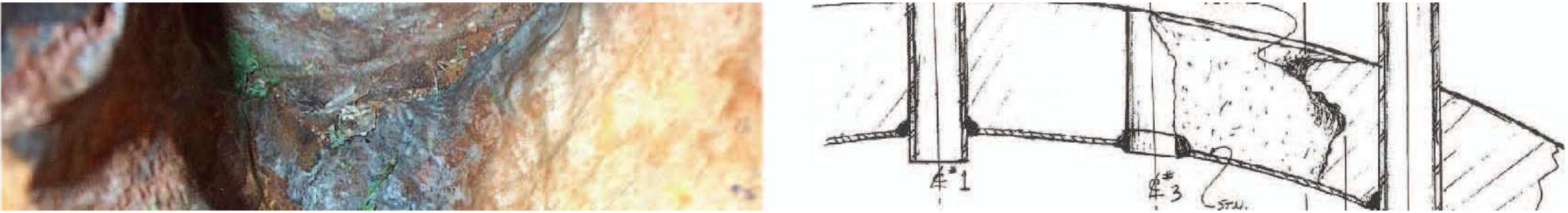


# Introduction to the Introduction to Nuclear Materials

22.14 – Intro to Nuclear Materials
February 3, 2014

# Materials in Nuclear Systems

- Course Goals
- Intro to Nuclear Materials Degradation
- LWR Specifics
- Fast Reactor Specifics
- Fusion Reactor Specifics
- Waste Canister Specifics
- Material Degradation and Failure

# Course Goals

- Obtain a basic knowledge of key degradation phenomena and material limitations in nuclear energy technologies

- Obtain a basic knowledge of mechanical properties; stress-strain relationship, plasticity, slip, fracture

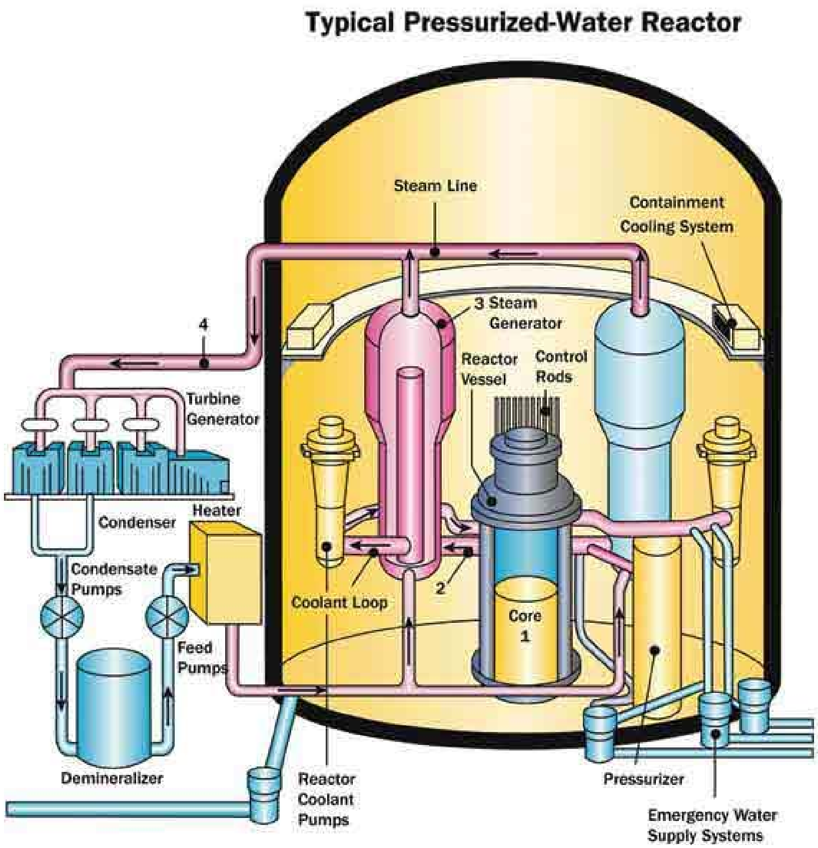
# Course Goals

- Understand and quantify radiation damage; energy transfer, displacement cross-sections, displacement rate
- Understand radiation effect mechanisms; radiation induced segregation, swelling, hardening, embrittlement

# Know Your Systems – LWRs

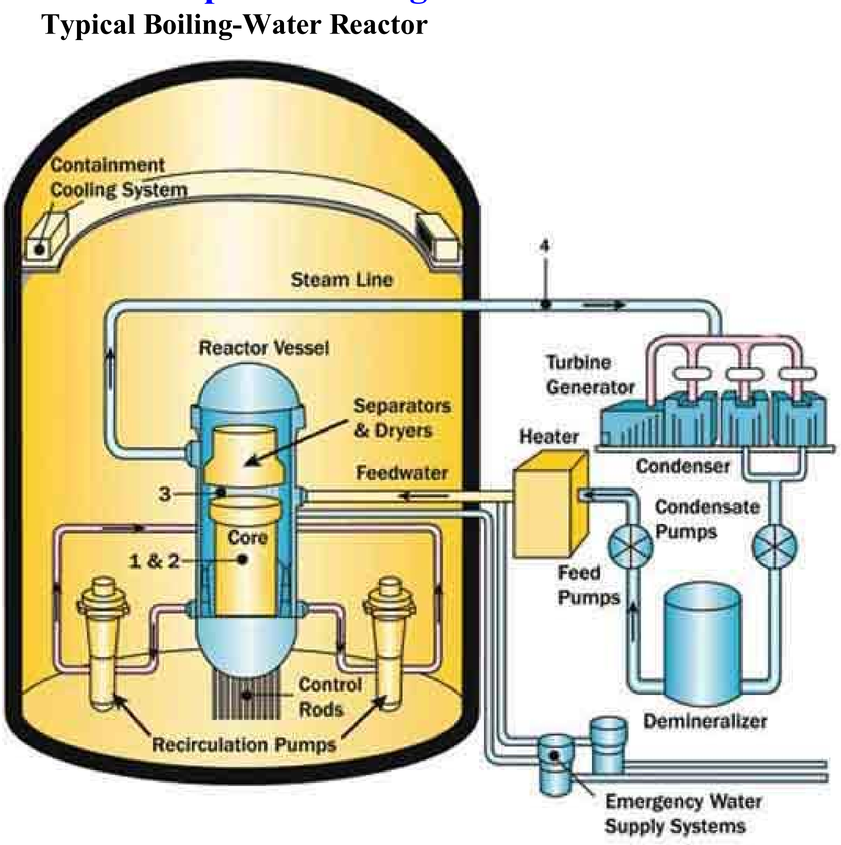
**Revisit: Mar. 17 (System Recap)**

http://www.nrc.gov/reactors/pwrs.html



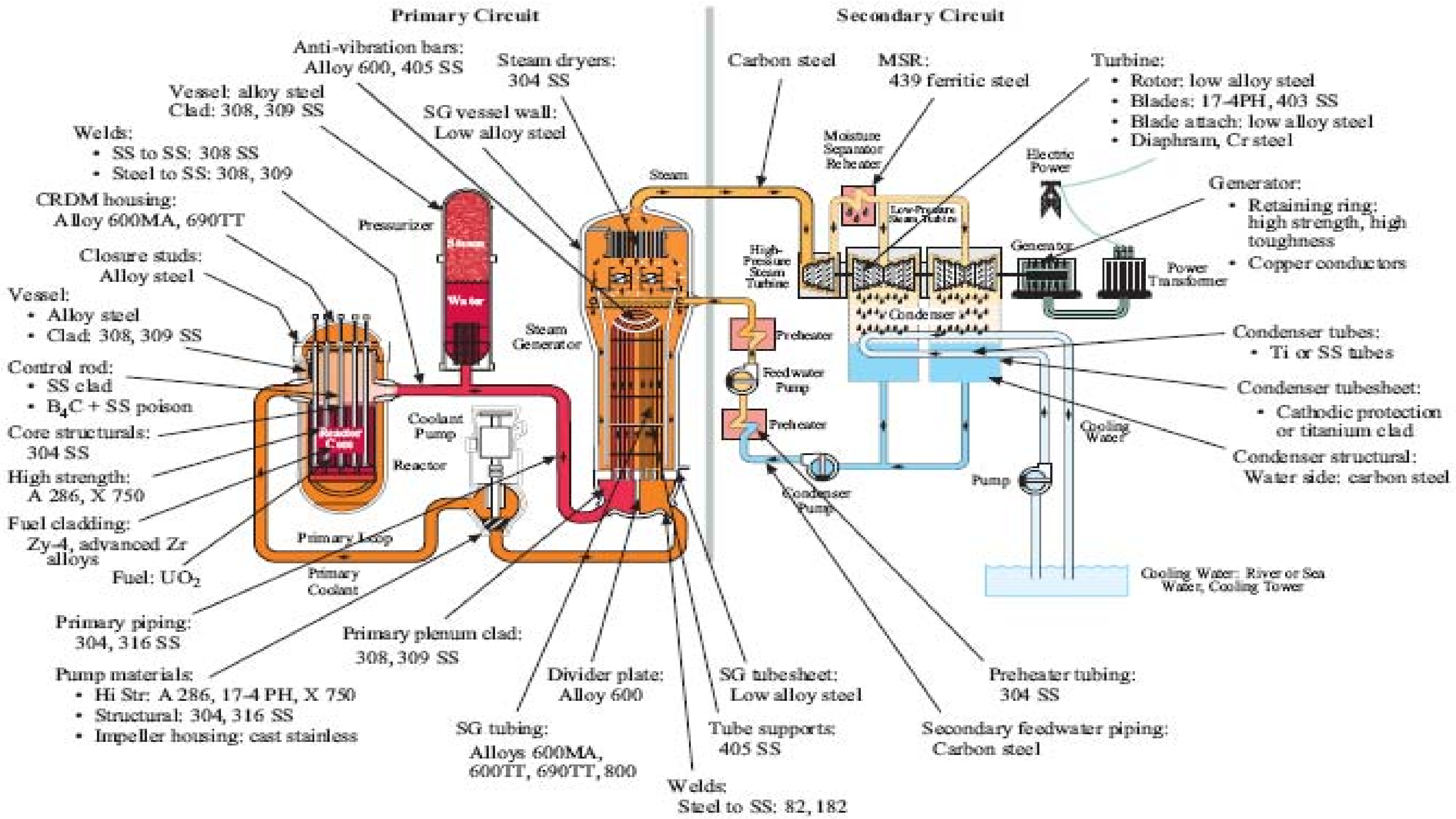

This image is in the public domain.

http://www.nrc.gov/reactors/bwrs.html



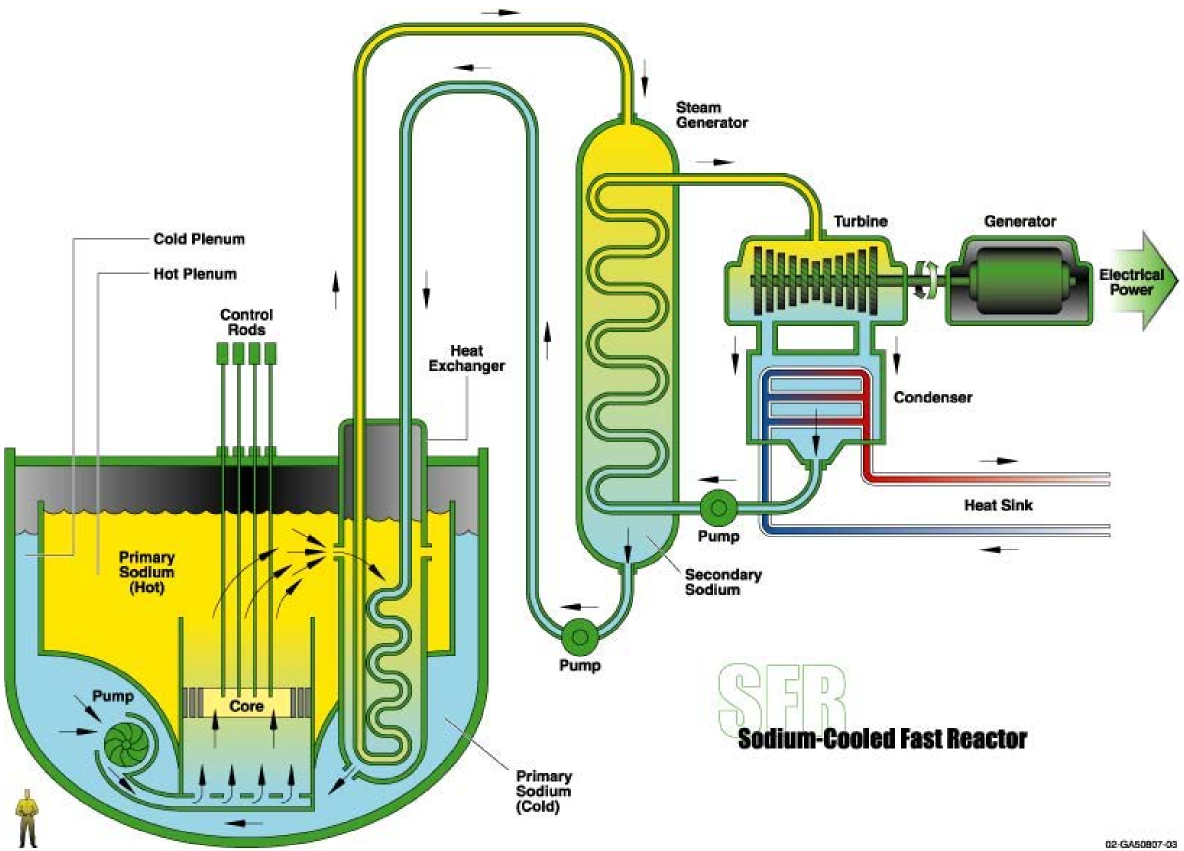

This image is in the public domain.

