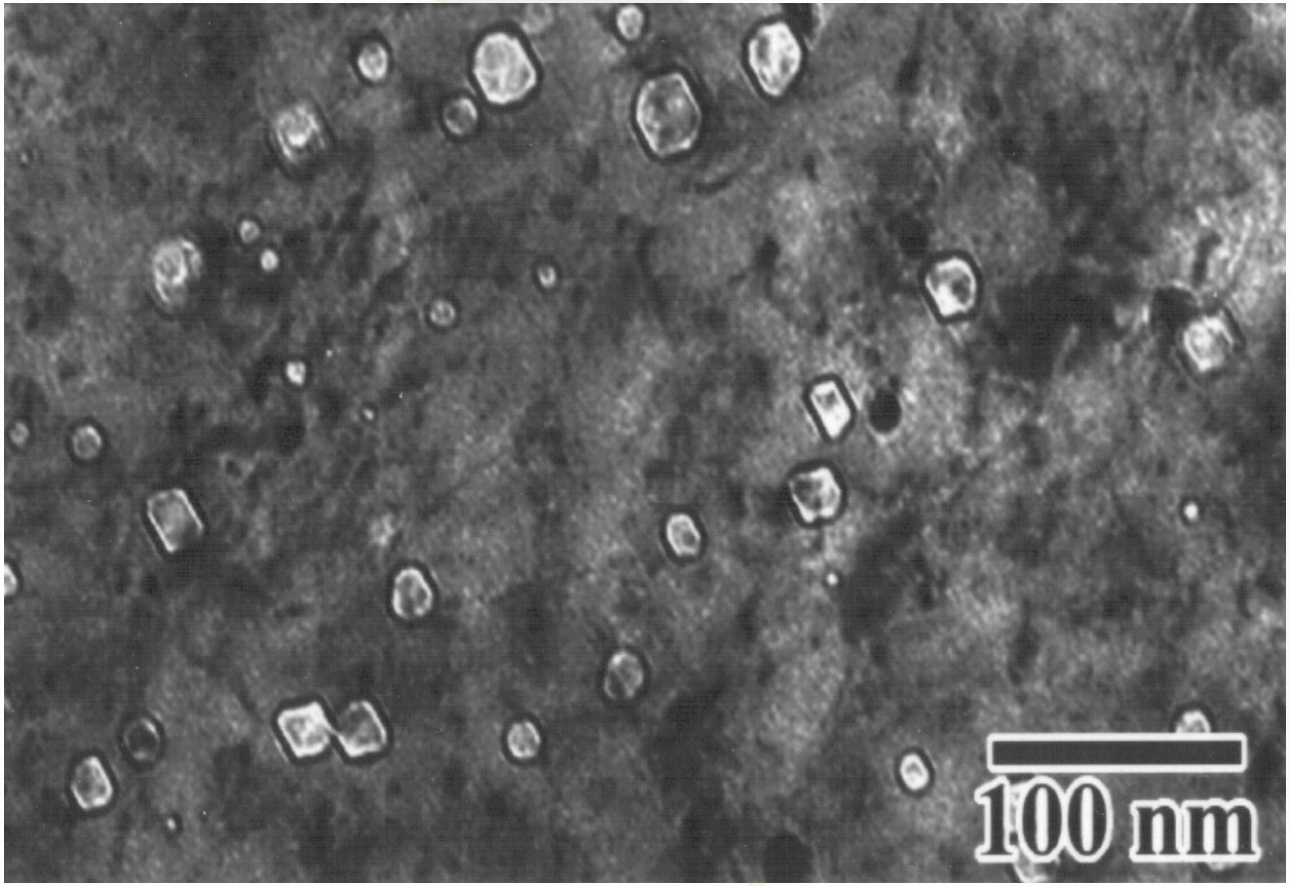


http://www-classes.usc.edu/engr/ms/125/MDA125/defects_files/frame.htm

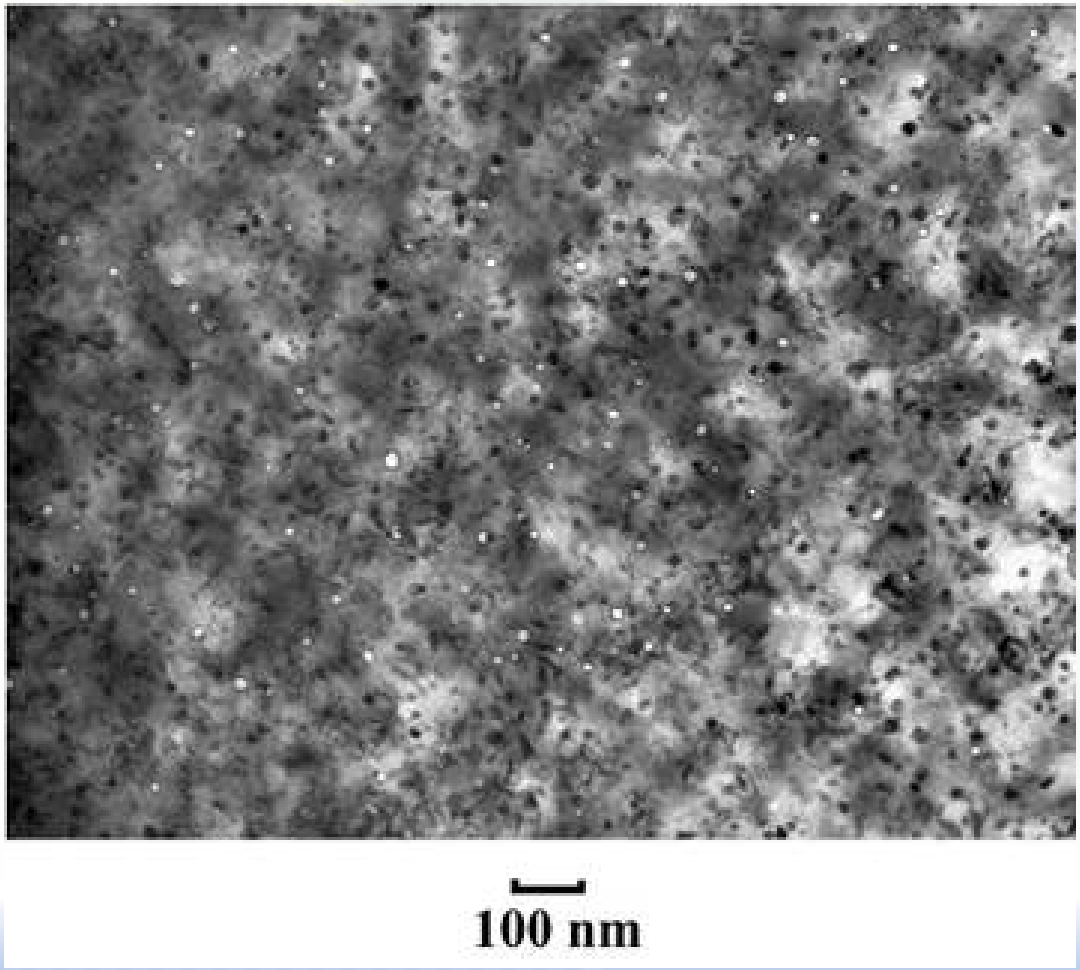
Dislocation Loops in Irradiated 316 Stainless Steel



