# Qualitative Radiation Effects in Structural Materials

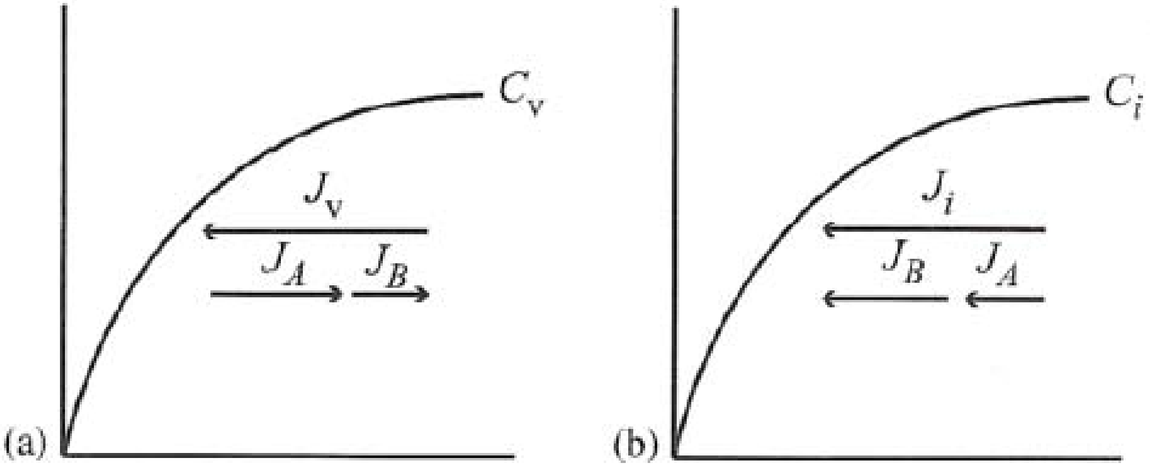
**Figures taken from G. S. Was, “Fundamentals of Radiation Materials Science” unless otherwise noted**

# Learning Objectives

- Intuitively understand a few radiation effects in structural materials
  - Phase instability
  - Radiation induced segregation
  - Void swelling
  - Dislocation loops
  - Hardening & embrittlement
- Understand material selection choices in nuclear systems with radiation present

# Phase Instability

- Precipitation and dissolution
  - Related to point defect movement towards sinks



Movement of vacancies (V), interstitials (I), and atoms A & B towards a defect sink in a binary A-B alloy

# Directions of Movement

**Atomic size helps determine whether an atom will move preferentially via vacancies or interstitials**

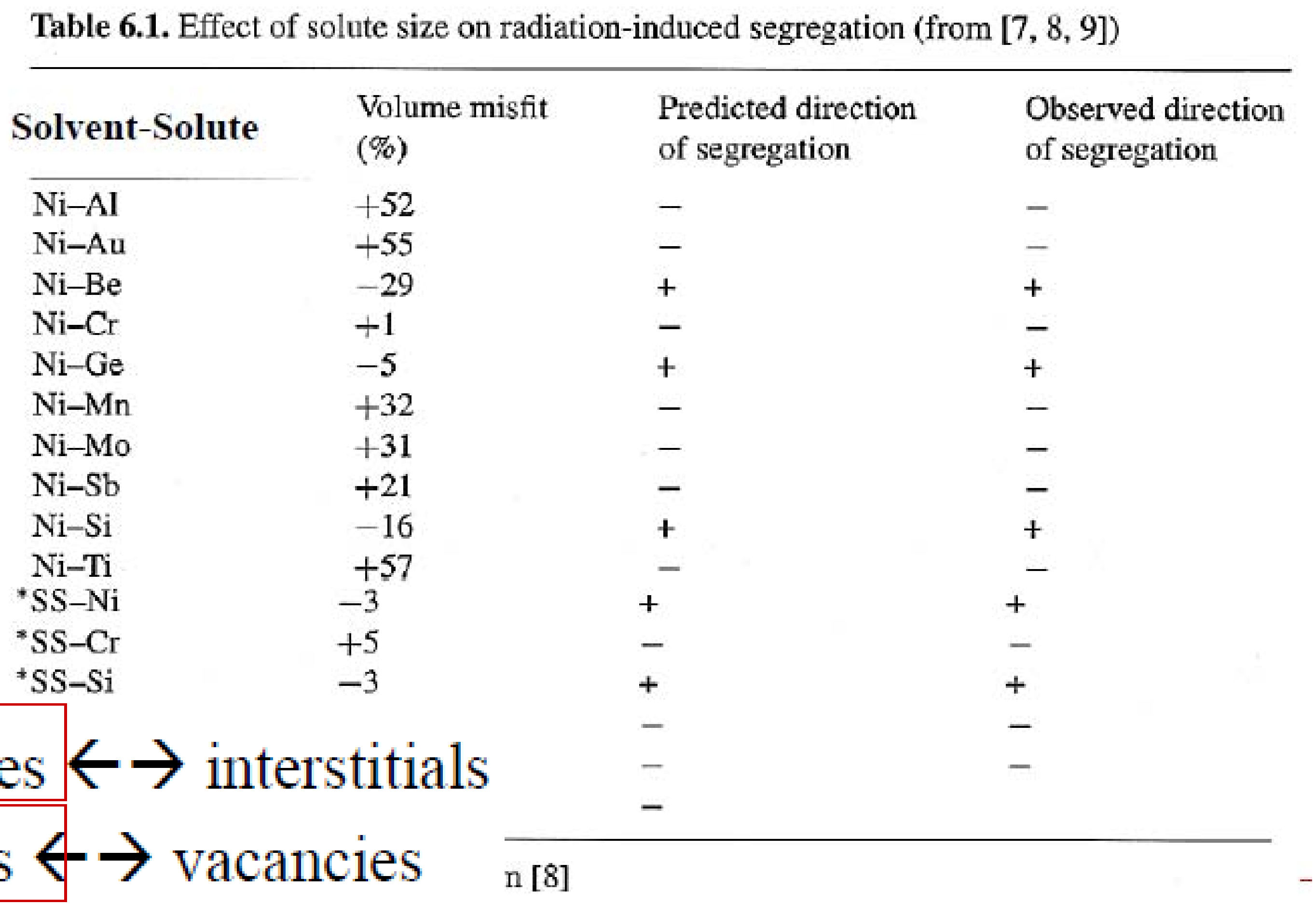


**Table 6.1.** Effect of solute size on radiation-induced segregation (from [7, 8, 9])

| Solvent-Solute | Volume misfit (%) | Predicted direction of segregation | Observed direction of segregation |
|---|---|---|---|
| Ni–Al | +52 | − | − |
| Ni–Au | +55 | − | − |
| Ni–Be | −29 | + | + |
| Ni–Cr | +1 | − | − |
| Ni–Ge | −5 | + | + |
| Ni–Mn | +32 | − | − |
| Ni–Mo | +31 | − | − |
| Ni–Sb | +21 | − | − |
| Ni–Si | −16 | + | + |
| Ni–Ti | +57 | − | − |
| *SS–Ni | −3 | + | + |
| *SS–Cr | +5 | − | − |
| *SS–Si | −3 | + | + |
| | | − | − |
| | | − | − |
| | | − | |

n [8]