# PWR Material Map



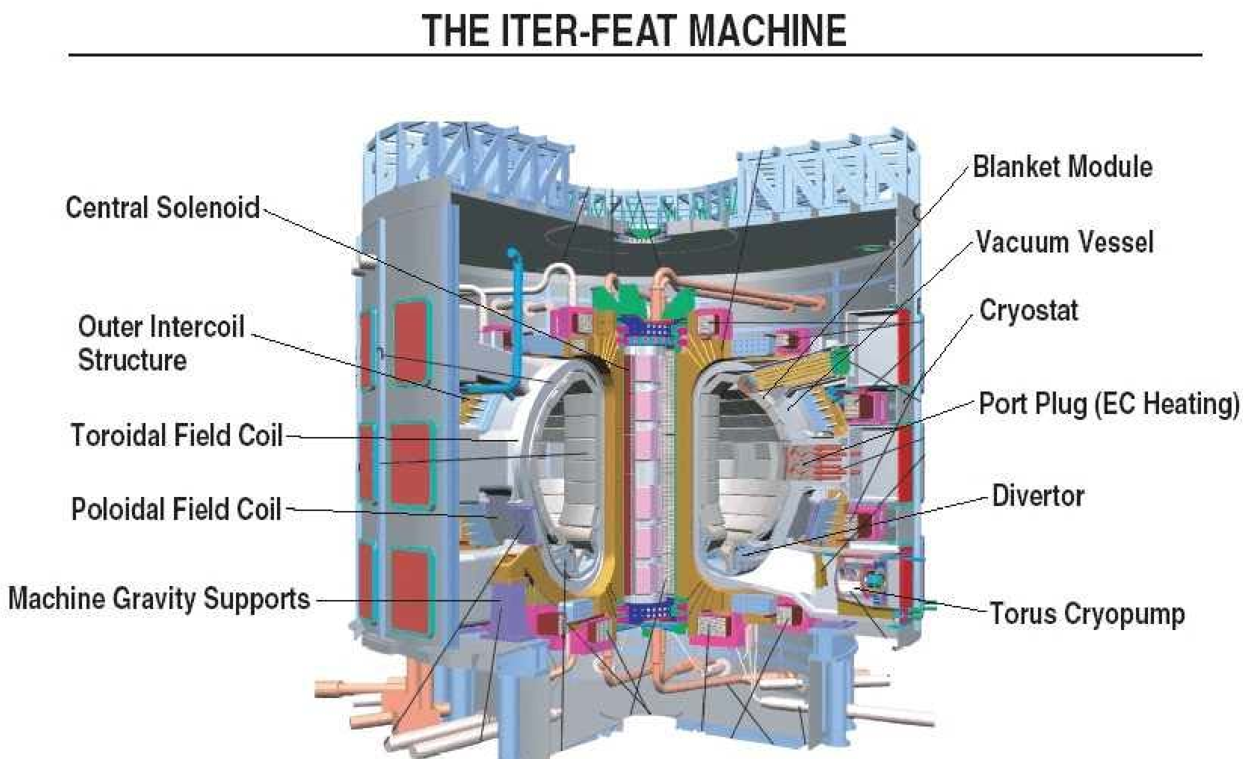
# Know Your Systems – Fast Reactors

**Revisit: Mar. 17 (System Recap)**



# Know Your Systems – Tokamak (Fusion), ITER

**Revisit: Mar. 17 (System Recap)**

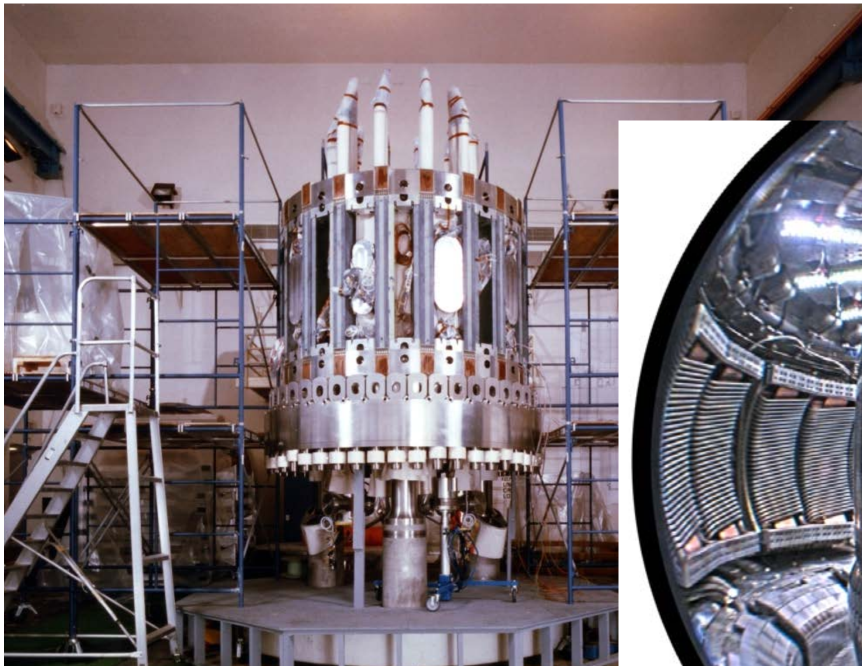




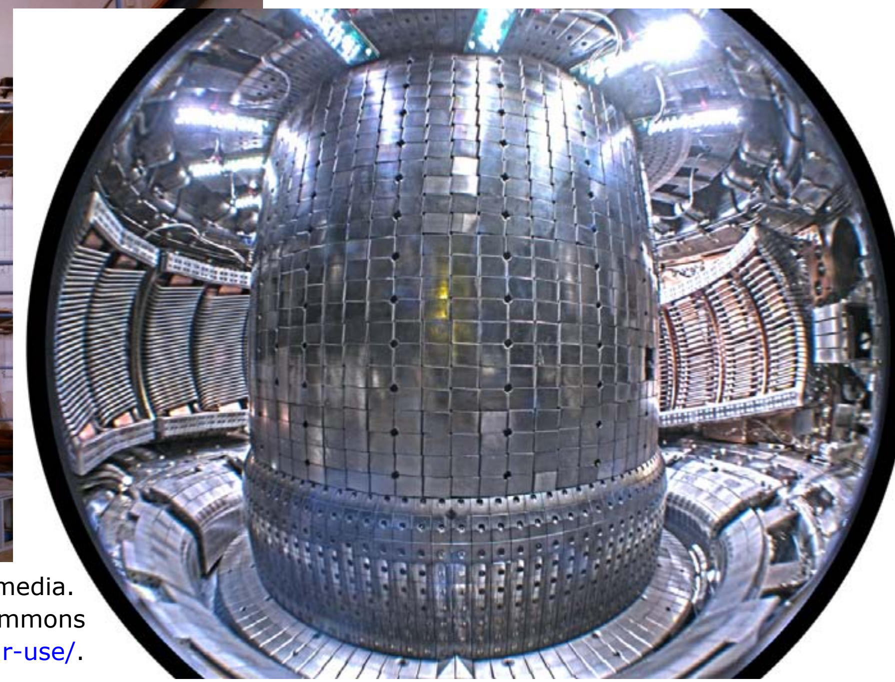

**http://www.odec.ca/projects/2007/ewar7j2/Nuclear%20Power%20%28Fusion%29.htm**

# Know Your Systems – Tokamak (Fusion), MIT Alcator

**Revisit: Mar. 17 (System Recap)**



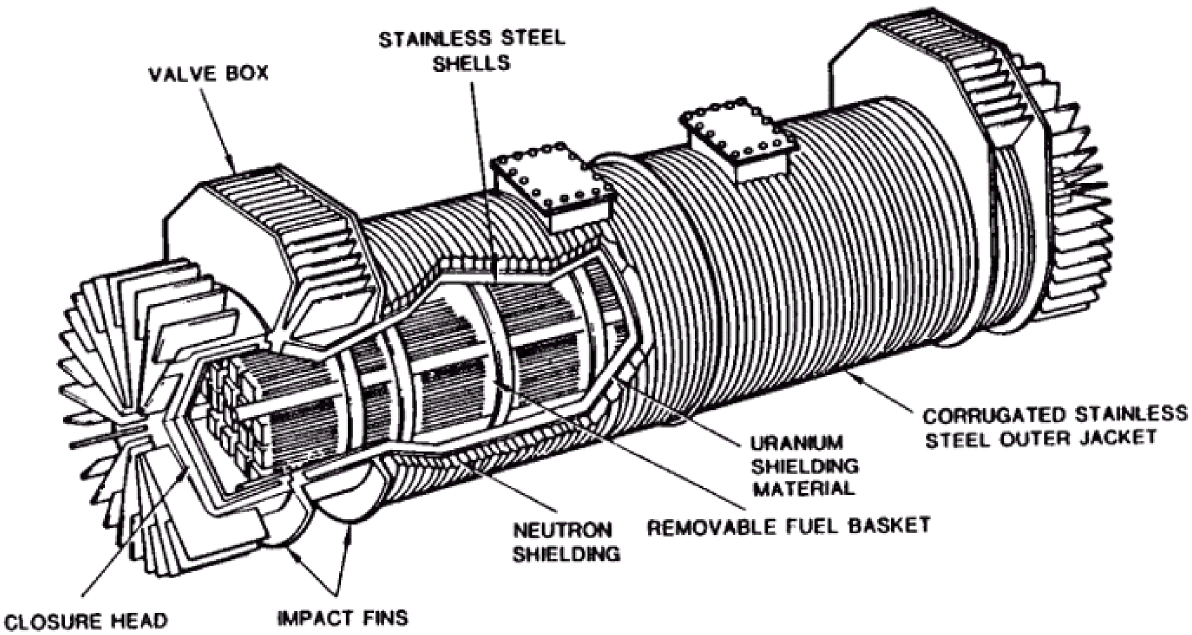




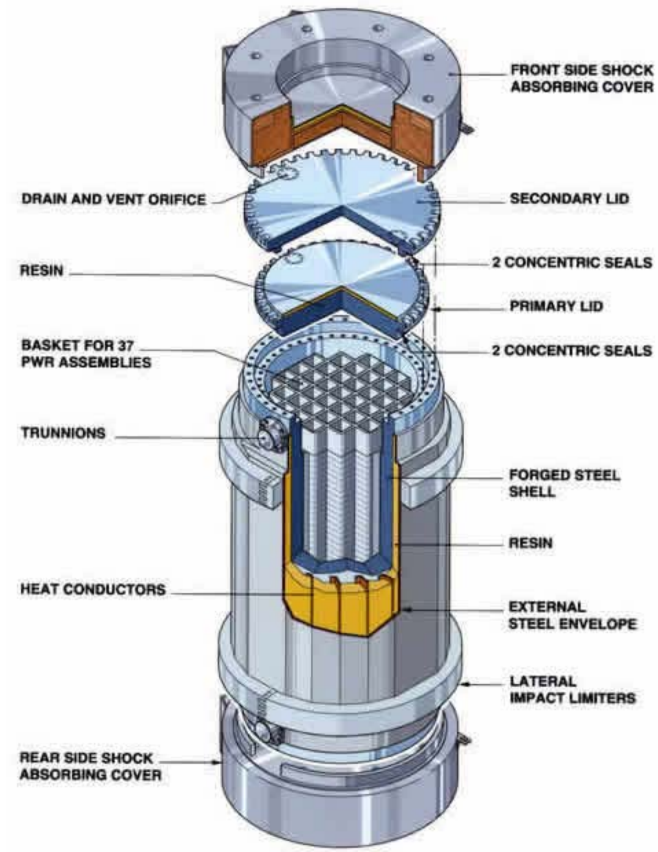
# Know Your Systems – Waste Canister

**Revisit: Mar. 17 (System Recap)**

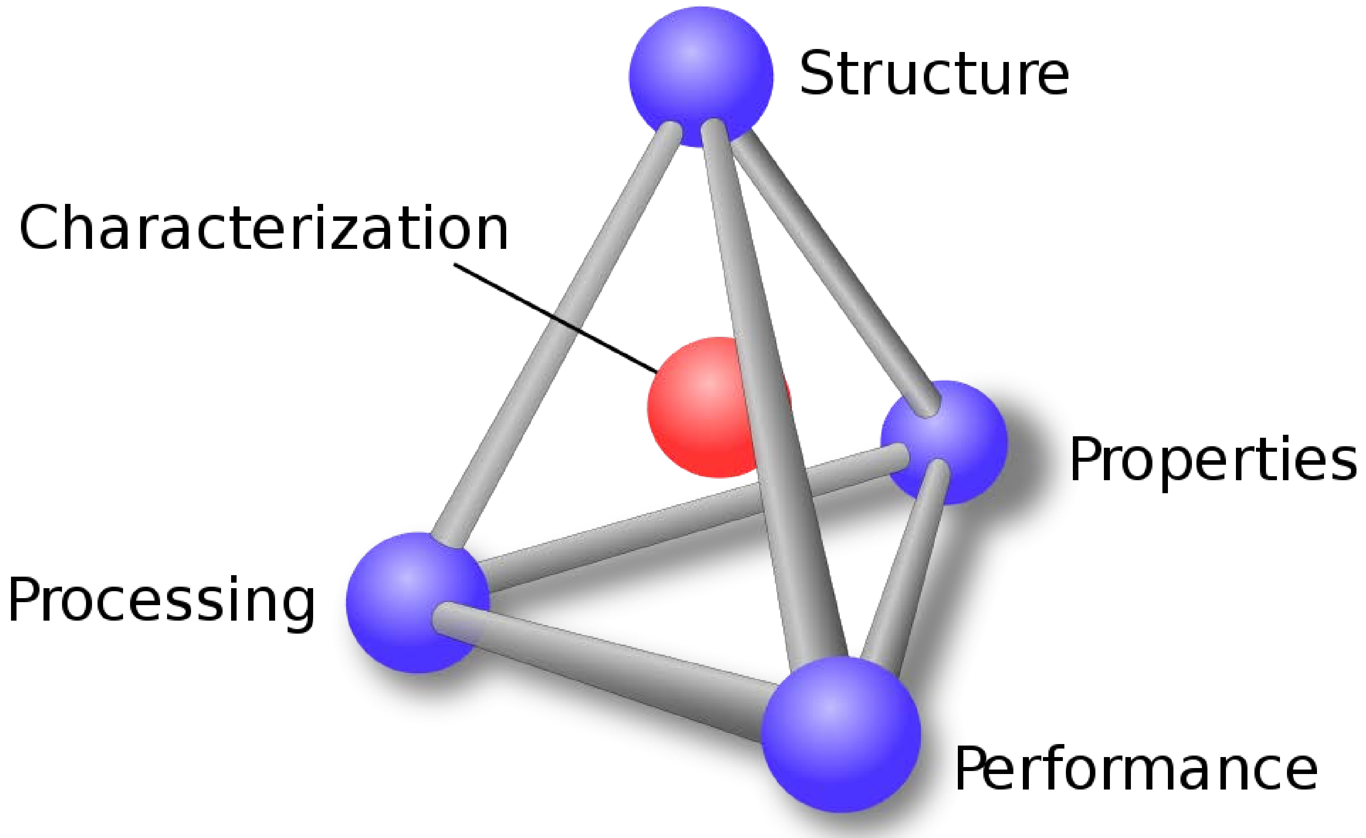
M. S. Yim and K. L. Murty. JOM, 52 (9) (2000), pp. 26-29





# Overall Materials Science Philosophy

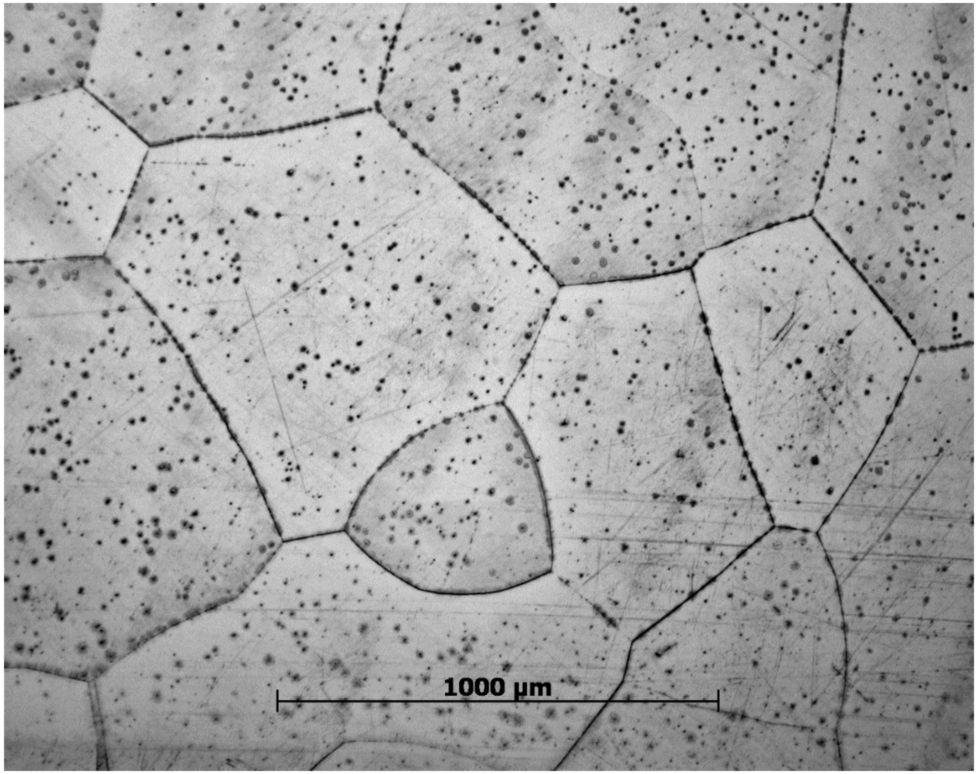





**Source: Wikimedia Commons, Materials Science Tetrahedron**

# Background: Grains

**Revisit: Feb. 10 (Crystal Structures)**

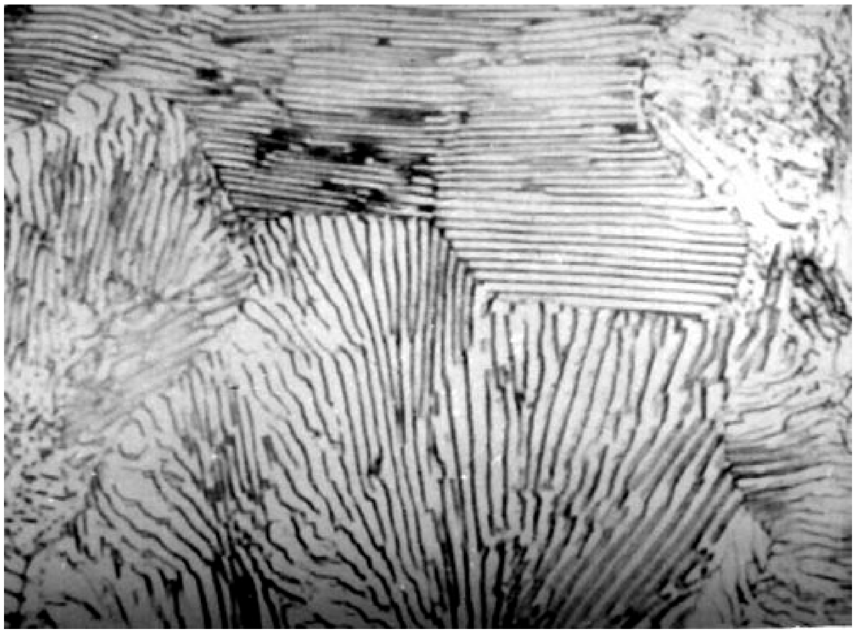



**Fe-12Cr-2Si ferritic alloy grains, 50x, etched with Kalling's reagent**

- Most metals are granular in nature
- **Grains** are single crystals
- **Grain boundaries** separate them

# Background: Phases

**Revisit: Feb. 10 (Crystal Structures)**





**Pearlite, or ferrite/cementite, phases in carbon steel**

Image source: http://hsc.csu.edu.au/engineering_studies/application/civil/1-1/answers.html

- When elements mix, different **phases** form
  - **Phase**: A coherent composition & microstructure
- Includes **alloys**, **intermetallic compounds...**
- Example: Steel (pearlite)