Voids in Stainless Steel

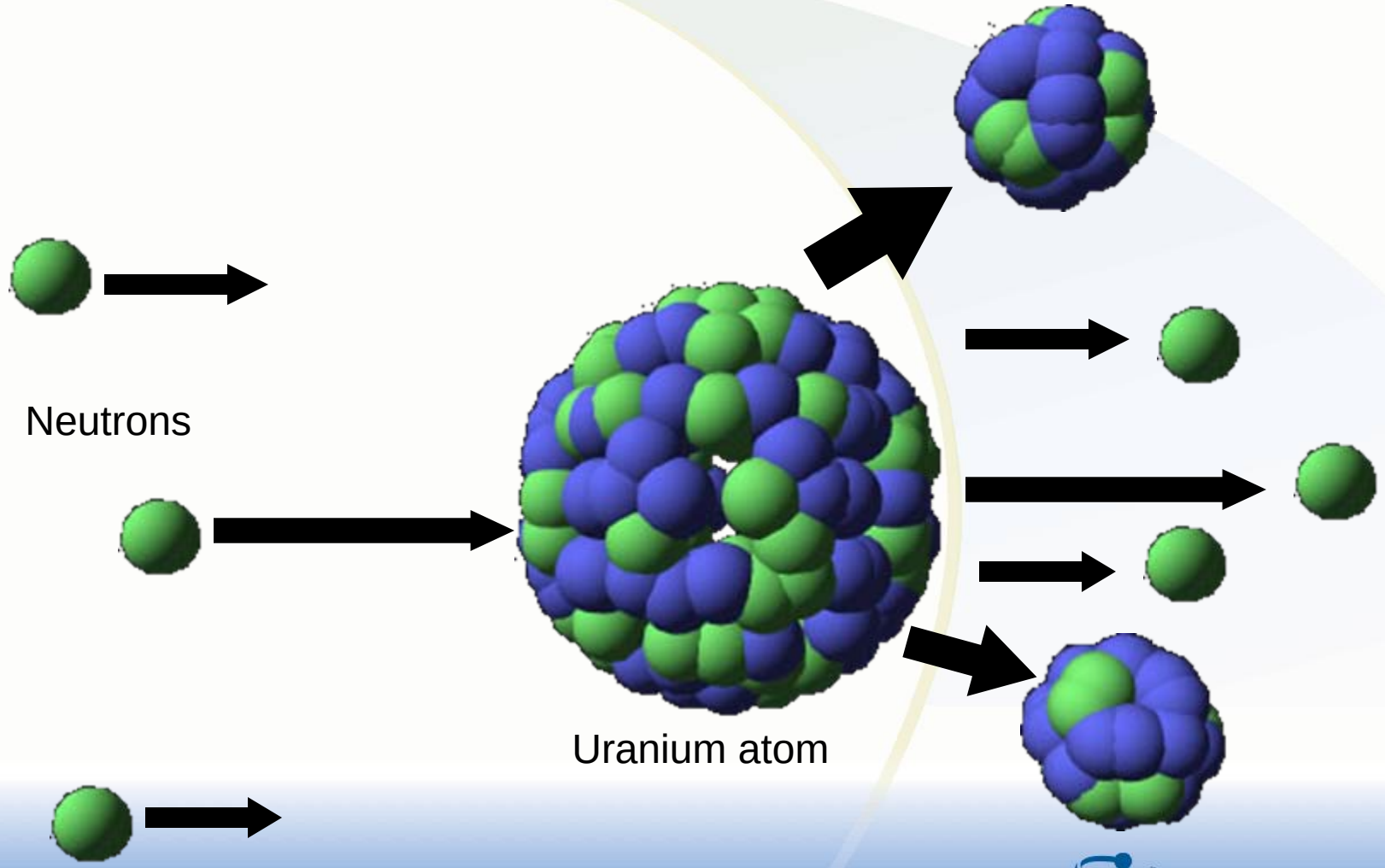


Carbide Precipitates & Voids

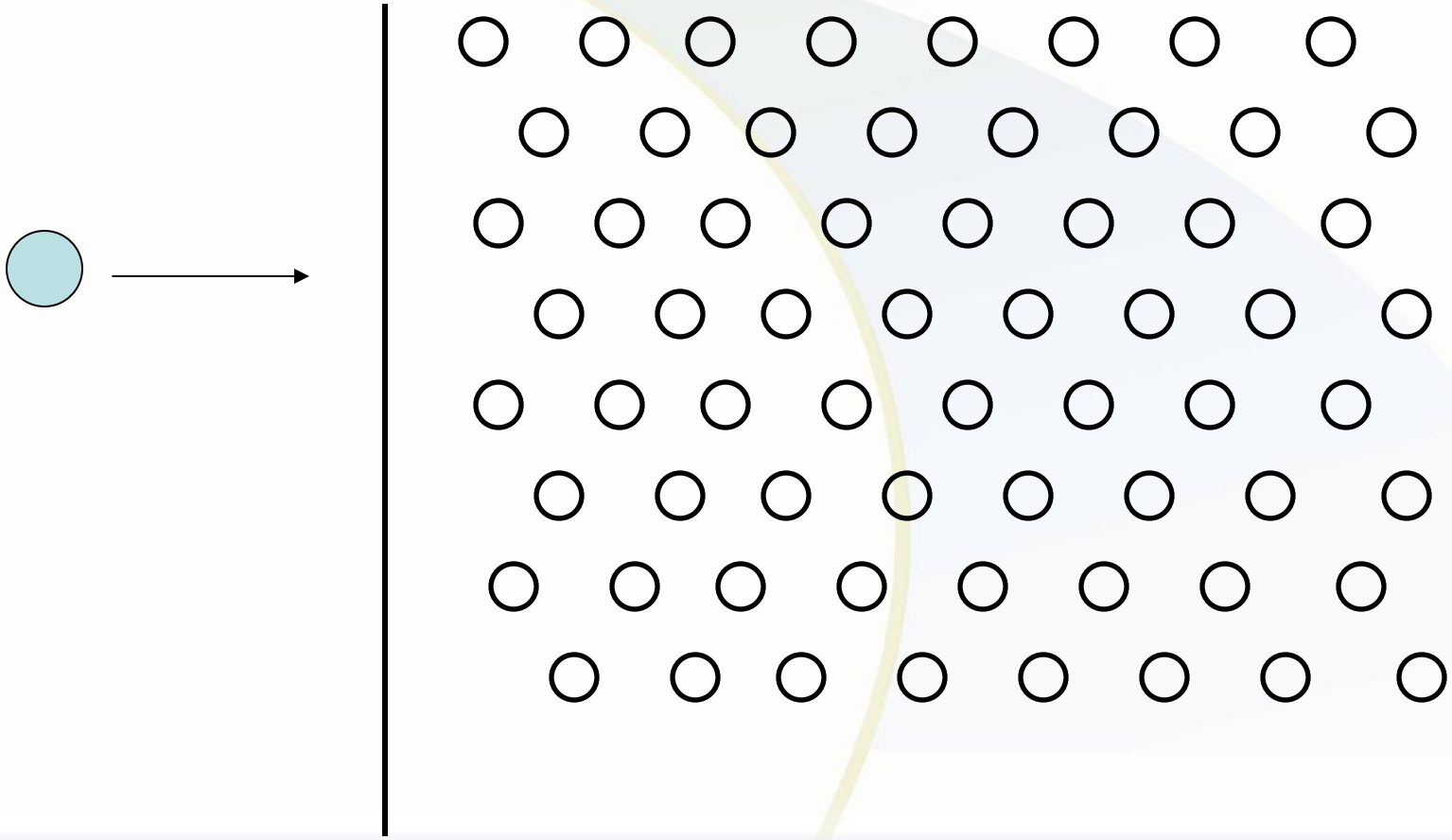


Garner

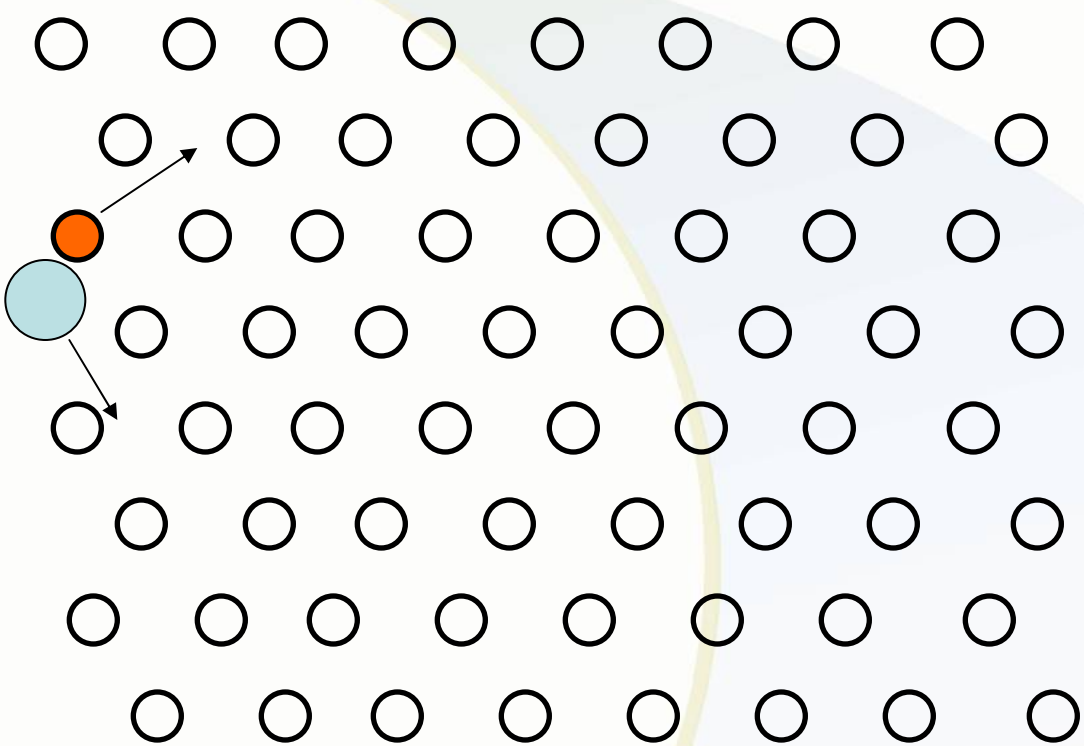
Nuclear Energy Comes From Fission



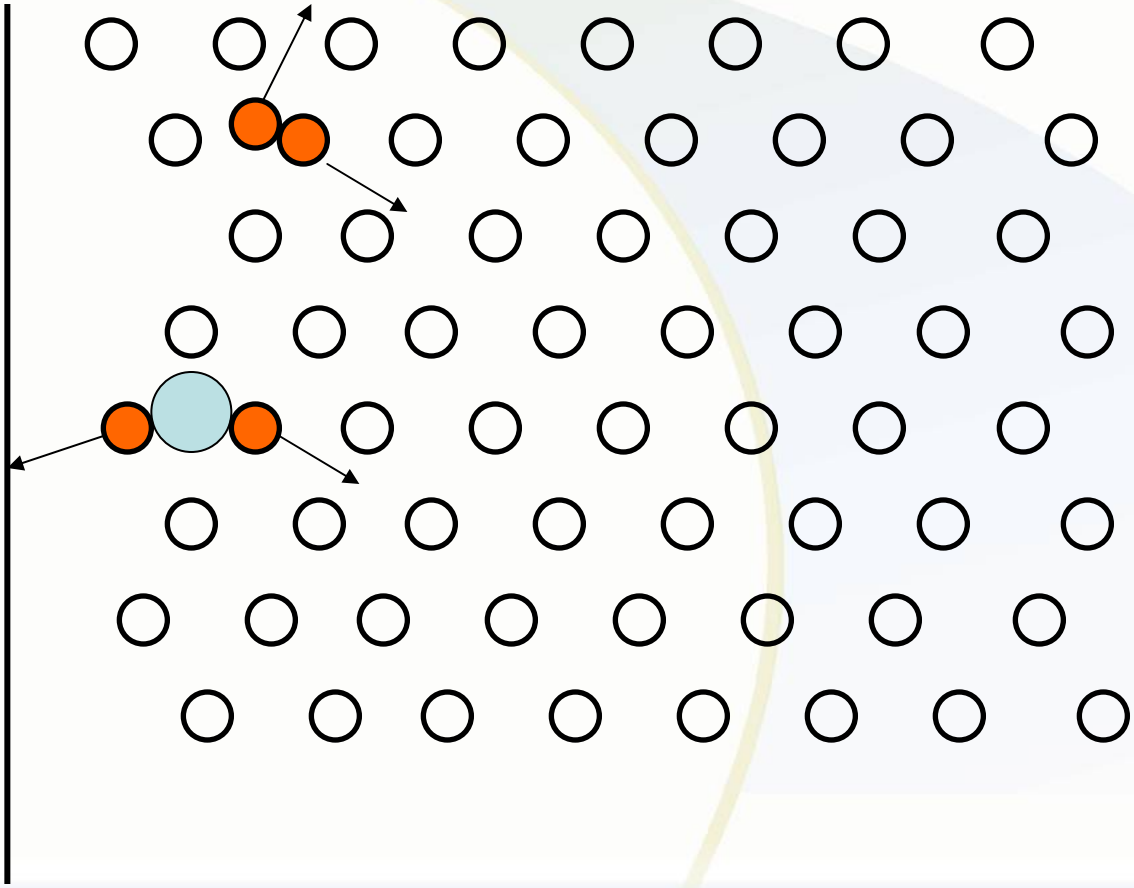
Radiation Damage Simple Picture



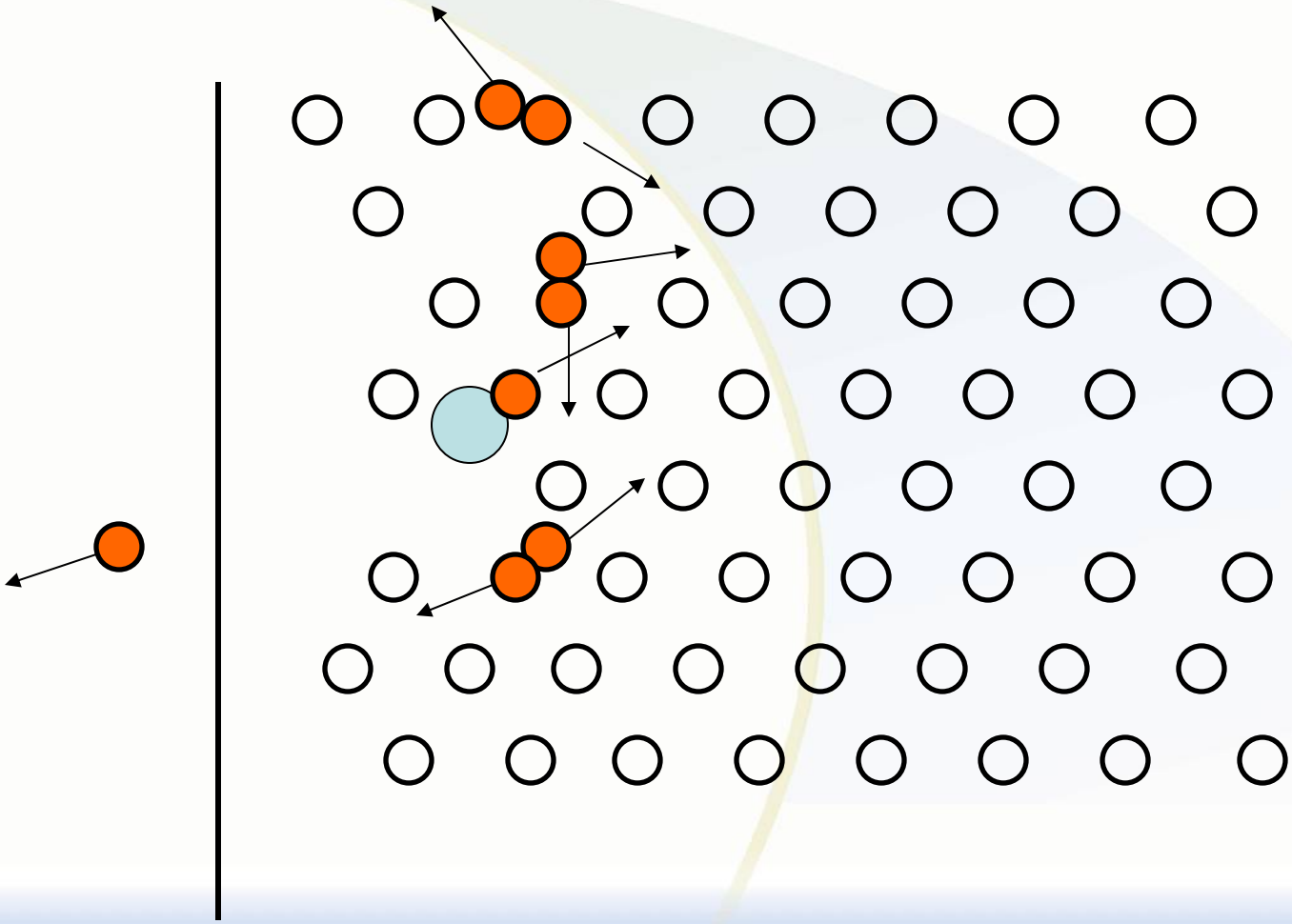
Radiation Damage Simple Picture



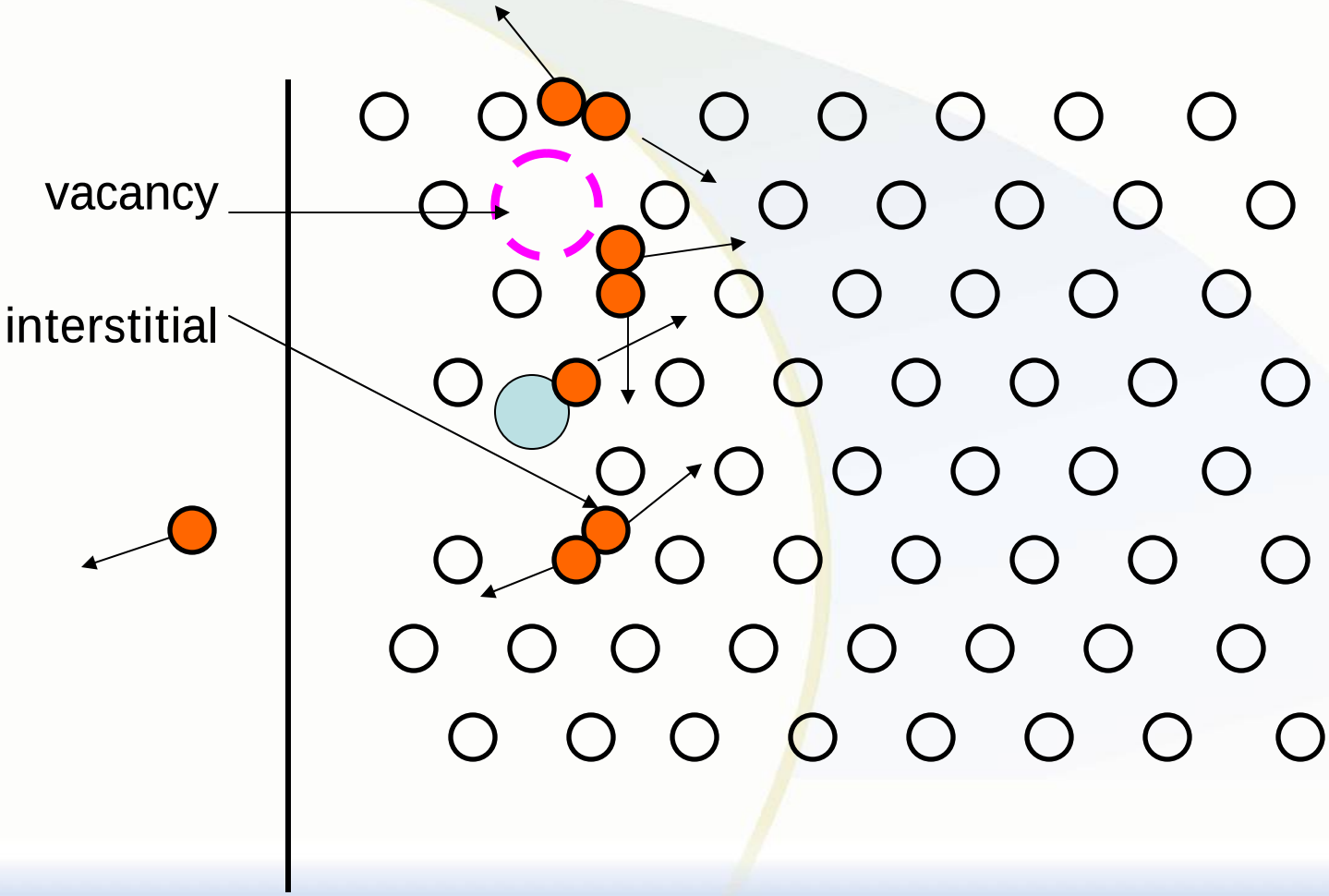