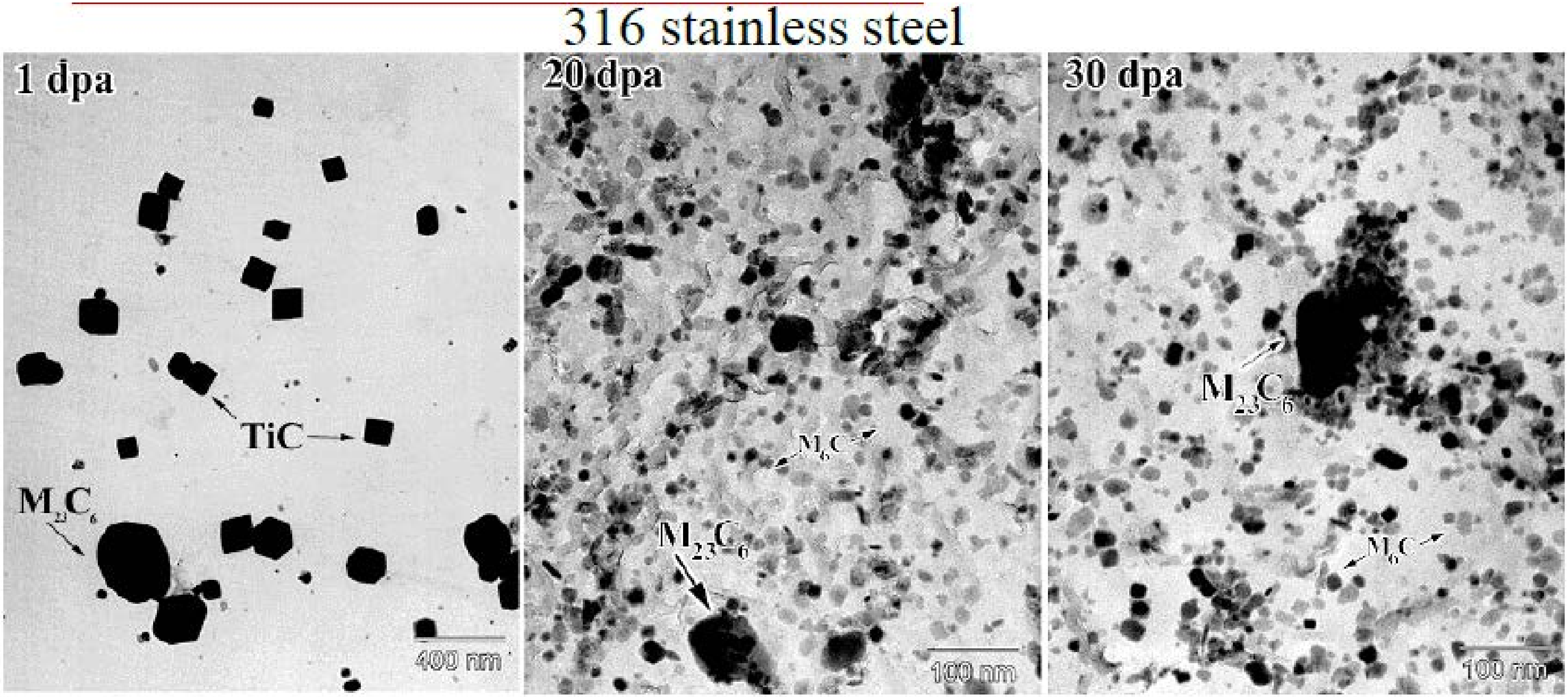
Undersize solutes ←→ interstitials

Oversize solutes ←→ vacancies

# Precipitation

[Fig. 9.2 from Gary S. Was. *Fundamentals of Radiation Materials Science*. ISBN: 9783540494713] removed due to copyright restrictions.

# Precipitation



# Dissolution

For systems with little solubility, dissolution would break up the particles into a set of finer particles. Mechanism would be independent of temperature.

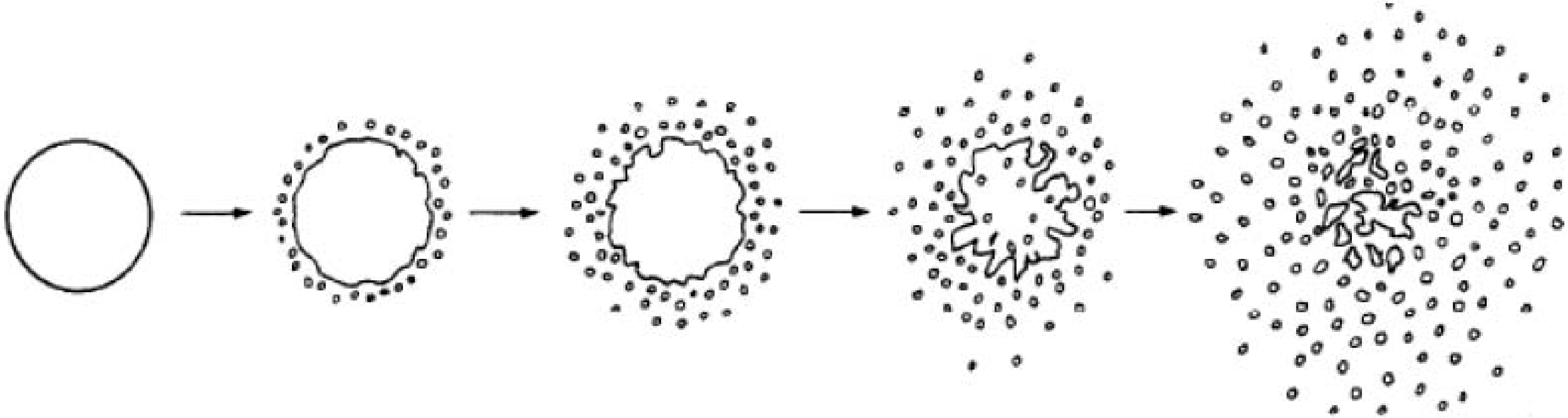


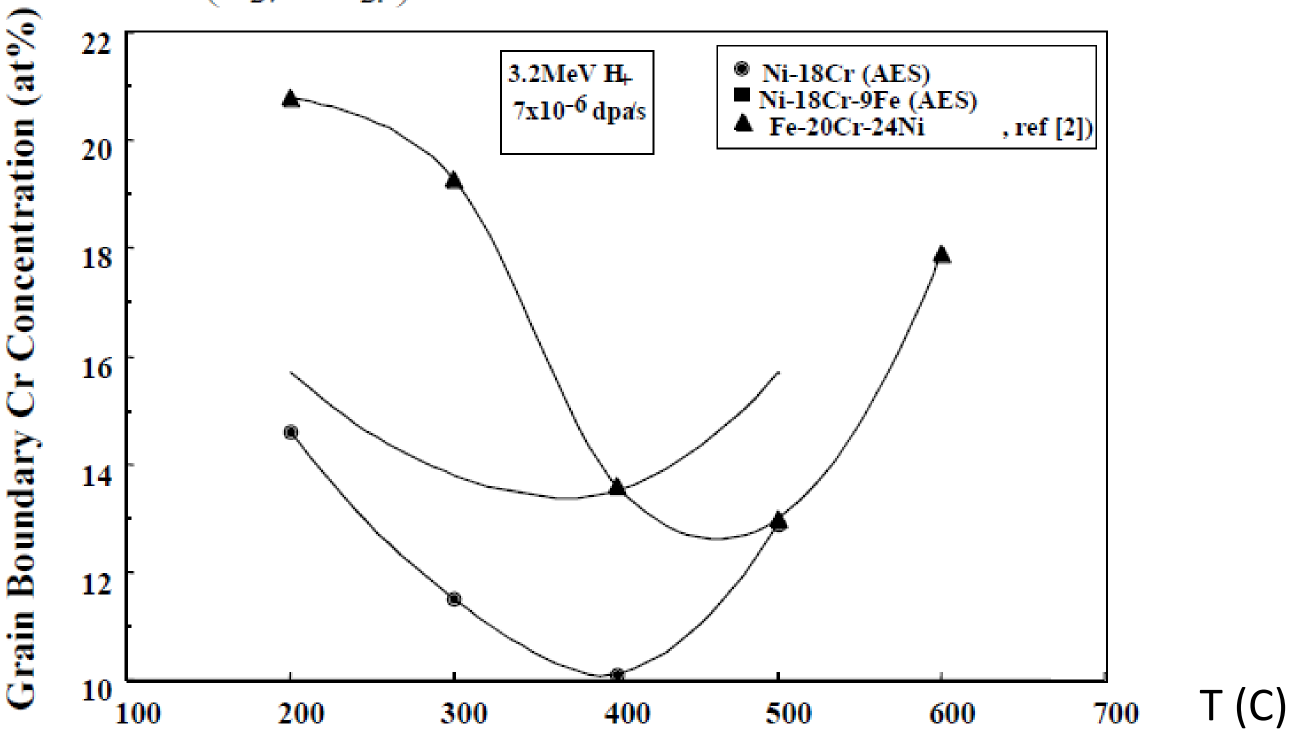
Fig. 6. Progress of dissolution and reprecipitation as visualized by Frost and Russell [9]. After very extended intense irradiation, the original particle distribution is replaced by much finer particles.

# Effects of Temperature

At low T: diffusion is reduced, recombination dominates.

At intermediate T: diffusion faster than recombination

At high T: $\left(\frac{d_{Av}}{d_{Bv}} \sim \frac{d_{Ai}}{d_{Bi}}\right)$, and back diffusion is significant.



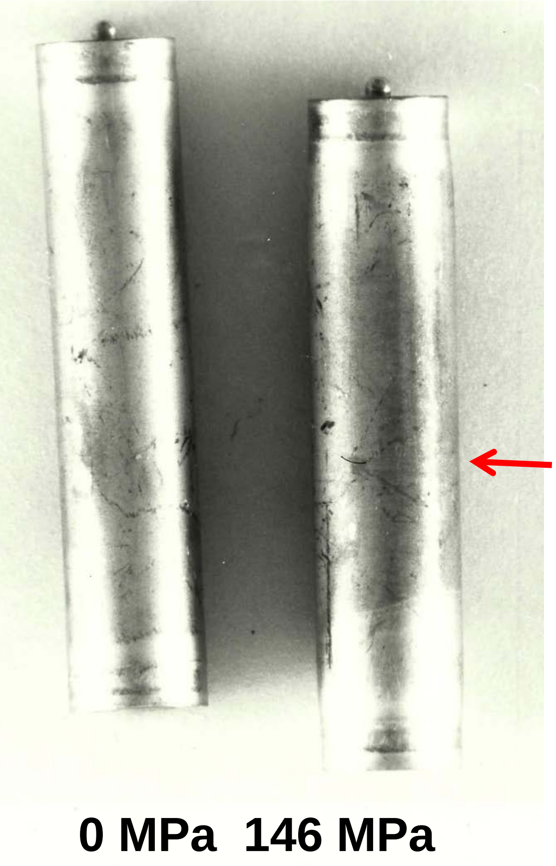
# Remember This?

