Chemical Engineering 412

Introductory Nuclear Engineering

Lecture 11
Nuclear Materials
Health Physics

Spiritual Thought

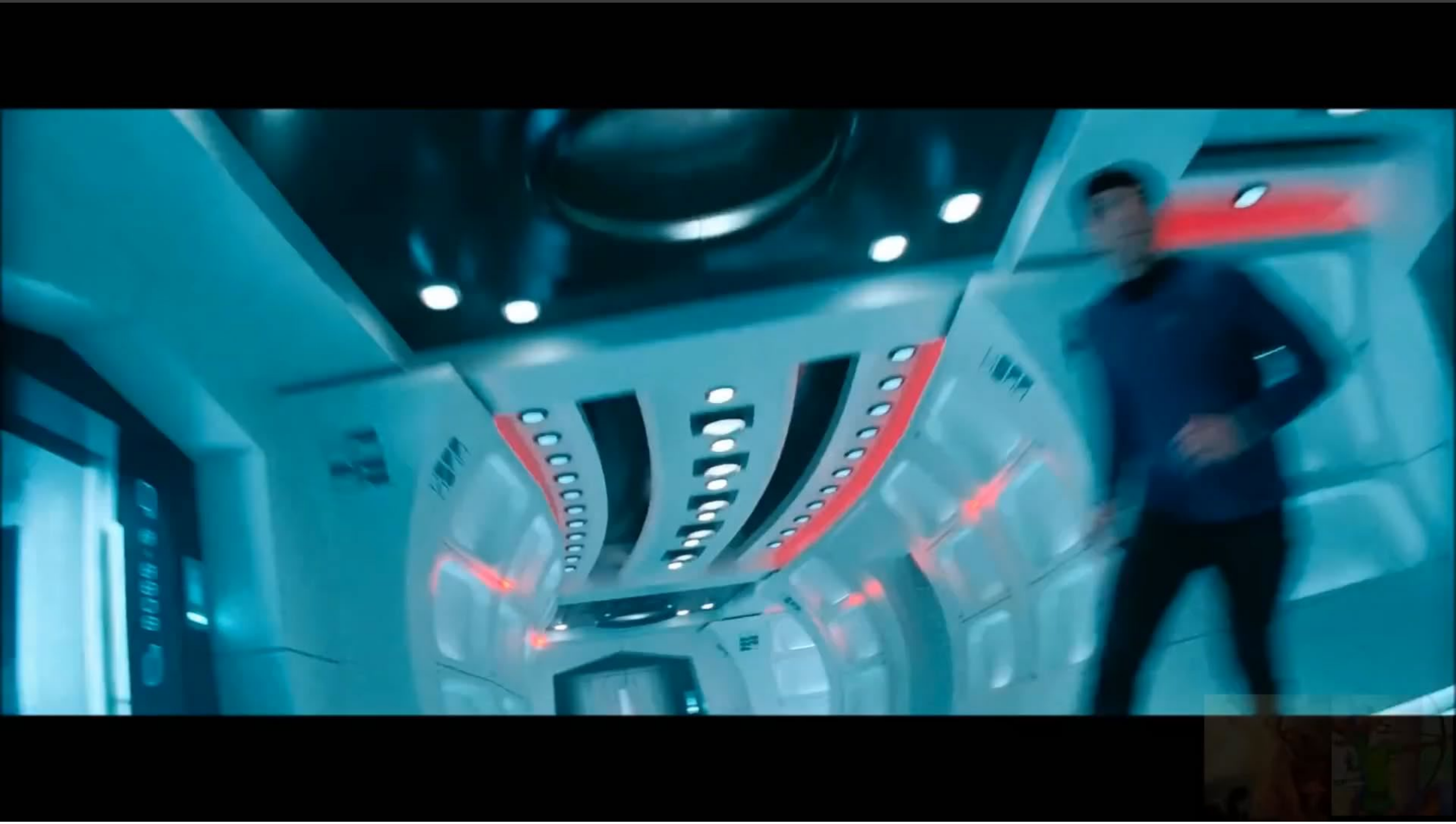
"They knew that they could trust God—even if things didn't turn out the way they hoped. They knew that faith is more than mental assent, more than an acknowledgment that God lives. Faith is total trust in Him.

Faith is believing that although we do not understand all things, He does. Faith is knowing that although our power is limited, His is not. Faith in Jesus Christ consists of complete reliance on Him.

Knowing all this, it was not difficult for those three young Hebrews to make their decision. They would follow God; they would exercise faith in Him. He would deliver them, *but if not*—and we know the rest of the story."