# Background: Phase Diagrams

**Revisit: Feb. 12 (Phase Diagrams)**

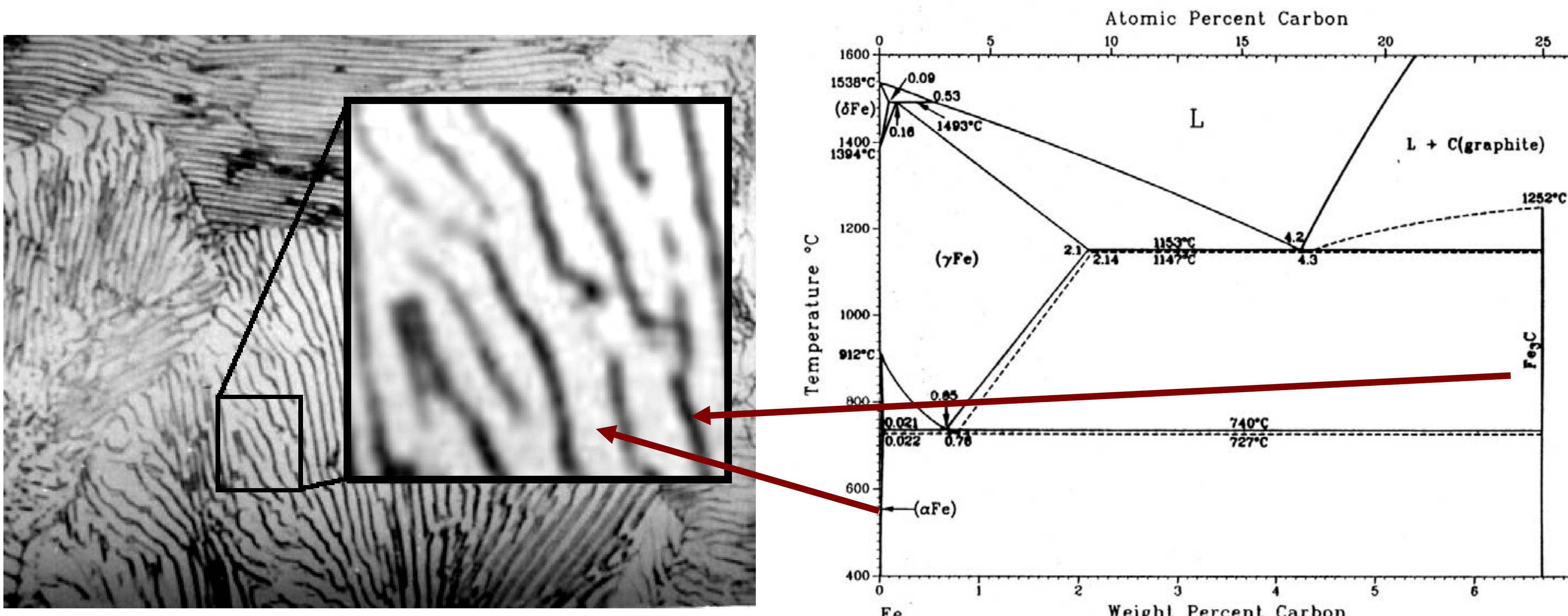





Image source: http://hsc.csu.edu.au/engineering_studies/application/civil/1-1/answers.html



**Iron-Carbon Binary Phase Diagram**

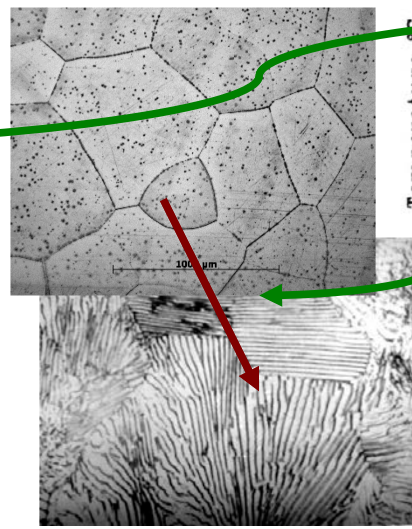
Image source: http://hsc.csu.edu.au/engineering_studies/application/civil/1-1/answers.html

# Background: Phase Transitions

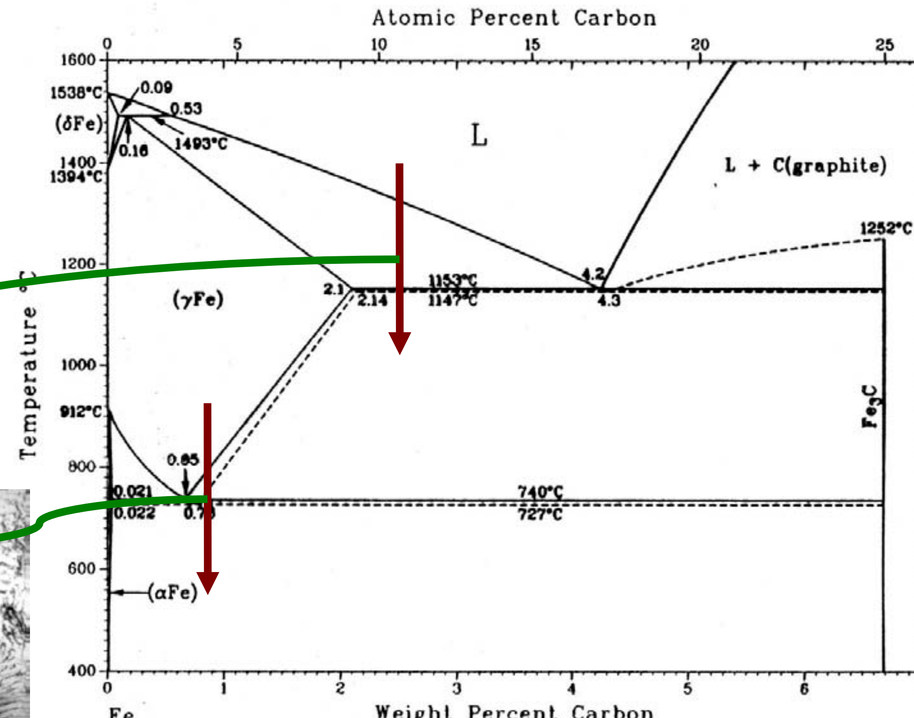
**Revisit: Feb. 12 (Phase Transitions)**

- One phase can **transform** into another









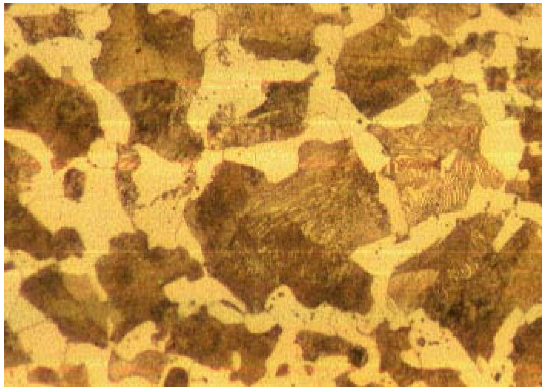



**Iron-Carbon Binary Phase Diagram**

Image source: http://hsc.csu.edu.au/engineering_studies/application/civil/1-1/answers.html

# Steel Heat Treatment and Microstructure

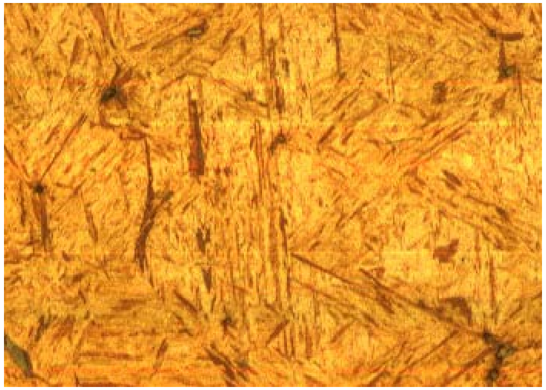
**Revisit: Feb. 12 (Phase Transitions)**
**Also see 22.71J (Physical Metallurgy)**



Normalized

Ductile fracture, tough, not very hard

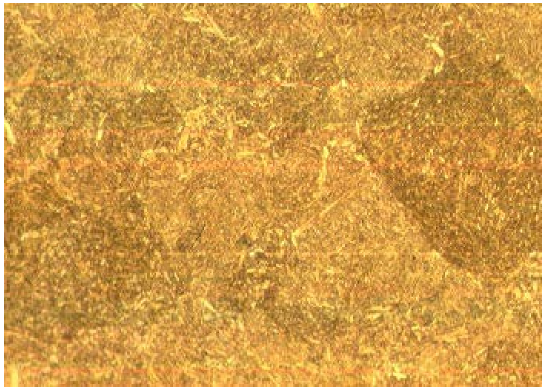
Larger grains, no/few cracks or major defects



Quenched

Very hard, NOT tough, brittle fracture

Small grains, can form microcracks



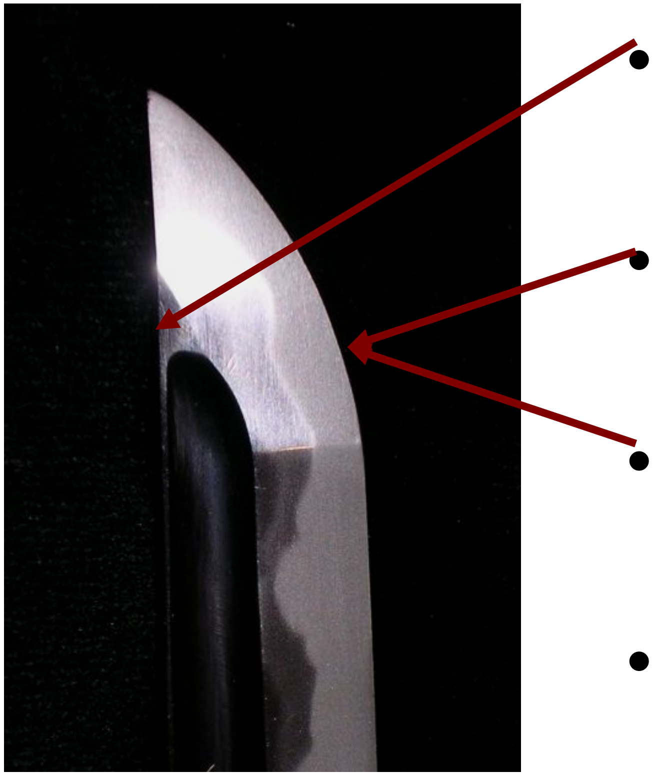
Tempered

Best of both, fairly hard, fairly tough, strong

Medium grains, partially relaxed internal stresses

# Heat Treatment

Revisit: Feb. 12 (Phase Transitions)
Also see 22.71J (Physical Metallurgy)





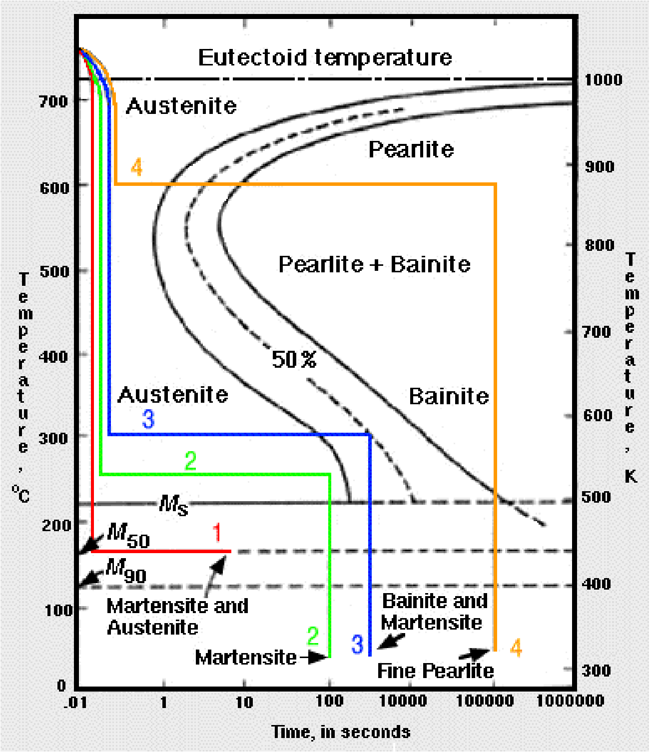
**Japanese sword tip, with heat treatment line**

Source: http://fudoshinken.com/?page_id=50

- **Annealing**: High heat to relax the microstructure
- **Quenching**: Rapid cooldown to freeze microstructure
- **Tempering**: Low, slow heat for balance of properties
- Proper heat treatment is *essential* to correct material properties
- Incorrect treatment can be *disastrous*

# Predicting Change: TTT

**Revist: Feb. 12 (Phase Transitions)**
**Also see 22.71J (Physical Metallurgy)**

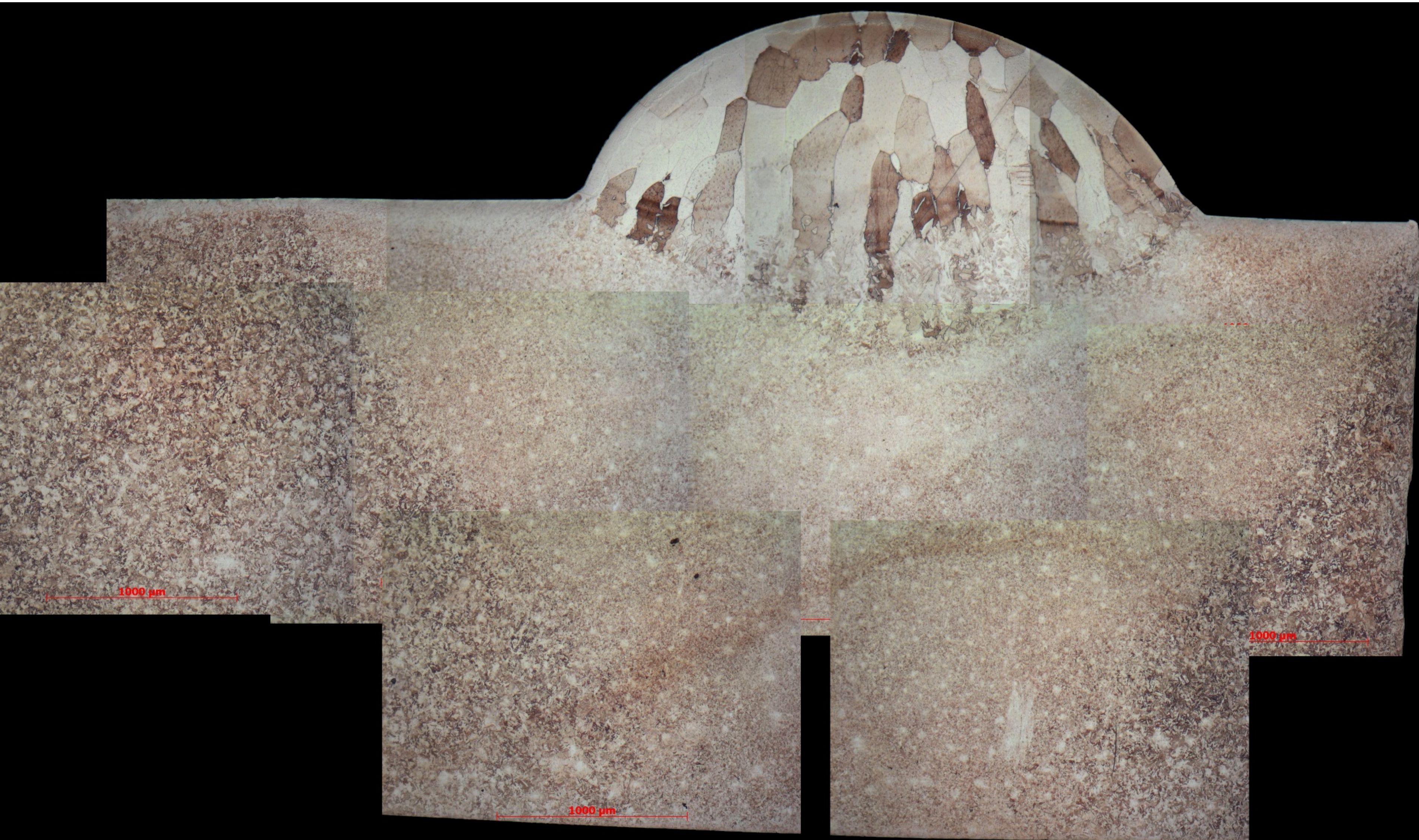



Courtesy of Ronald D. Kriz. Used with permission.

**Source:**
**www.sv.vt.edu/classes/MSE2094_NoteBook/96ClassProj/examples/kimttt.html**

- Time Temperature Transformation diagram
- Predict microstructure, properties vs. time at temperature (kinetics)
- Choose your heat treatment & effects

# Welding and the HAZ



# HAZ Cracking in a BWR

Fig. 1-1, 1-3 (a) and (b) in Ford, F. Peter. "Environmentally-Assisted Degradation of Structural Materials in Water Cooled Nuclear Reactors." *Advanced Nuclear Technology International Europe AB*, October 2006 removed due to copyright restrictions.