[Fig. 6.1 from Gary S. Was. *Fundamentals of Radiation Materials Science*. ISBN: 9783540494713] removed due to copyright restrictions.

Why do you think Cr moves away from the grain boundary?

# Irradiation Creep

**D9 steel at 40 dpa, 520°C**



**0 MPa 146 MPa**

~6% uniform strain

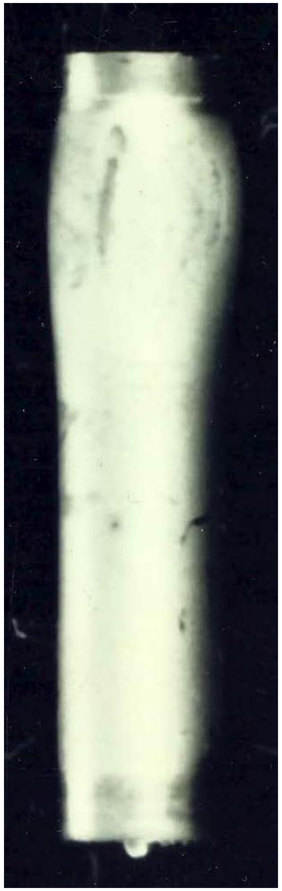
**HT9**

Irradiated at 45 Mpa and nominal temperature of 605°C

Top of tube ~30°C higher in temperature

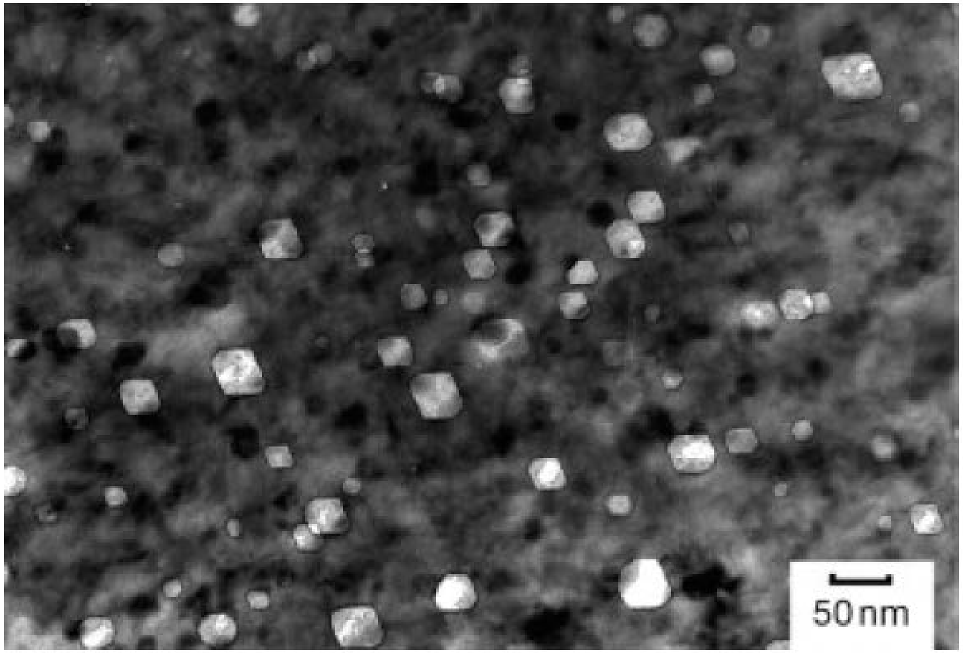
Average diametral strain of ~8%

Maximum strain ~25%



Courtesy of Garner, F. A. et al. Used with permission.

# Void Swelling



- Void swelling (~1%) and $M_{23}C_6$ carbide precipitation produced in annealed 304 stainless steel after irradiation in the reflector region of the sodium-cooled EBR-II fast reactor at 380 °C to 21.7 dpa at a dpa rate of $0.84 \times 10^{-7}$ dpa $s^{-1}$.
- Reproduced from Garner, F. A.; Edwards, D. J.; Bruemmer, S. M.; *et al*. In *Proceedings, Fontevraud 5, Contribution of Materials Investigation to the Resolution of Problems Encountered in Pressurized Water Reactors*; 2002; paper #22. Dislocations and dislocation loops are present but are not in contrast.

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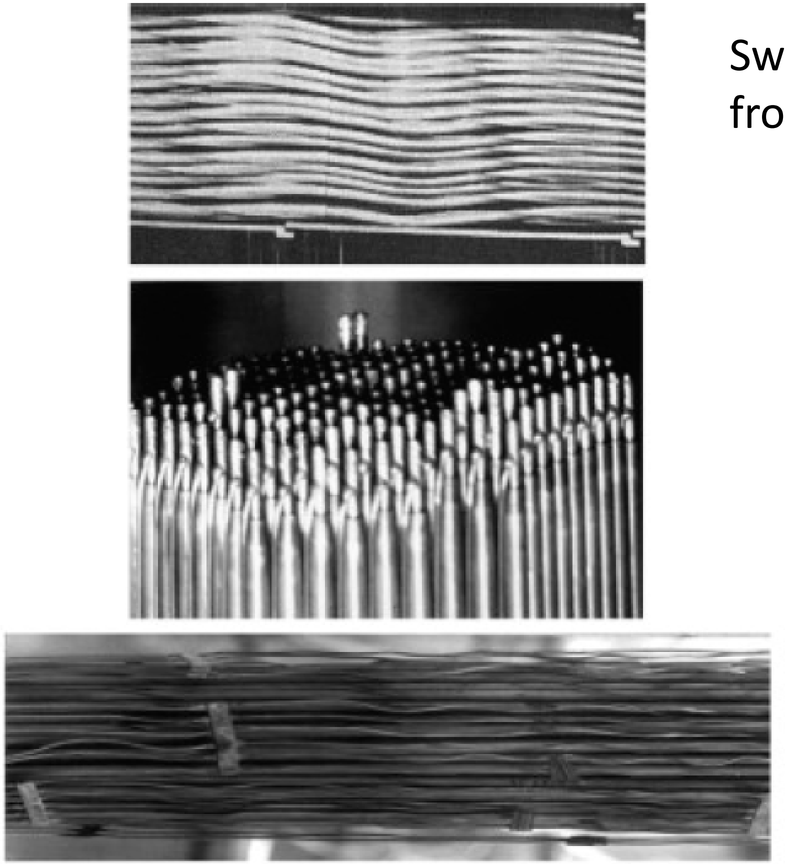
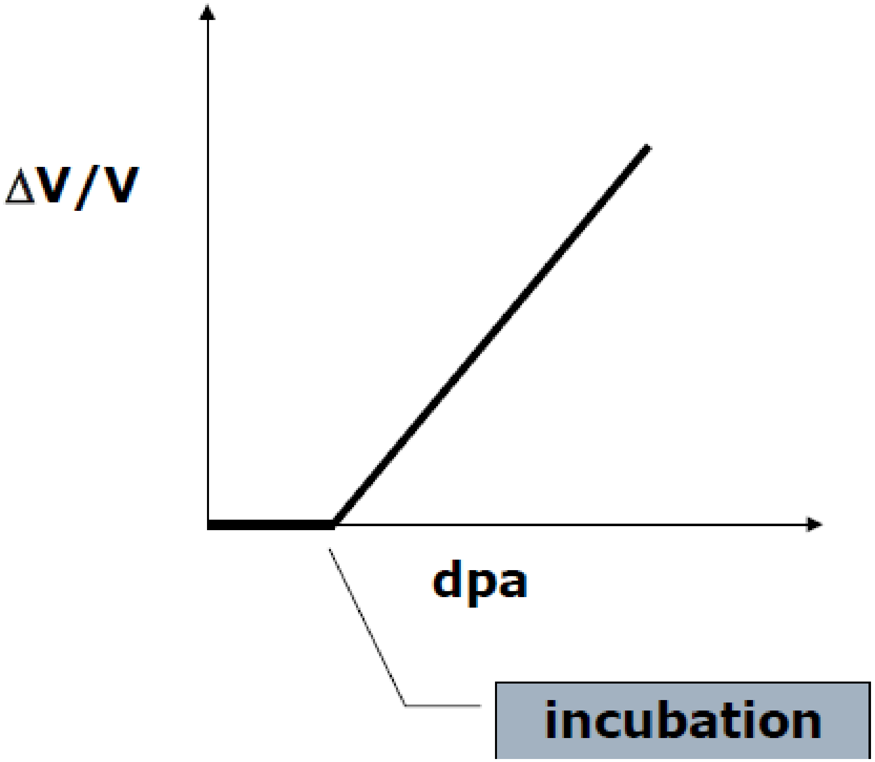
# Macroscale Void Swelling