Dennis E. Simmons

OEP 3 (Clip)



OEP 3

Open Ended Problem #3

The Death of Captain Kirk

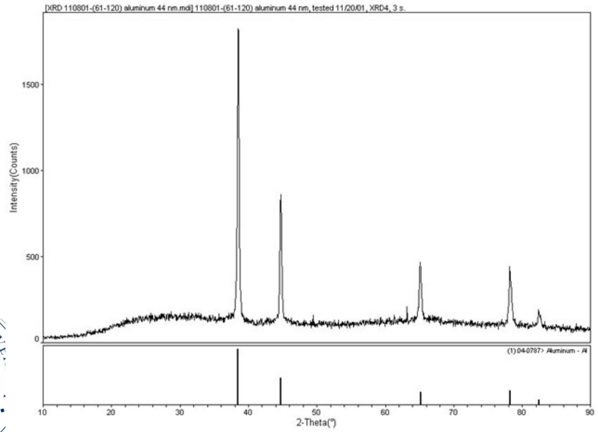
Group work okay, Due 2/22/24 at beginning of class

(Don't be afraid to "Google" good assumptions!)

Curse you Kahn! In the epic battle against the USS Vengeance, The Enterprise is badly damaged, and begins careening towards San Francisco on earth (I know, I know… but on this planet earth, San Francisco is the headquarters for Starfleet). Kirk heroically enters the fusion core chamber to realign the broken fission supports. In so doing, he is exposed to a lethal neutron dose, which permeates the chamber he is in. In this scene, Spock is coming to grips with the fact that his friend is dying, and a “touching” moment ensues in which they touch the glass opposite of each other’s hand with their own hand. In order for Spock to not also die from neutron radiation poisoning, the flux (uncollided) must be reduced by 1000 times. Is this possible?

Materials Review

- Crystal Lattices
  - Planes/directions
    - FCC
    - BCC
- X-ray diffraction
  - Structure
  - Dimensions



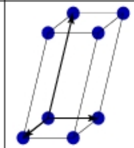
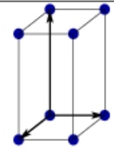
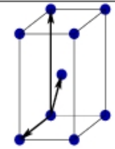
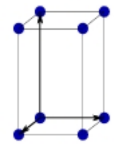
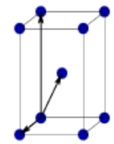
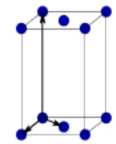
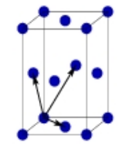
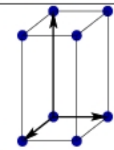
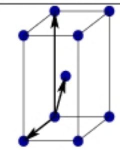
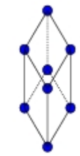
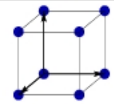
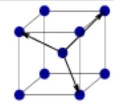
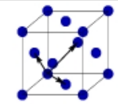
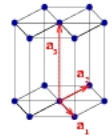
Bravais lattice	Parameters	Simple (P)	Volume centered (I)	Base centered (C)	Face centered (F)
Triclinic	$a_1 \neq a_2 \neq a_3$ $\alpha_{12} \neq \alpha_{23} \neq \alpha_{31}$				
Monoclinic	$a_1 \neq a_2 \neq a_3$ $\alpha_{23} = \alpha_{31} = 90°$ $\alpha_{12} \neq 90°$				
Orthorhombic	$a_1 \neq a_2 \neq a_3$ $\alpha_{12} = \alpha_{23} = \alpha_{31} = 90°$				
Tetragonal	$a_1 = a_2 \neq a_3$ $\alpha_{12} = \alpha_{23} = \alpha_{31} = 90°$				
Trigonal	$a_1 = a_2 = a_3$ $\alpha_{12} = \alpha_{23} = \alpha_{31} < 120°$				
Cubic	$a_1 = a_2 = a_3$ $\alpha_{12} = \alpha_{23} = \alpha_{31} = 90°$				
Hexagonal	$a_1 = a_2 \neq a_3$ $\alpha_{12} = 120°$ $\alpha_{23} = \alpha_{31} = 90°$				

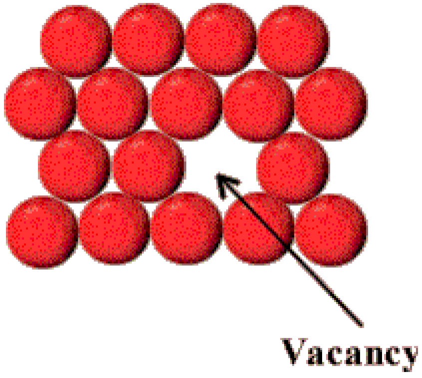
Table 1.1: Bravais lattices in three-dimensions.

Imperfections

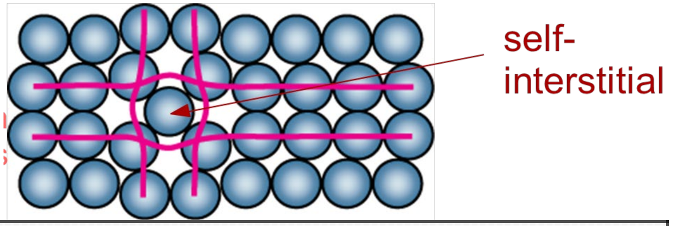
- Inherently disorder in crystals
  - Good or Bad?
- Allows for transport of charge and forces
  - Semiconductors
  - 1B in 1×10^{11} Si atoms doubles the conductivity of pure Si
  - Steel dislocations can decrease strength by 100x!