Radiation Damage Simple Picture



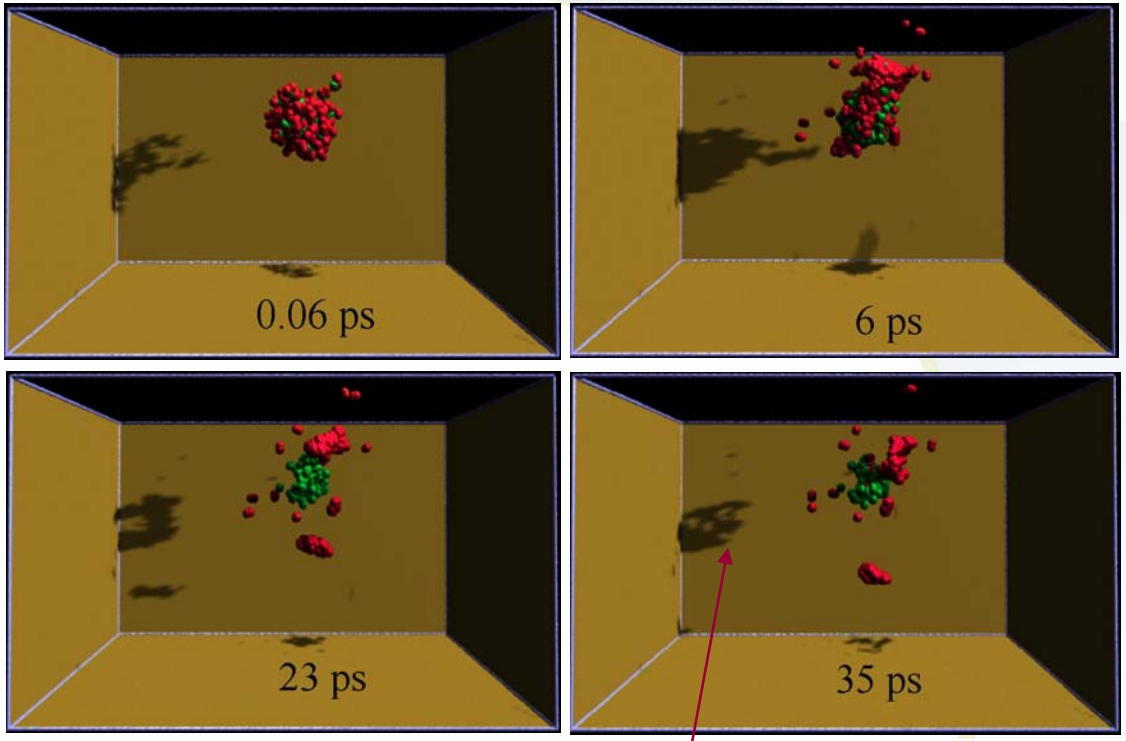
Radiation Damage Simple Picture



Radiation Damage Simple Picture



Displacement Damage

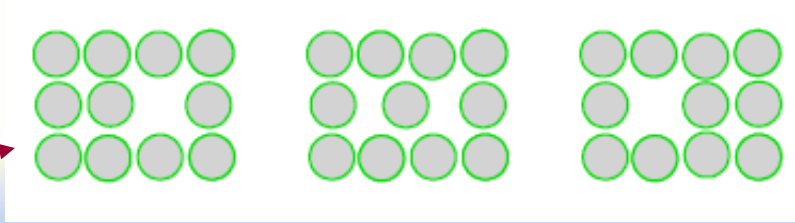


Cu 20keV → Cu

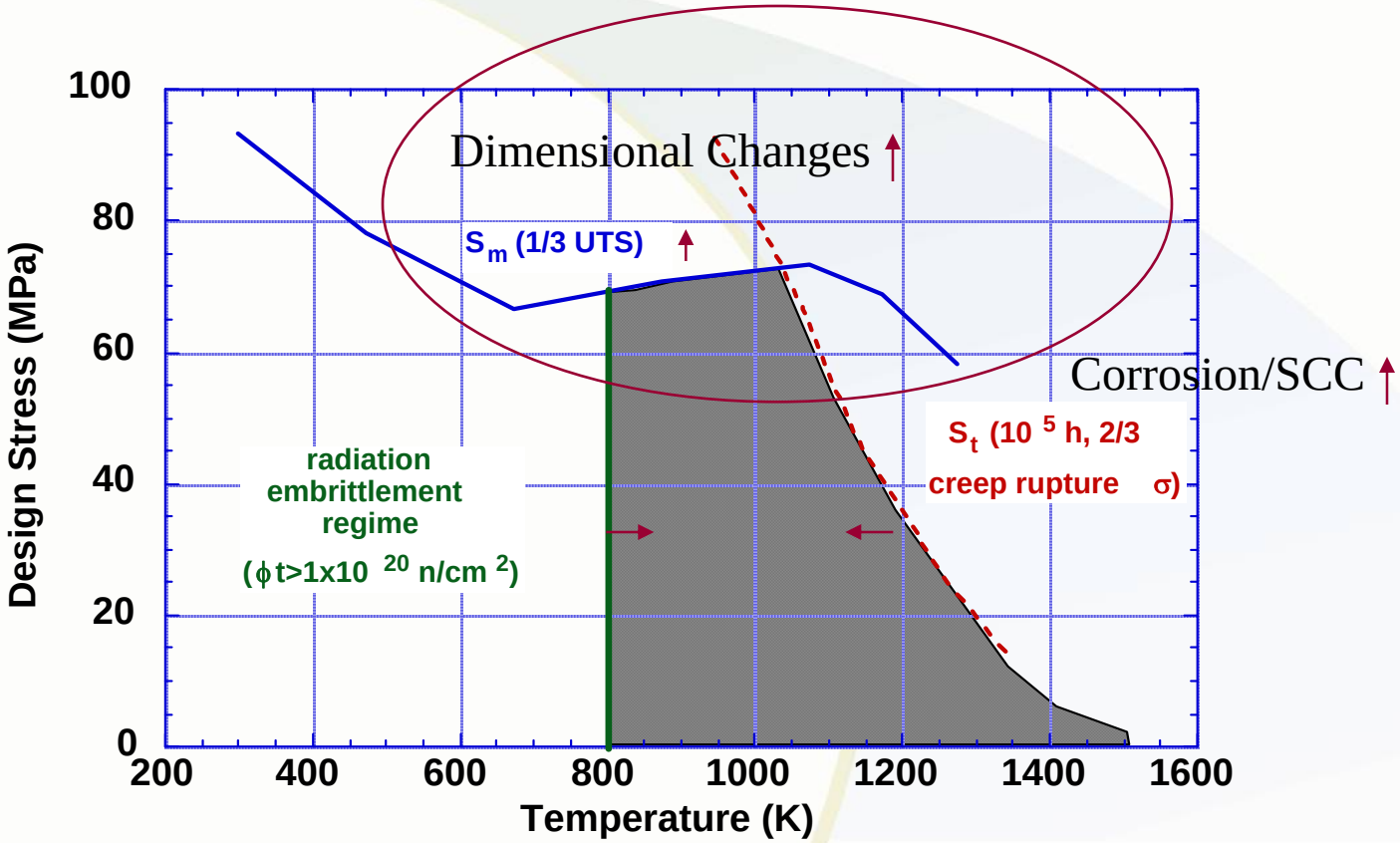
- Vacancies
- Interstitials

Brian Wirth, UCB

- Radiation-induced damage can come from
  - Immobile point defect clusters
  - Mobile point defects and point defect clusters