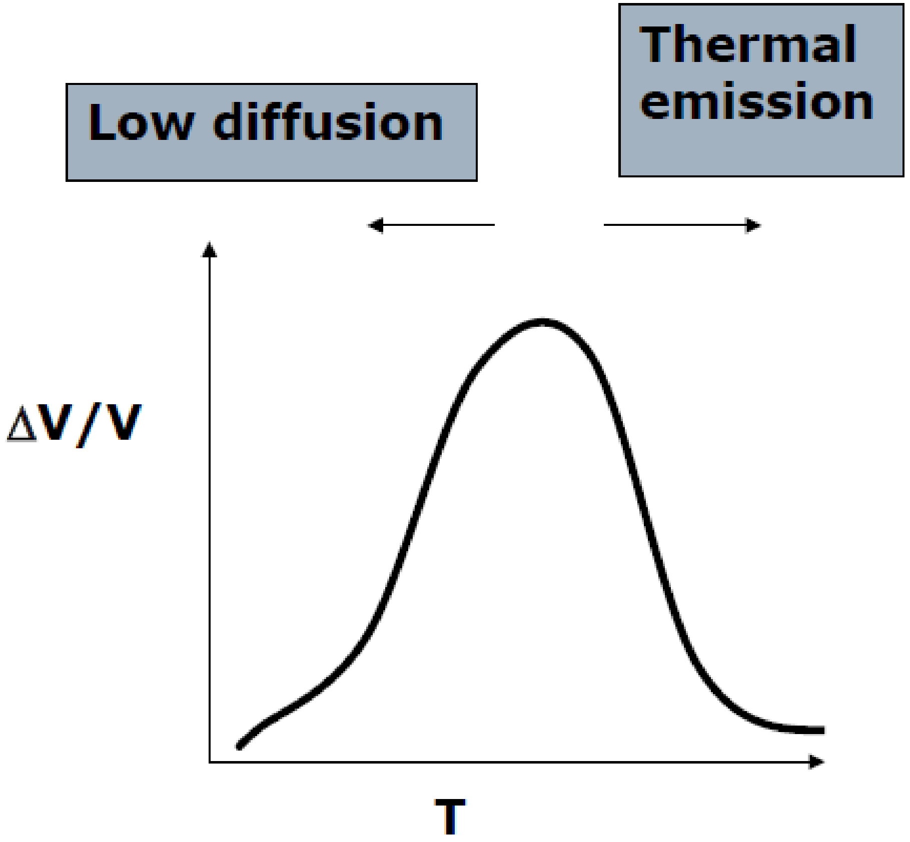


Swelling of spiral wrapped 316SS fuel cladding from the fast flux test reactor (FFTF)

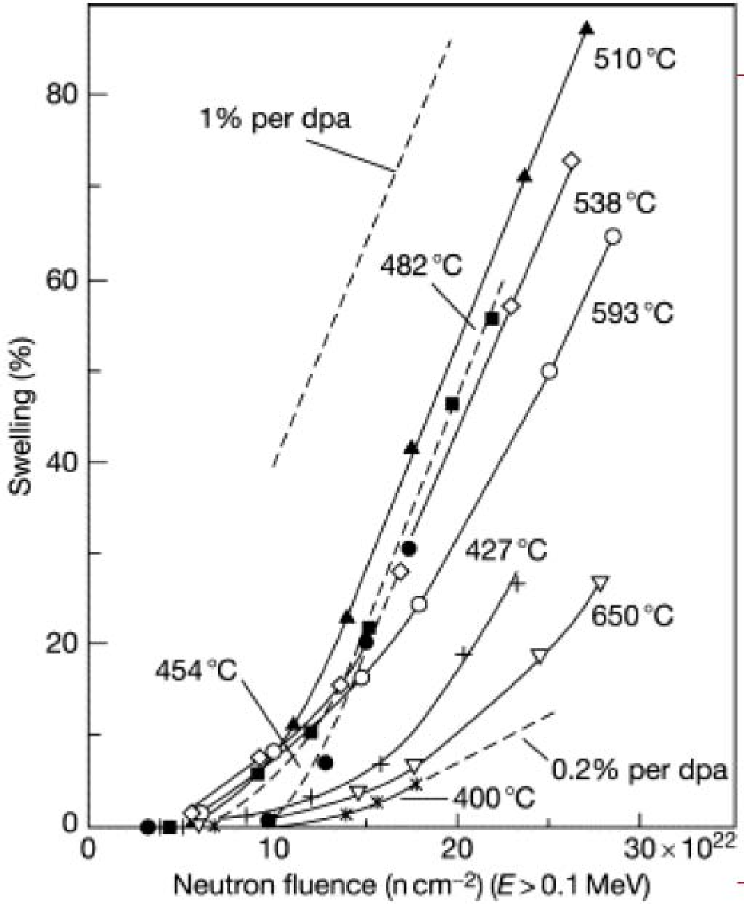
Reproduced from Makenas, B. J.; Chastain, S. A.; Gneiting, B. C. In *Proceedings of LMR: A Decade of LMR Progress and Promise*; ANS: La Grange Park, IL, 1990; pp 176–183; (middle) Swelling-induced changes in length of fuel pins of the same assembly in response to gradients in dose rate, temperature, and production lot variations as observed at the top of the fuel pin bundle. Reproduced from Makenas, B. J.; Chastain, S. A.; Gneiting, B. C. In *Proceedings of LMR: A Decade of LMR Progress and Promise*; ANS: La Grange Park, IL, 1990; pp 176–183; (bottom) swelling-induced distortion of a BN-600 fuel assembly and an individual pin where the wire swells more than the cladding. Reproduced from Astashov, S. E.; Kozmanov, E. A.; Ogorodov, A. N.; Roslyakov, V. F.; Chuev, V. V.; Sheinkman, A. G. In *Studies of the Structural Materials in the Core Components of Fast Sodium Reactors*; Russian Academy of Science: Urals Branch, Ekaterinburg, 1984; pp 48–84, in Russian.

# Void Swelling Behavior





# Void Swelling vs. Temperature



Swelling determined by density change as a function of irradiation temperature and dose, as observed in 20% cold-worked AISI 316 irradiated in the EBR-II fast reactor.

Reproduced from Garner, F. A.; Gelles, D. S. In *Proceedings of Symposium on Effects of Radiation on Materials: 14th International Symposium*; ASTM STP 1046; 1990; Vol. II, pp 673–683. All measurements at a given temperature were made on the same specimen after multiple exposures with subsequent reinsertion into the reactor. This procedure minimized specimen-to-specimen data scatter and assisted in a clear visualization of the posttransient swelling rate.

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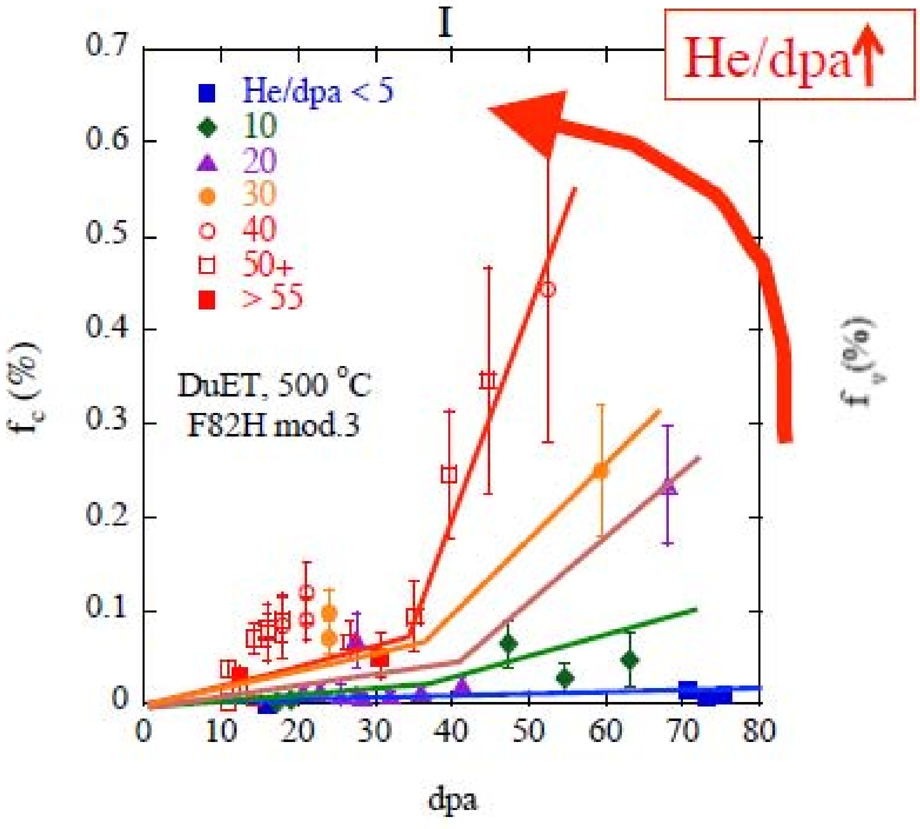
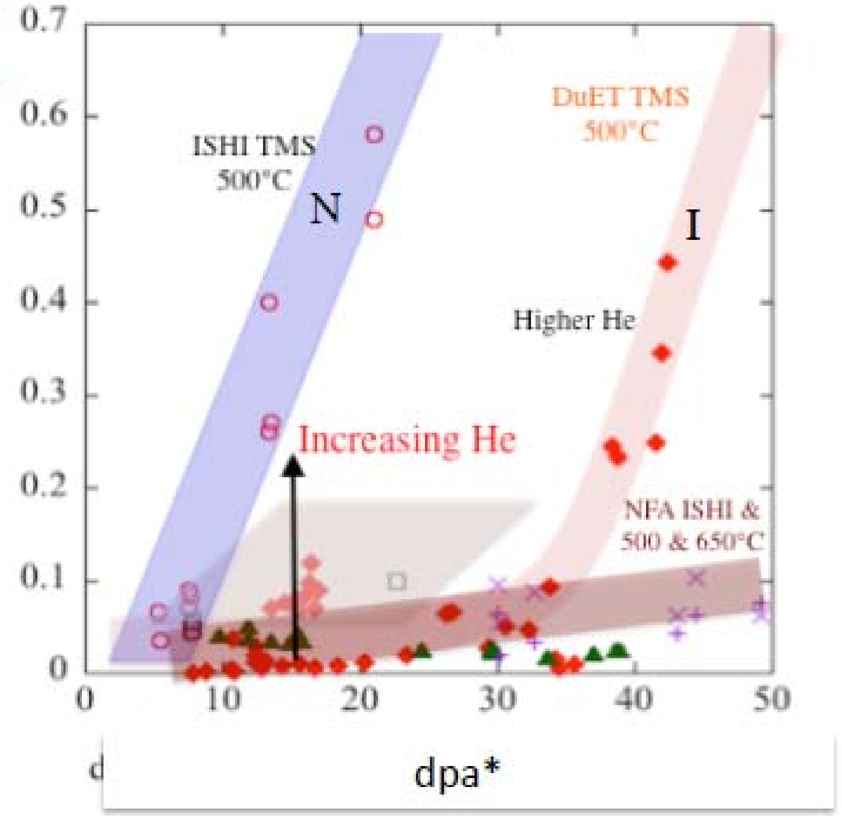
# Void Swelling vs. Temperature