**P. Ford. "Environmentally-Assisted Degradation of Structural Materials in Water Cooled Nuclear Reactors." ANT International, 2006.**

# The Davis-Besse Incident

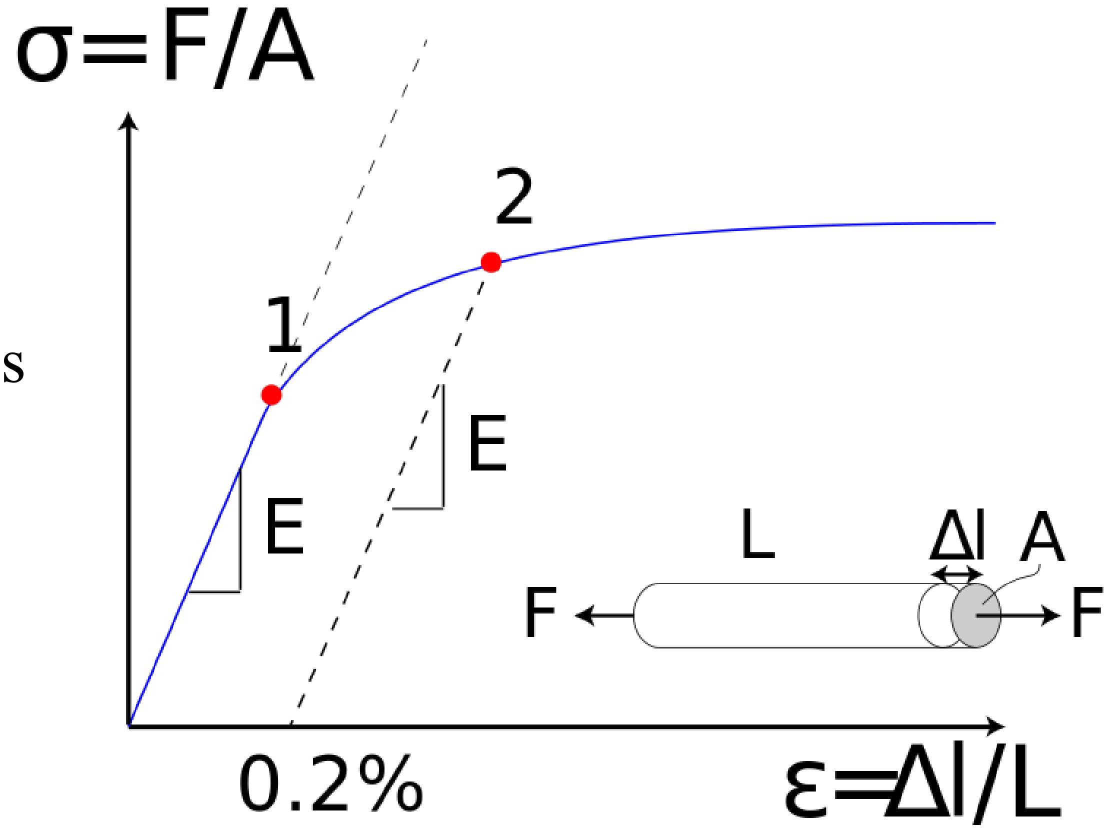
Fig. 1-1, 1-3 (a) and (b) in Ford, F. Peter. "Environmentally-Assisted Degradation of Structural Materials in Water Cooled Nuclear Reactors." *Advanced Nuclear Technology International Europe AB*, October 2006 removed due to copyright restrictions.

**P. Ford. "Environmentally-Assisted Degradation of Structural Materials in Water Cooled Nuclear Reactors." ANT International, 2006.**

# Young's Modulus (E)

**Revisit: Feb. 26 (Mechanical Properties)**

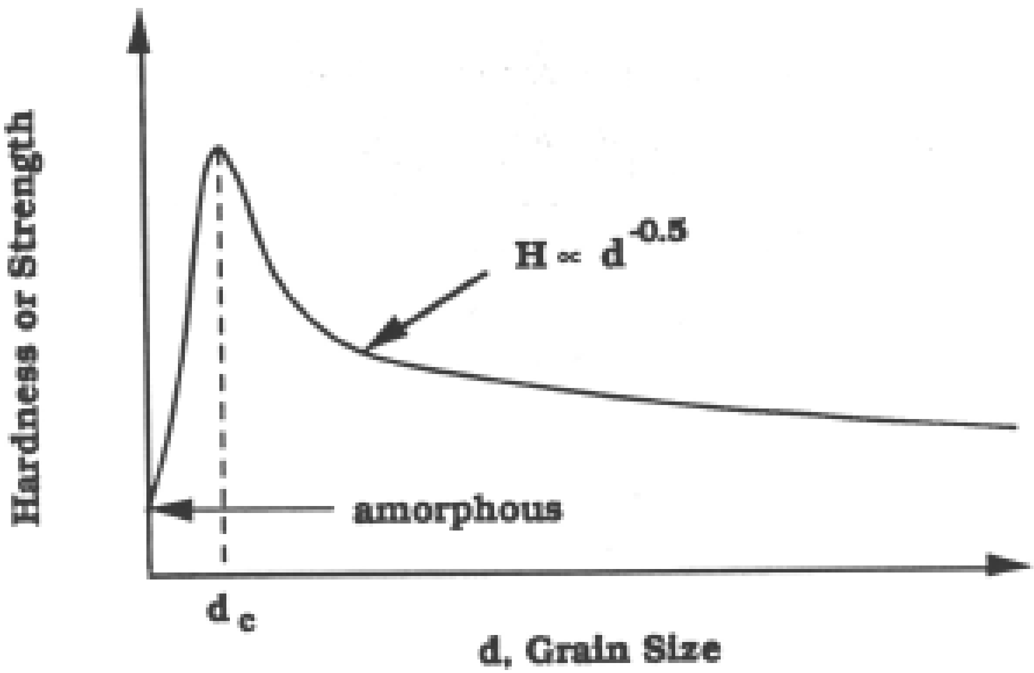
Measures elastic deformation vs. stress




Source: Wikimedia Commons

# Grain Size vs. Strength

Revisit: Feb. 26 (Mechanical Properties)



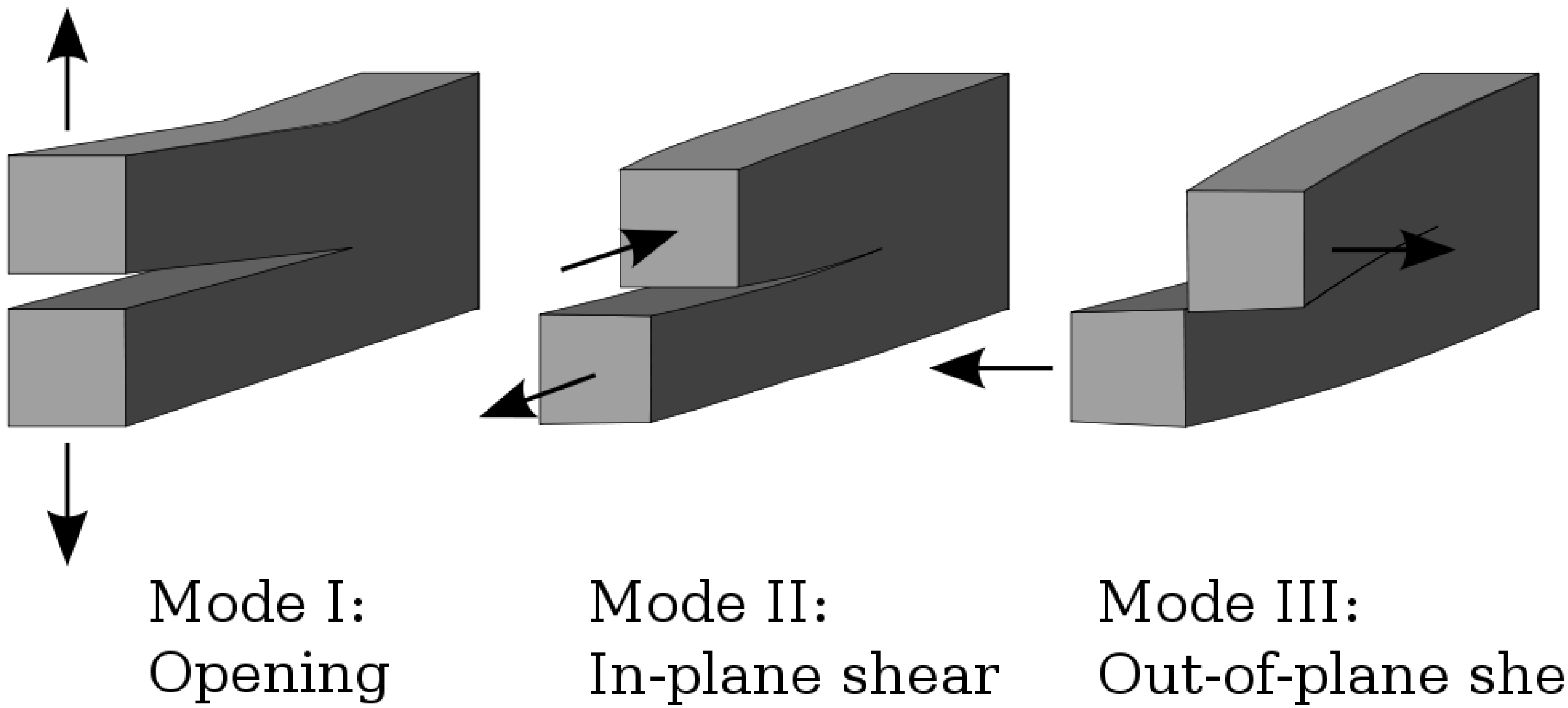



**Hall-Petch effect of grain size vs. strength**

- Microstructure changes many properties
- Smaller grain size leads to higher strength
- Called the **Hall-Petch** effect

# Fracture Toughness

**Revisit: Feb. 26 (Mechanical Properties)**






Source: Wikimedia Commons

# Fracture Toughness ($K_{Ic}$)

**Revisit: Feb. 26 (Mechanical Properties)**

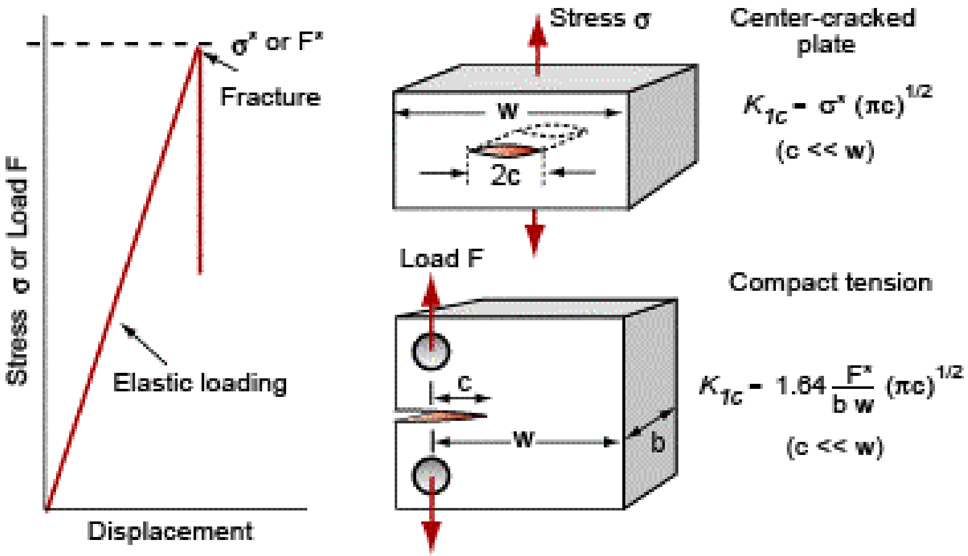
$$K_{Ic} = Y_1 \sigma^* \sqrt{\pi c} \text{ or } K_{Ic} = Y_2 \frac{F^*}{bw} \sqrt{\pi c}$$

Resistance to crack propagation

-$Y_1$, $Y_2$ are geometric factors near 1

-$\sigma^*$, $F^*$ are critical stress and force, respectively

Source: inventor.grantadesign.com

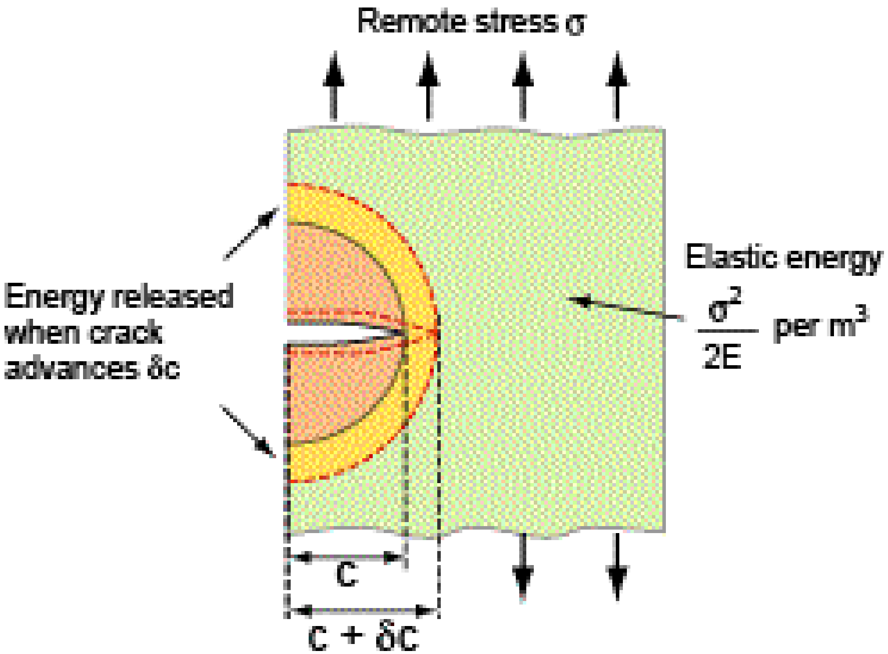


# Toughness ($G_c$)

**Revisit: Feb. 26 (Mechanical Properties)**

Measures the energy it takes to separate a material

$$K_{Ic} = \sqrt{EG_c}$$

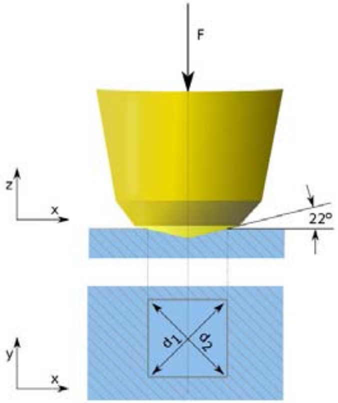



Source: inventor.grantadesign.com

# Hardness

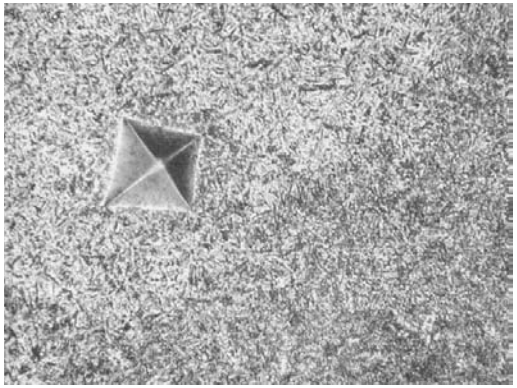
**Revisit: Feb. 26 (Mechanical Properties)**

- Measures the resistance to plastic deformation
  - NOT toughness!!! NOT strength!!!
- Measured with small indentations





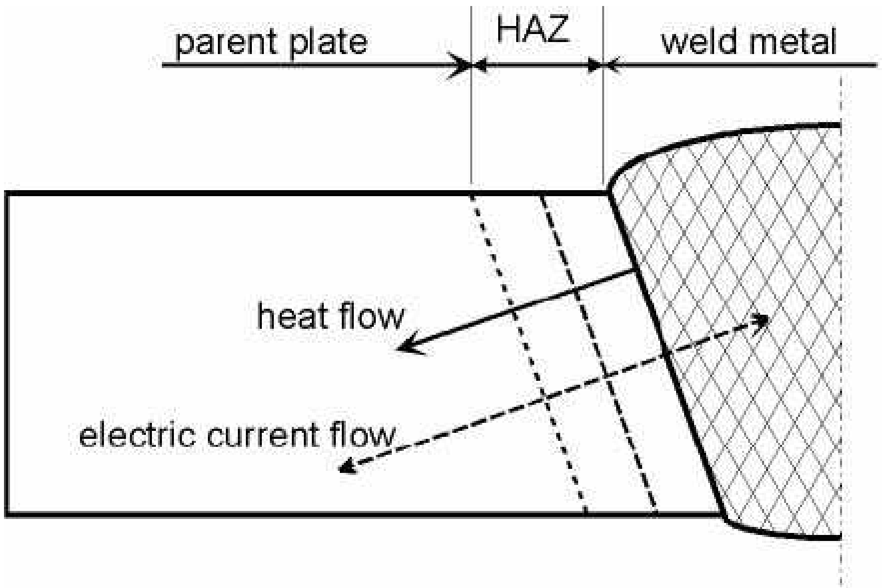




Source: Wikimedia Commons: Vickers hardness test schematic, indenter, and indentation on steel

# Welding and the HAZ




Courtesy of Stan T. Mandziej. Used with permission.

- HAZ: Heat Affected Zone
- Gets heat treated by virtue of proximity to weld
- Much cracking happens here!