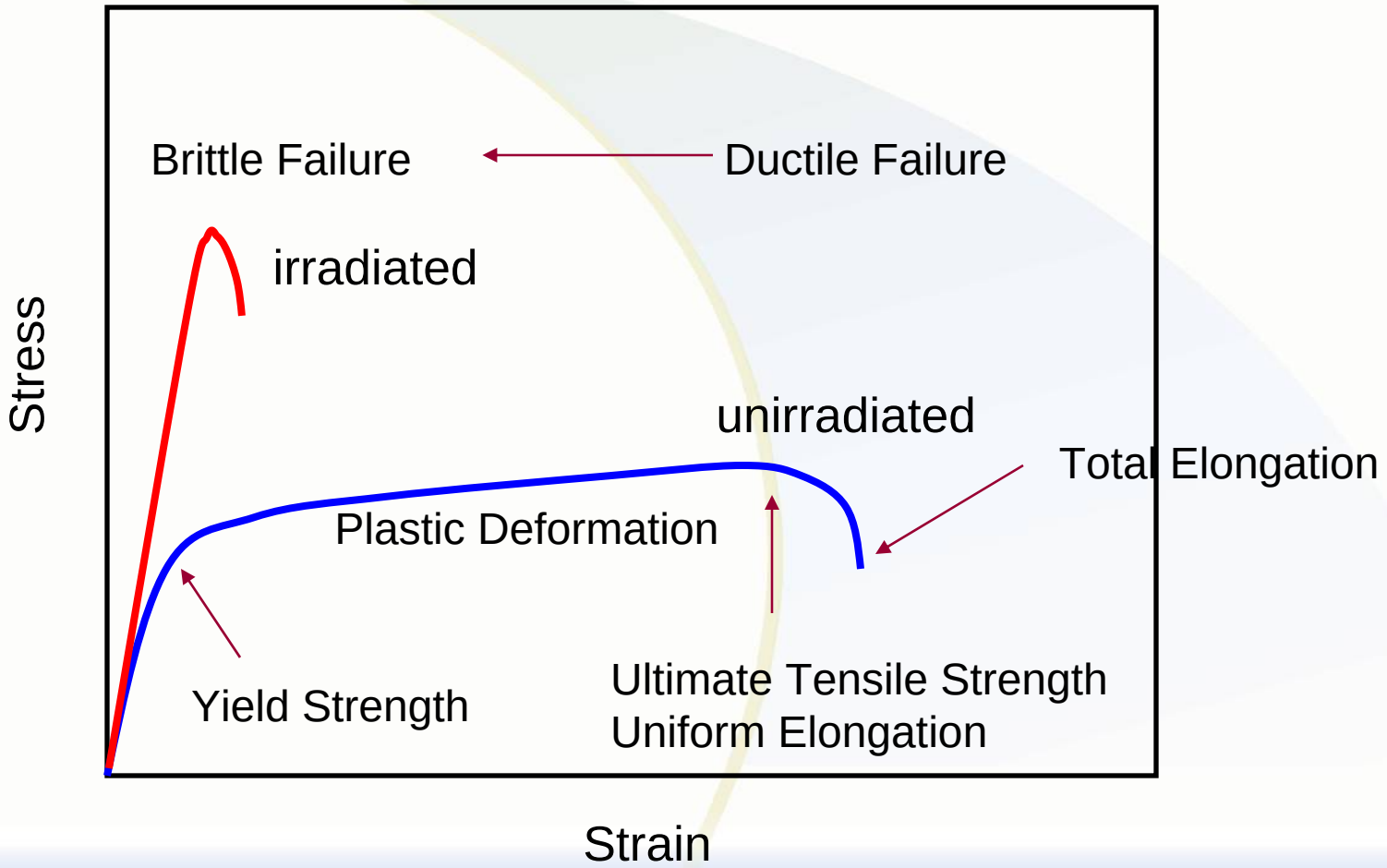


Design Windows



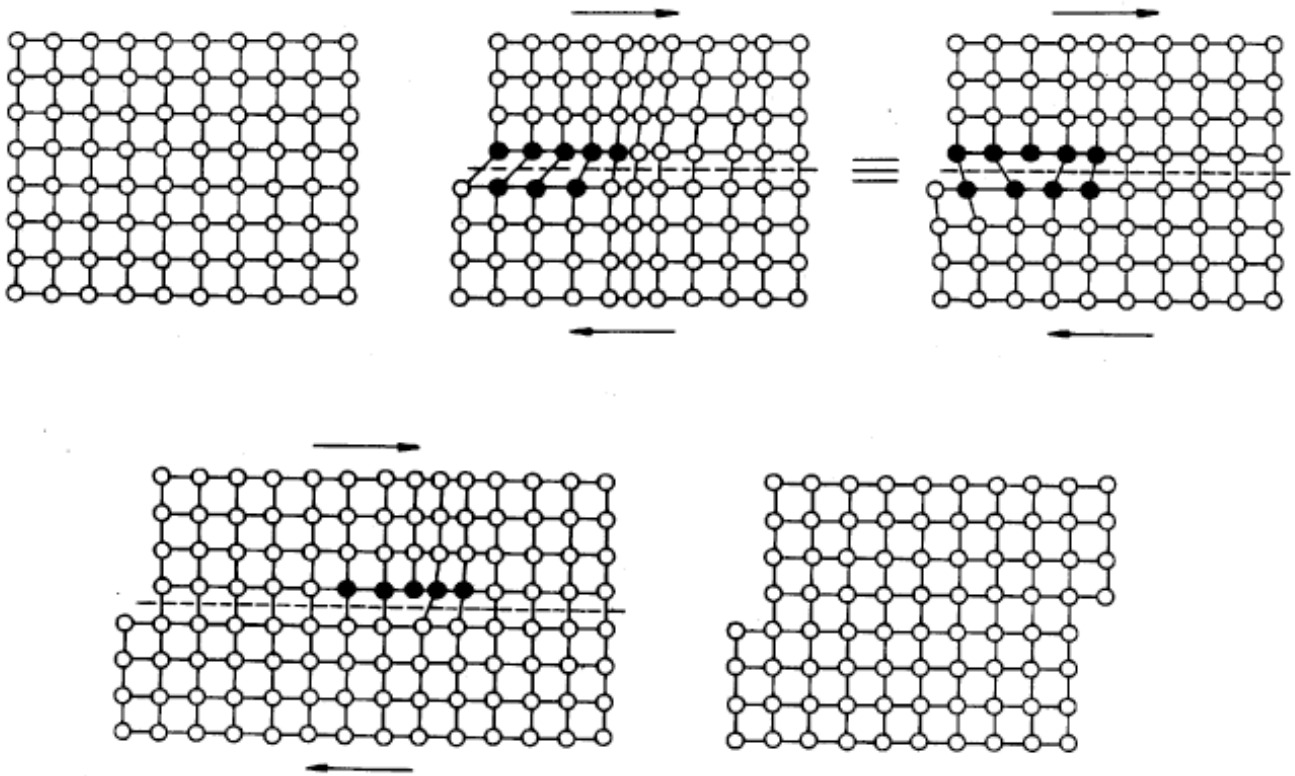
Properties change with radiation

Radiation Hardening



Loss of ductility is the concern

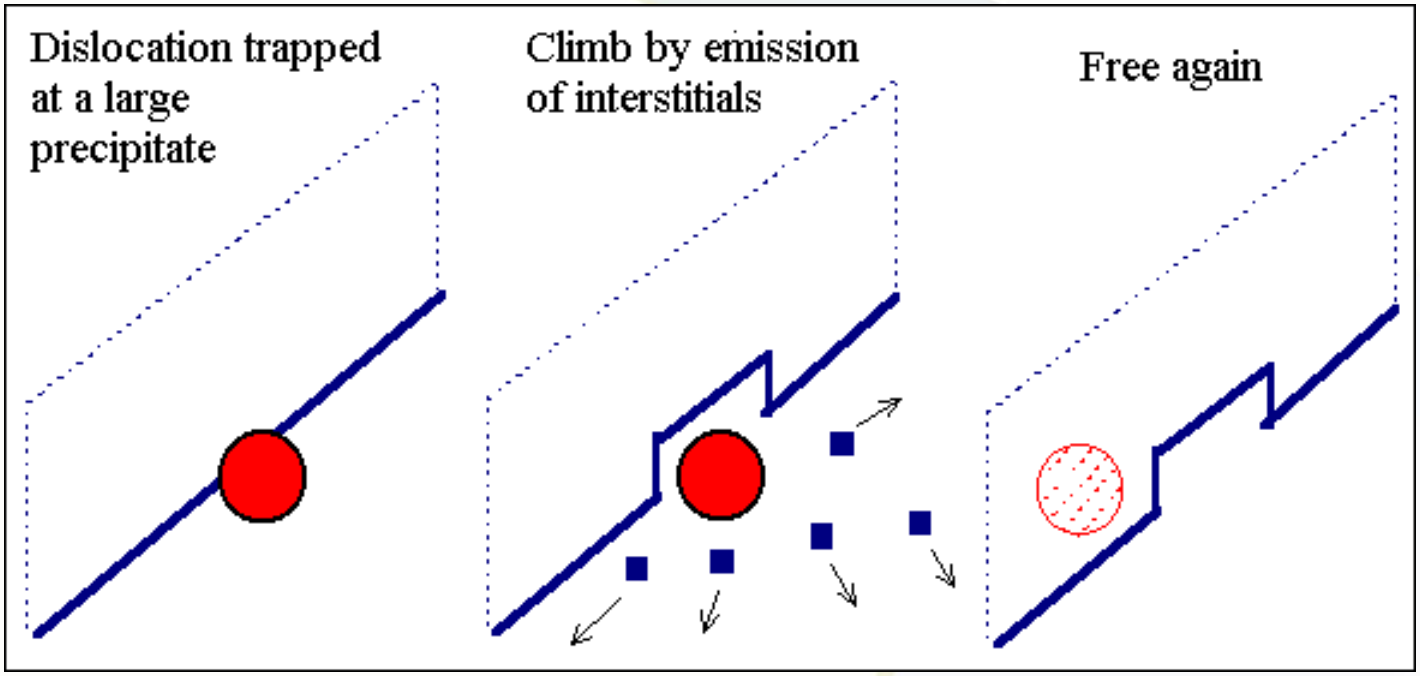
Plastic Deformation



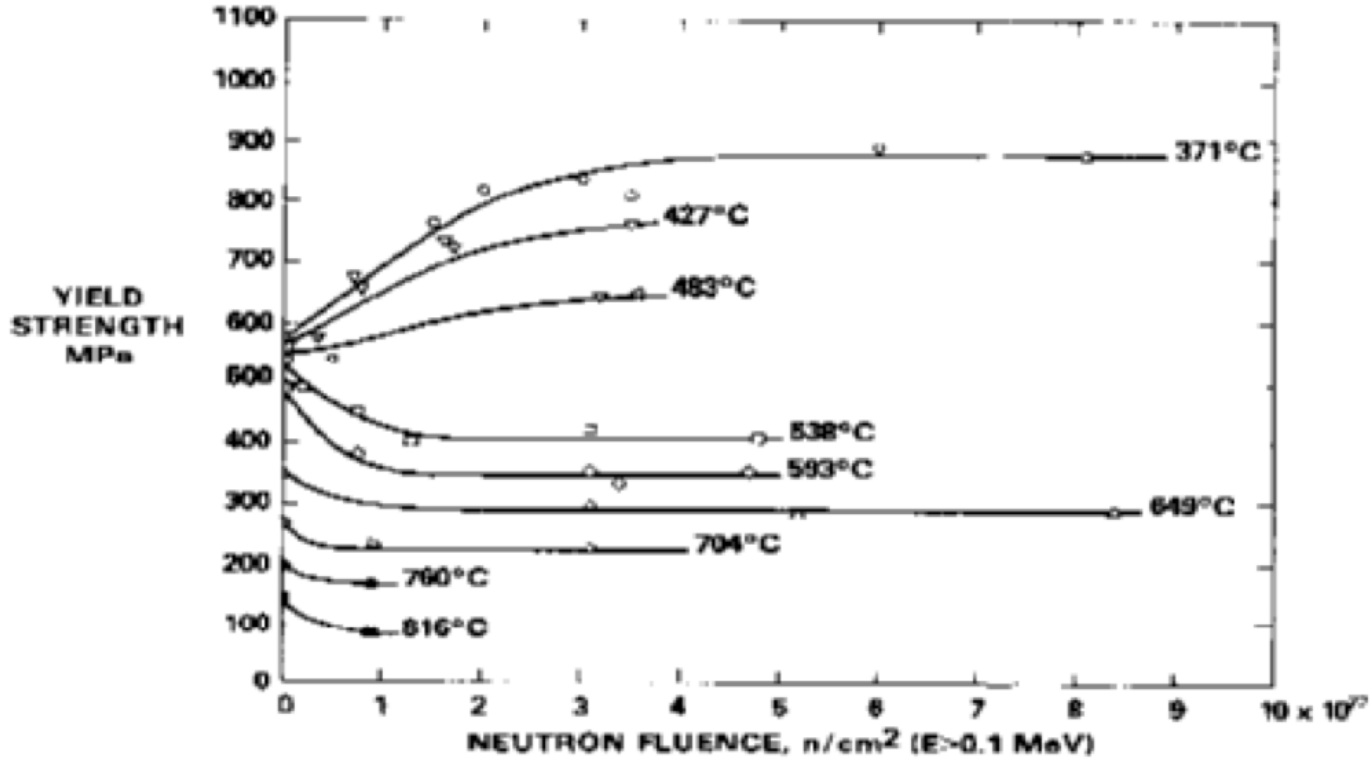
Hartmut Leipner

If the top half of the crystal is slipping one plane at a time, then only a small fraction of the bonds are broken at any given time and this would require a much smaller force.

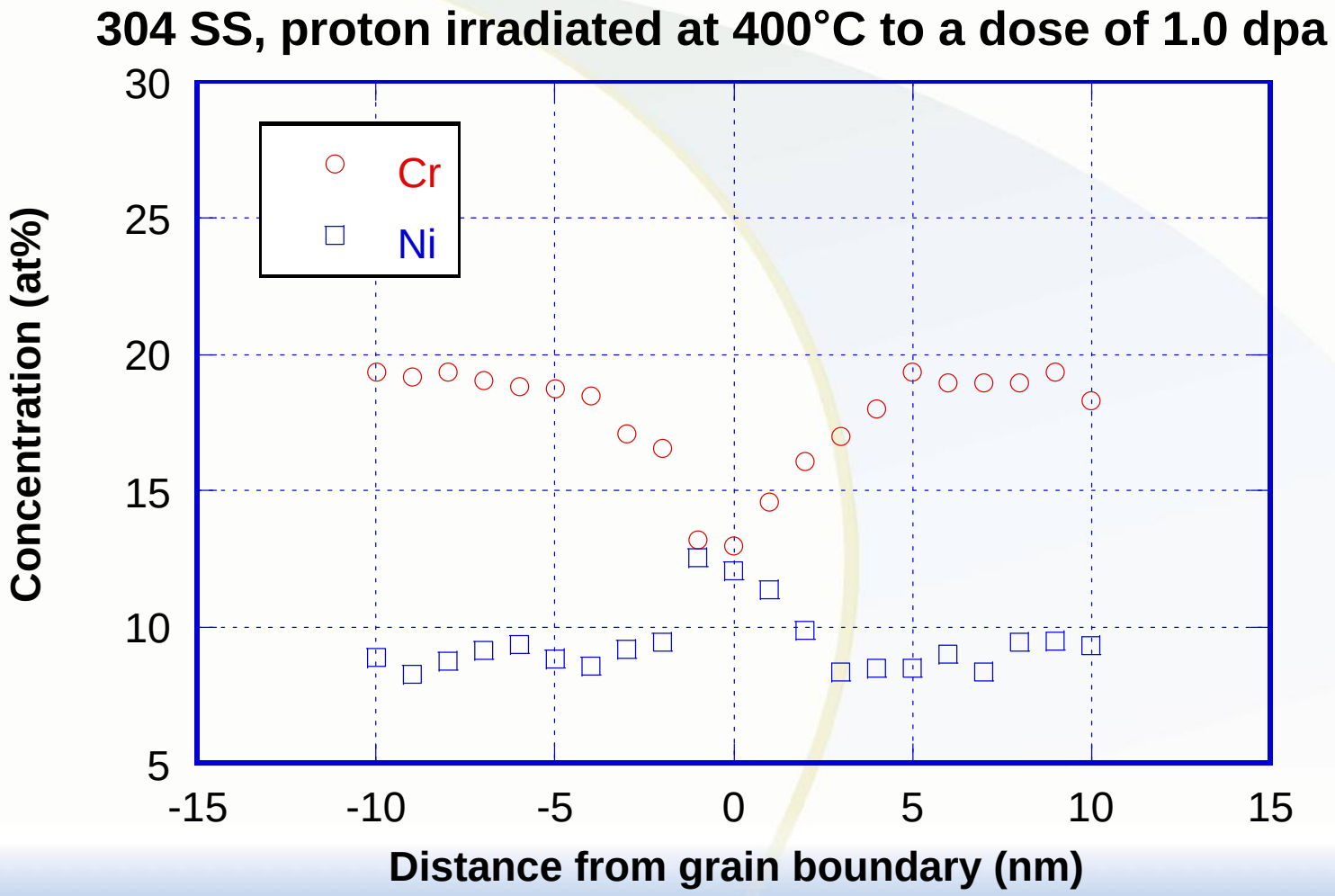
Overcoming Obstacles



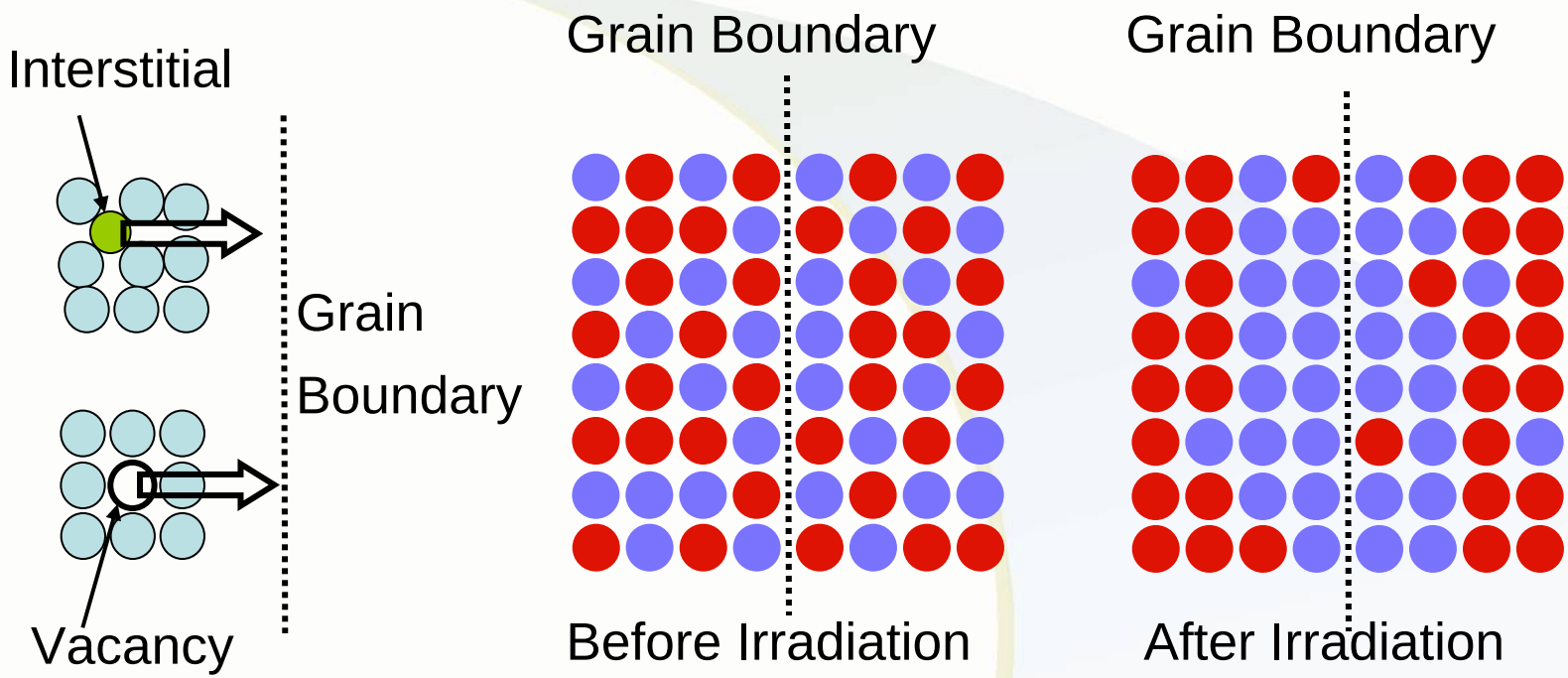
Hardening of Austenitic Steels



Grain Boundary Segregation



What is Radiation-induced Segregation?



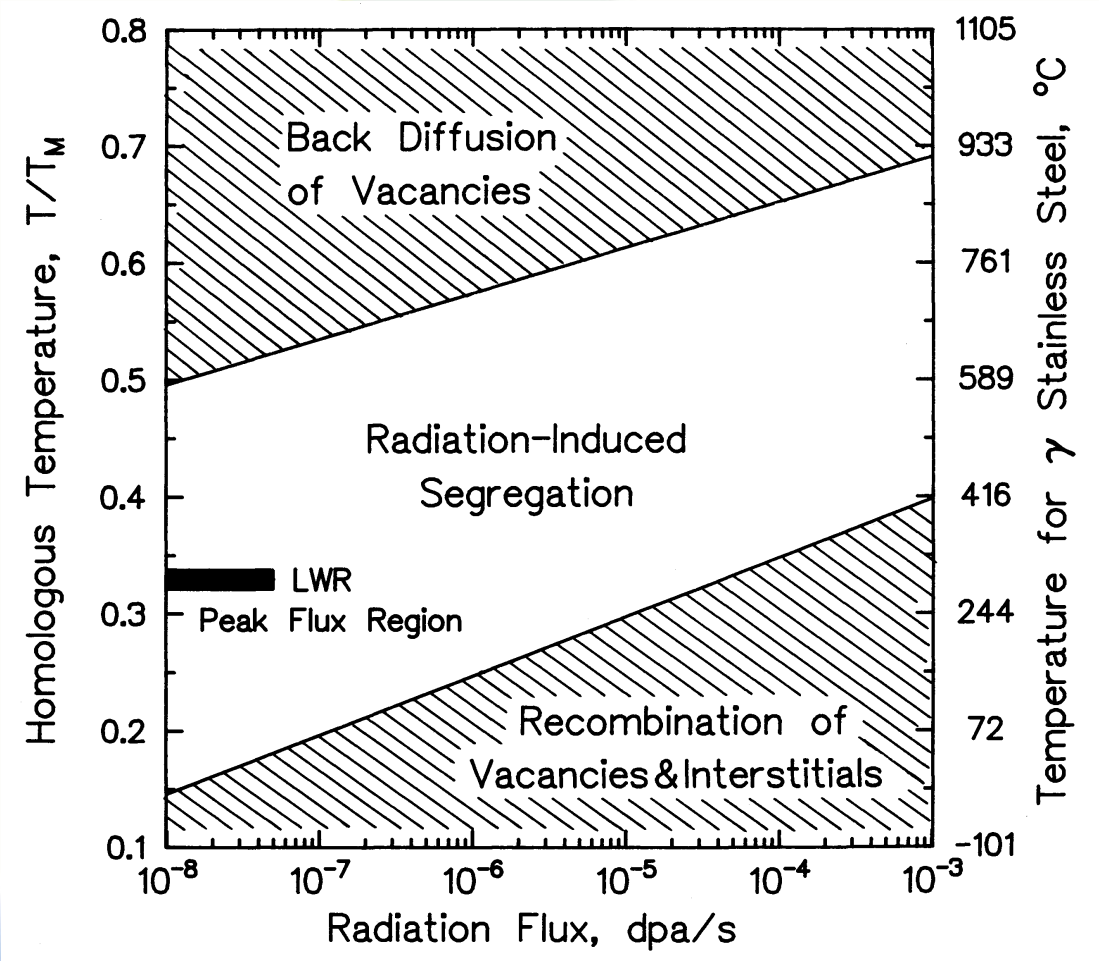
Possible RIS Mechanism to Enrich Blue

- Migrates preferentially as interstitials
- Exchanges preferentially with vacancies
- Vacancies drag species to sink