[Fig. 8.19 from Gary S. Was. *Fundamentals of Radiation Materials Science*.
ISBN: 9783540494713] removed due to copyright restrictions.

# Void Swelling vs. Gas Pressure



This graph is in the public domain.

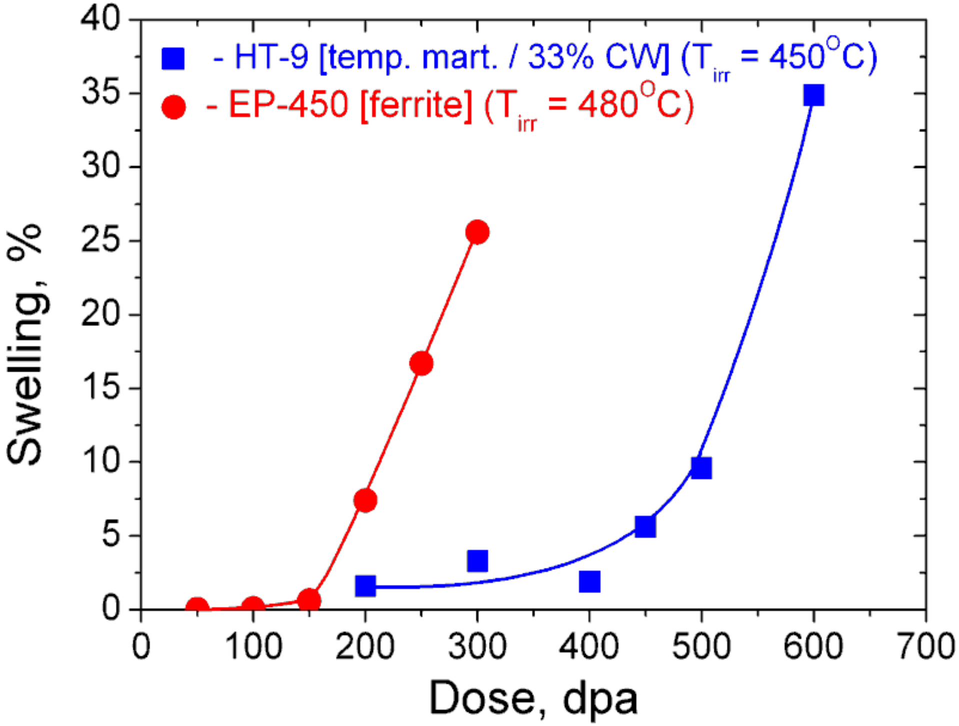


This graph is in the public domain.

G. R. Odette, T. Yamamoto and P. Wells. Michigan Ion Beam Workshop (2014)

# Void Swelling vs. Precipitates

- Why would tempered martensite resist void swelling better?
- Think about density of defect sinks

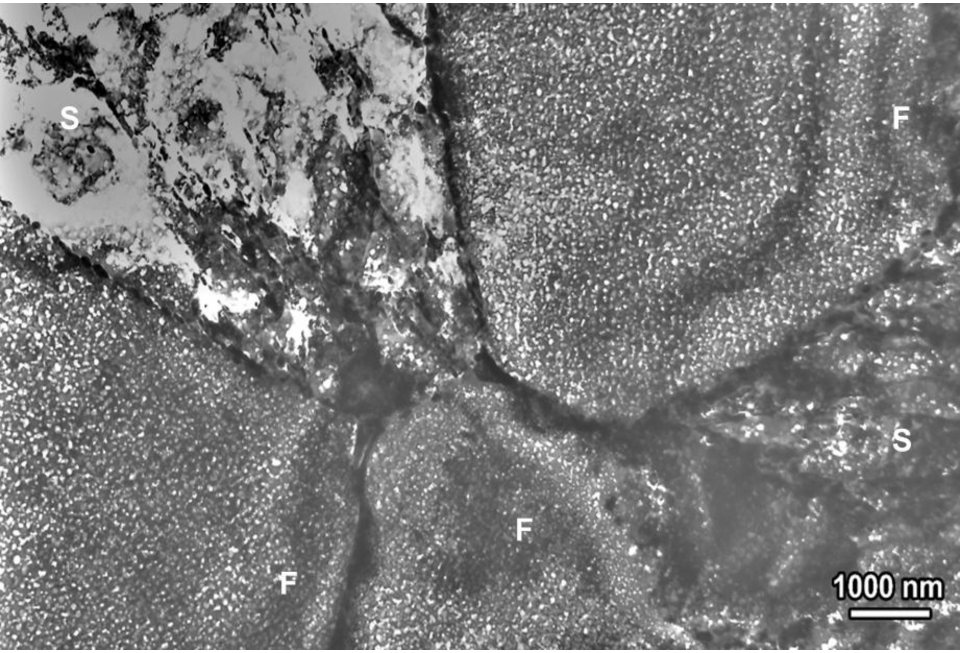


Courtesy of Garner, F. A. et al. Used with permission.

**Voyevodin, Bryk, Borodin, Melnichenko, Kalchenko, Garner, 2012**

# Void Swelling vs. Crystal Structure

EP-450 at 480$^{o}$C and 300 dpa without gas, showing swelling is strongest in ferrite grains



**Surface of Uranus 50 duplex alloy irradiated at 625°C to 140 dpa**

**Ferrite grains swell less than austenite grains due to different swelling rate and different temperature regime of swelling**

# When Does Void Swelling Happen?

- Vacancy clustering can either form:
  - Vacancy clusters (mini-voids)
  - *Dislocation loops*

# Energy Balance Determines

$$E_{void}^{f} = 4\pi\gamma\left(\frac{3m\Omega}{4\pi}\right)^{2/3} = K_1 m^{2/3}$$