Point Defects

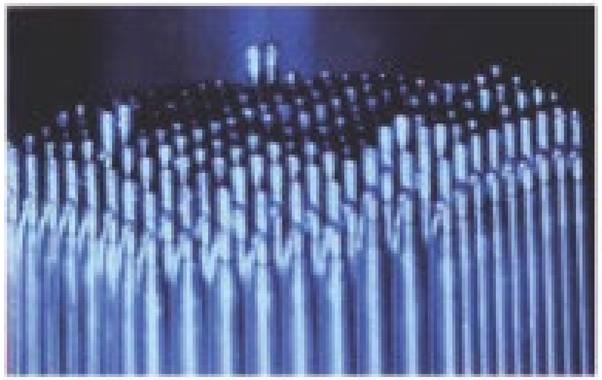
- Vacancy – Lattice site empty
  - Radiation → Voids → swelling



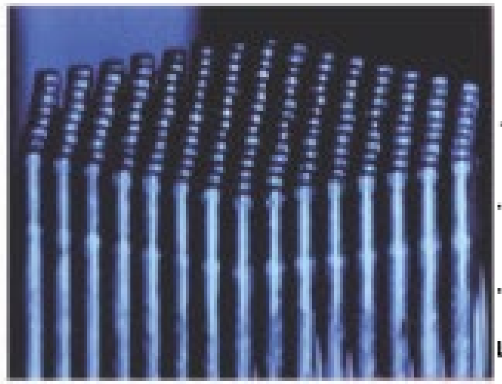
- Self Interstitial – crystal atom crowded into interstitial site
  - Radiation → Embrittlement