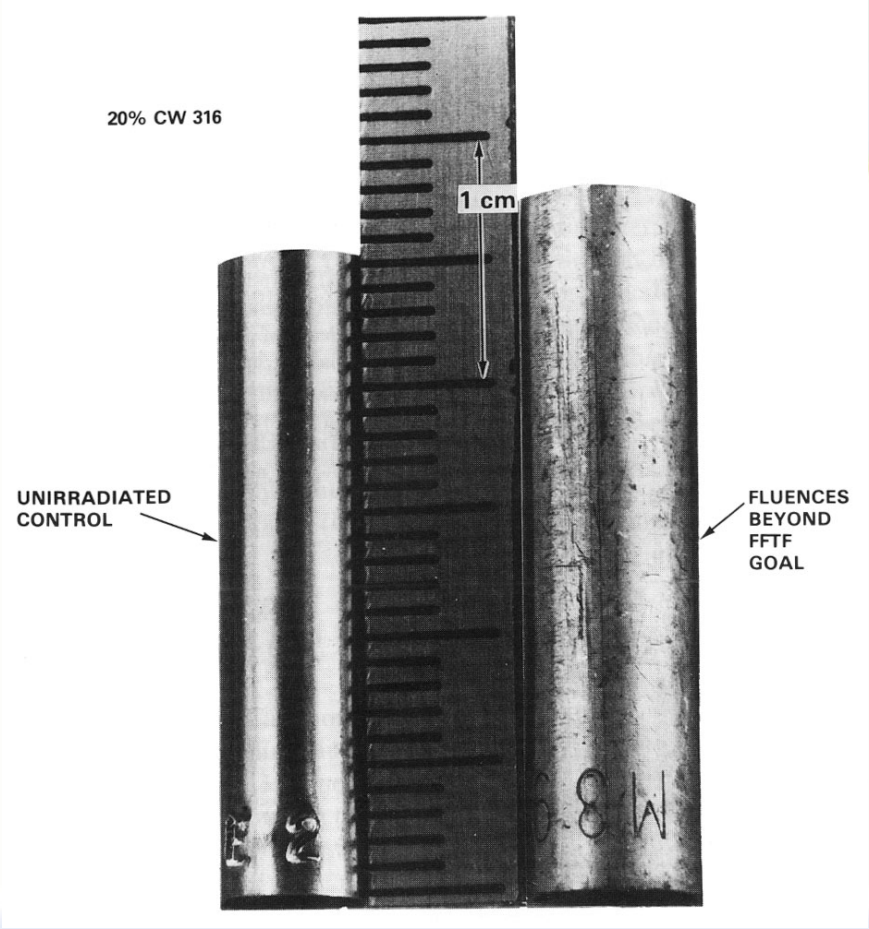
$$D^{I}_{Blue} > D^{I}_{Red}$$
$$D^{V}_{Blue} < D^{V}_{Red}$$
$$D^{V}_{Blue} > D^{V}_{Red}$$

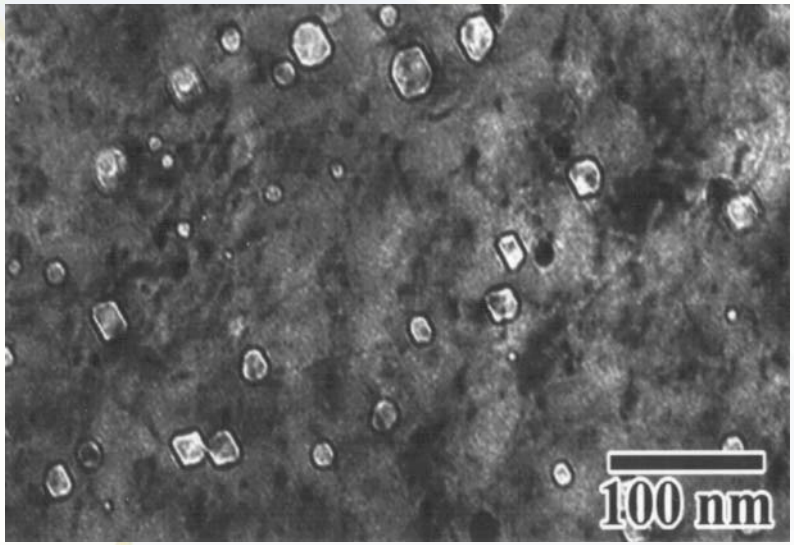
J. Tucker

Temperature-Displacement Rate Relationship in RIS

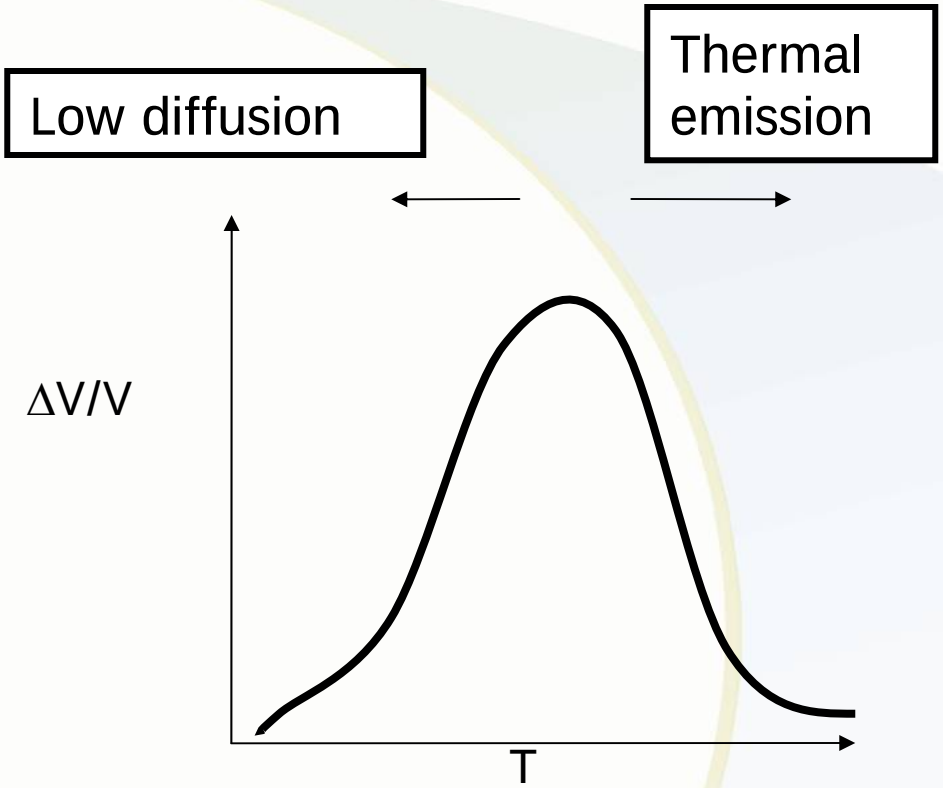


Easily Observed Swelling





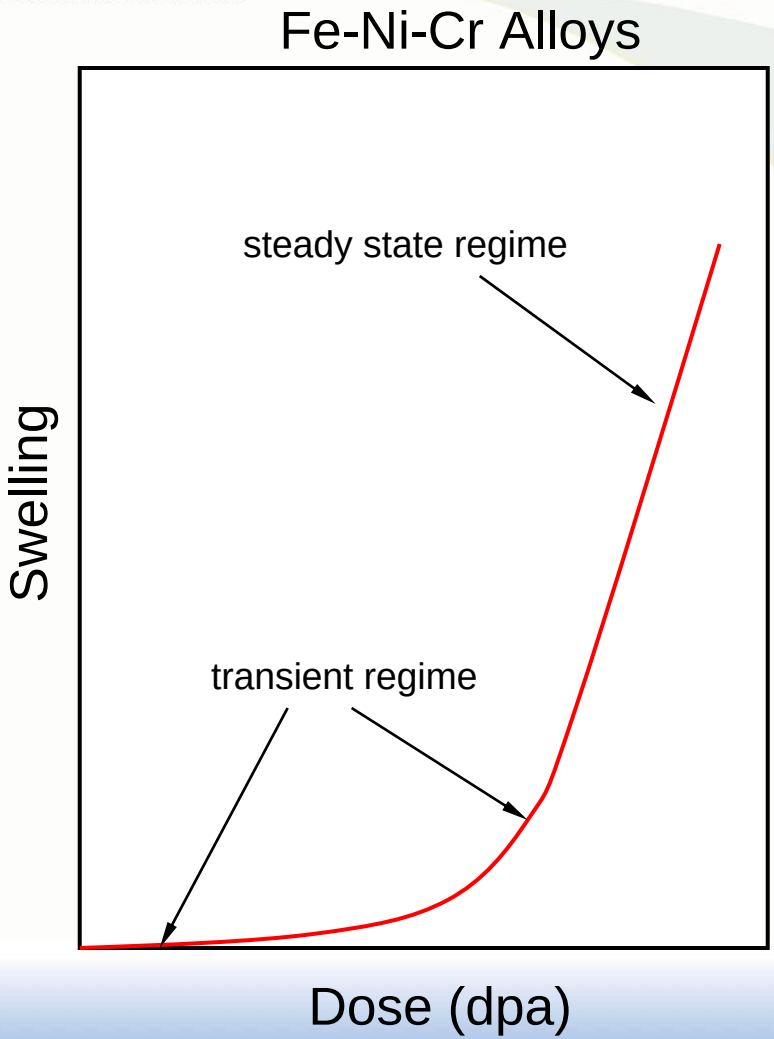
Temperature Regimes



Similar to RIS

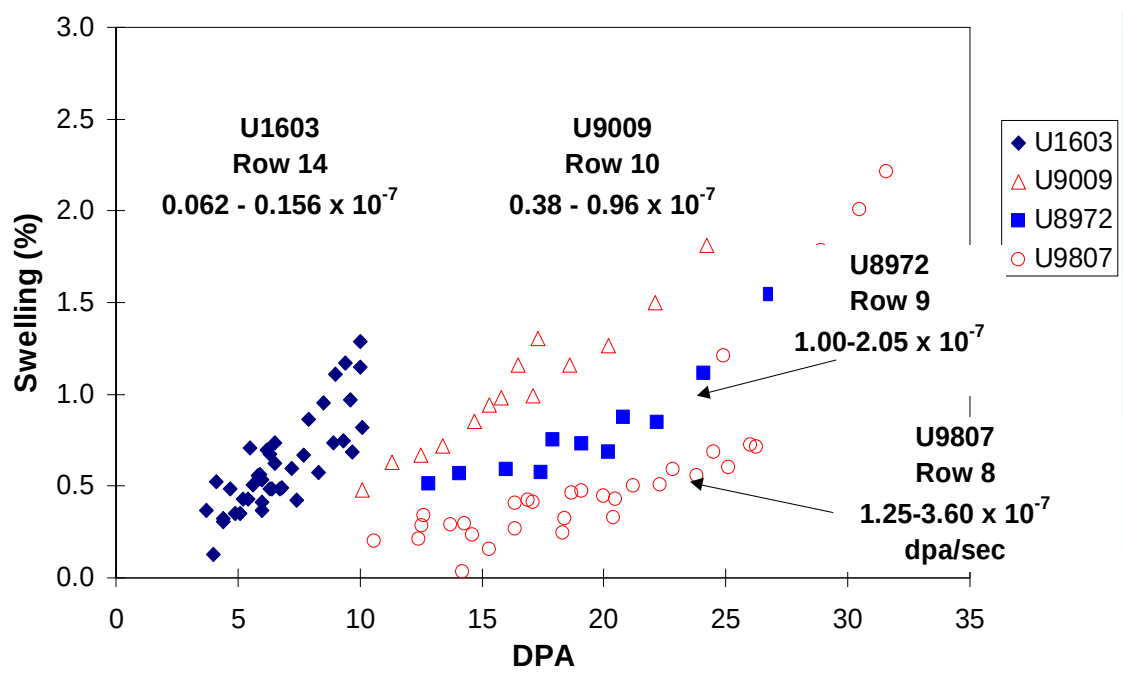
Most metals swell in temperature range of 0.3 T_m<T<0.55 T_m

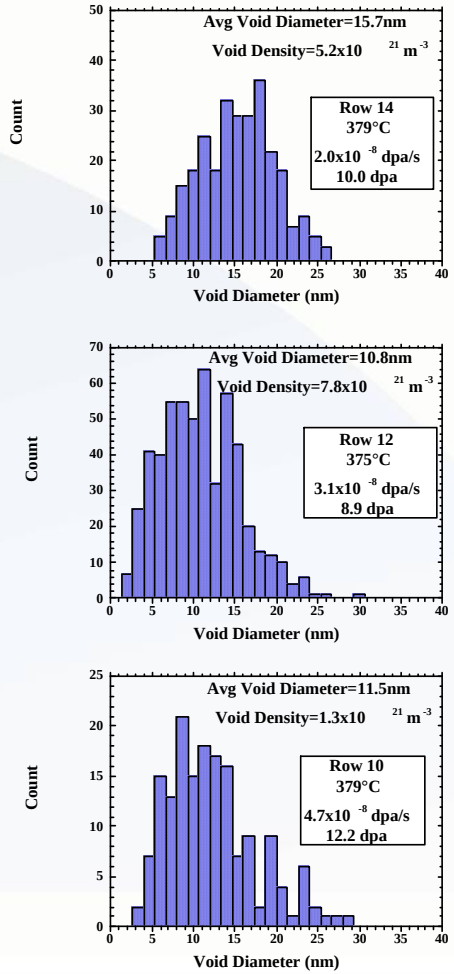
Transient Swelling Regime



- 1%/dpa for austenitic stainless steel
- 304 swells more (earlier) that 316
- 0.2%/dpa for ferritic-martensitic stainless steel