$E_{void}^{f} = 4\pi\, r^2 \gamma$

$\gamma \approx 1500\ ergs / cm^2$

$m = \#\ vacancies\ per\ void$

$\Omega = atomic\ volume \approx 8 \times 10^{-23}\ cm^3$

$m = \frac{4}{3}\frac{\pi\, r^3}{\Omega}$

~~$r = \left(\frac{3m\Omega}{4\pi}\right)^{1/3}$~~

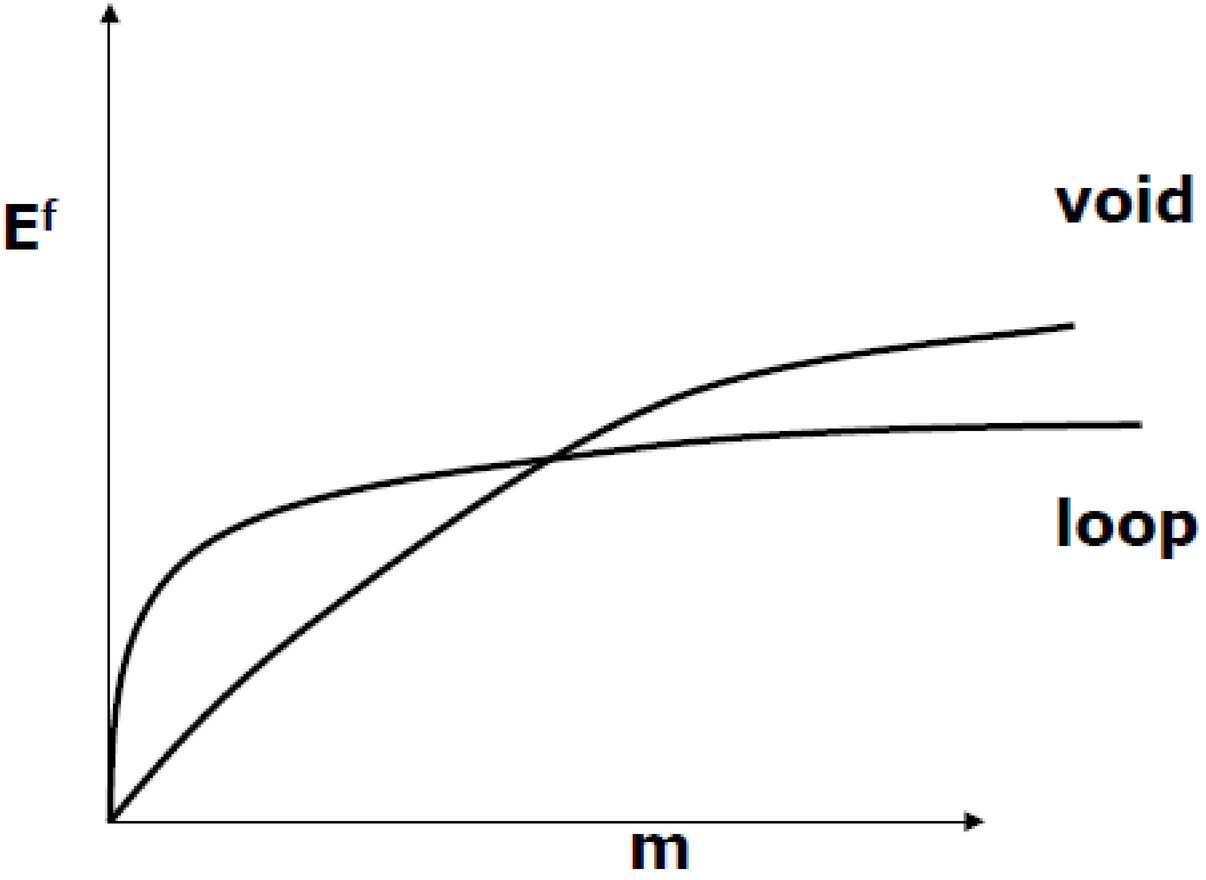
$Loops$

$$E_{loop}^{f} = 2\pi\, r T_d + \pi\, r^2 \gamma_{sf}$$

$T_d = line\ tension$

$\gamma_{sf} = stacking\ fault\ energy$

# Which One Is Stable?

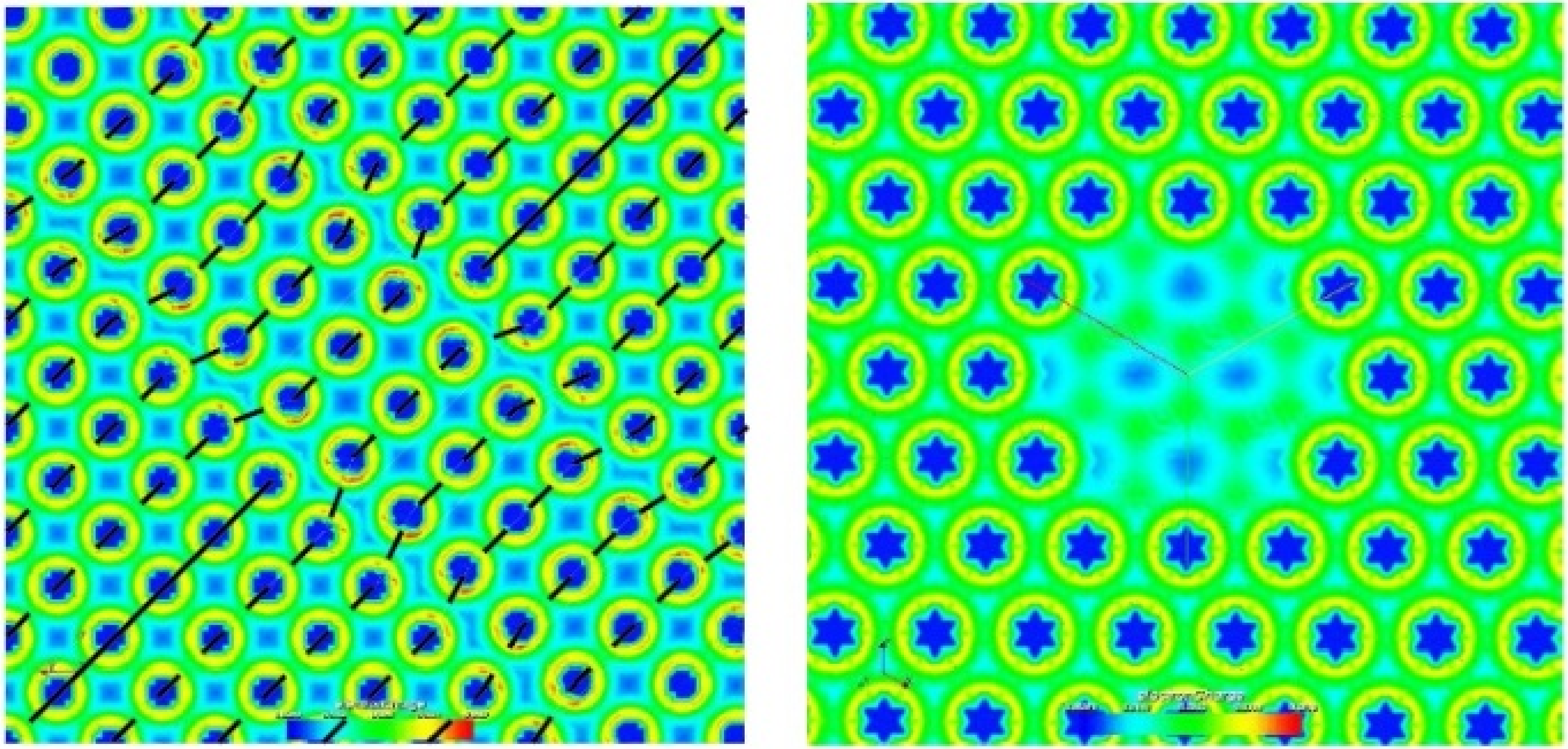


What can stabilize voids for small size (m)?

- Gas pressure
- High stacking fault energy (harder to form loop)