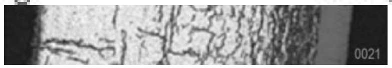
FFTF fuel pin bundles

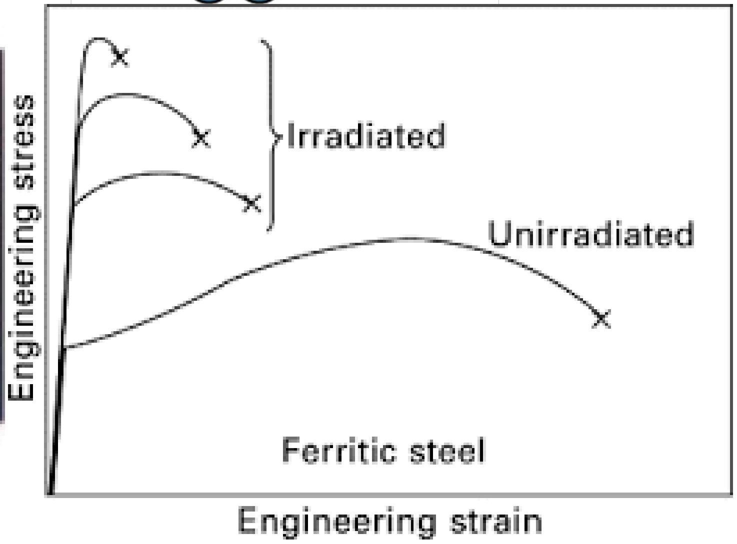


Stainless steel, swelling



HT9, no swelling



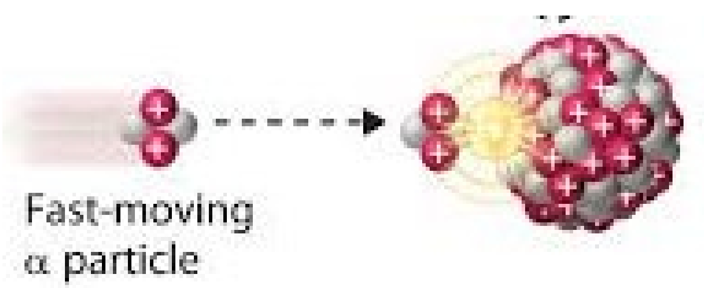


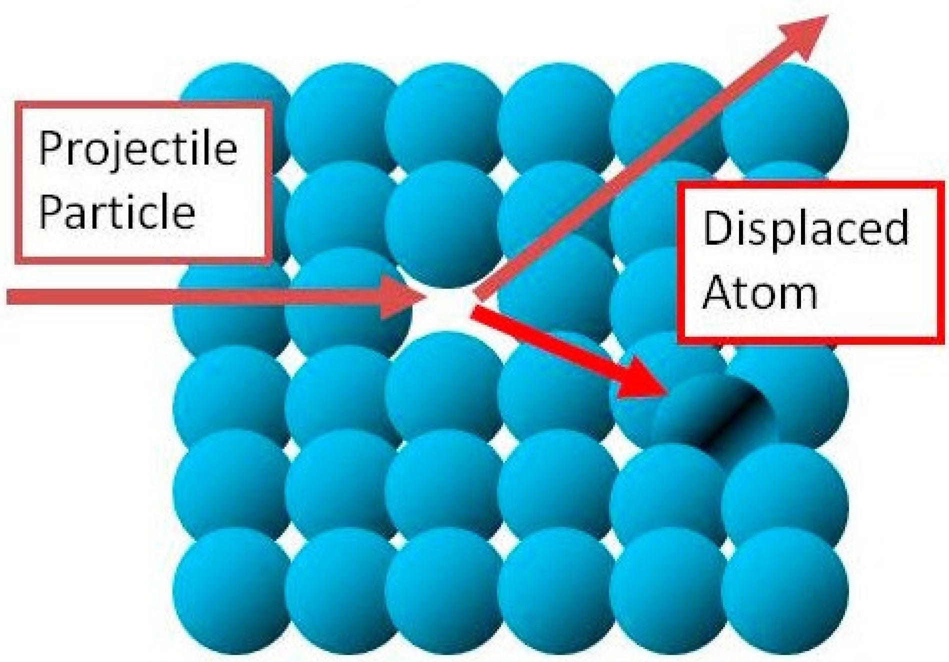
Defects Impacts

- Hardening
  - Cold Working
- Energy Changes
  - Surface or volume
- Plastic Deformation
  - Slip
- Crack Propagation
- Electrical conductivity, energy bands

Radiation Impact on Materials

- Linear Attenuation coefficient
  - What actually happens
  - What if the atom gains more energy than the bond energy in the lattice?



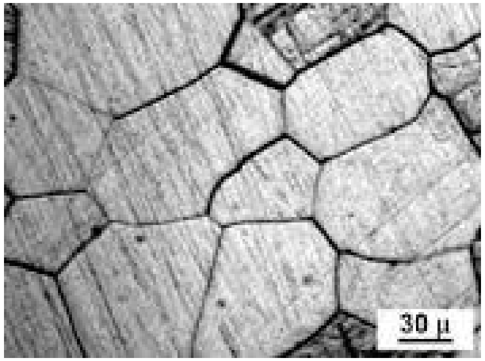


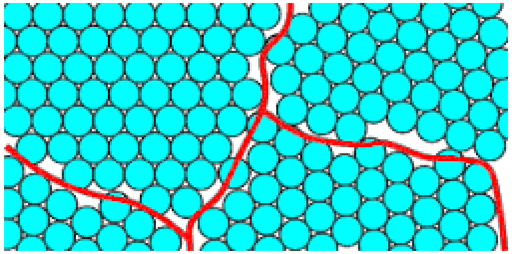
Primary Knock-On Atom

- Knocked free from lattice
  - Become Interstitial
  - Fill a different vacancy
  - Knock off MORE atoms if E is high enough
- Linear Cascades
- Heat (0.1 – 0.5 ps) Spikes
- Defect Production
- Evolution of Microstructure