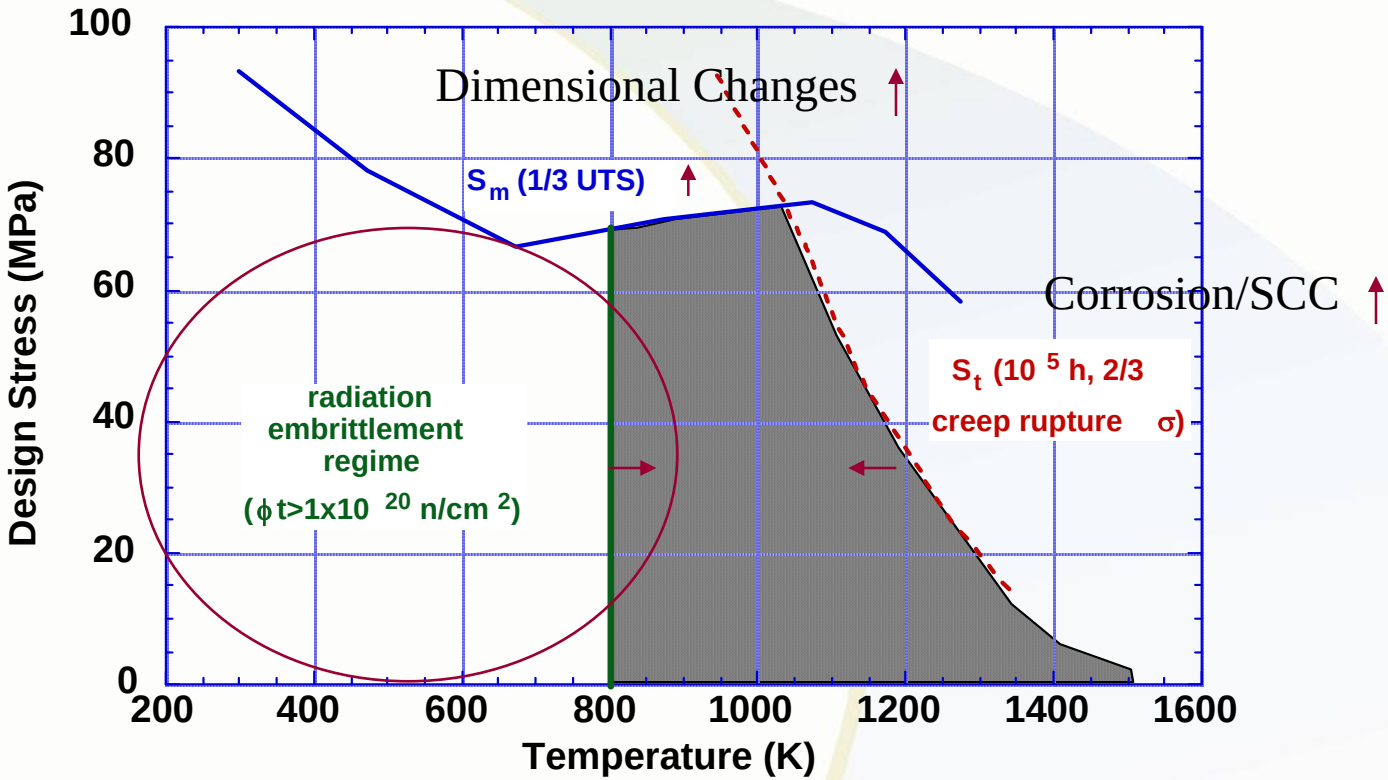
Dose Rate





Row 14
$\Delta V/V=1.3\%$

Design Windows

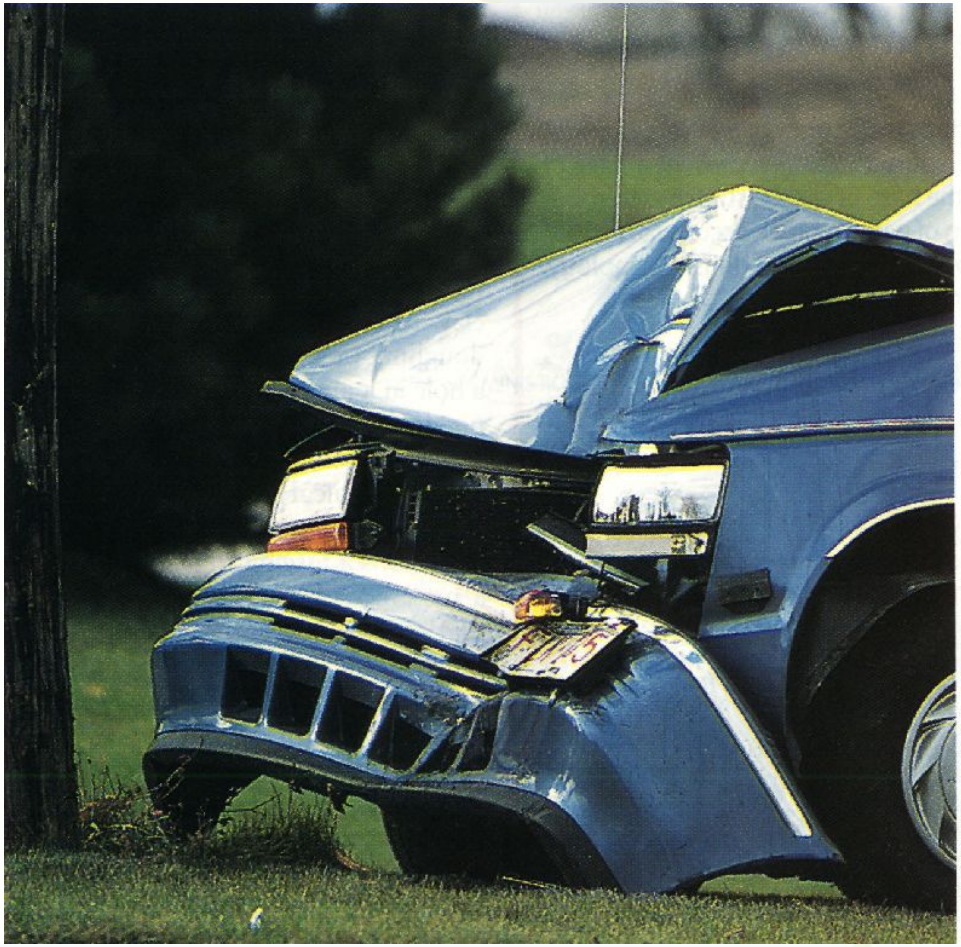


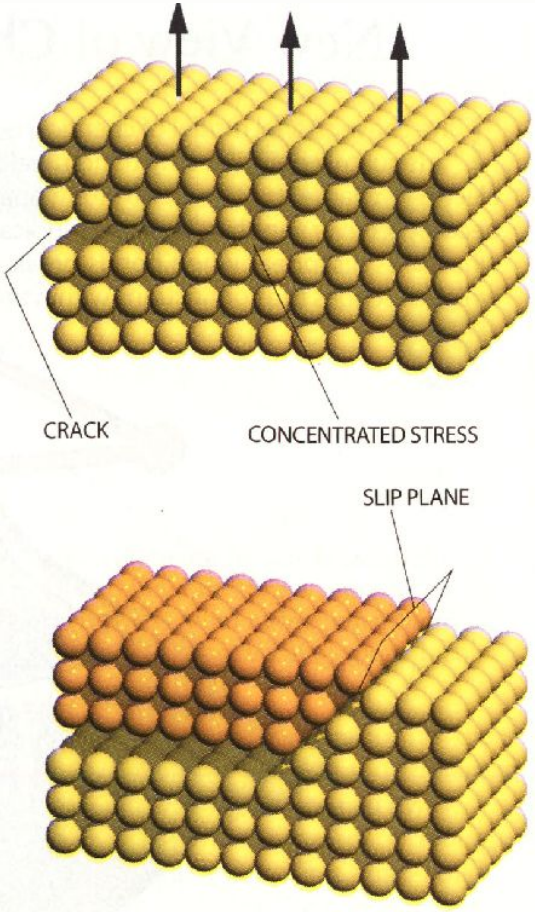
Properties change with radiation →

S. M. Zinkle, ORNL

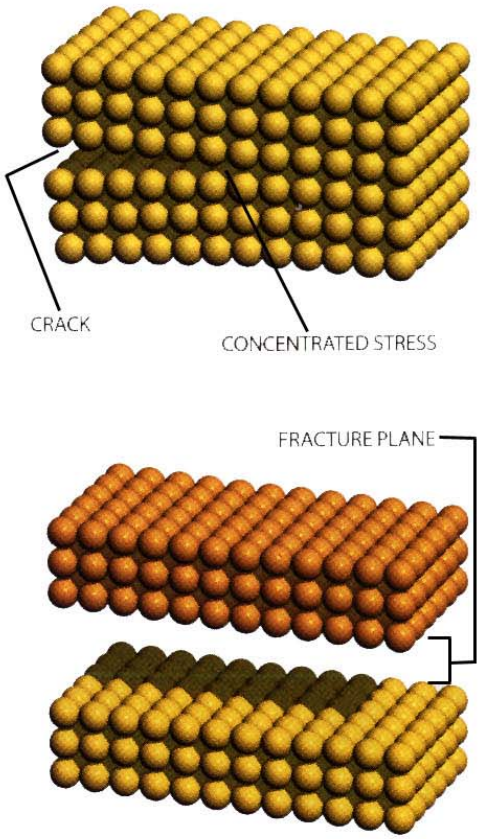
Idaho National Laboratory

Ductile Material





Brittle Material



Toughness-ability to absorb energy without fracture

Effect of T on Yield & Fracture Stresses

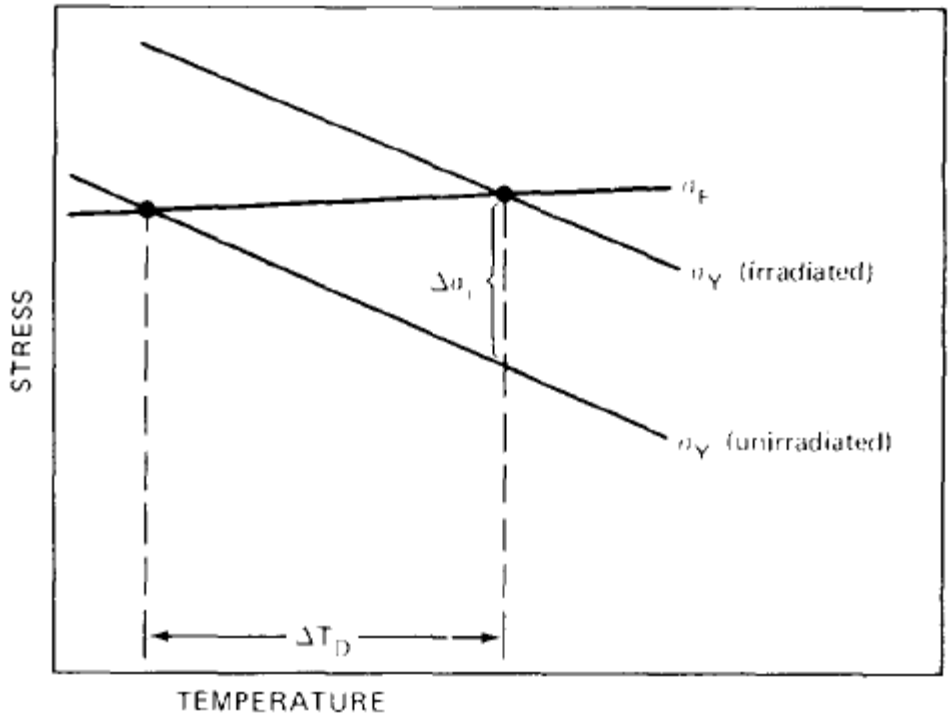
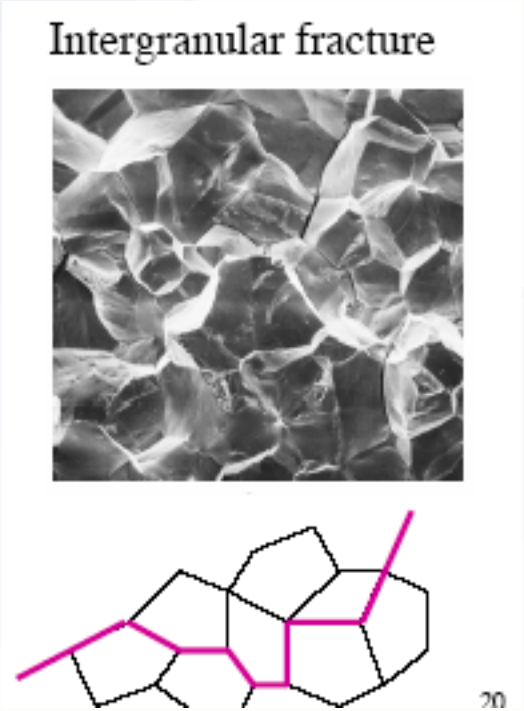
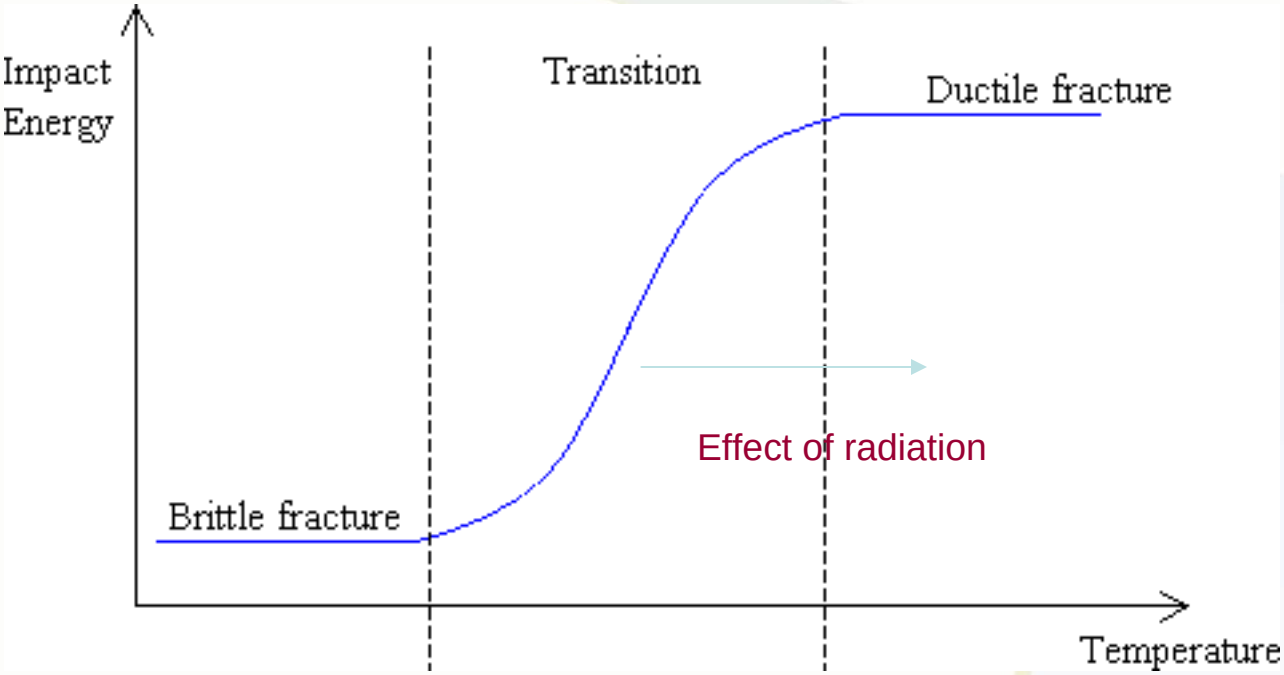


Fig. 18.45 Effect of temperature on the yield and fracture stresses of unirradiated and irradiated ferritic steel.