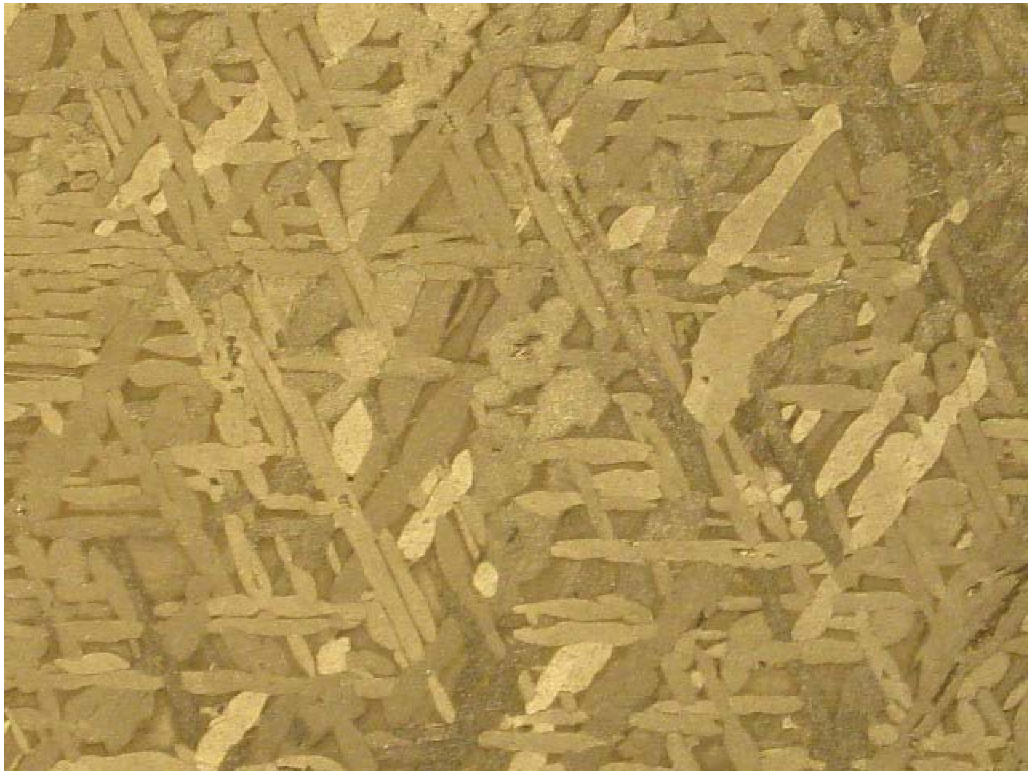
Source: http://www.china-weldnet.com/English/information/II-1553-05.htm

# Processing Methods

Images removed due to copyright restrictions.

Source: http://sifco100.com/when-only-a-hammer-will-do/

# Casting

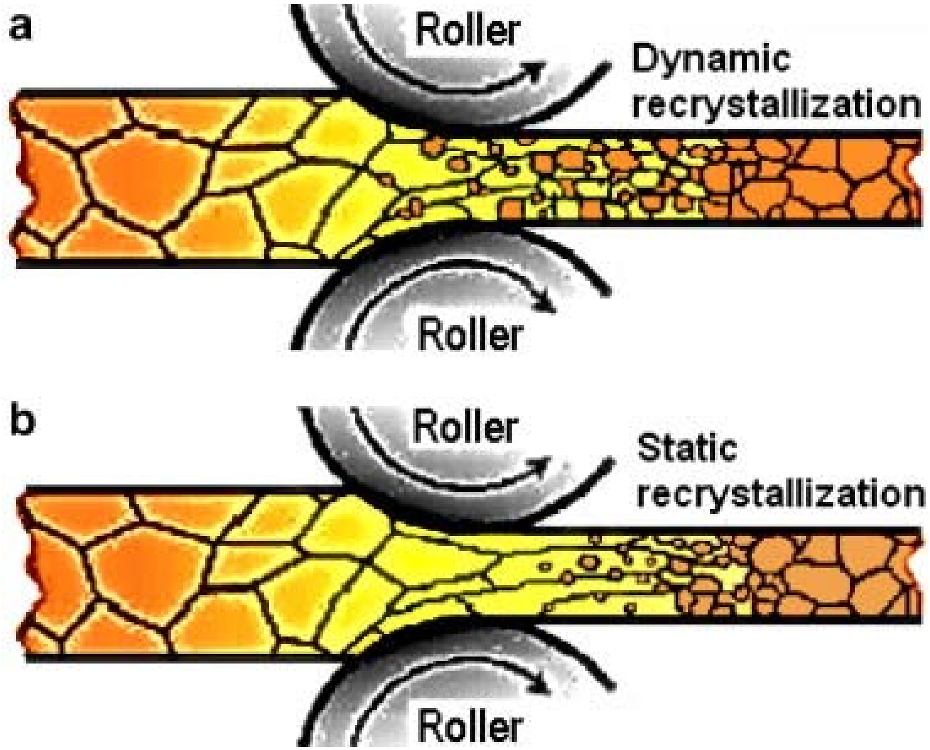




Source: Wikimedia Commons

- Cooling molten metal from a melt
- Huge grains, dendrites from cooling
- Left: A meteorite, the ultimate cast microstructure

# Rolling




Courtesy of Elsevier, Inc., http://www.sciencedirect.com. Used with permission. Source: Zheng, C et al. "Microstructure Prediction of the Austenite Recrystallization during Multi-pass Steel Strip Hot Rolling: A Cellular Automaton Modeling." *Computational Materials Science* 44 (2008): 507-14.

Source: C. Zheng et al. *Comp. Mat. Sci.* 44(2):507 (2008).

- Directionalized force
- Can elongate grains, induce recrystallization (reformation of grains)
- Can be done hot or cold

# Forging

Image of forging removed due to copyright restrictions.

- Breaking up the microstructure with mechanical force
- Usually done hot
- Reduces grain size
- Directionally works steel

Source: themidnightcarver.blogspot.com/2011/01/forged.html

# Forging

Images removed due to copyright restrictions.

Source: http://sifco100.com/when-only-a-hammer-will-do/

# How Do Things Fail?

Revisit: Mar. 3 (Failure)

**Everyone**

1. Overload
2. Creep Rupture
3. Fatigue
4. Brittle Fracture
5. Wastage
6. Environmentally Enhanced
    - General Corrosion
    - Stress Corrosion Cracking
    - Hydrogen Embrittlement
    - Corrosion Fatigue
    - Intergranular Attack
    - Erosion/Corrosion
    - Creep/Fatigue Interaction
    - Liquid Metal Embrittlement
    - Pitting
    - Fretting
    - Dezincification

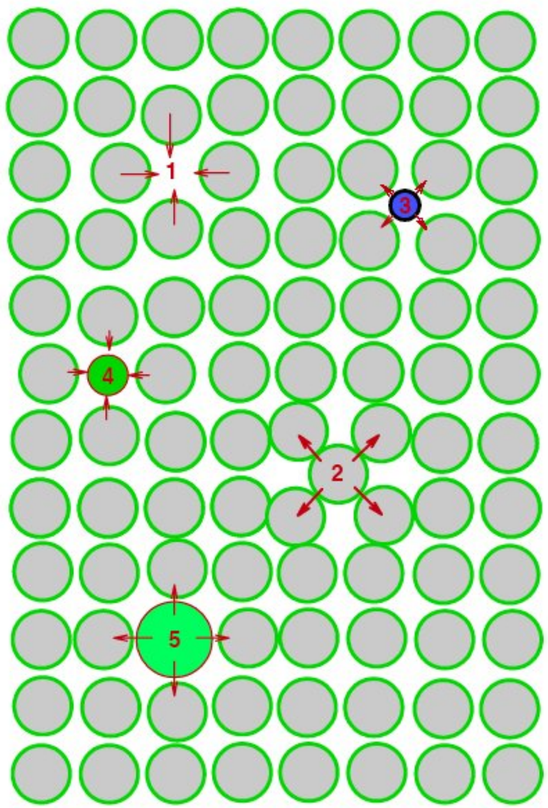
**Just us...**

7. Radiation Damage

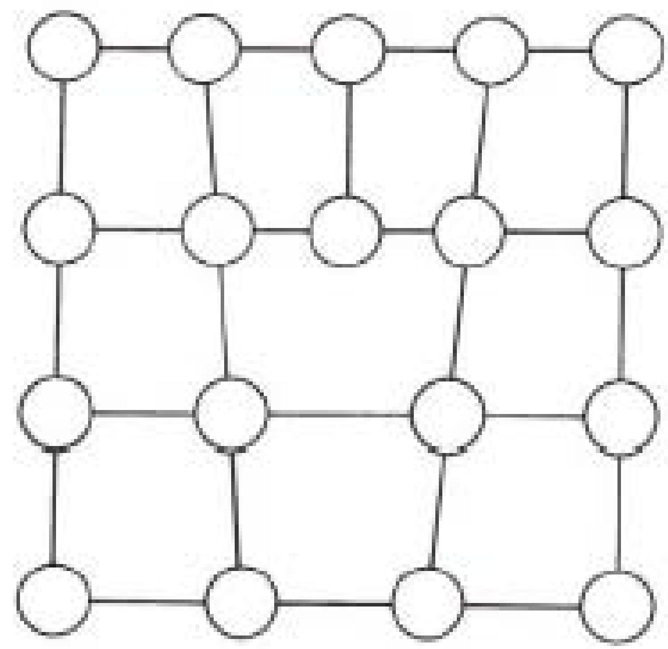
-Swelling
-Void nucleation
-Helium embrittlement
-Radiation induced segragation
-Irradiation creep
-Loss of ductility
-Defect accumulation
-Fracture toughness reduction
-Activation
-Phase dissolution

# Creep: Background
# 0-D and 1-D Defects

**Revisit: Feb. 24 (Defects, Dislocations)**




Courtesy of Leonid V. Zhigilei. Used with permission.

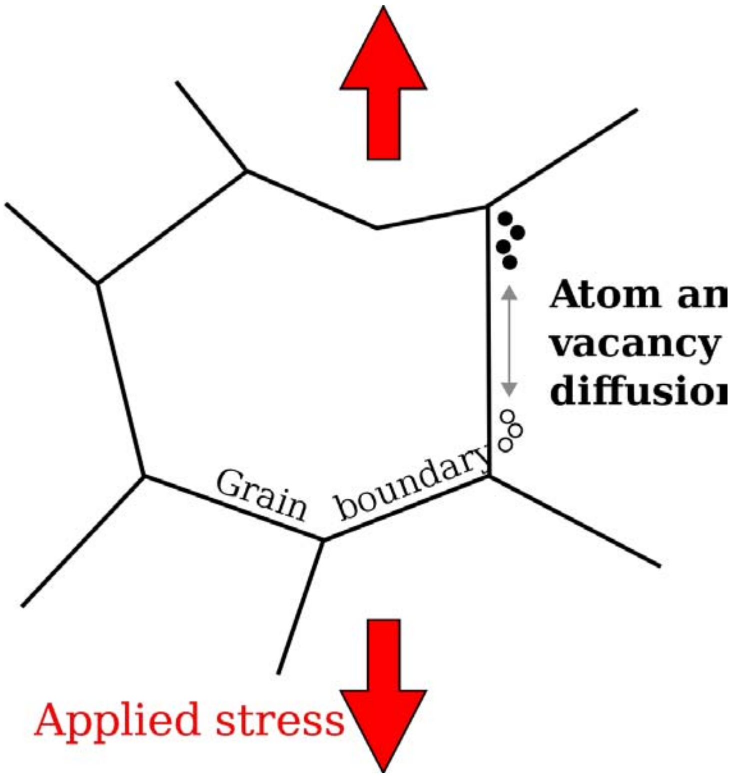


Edge Dislocation

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

# Creep

**Revisit: Mar. 3 (Creep, Plasticity)**



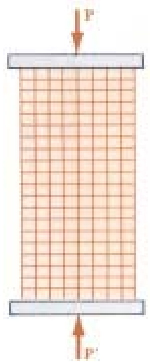
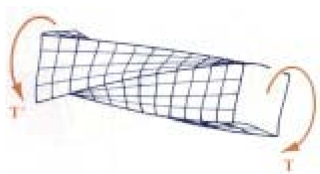
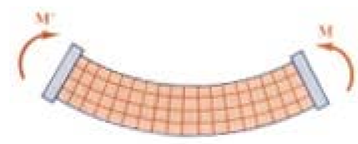
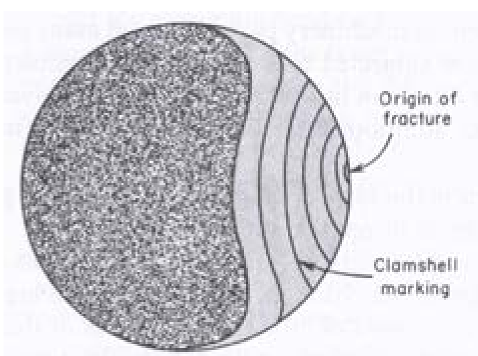


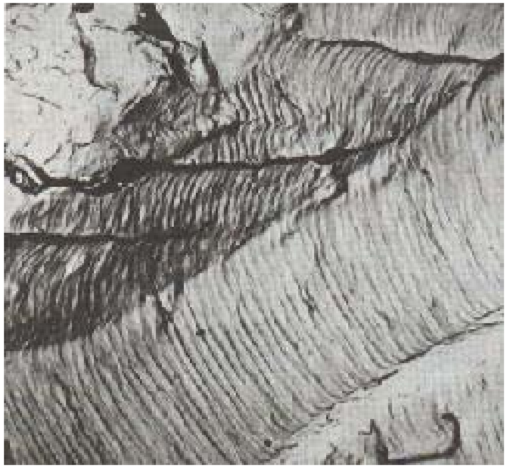

- Plastic flow under constant stress
- Tension, gravity...
- Happens well below yield stress
- Multiple modes (Coble, Nabarro-Herring...)

Source: Wikimedia Commons

# Fatigue

**Revisit: Mar. 3 (Fatigue)**



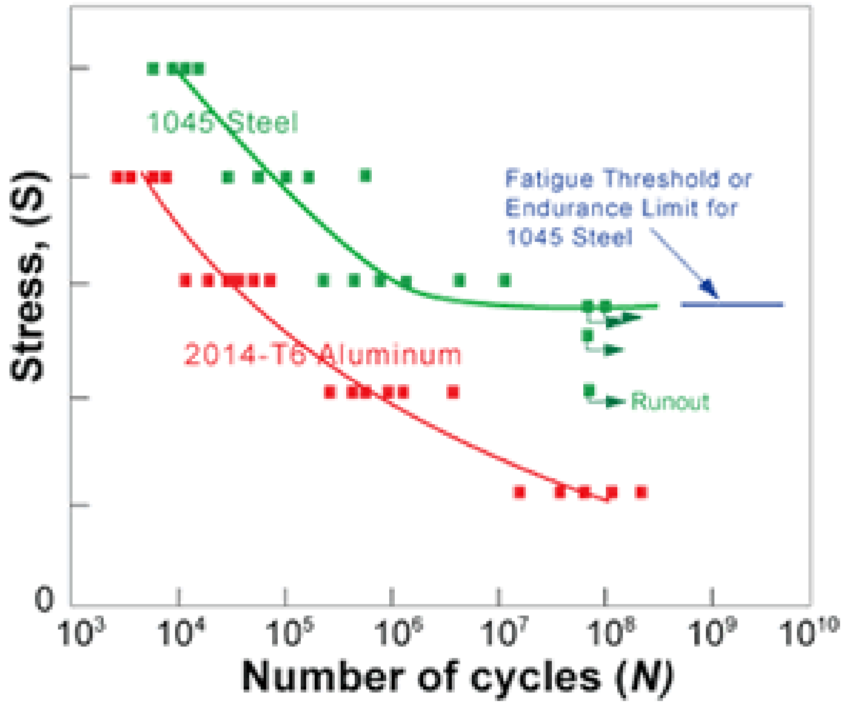
- Repeated application of stress
- Can cause cracks to grow
- Induced by vibrations, mechanical loading
- Telltale “fatigue striations”



Source: www.sv.vt.edu/classes/MSE2094_NoteBook/97ClassProj/anal/kelly/fatigue.html

# Fatigue: S-N Curves

**Revisit: Mar. 3 (Fatigue)**



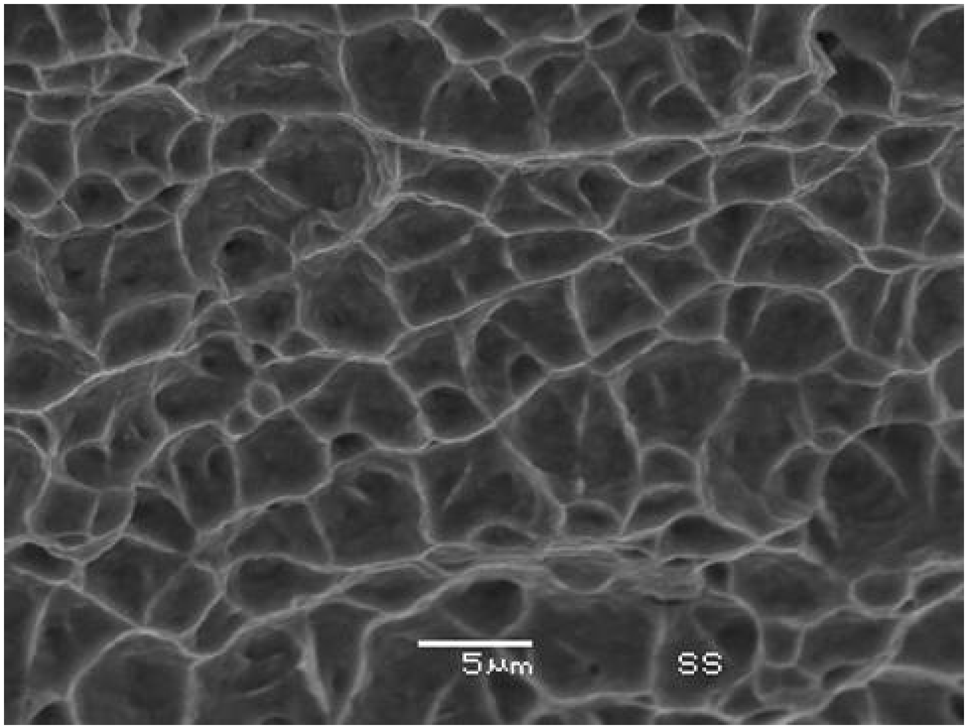



- Stress (S) vs. number of cycles (N)
- Lower limit of stress (where N is infinite) is the "safe zone"