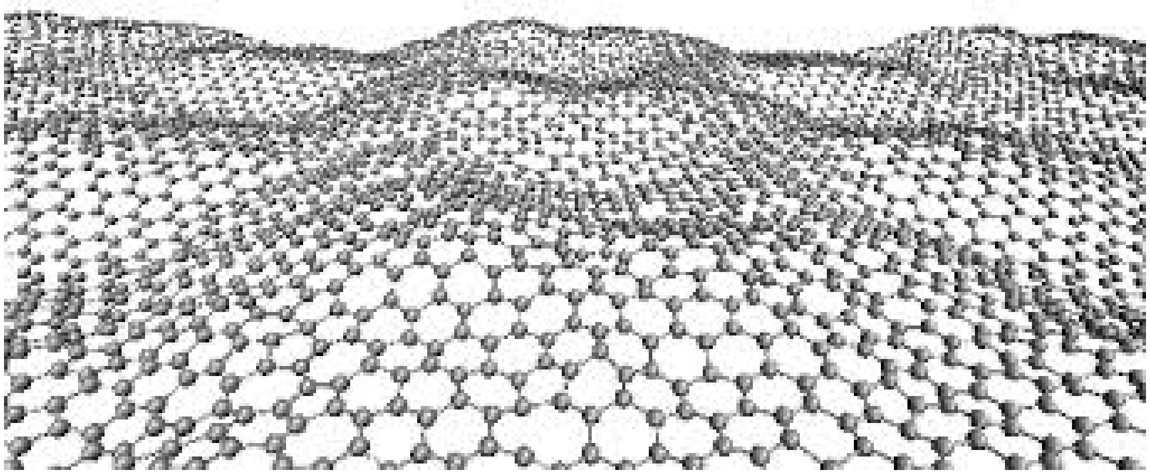
Planar Defects

- Grain Boundaries



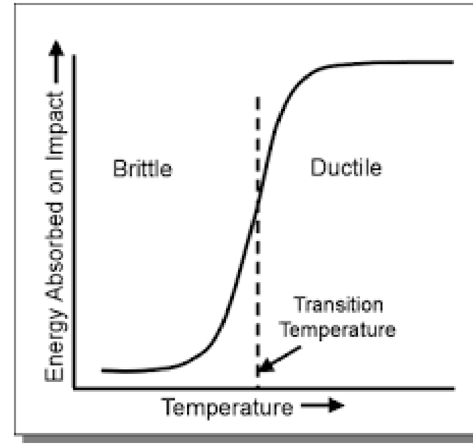


- External Surfaces

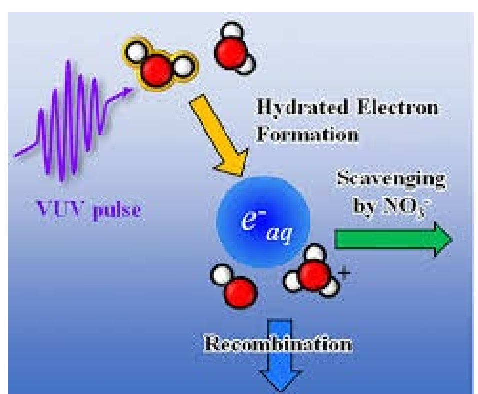


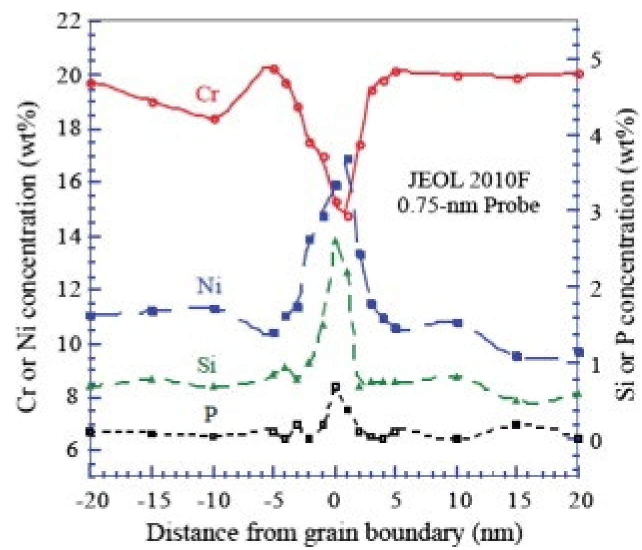
Radiation Effects on Materials

- Radiation Embrittlement
  - Raises Nil Ductility Temperature



- Radiation Enhanced Creep
- Radiation Induced Segregation
- Swelling
- Radiation Induced Growth
- Radiolysis



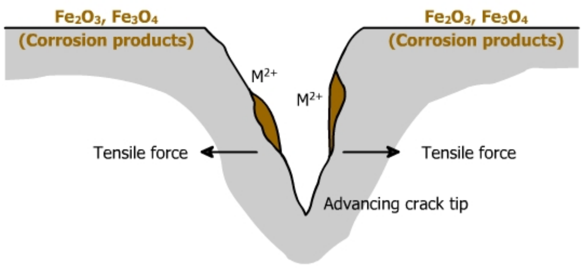


Add to this…

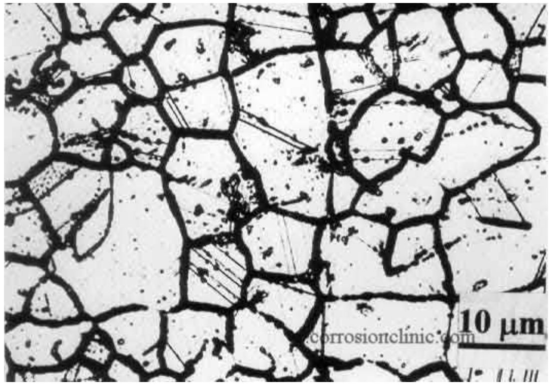
- Thermal Transients
- Electrochemical Effects
- Bulk vs. Local corrosion
- Creep
- Fatigue
- Errosion

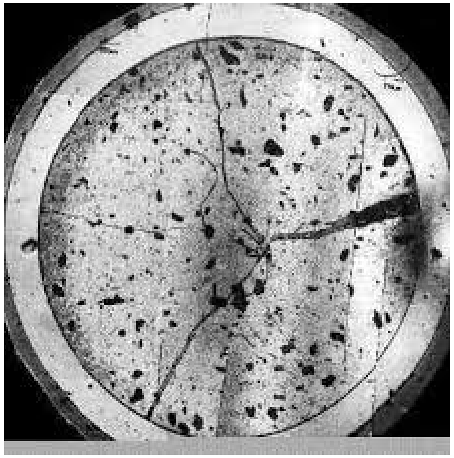
Failure Modes in Reactor

- Stress Corrosion Cracking
- Hydrogen Embrittlement
- Corrosion Fatigue
- Intergranular Attack
- (Flow Assisted Corrosion)
- Fretting
- Creep-Fatigue Interaction
- Pellet-Clad Interaction



Schematic of stress corrosion cracking.