Fracture stress can be affected by grain boundary impurities



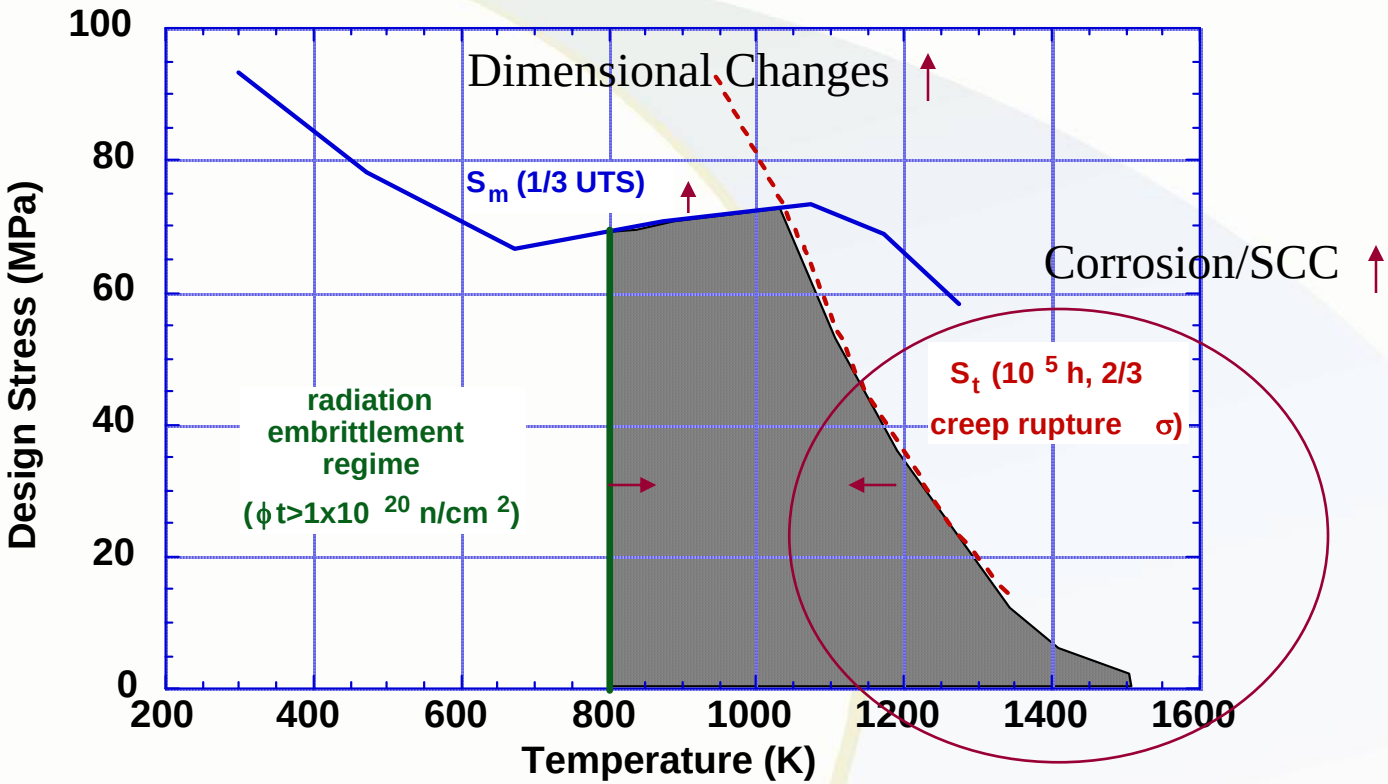
Toughness/DBTT



Change in GB composition
Matrix hardening
Void or bubble network
Precipitate network

If the stress required to move the dislocation is too high, the metal will fail instead by the propagation of cracks and the failure will be brittle

Design Windows



Properties change with radiation →

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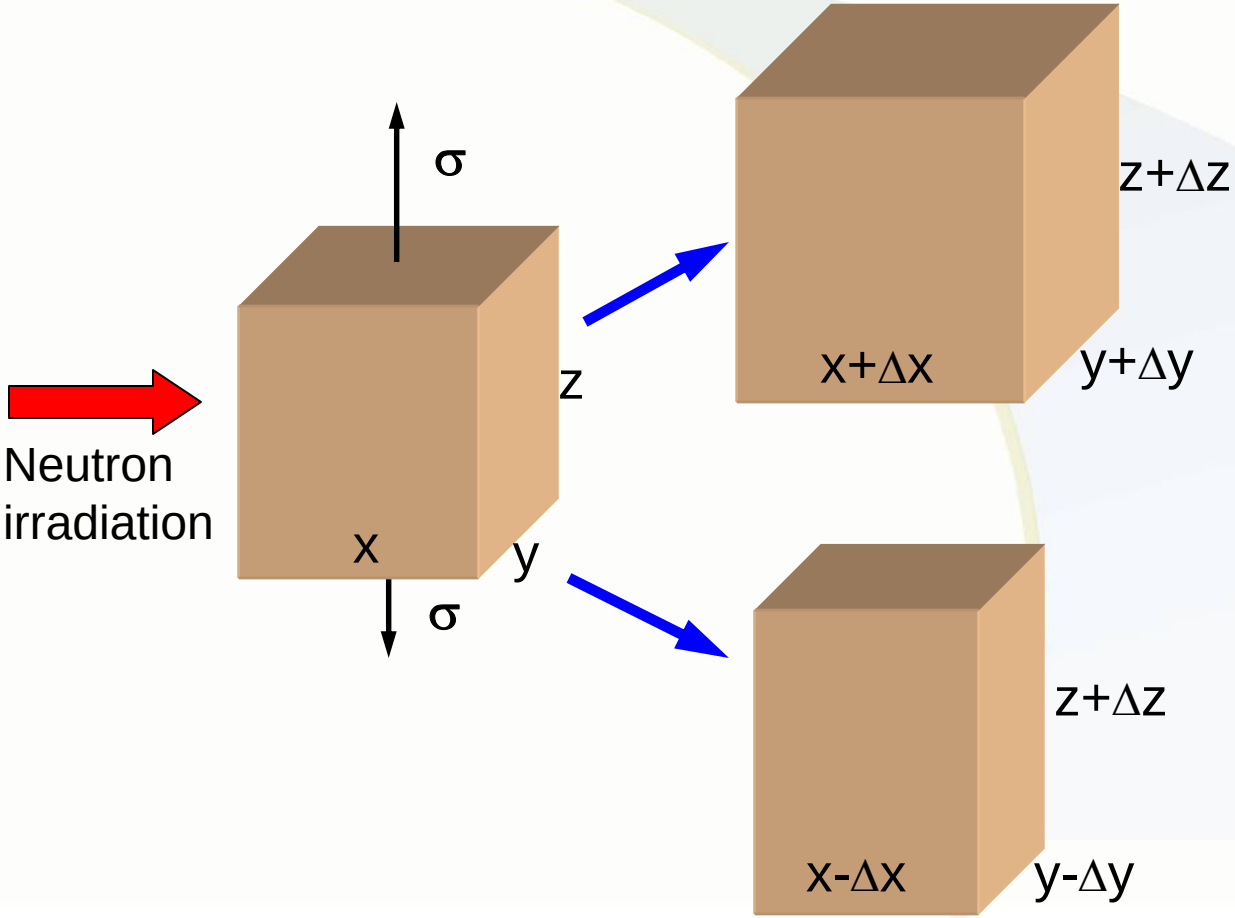
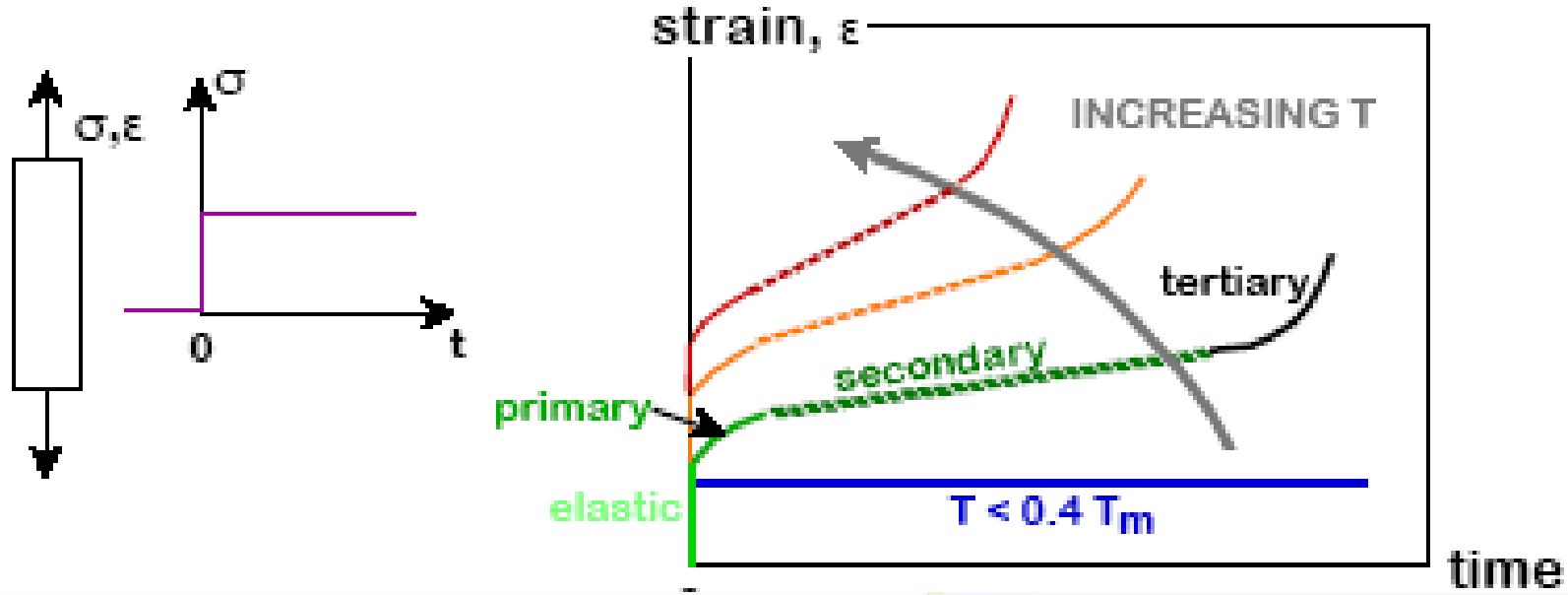
Swelling & Creep



Swelling:
- Volume increase
- Isotropic Shape Change
- Radiation-induced

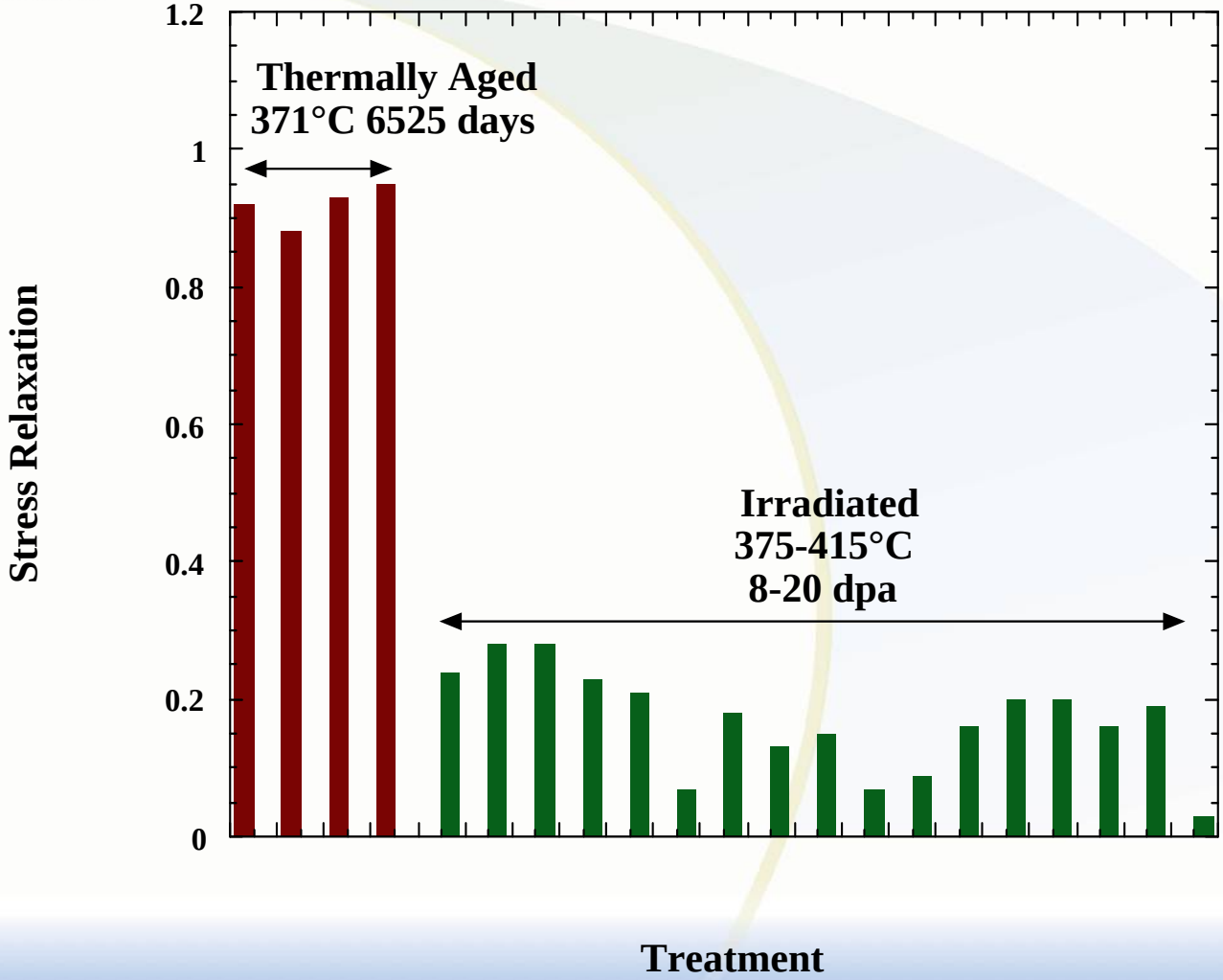
Creep:
- No volume change
- Shape Change
- Radiation-influenced

Creep



- **Radiation produced point defects increase diffusion and allow creep at lower temperatures**