Source: www.nde-ed.org/EducationResources/CommunityCollege/Materials/Mechanical/S-NFatigue.htm

# Ductile/Brittle Fracture

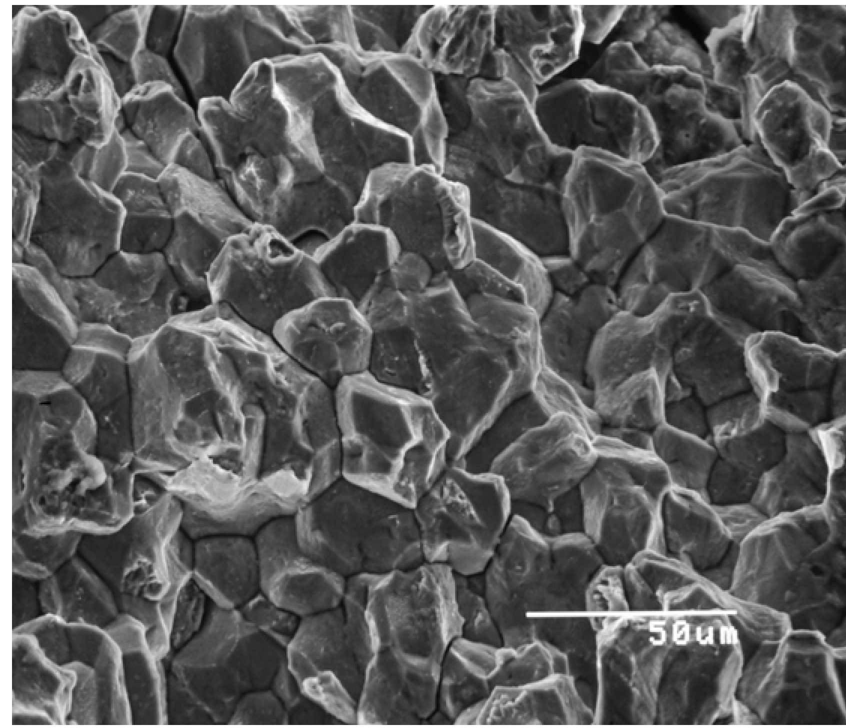
**Revisit: Mar. 3 (Fracture)**






**Ductile Fracture**

www.ijme.us/issues/spring2004/IJME_Biomaterial_Revised2.htm



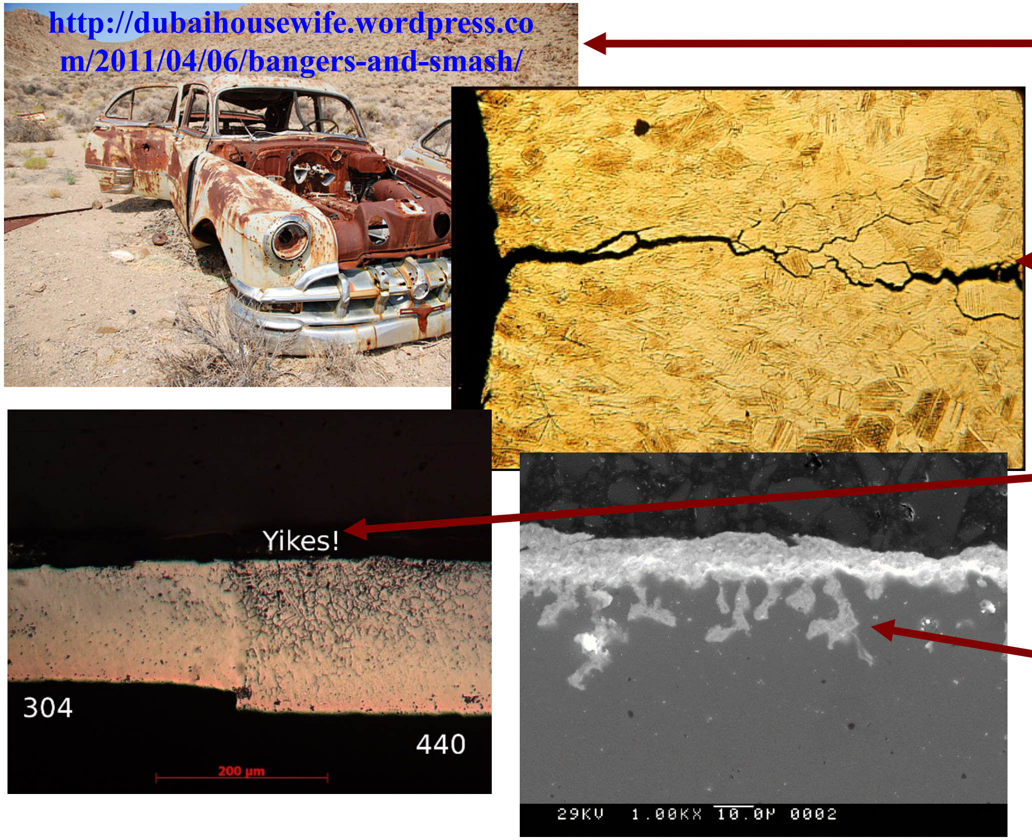



**Brittle Fracture**

http://site.christensenmaterials.com/Services.html

# Types of Corrosion

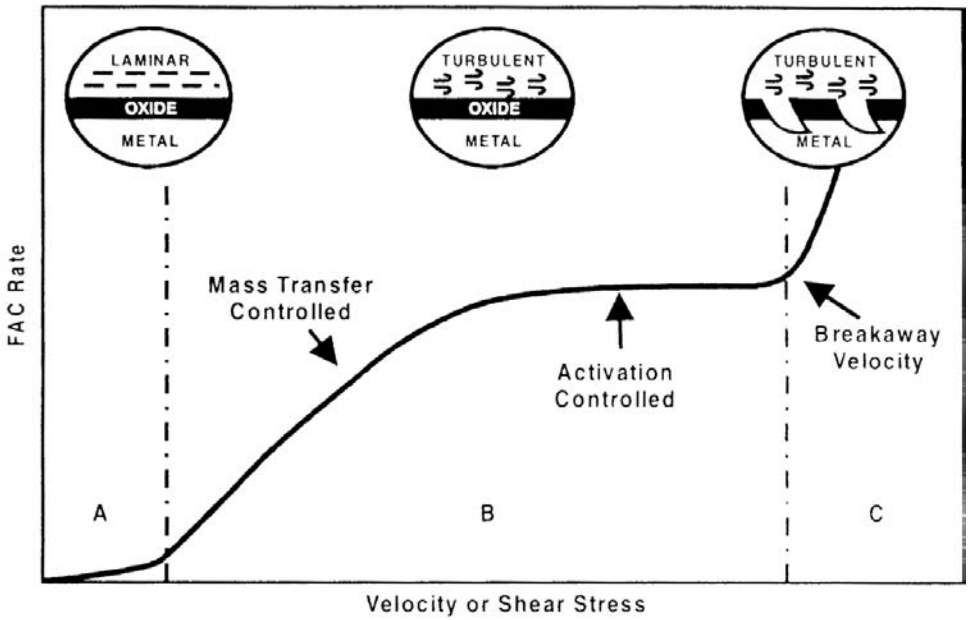
See 22.72J (Corrosion)




- General
- Flow-Assisted
- Stress Corrosion Cracking
- Galvanic
  - Dissimilar metals
- Dissolution
- Others!

# Flow Assisted Corrosion

See 22.72J (Corrosion)





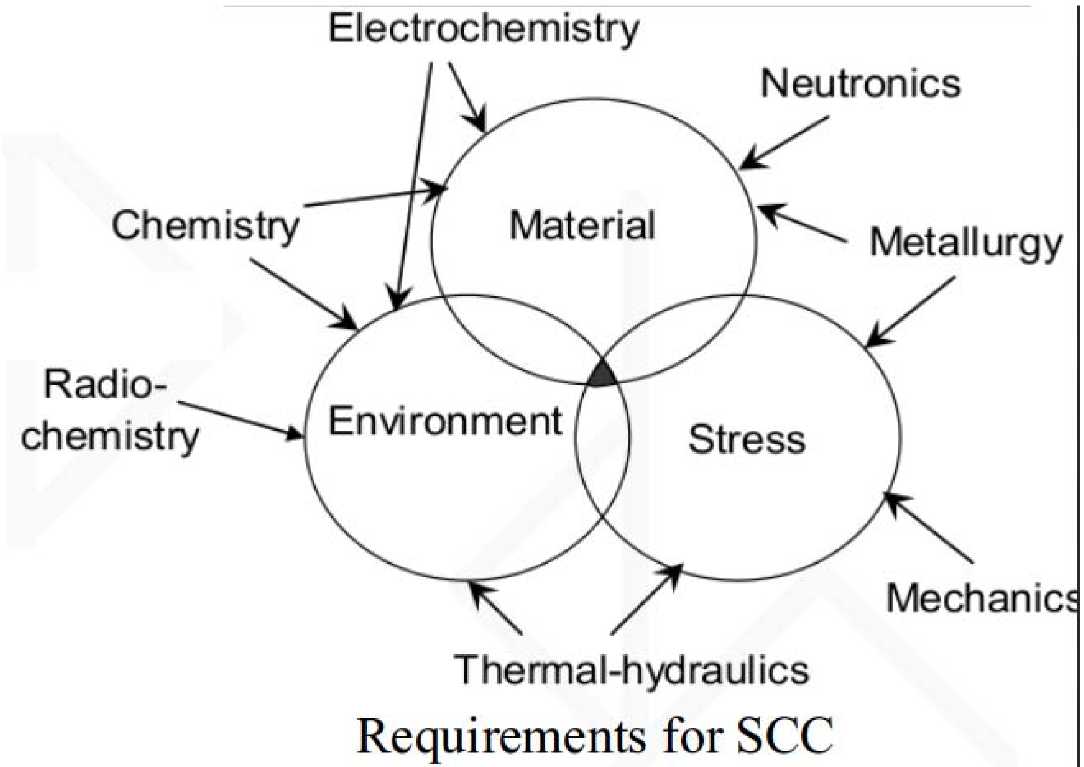
Source: Balbuad-Celerier, F., and F. Barbier. "Investigation of Models to Predict the Corrosion of Steels in Flowing Liquid Lead Alloys." *Journal of Nuclear Materials* 289, no. 3 (2001): 227-42.

- Corrosion can be limited by solubility in solvent
- Flow can transport mass away, letting more dissolve
- Fast flow can erode your materials

Source: F. Balbaud-Celerier and F. Barbier. *J. Nucl. Mater.*, 289(3):227-242 (2001).

# SCC

See 22.72J (Corrosion)



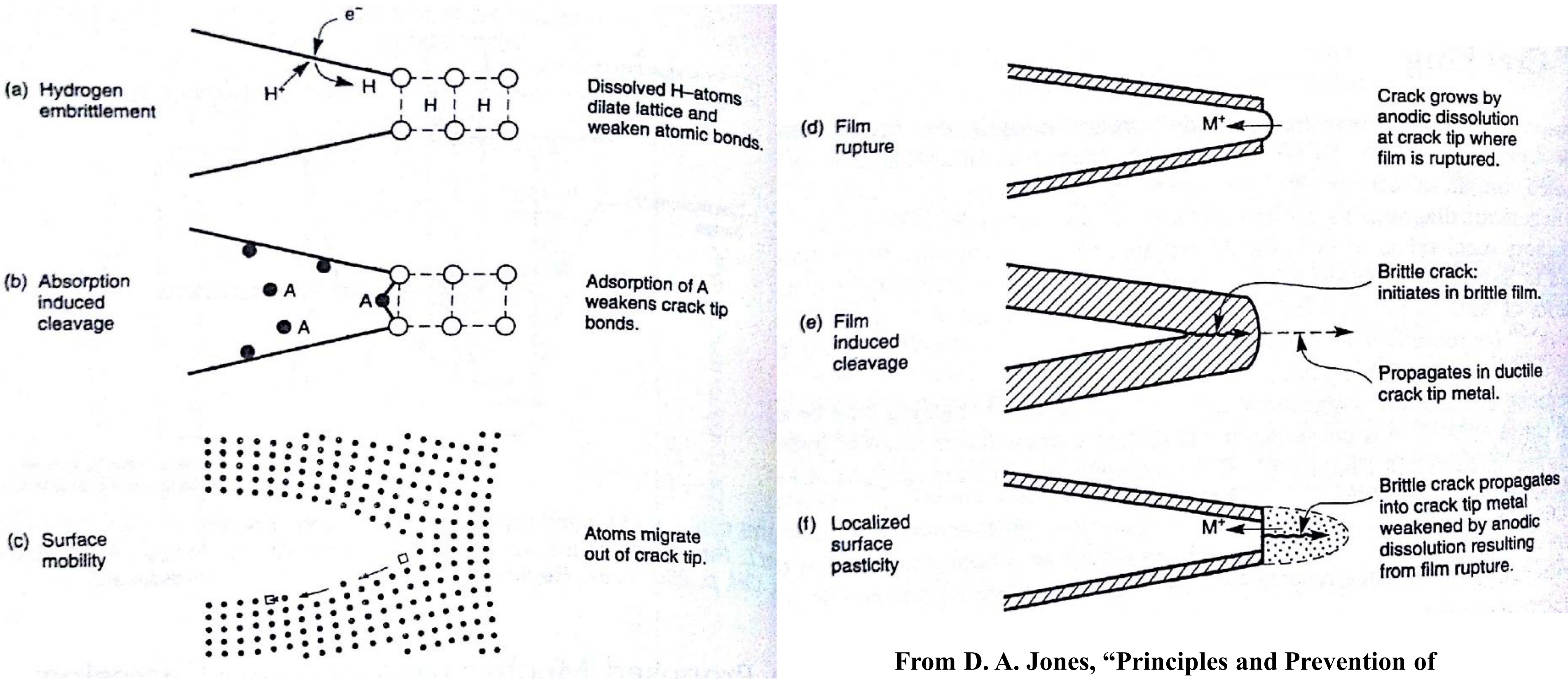

- Stress corrosion cracking
- Requires tensile stress, susceptible material, aggressive environment



Source: P. Combrade, INEST SCC Workshop, Idaho Falls, ID (2013).