Radiation Impacts - Big Picture

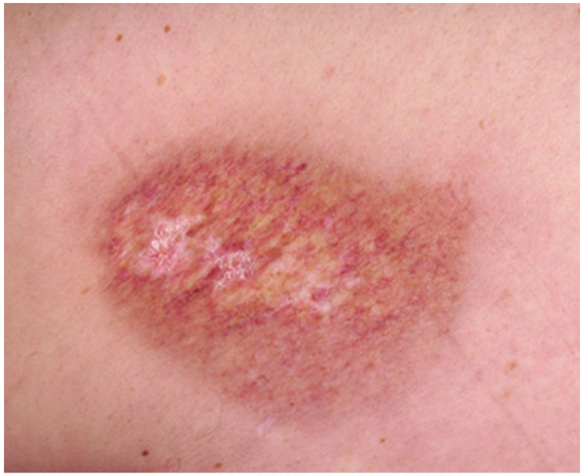
- Background (natural) radiation far exceeds other radiation risks. BUT
- Radiation scares people more than, for example, a car accident.
- IAEA order of top 4 health risks (for Chernobyl)
  - Chemical and other pollution in the region
  - Economic stagnation and associated collapse of public health care related to plant shutdown
  - Anxiety regarding potential radiation exposure
  - Radiation exposure
- Stress associated with dislocating most people, especially the elderly, from their homes had greater health effect than the radiation exposure

Summary Points

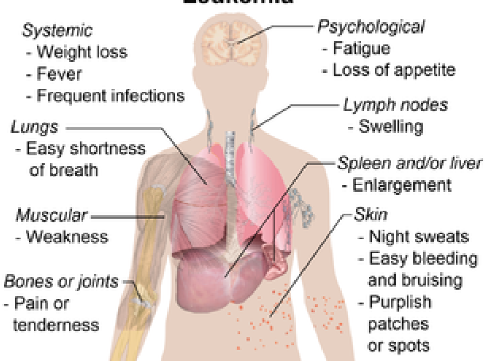
- Biological systems are most vulnerable to radiation-induced illness during replication.
  - All pre-adults, with sensitivity increasing as age decreases
  - All adult biological systems that constantly change:
    - Skin (constantly regrowing)
    - Intestinal lining (constantly repairing)
    - Blood cells/bone marrow (constantly replenishing)
    - Reproductive systems of both men and women
- Radiation illness appears first and most severely in these systems

Radiation Damage

– Radiation burns
  - deeper
  - heal much more slowly



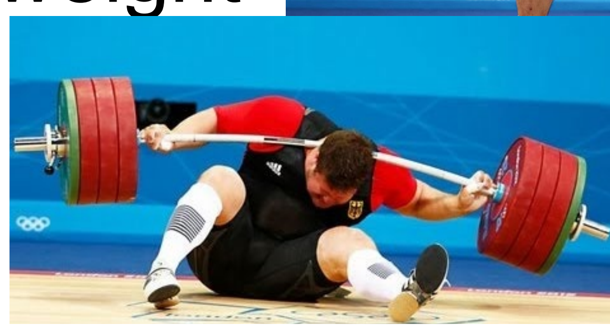
– Other Impacts:
  - High latencies (leukemia, many other cancers)
  - Don't know for long times



– Radiation Detection
  - more difficult to detect by normal senses
  - Even for fatal exposures – minimally felt.

Radiation = weight lifting

- Moderate weights
  - Small muscle tears
  - Build back stronger
- Much higher weight
  - Large muscle tears
  - Strains, sprains
- Massively large weight
  - Serious injury
  - Death



Radiation Effects

- Low – moderate
  - Destroys/kills weak damaged cells
  - Build back stronger/healthier
- Higher Radiation
  - Overwhelms cell repair
  - Burns, hair loss, vomiting
- Massive Radiation
  - Damages DNA
  - Cancer
  - Death

3 Big Challenges

- Emotion: Radiation illness is a highly emotional topic. It is easy to find extreme views, in both directions, from seemingly credible sources. (silent Killer)
- Lack of fundamental understanding: Radiation hormesis has a significant evidence database, but conservative linear model still used
- Unit Confusion: News reports…Rad vs Gray vs Sv – 900,000 nSv sounds HUGE!!

Environmental Impact

- Flora and fauna in and near Chernobyl has never been healthier:
  - population and diversity
  - forced evacuations removed the threat of humans
- Biolog
  - mal
    grov
  - thes short
    time
- Biolog
  - bac
    - i
    - f

Radiation Illnesses

- Chernobyl results:
  - significantly under predicted thyroid cancer
  - Over predicted other cancer deaths
  - NO thyroid cancer deaths
- no observable change in leukemia
- Fundamental aspects of radiation illness remain unknown:
  - Can't prove! Why?
    - Who wants to get tested for radiation damage?
  - illness scales linearly with dose?
    - most agree it does not and most agree small doses are proportionally less significant
    - a system's ability to repair radiological damage.