# What Are These Loops?

**V. Gavini, K. Bhattacharya, M. Ortiz. *Phys. Rev. B*, 76, 180101(R)**

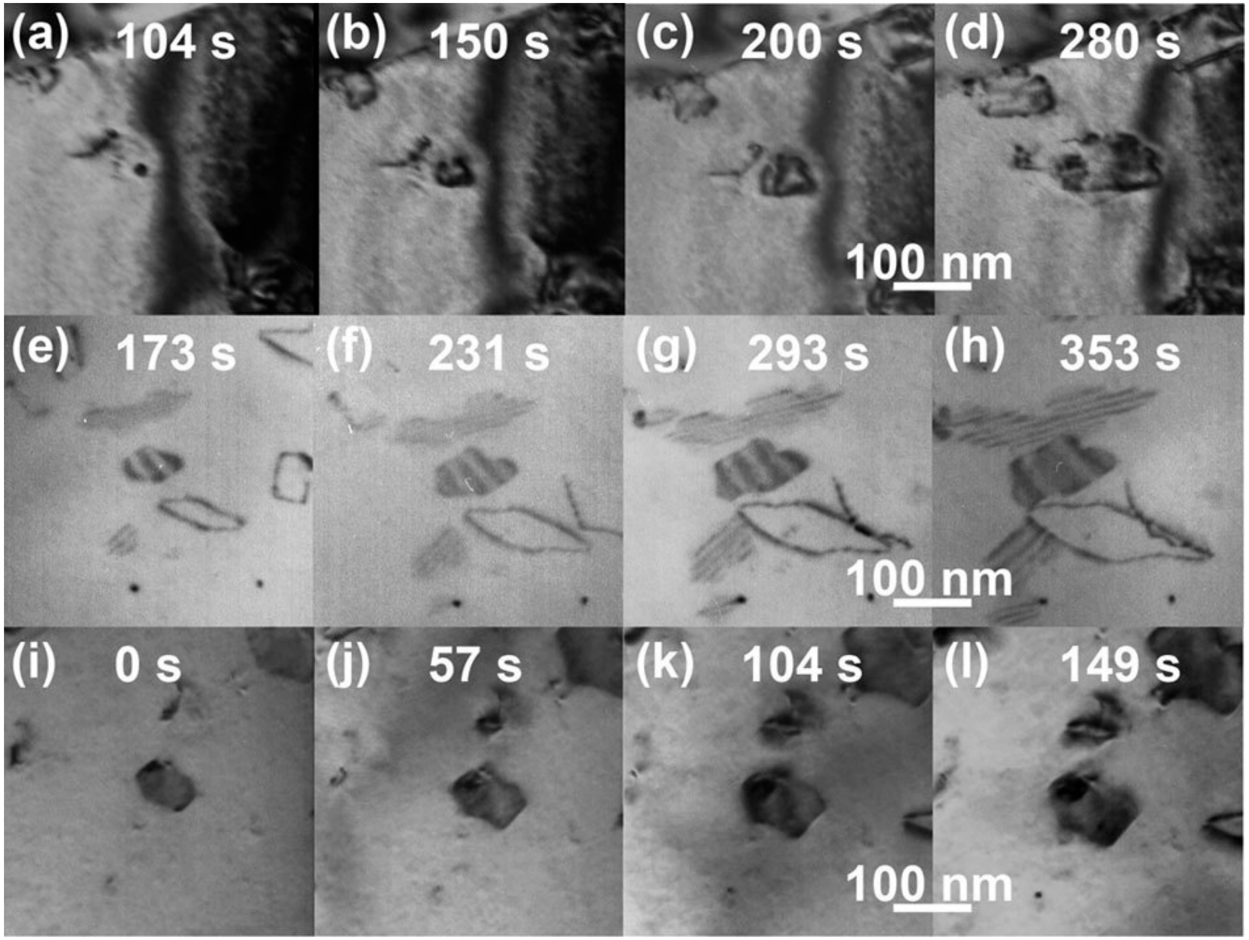


(a)

(b)

# Visualizing Interstitial Loops

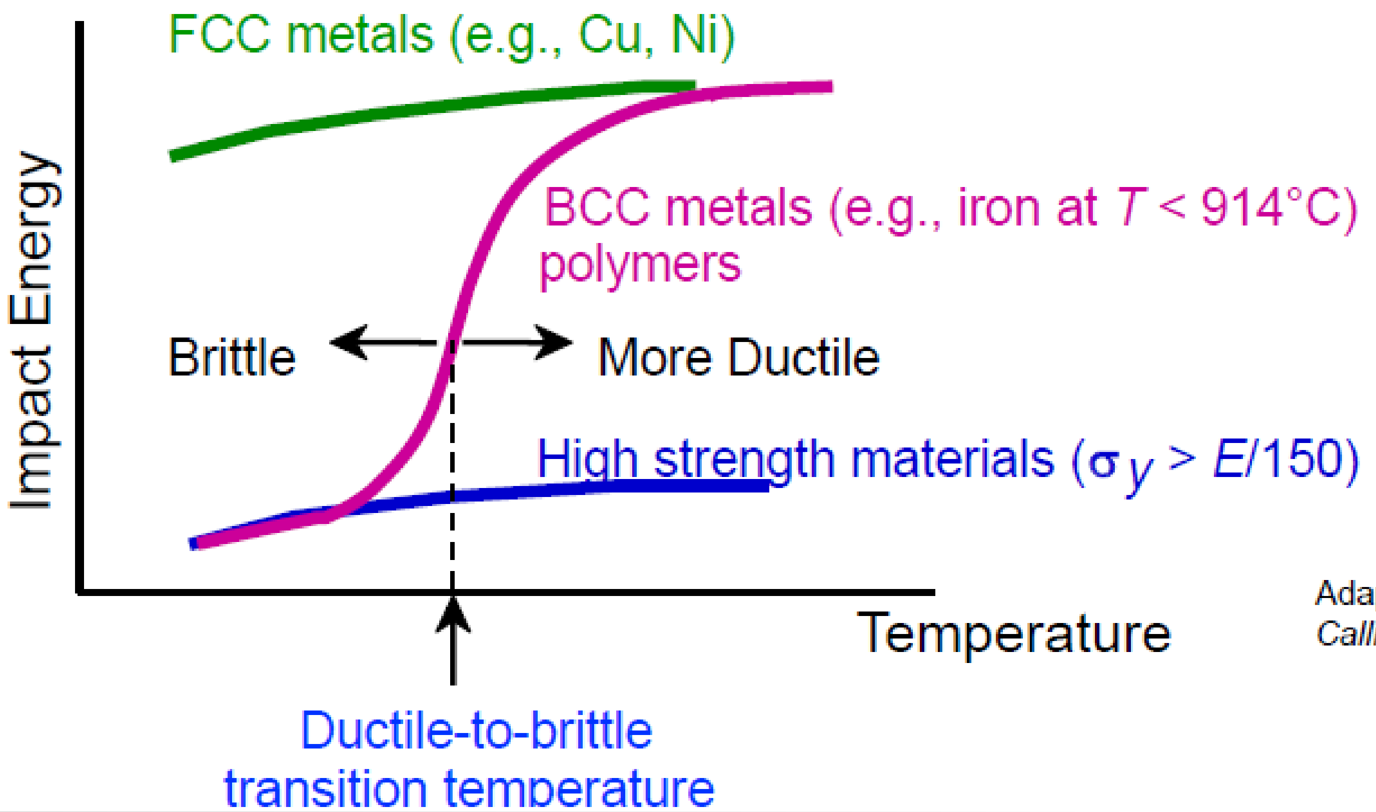
doi:10.1038/srep00190



Reprinted by permission from Macmillan Publishers Ltd: Scientific Reports. Source: Yang, Z. et al, "Dislocation Loop Formation and Growth under In Situ Laser and / or Electron Irradiation." *Scientific Reports* 1, Article number: 190 (2011). © 2011.

# Hardening, Embrittlement

- **Ductile-to-Brittle Transition Temperature (DBTT)...**



Adapted from Fig. 9.21, *Callister & Rethwisch 3e.*

# Radiation Embrittlement

1. Defects are produced
2. Defects cluster, forming dislocation loops, precipitates, amorphous regions…
3. Dislocations can’t move as easily
4. Balance between slip & fracture is shifted

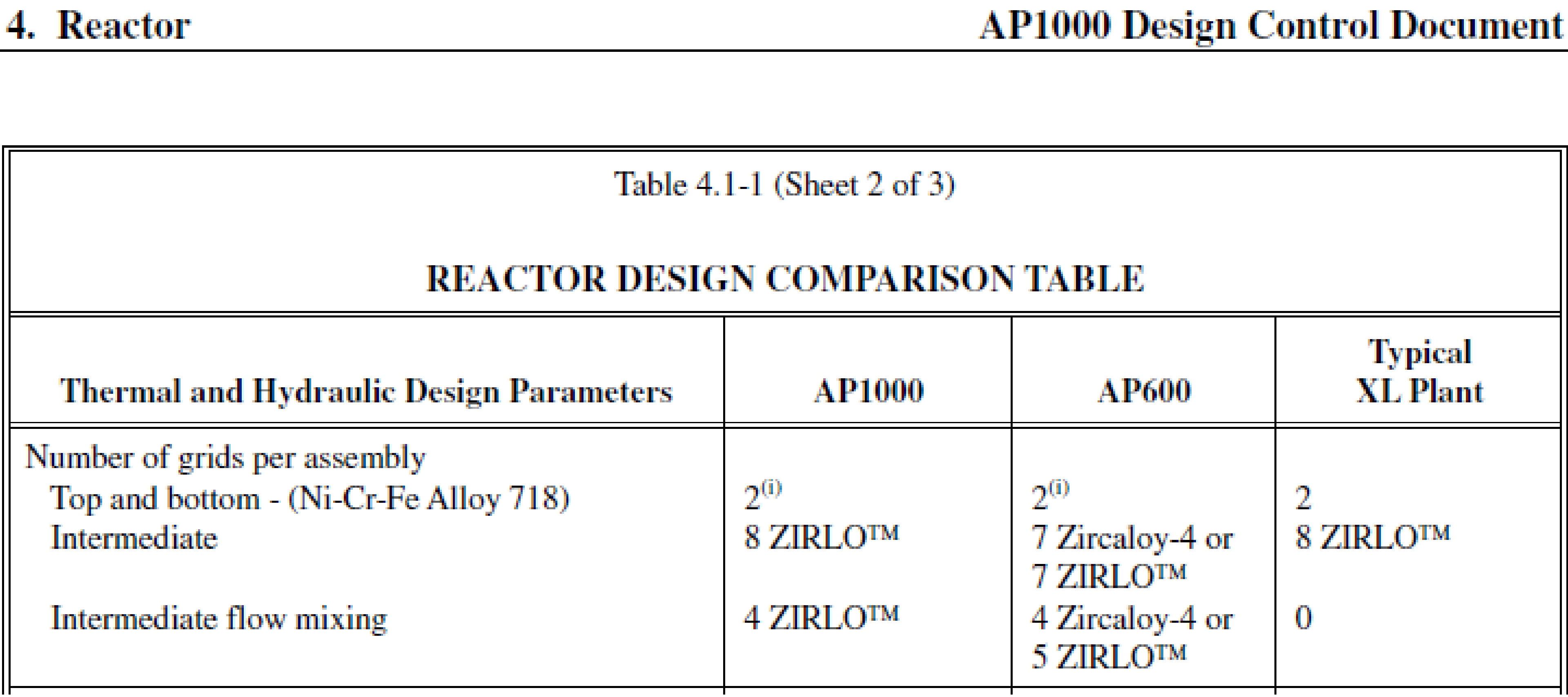
# Embrittlement: Discuss

- Fuel unloading

- Pressurized thermal shock (PTS)