# Proposed SCC Mechanisms

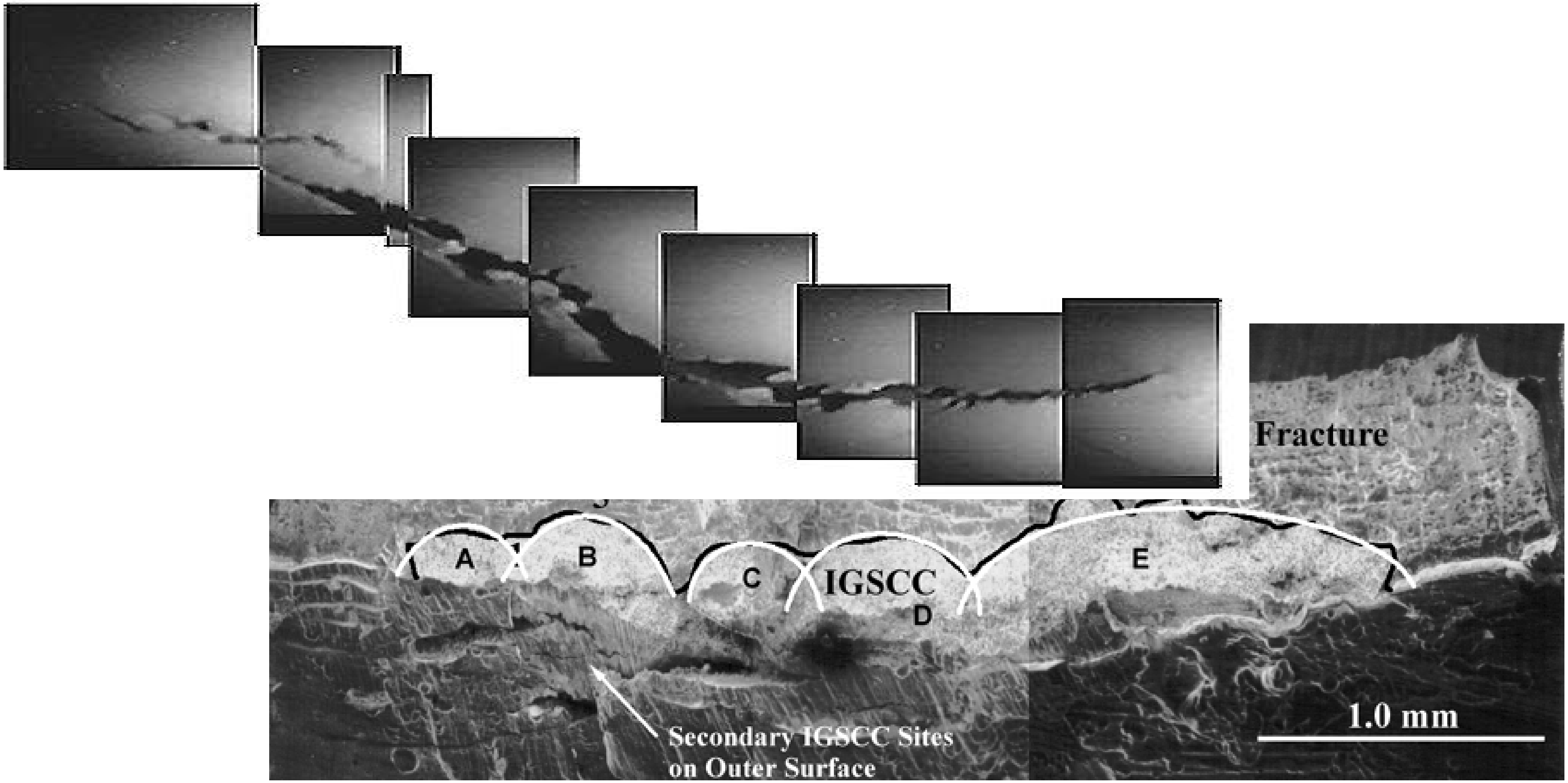
See 22.72J (Corrosion)




**From D. A. Jones, "Principles and Prevention of Corrosion," p. 279 (1996).**

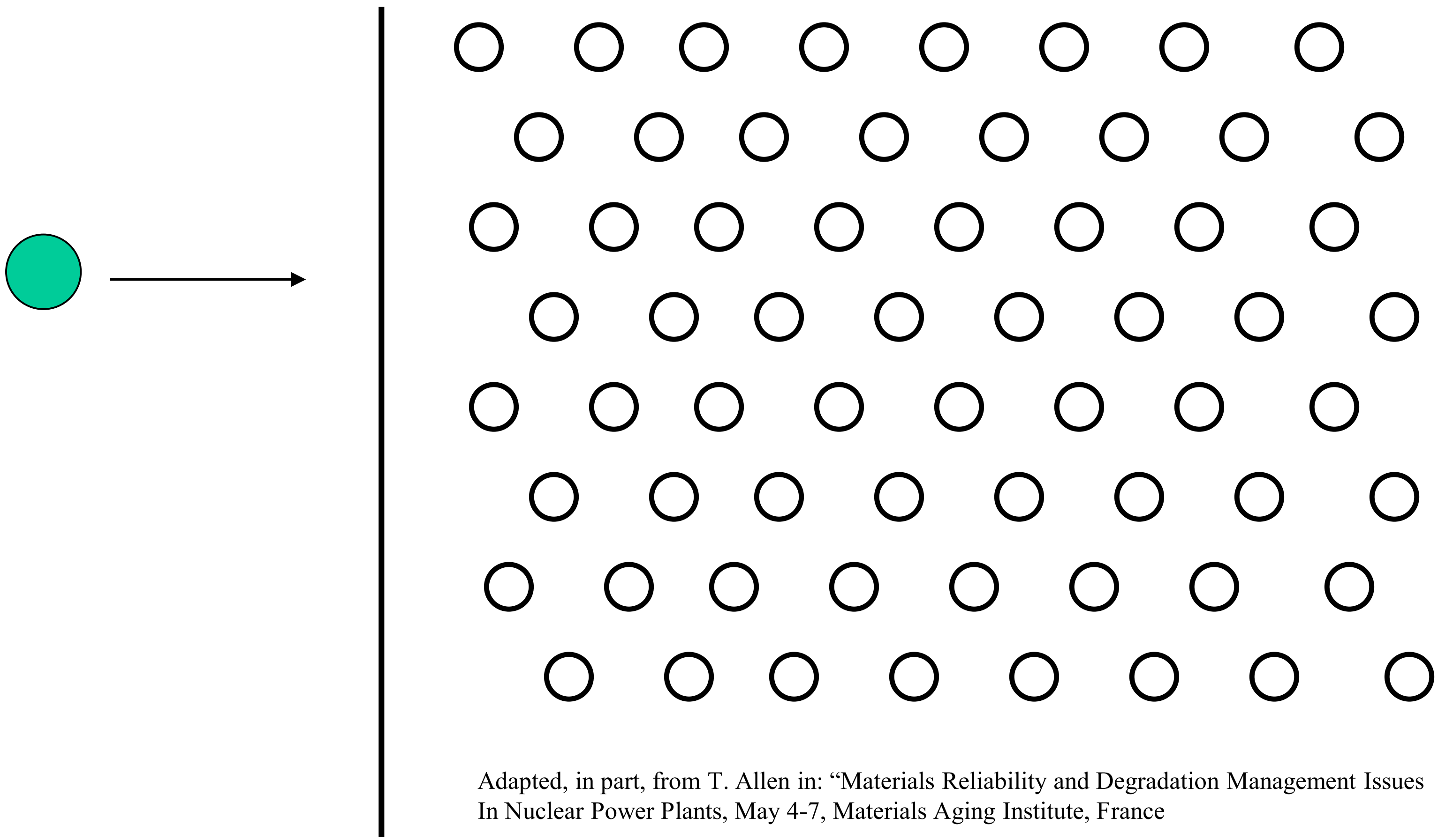
# SG Tube SCC Crack

See 22.72J (Corrosion)



# Radiation Damage: Simple Mechanism

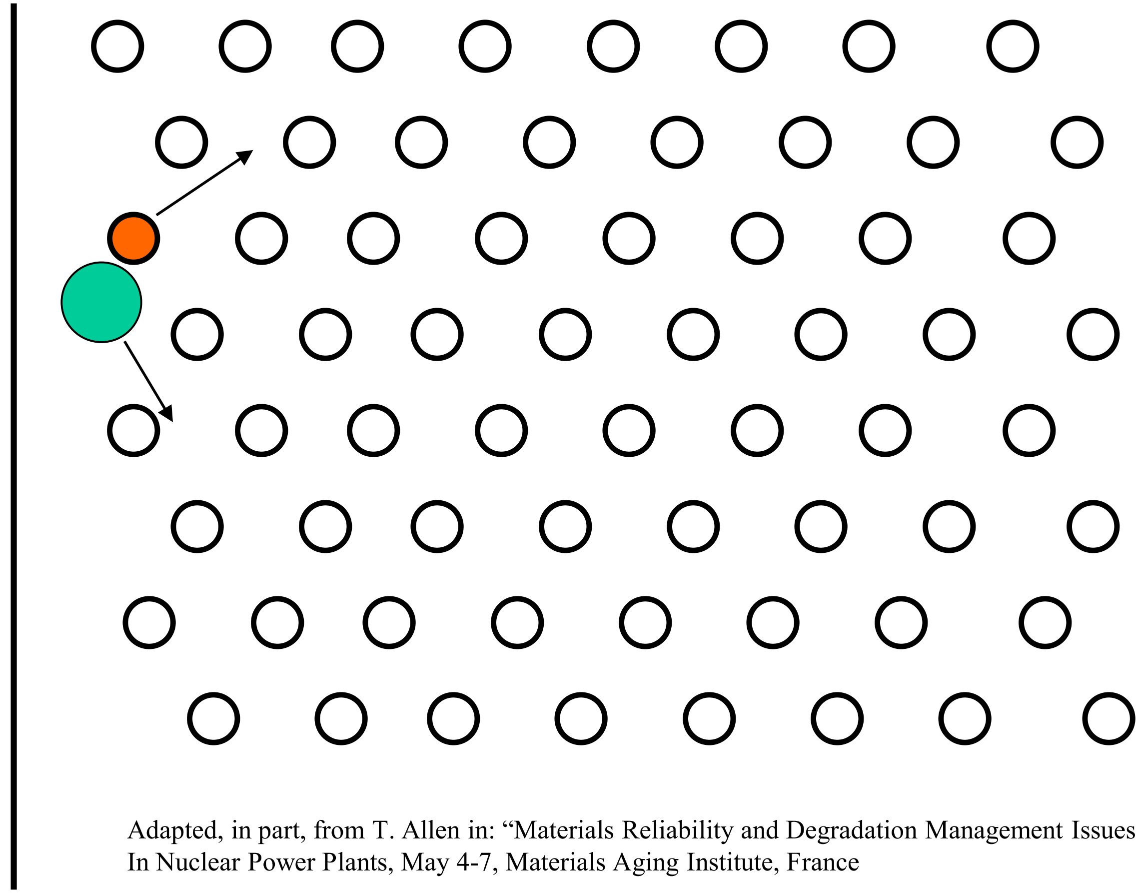
Revisit: Mar. 5 (Radiation Damage)



Adapted, in part, from T. Allen in: "Materials Reliability and Degradation Management Issues In Nuclear Power Plants, May 4-7, Materials Aging Institute, France

# Radiation Damage: Simple Mechanism

**Revisit: Mar. 5 (Radiation Damage)**



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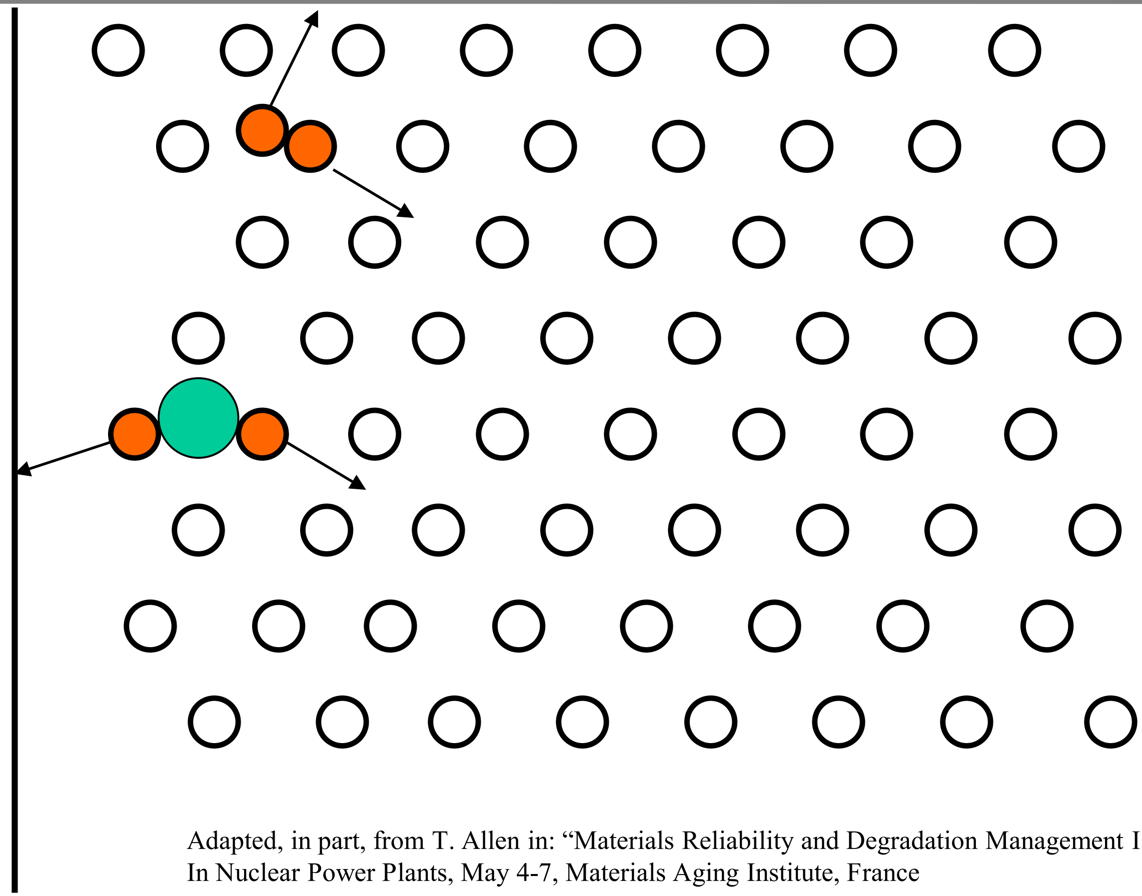

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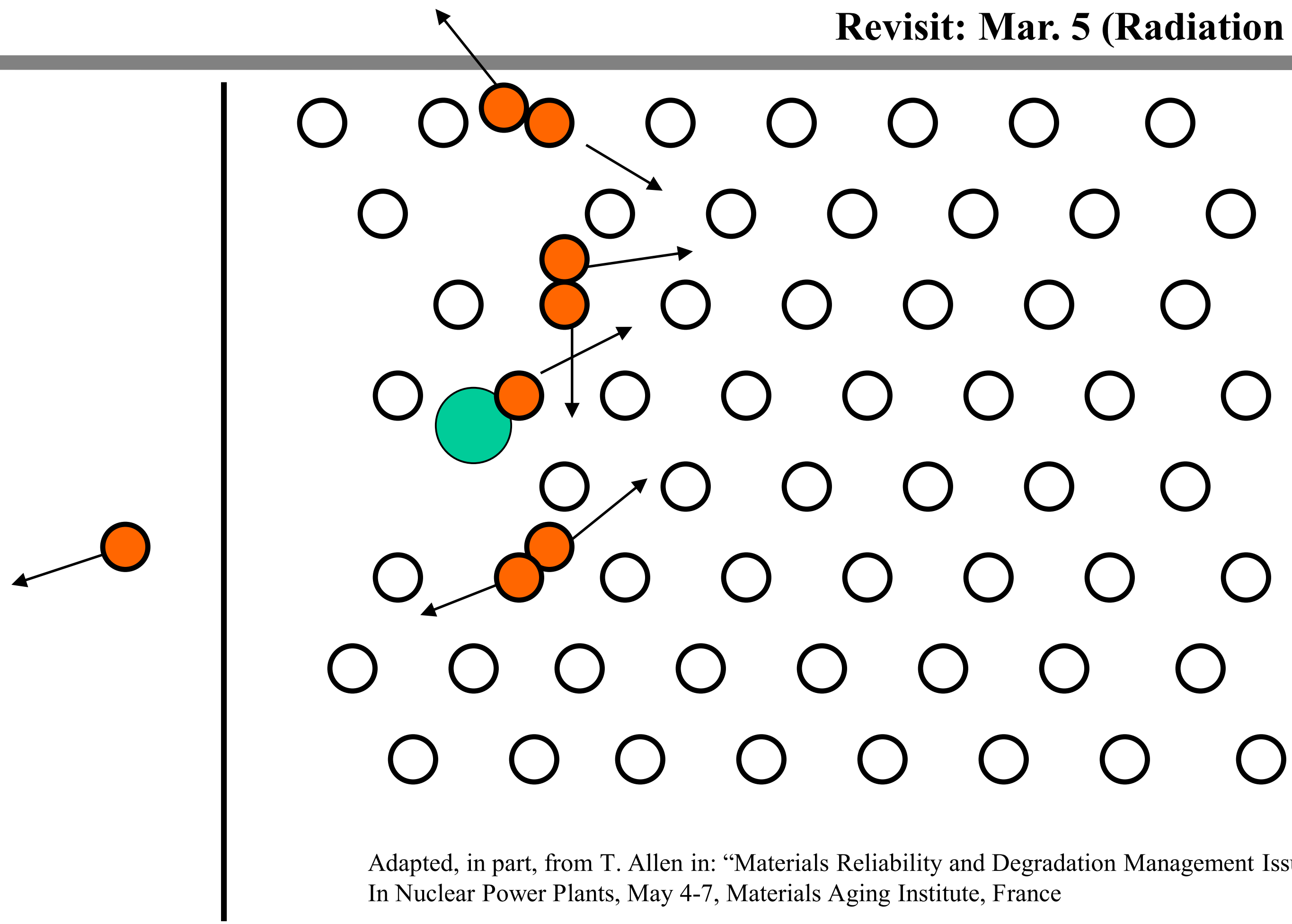