Radioactivity

- Defined as decays/time
- Conventionally measured in curies, where 1 Ci is the decay rate/radioactivity of 1 g of radium-226 = 3.7×10^{10} decays/s.
- SI unit is becquerel, where 1 Bq = 1 decay/s
- 1 Ci = 3.7×10^{10} Bq = 37 GBq

Exposure Definition

- Units (Conventional and SI)
  - Exposure
    - Pertains to gamma rays (x-rays) outside the body, which ionize air and biological systems (such as humans)

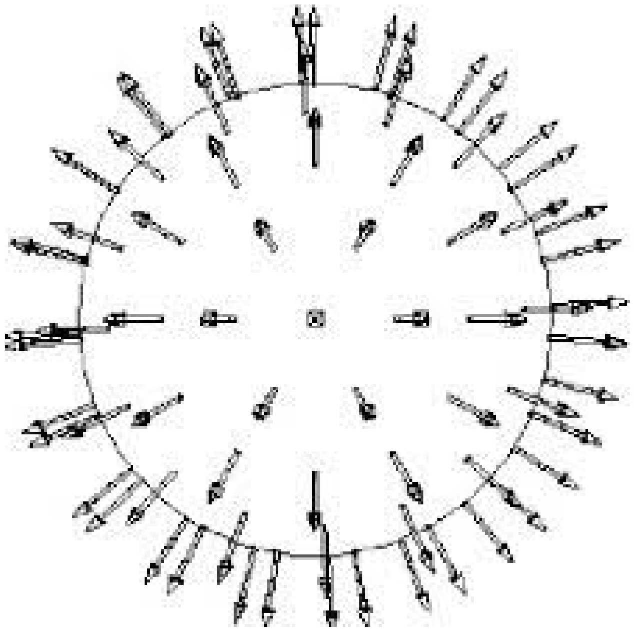
$$x = \frac{\Delta q}{\Delta m} = \frac{sum\ of\ total\ ions\ (+\ \&\ -)}{mass}$$

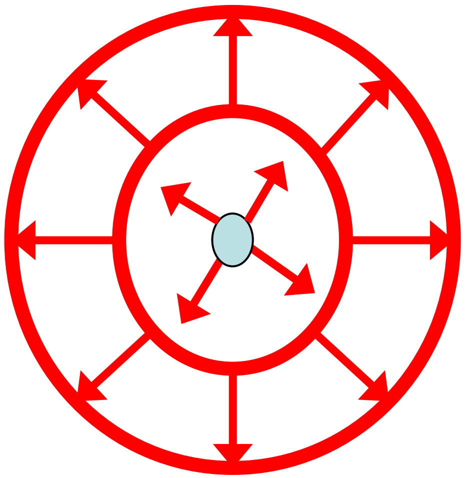
  - Conventional unit = Roentgen (R) = 2.58×10^{-4} coul/kg = 1 esu charge/cm^3 air
  - SI unit = exposure unit = 1 coulomb/kg of air = 3876 R
  - Exposure Rate: $\dot{X} = 1.835 \cdot E \left(\frac{\mu_{en}(E)}{\rho}\right)_{air} \phi^{o}$

Understanding Point Sources

- Nucleus is like a **point**
- Radiation → isotoropic
- Called a "point source"

- Radiation expands outward





$$\emptyset^{o} = \frac{S_p}{4\pi r^2} e^{-\mu r} = \frac{A \cdot f_i}{4\pi r^2} e^{-\mu r}$$

Imparted Energy (Dose)

- Biological effects generally scale with deposited energy

$$\bar{\epsilon} = \Sigma E_{in} - \Sigma E_{out} + Q$$

- Absorbed dose rate

$$D \equiv \lim_{\Delta m \to 0} \frac{\Delta \bar{\epsilon}}{\Delta m}$$

- conventional unit = rad (radiation absorbed dose) = 0.01 J/kg = 100 erg/g; mrad is for millirad
- SI unit = gray = 1 Gy = 1 J/kg; mGy is milligray
- Absorbed dose <u>rate</u> = D = Gy/s, mrad/hr, etc.

Gray or rad is a measure of dose with dimensions energy/mass

Kerma

- Acronym for kinetic energy of radiation absorbed per unit mass
- A concept most associated with non-charged radiation (neutrons, gamma rays).
- Sum of initial kinetic energies of all charged, ionizing particles released by indirectly ionizing radiation (neutrons, gamma rays) per unit mass.
- Same units as dose
- Easier to measure and compute
- Commonly nearly identical to dose, which is generally the most important quantity.

$$K \equiv \lim_{\Delta m \to 0} \frac{\Delta \bar{E}_{tr}}{\Delta m}$$

Insufficient

- These metrics are insufficient for bio impact:
  - Dose
  - Kerma
  - Exposure
- Why?
- Biological damage varies with:
  - radiation type
  - deposition profile

Linear Energy Transfer

$$LET = \left(\frac{dE}{dx} \right)_{collisions}$$

- The linear energy transfer (LET) is a second important characteristic. It is large/high for charged or massive particles (alpha particles, neutrons) and small/low for light particles (beta and gamma).

- Neutrons and alpha particles are more damaging at the same dose than are beta and gamma particles
- These differences are referred to as different qualities.

Biological Characterization

- Relative biological effectiveness (RBE) = effect normalized to 200 keV gamma rays.
- RBE depends on tissue, biological effect, dose, and sometimes dose rate.
- More useful in scientific studies than in general radiation protection due to complexity.

Quality Factor

- A poor man's RBE
- Assigned based on average RBE behavior.
- Weight factor is appx. equiv.