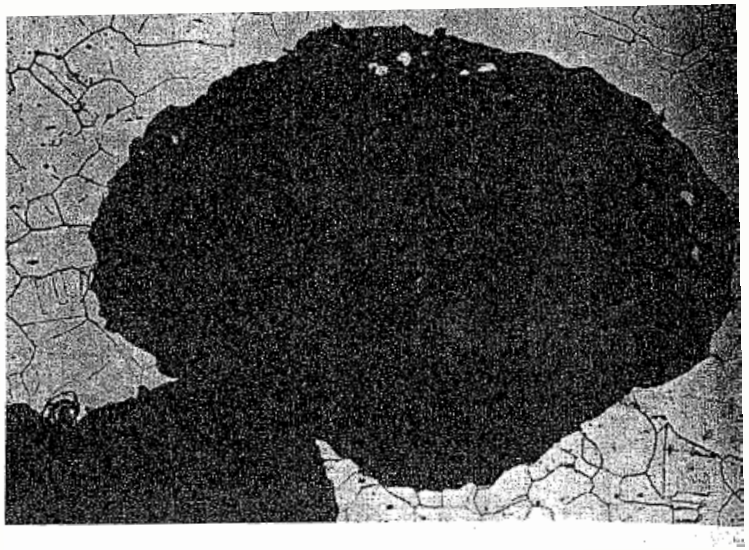
Radiation-Induced Stress Relaxation

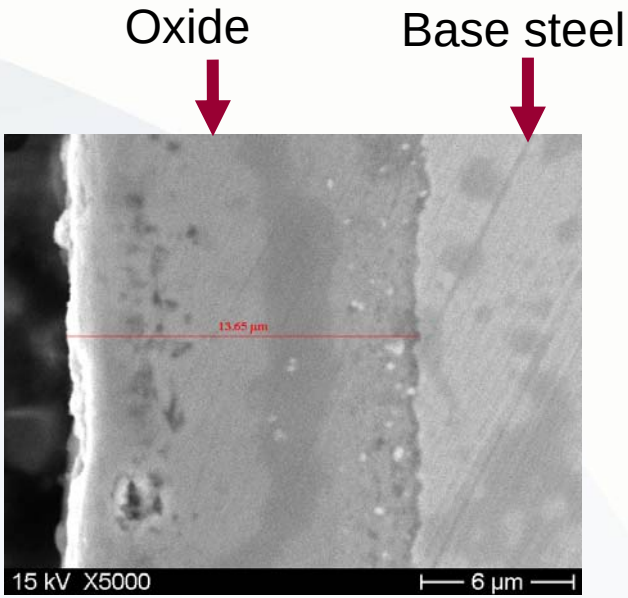


Corrosion

- General Corrosion, cation release & fouling
- Flow Assisted Corrosion
- Erosion-corrosion (Steam cutting)
- Localized corrosion (Pitting, crevice and microbial corrosion)
- Stress corrosion cracking and hydrogen embrittlement
- Corrosion fatigue

Broadly - two types of corrosion



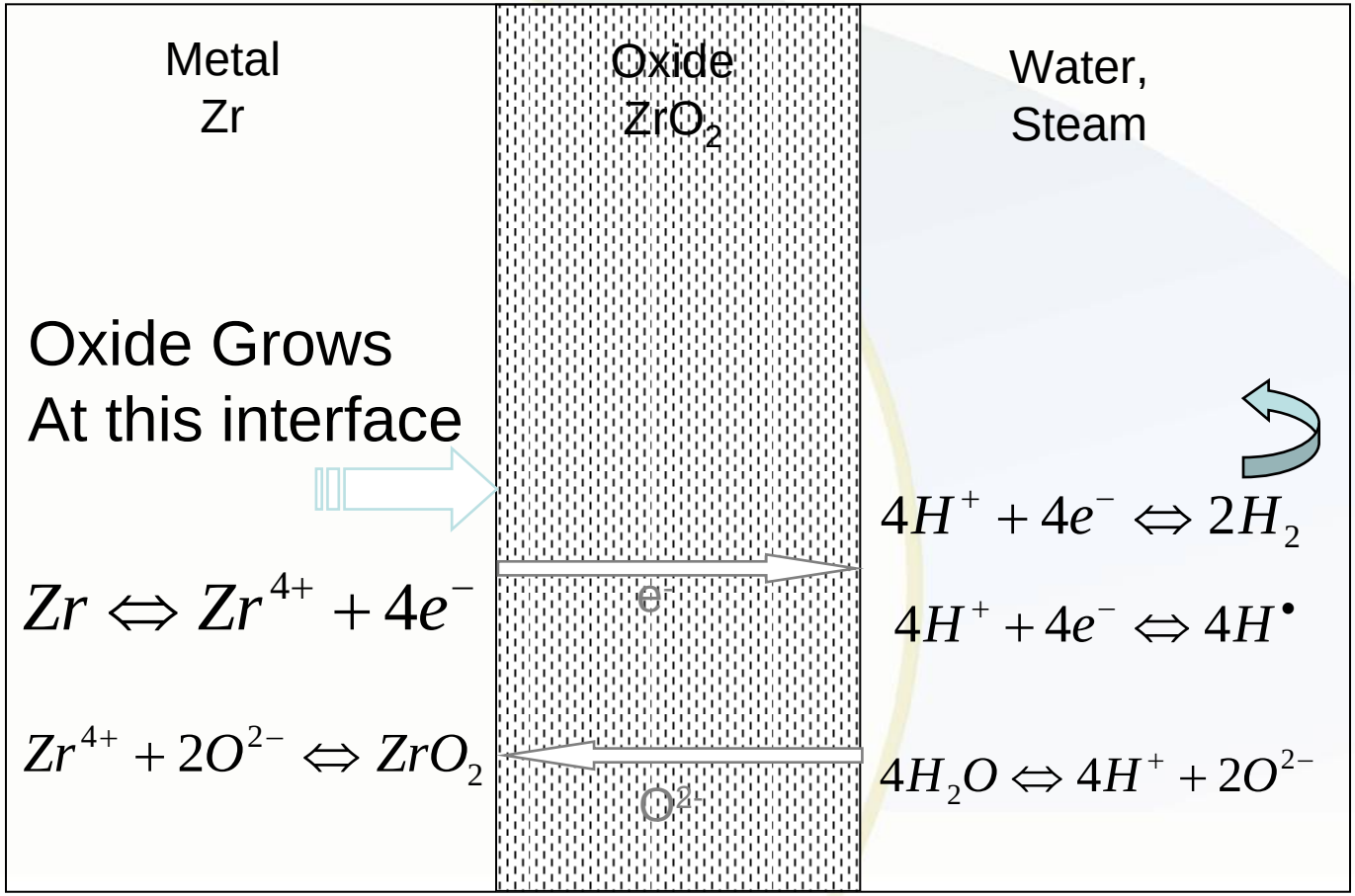


Removal of material (uniform corrosion or pitting) into the environment, usually low temperature aqueous corrosion (weight loss)

(*pitting on 316 stainless steel*)

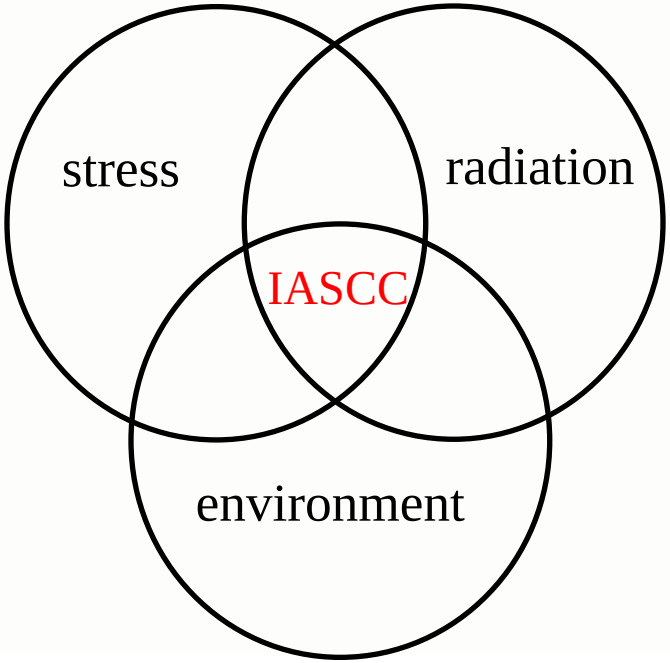
Build-up of corrosion product, usually an oxide, usually high temperature corrosion (weight gain)

Oxide film formation mechanism



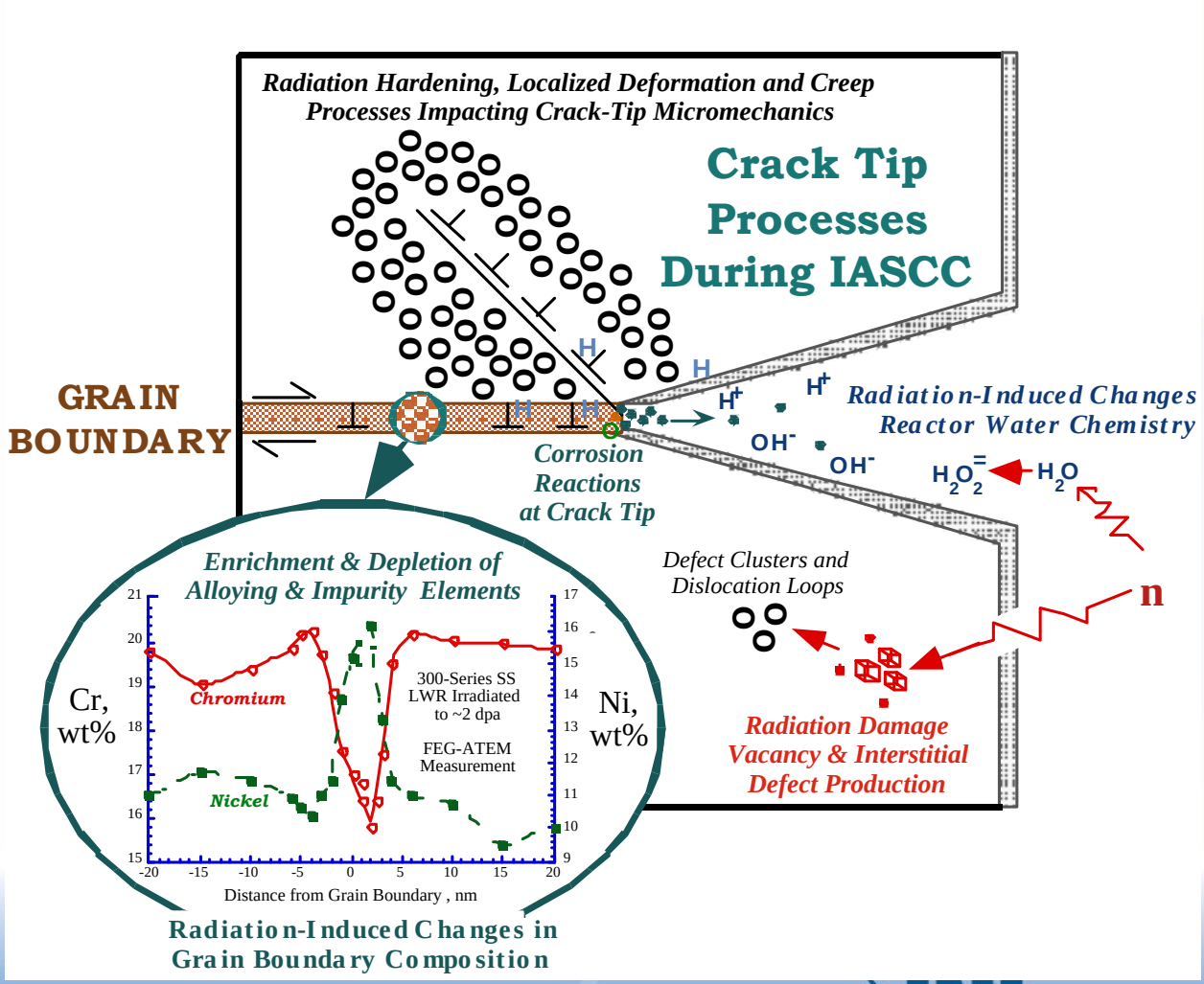
Irradiation Assisted Stress Corrosion Cracking

- IASCC occurs in Fe, and Ni base austenitic reactor materials
- Component cracking occurs at stress levels well below design stress

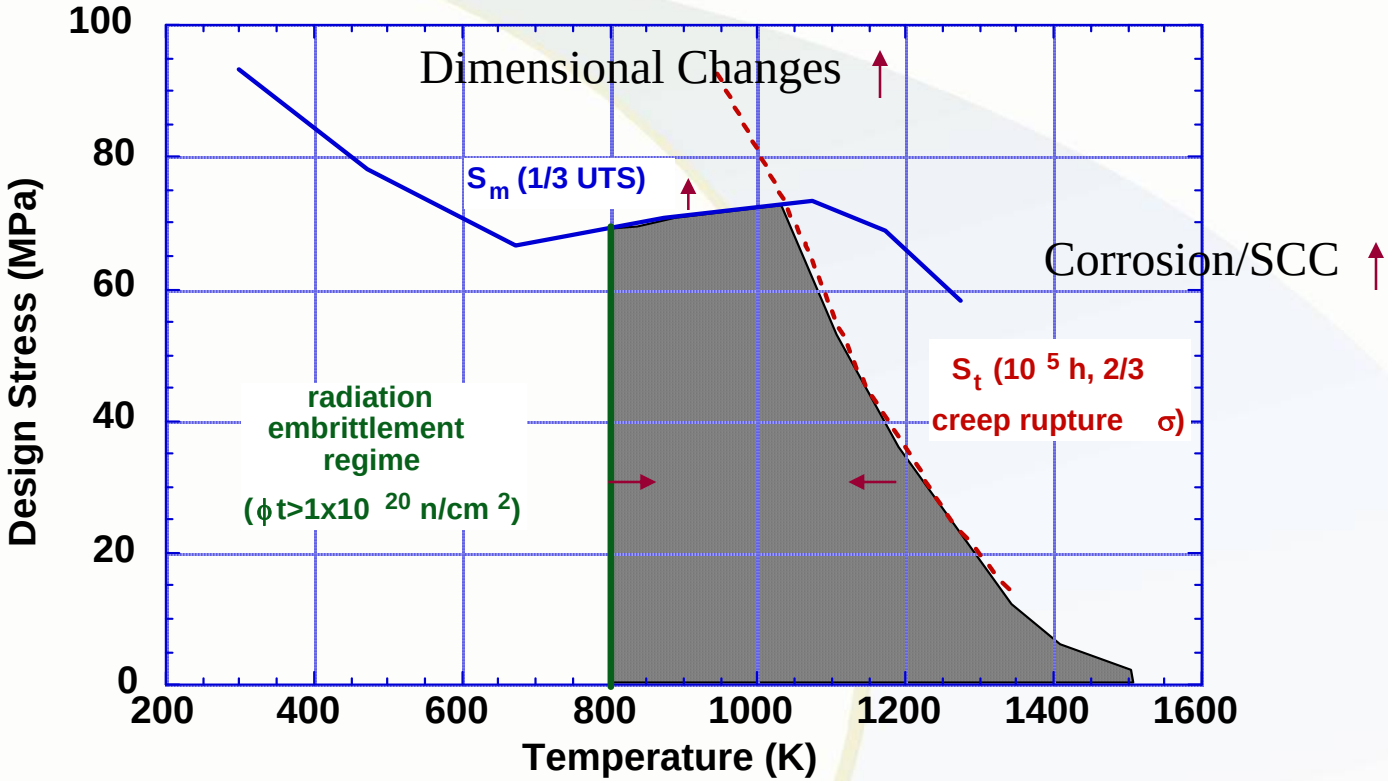


Intergranular cracking

Irradiation Assisted Stress Corrosion Cracking



Design Windows



Properties change with radiation →

S. M. Zinkle, ORNL