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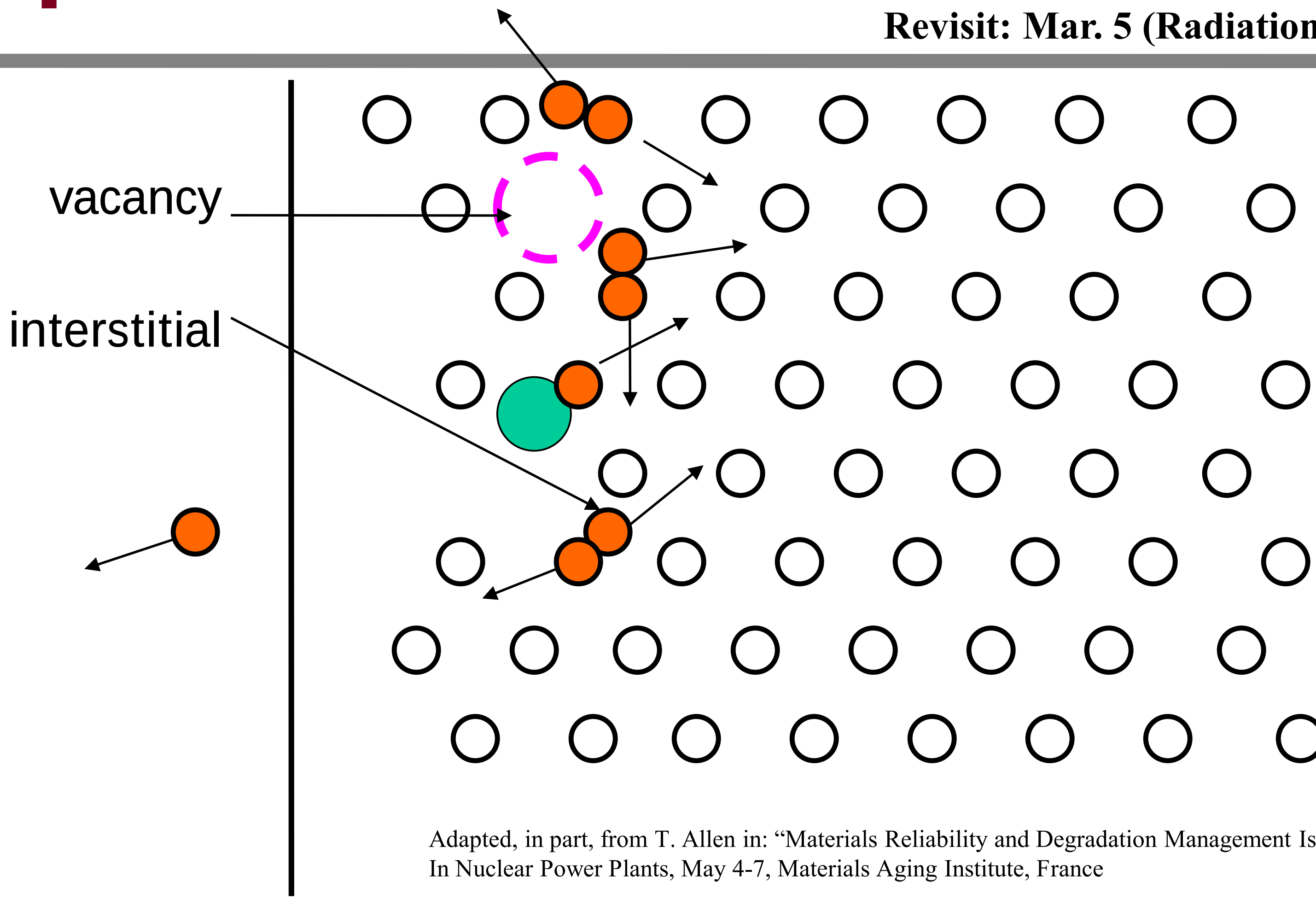
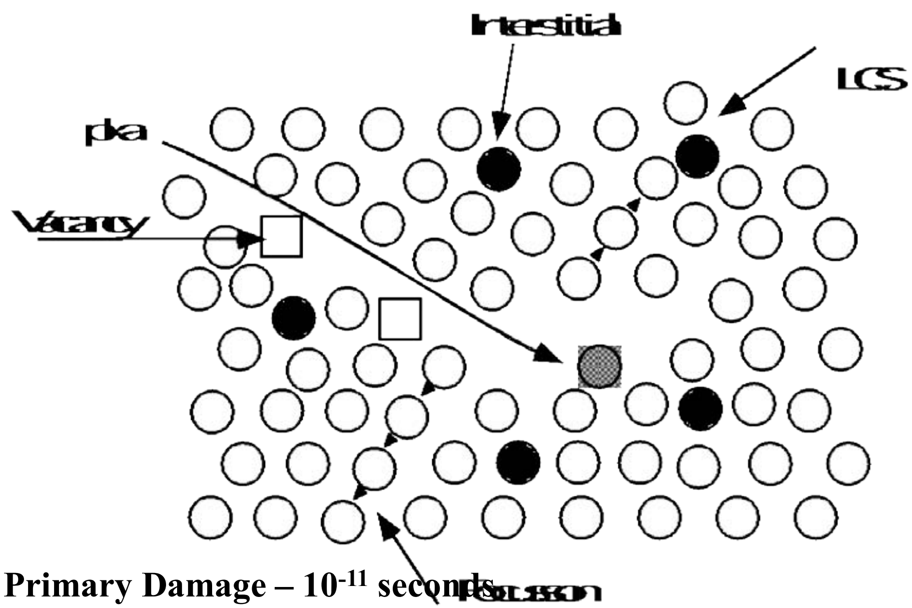



Adapted, in part, from T. Allen in: “Materials Reliability and Degradation Management Issues In Nuclear Power Plants, May 4-7, Materials Aging Institute, France

# Radiation Damage: DPA

**Revisit: Mar. 10 (Stopping Power, DPA)**




- **Primary Damage – $10^{-11}$ seconds**
- **Migration of Defects – seconds**
- **Property Changes – hours, days, months**

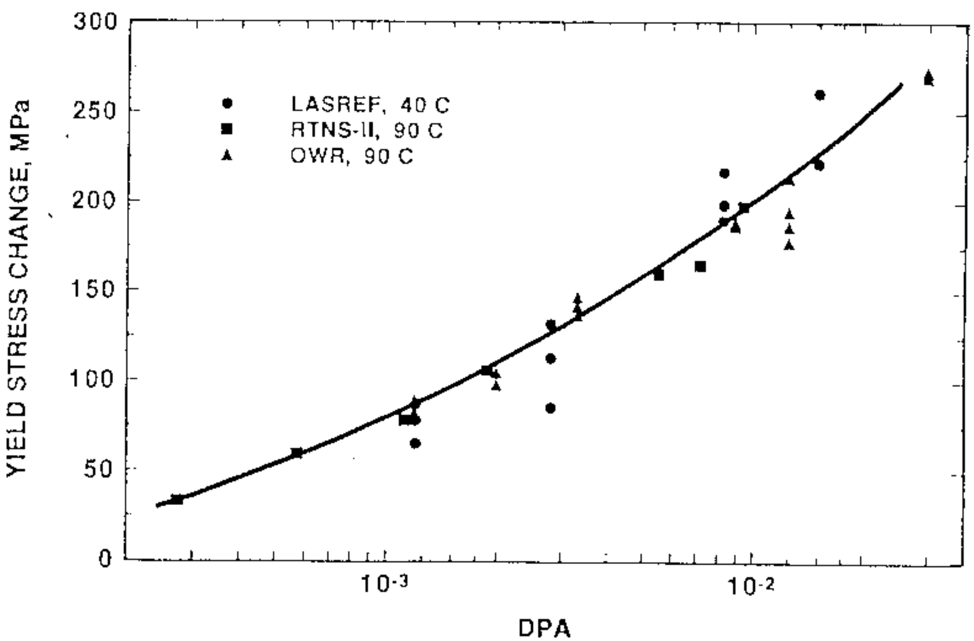


Adapted, in part, from T. Allen in: "Materials Reliability and Degradation Management Issues In Nuclear Power Plants, May 4-7, Materials Aging Institute, France

- DPA – Displacements per atom
- Measures average number of times each atom is knocked out of position

# Radiation Damage: DPA vs. Properties

**Revisit: Mar. 12 (Radiation Effects)**



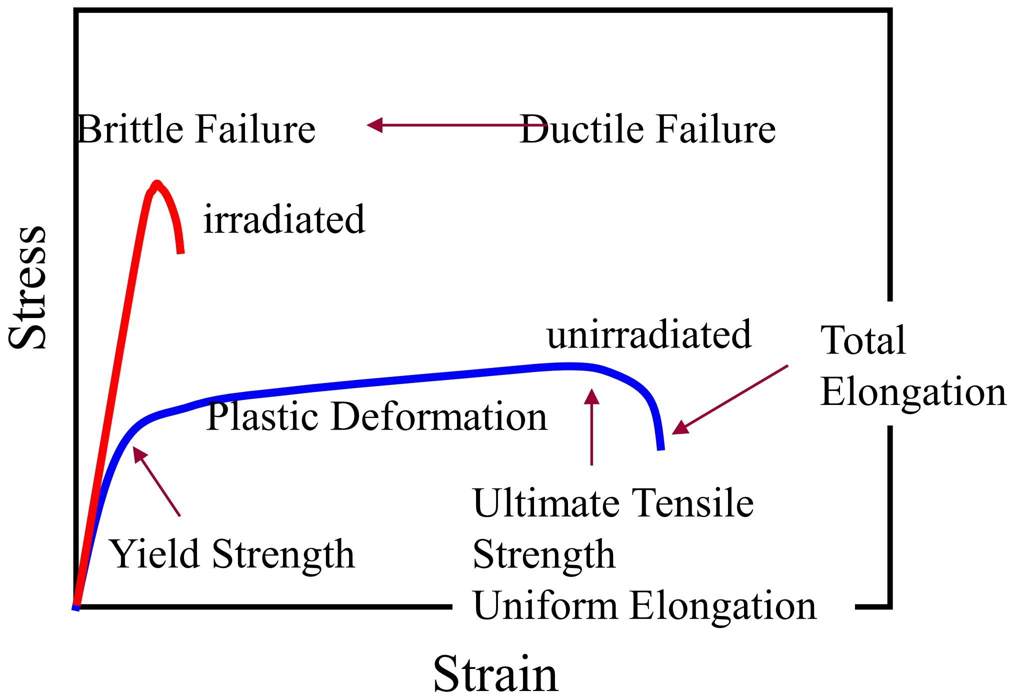



Adapted, in part, from T. Allen in: "Materials Reliability and Degradation Management Issues In Nuclear Power Plants, May 4-7, Materials Aging Institute, France

- Mechanical properties change as a function of DPA, temperature
- Normally reduction in strength, higher Young's modulus, lower fracture toughness

# Radiation Damage: DPA vs. Properties

**Revisit: Mar. 12 (Radiation Effects)**

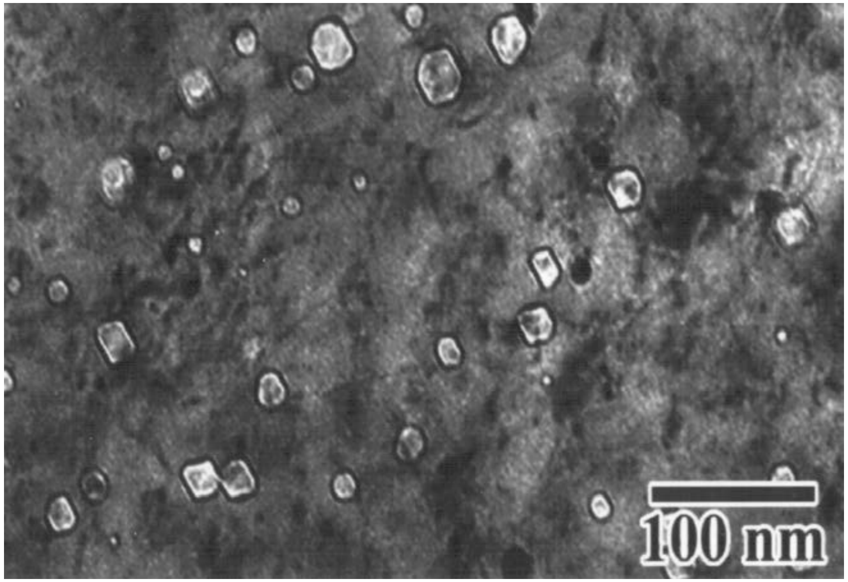



Adapted, in part, from T. Allen in: "Materials Reliability and Degradation Management Issues In Nuclear Power Plants, May 4-7, Materials Aging Institute, France

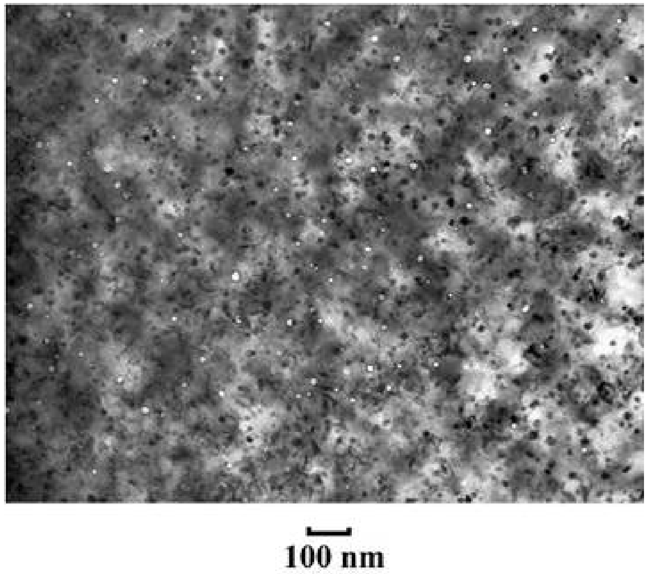
- Mechanical properties change as a function of DPA, temperature
- Normally reduction in strength, higher Young's modulus, lower fracture toughness

# Radiation Damage: Defect Accumulation

Revisit: Mar. 12 (Radiation Effects)



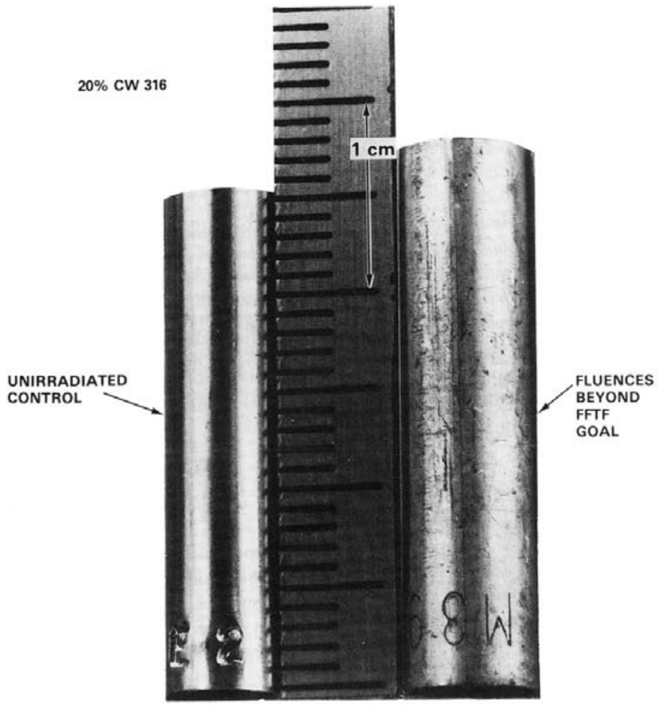

Void creation




Carbide precipitation

# Radiation Damage: Void Swelling

**Revisit: Mar. 12 (Radiation Effects)**



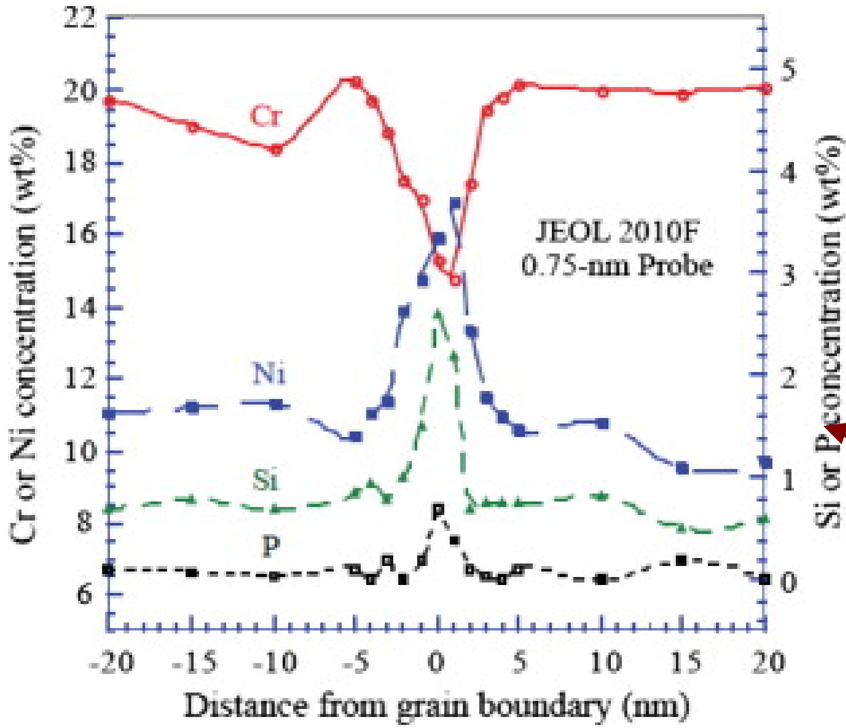



- Void creation (defect accumulation) combined with hydrogen/helium stabilization
- Causes actual dimensional changes!

Adapted, in part, from T. Allen in: "Materials Reliability and Degradation Management Issues In Nuclear Power Plants, May 4-7, Materials Aging Institute, France

# Radiation Damage

**Revisit: Mar. 12 (Radiation Effects)**





Source: Was, G. S., et al. "Assessment of Radiation-induced Segregation Mechanisms in Austenitic and Ferritic–martensitic Alloys." *Journal of Nuclear Materials* 411, no. 1-3 (2011): 41-50.

**Radiation-induced segregation in 300-series stainless steel**

Source: G. S. Was et al., J. Nucl. Mater., 411(1–3), pp. 41-50, 2011.

- Radiation accelerates damage mechanisms
  - Stabilizes voids
  - Induces creep
  - Radiation induced segregation (RIS)
    - Grain sensitization
- Damage types change with temperature

22.14 Materials in Nuclear Engineering
Spring 2015