TABLE 9.1 QUALITY FACTOR AS A FUNCTION OF LET

LET, keV/micron	Q
3.5 or less	1
7	2
23	5
53	10
175 and above	20

TABLE 9.2 QUALITY FACTORS FOR VARIOUS TYPES OF RADIATION*

Type of radiation	Q	W_R
x-rays and γ-rays	1	1
β-rays, $E_{max} > 0.03$ MeV	1†	
β-rays, $E_{max} < 0.03$ MeV	1.7†	
Naturally occurring α-particles	10	
Heavy recoil nuclei	20	20
Neutrons:		
Thermal to 1 keV	2	5
10 keV	2.5	10
100 keV	7.5	10
500 keV	11	20
1 MeV	11	20
2.5 MeV	9	5
5 MeV	8	5
7 MeV	7	5
10 MeV	6.5	5
14 MeV	7.5	5
20 MeV	8	5
Energy not specified	10	

*Based on 10CFR20 (Q) and ICRP 60 (W_R).
†Recommended in ICRP Publication 9.

Equivalent Dose

$$H = QF \cdot D$$

- Quality-factor or weighting factor modified dose
- NCRP distinguished between equivalent dose (average dose in organ weighted by weighting factor) and dose-equivalent (absorbed dose at a point in tissue weighted by quality factor determined from LET of radiation at that point).
- Any given tissue should have about the same response to an equivalent dose, regardless of radiation source.
- Different tissues differ in responses, even if equivalent dose is similar.
- Measured in rem (roentgen equivalent man - by NRC) or sievert (SI), where 1 Sv = 100 rem.

Equivalent Rate

- Symbol is $\dot{H}$ and is given as product of dose rate and quality (dose equivalent rate)/weighting factor (equivalent dose rate).
- 1 rem effective dose has about a 0.055% chance of causing cancer, which is high. The mrem (millirem) is a more common unit and equal to 10 μSv.
- Population dose or collection dose, H_{pop} is the dose equivalent to a group of people, measured in man/person-rems, man-Sieverts

$$H_{pop} = \int_0^\infty N(H) H \, dH$$

Example

0.7 mCi sample of ^{137}Cs emits 0.662 MeV gamma rays from ^{137m}Ba with a frequency of 0.845 per decay. If the source propagates through 0.5 m of water, find (a) the exposure rate, (b) the kerma rate in air, and (c) the dose equivalent rate.

Linearly interpolate water data in Ap. C to find $\boldsymbol{\mu = 0.08604/cm}$ – then find uncollided flux density (Eq. 7.23)

$$\phi^0 = \frac{S_p \exp -\mu r}{4\pi r^2} =$$

$$\frac{(0.0007\ Ci)\left(3.7 \times 10^{10}\,\frac{decays}{Ci}\right)\left(0.845\,\frac{\gamma s}{decay}\right)\exp -0.08604 \times 50}{4\pi(50cm)^2}$$

et= 9.433 1/(cm^2 s)

Exposure Rate

Linearly interpolate the interaction data for air in Ap. C for E=0.662 MeV to get $\left(\frac{\mu_{en}}{\rho}\right)_{air} = \mathbf{0.02931}$

Eq. 9.9

$$\dot{X} = 1.835 \times 10^{-8} E \left(\frac{\mu_{en}}{\rho}\right)_{air} \phi^0$$

$= (1.835 \times 10^{-8})(0.662)(0.02931)(9.433) = 3.36 \times \frac{10^{-9} R}{s}$

$$= 12.1 \mu R/h$$

Kerma rate in air

Linearly interpolate the interaction data for air in Ap. C for E=0.662 MeV to get $\left(\frac{\mu_{tr}}{\rho}\right)_{air} = \mathbf{0.02937}$

Eq. 9.5

$$\dot{K} = 1.602 \times 10^{-10} E \left(\frac{\mu_{tr}}{\rho}\right)_{air} \phi^0$$

$$= (1.602 \times 10^{-10})(0.662)(0.02937)(9.433) = 2.94 \times \frac{10^{-11} Gy}{s}$$

$$= 0.106\ \mu Gy/h$$

Equivalent Dose Rate

Assume charged particle equilibrium so kerma rate is the same as absorbed dose rate, $\boldsymbol{\dot{K}} = \boldsymbol{\dot{D}}$. Equivalent dose is quality factor for photons (1) times the absorbed dose in tissue. Approximate tissue with water. Linearly interpolate the interaction data for air in Ap. C for E=0.662 MeV to get

$$\left(\frac{\mu_{tr}}{\rho}\right)_{water} = \mathbf{0.03260}$$

Eq. 9.5 & 9.10

$$\dot{H} = QF \times \dot{D} = 1.602 \times 10^{-10} E \left(\frac{\mu_{tr}}{\rho}\right)_{H_2O} \phi^0$$

$$= 1(1.602 \times 10^{-10})(0.662)(0.03260)(9.433)$$

$$= 3.26 \times 10^{-11} \frac{Sv}{s} = \frac{0.117\mu Sv}{h}$$