- **Foreign Material Exclusion (FME)**
  - **Currently the largest source of LWR shutdowns**

# AP-1000 Material Selection



4. Reactor AP1000 Design Control Document

Table 4.1-1 (Sheet 2 of 3)

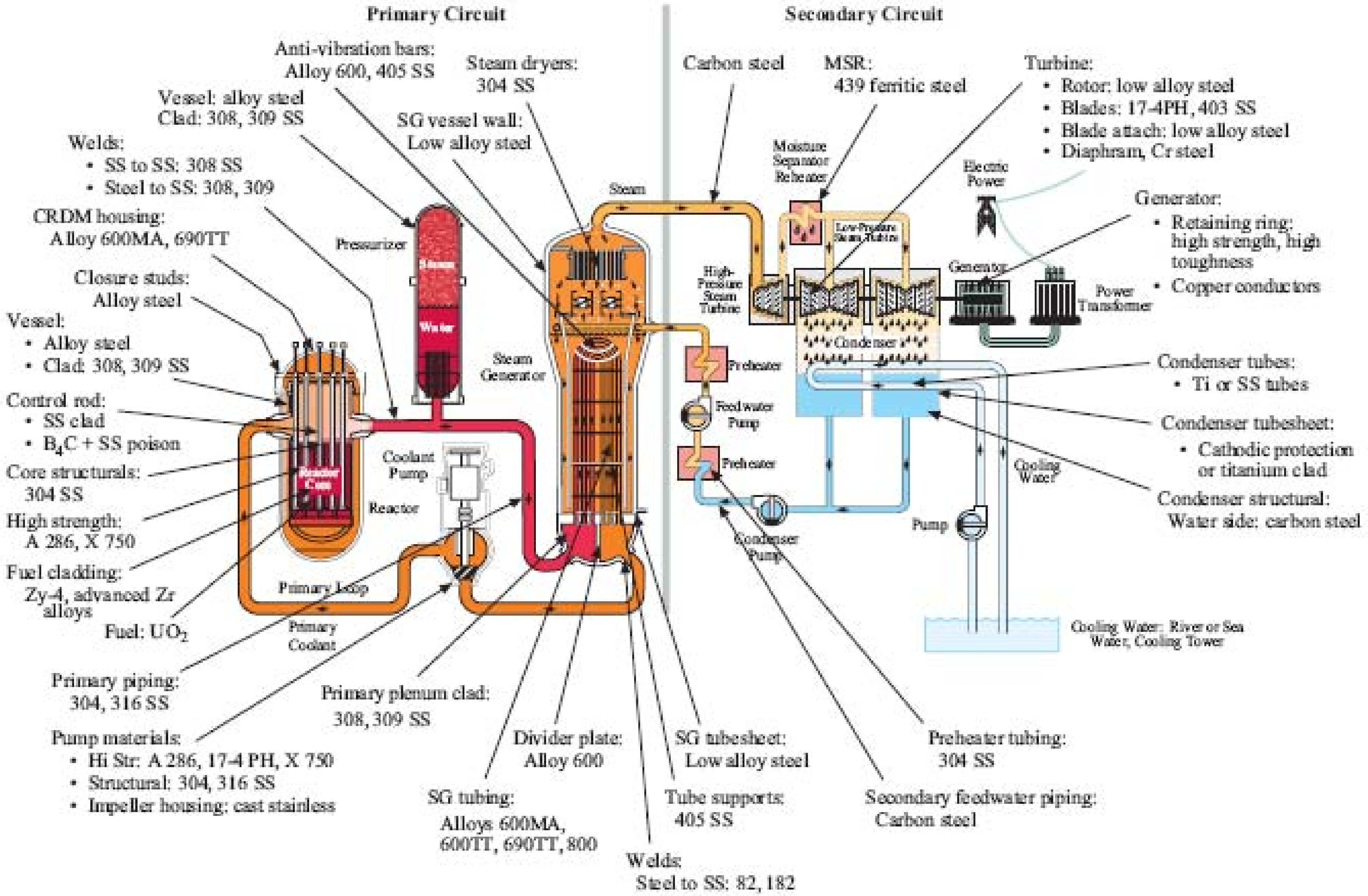
**REACTOR DESIGN COMPARISON TABLE**

| Thermal and Hydraulic Design Parameters | AP1000 | AP600 | Typical XL Plant |
|---|---|---|---|
| Number of grids per assembly | | | |
| Top and bottom - (Ni-Cr-Fe Alloy 718) | 2(i) | 2(i) | 2 |
| Intermediate | 8 ZIRLO™ | 7 Zircaloy-4 or<br>7 ZIRLO™ | 8 ZIRLO™ |
| Intermediate flow mixing | 4 ZIRLO™ | 4 Zircaloy-4 or<br>5 ZIRLO™ | 0 |

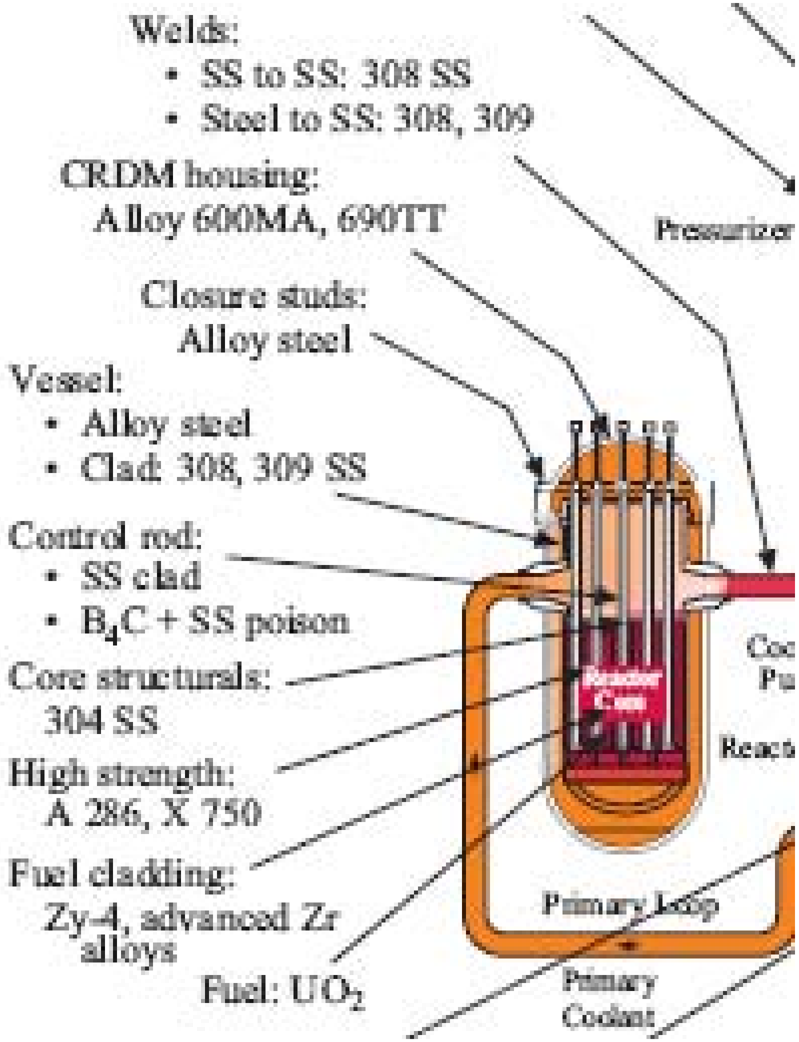
**Why are there only Alloy 718 grids on the top & bottom of the core?**

This table is in the public domain.

# Revisit Material Selection



# Material Selection: Core



Welds:
- SS to SS: 308 SS
- Steel to SS: 308, 309

CRDM housing:
Alloy 600MA, 690TT

Closure studs:
Alloy steel

Vessel:
- Alloy steel
- Clad: 308, 309 SS

Control rod:
- SS clad
- $B_4C$ + SS poison

Core structurals:
304 SS

High strength:
A 286, X 750

Fuel cladding:
Zy-4, advanced Zr alloys

Fuel: $UO_2$

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