Chemical Engineering 412

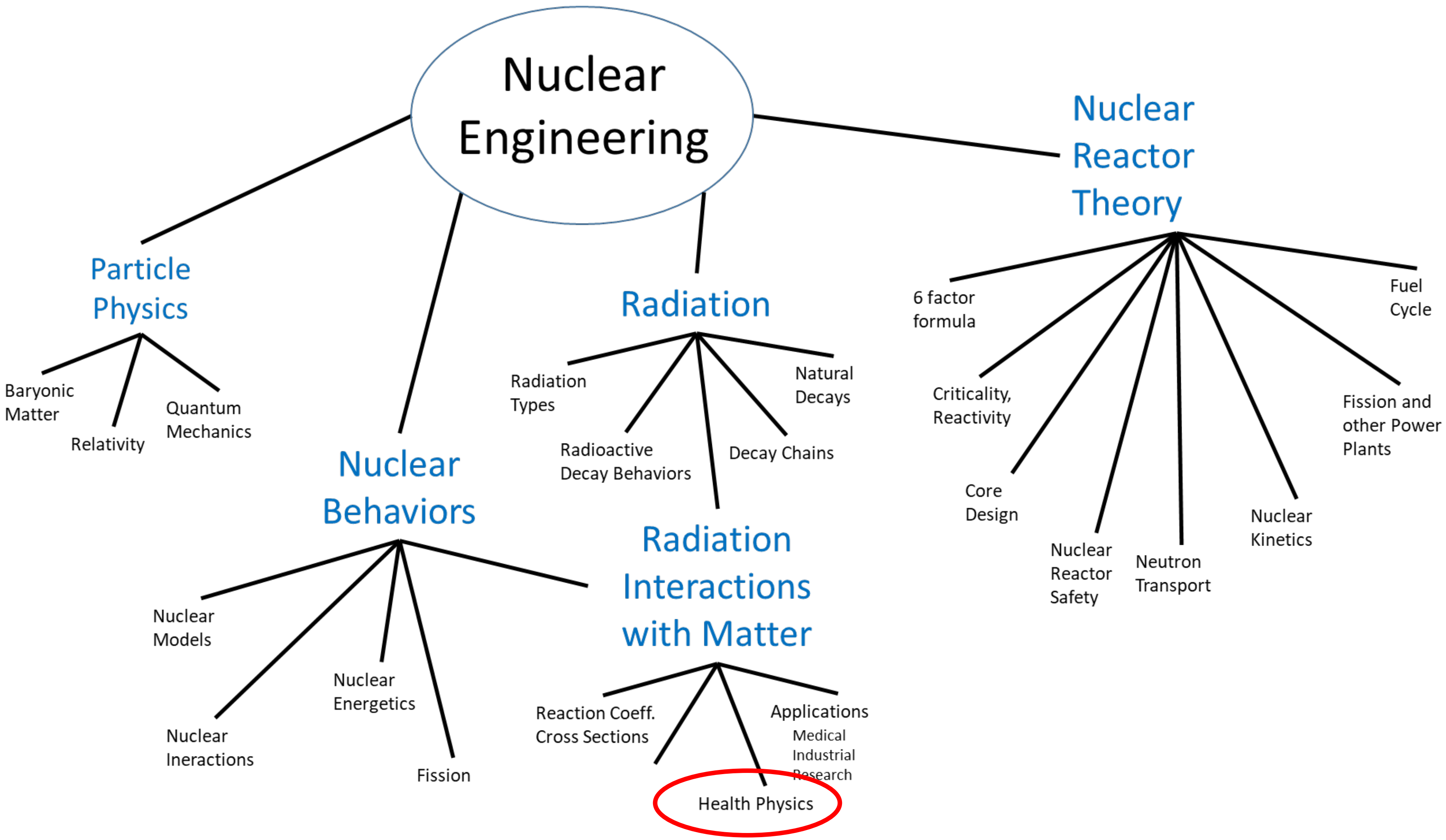
Introductory Nuclear Engineering

Lecture 28

Heath Physics 1: Radiation Dose

Spiritual Thought

The BIG Picture



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

Big Picture (cont)

- Background (natural) radiation far exceed radiation risks.

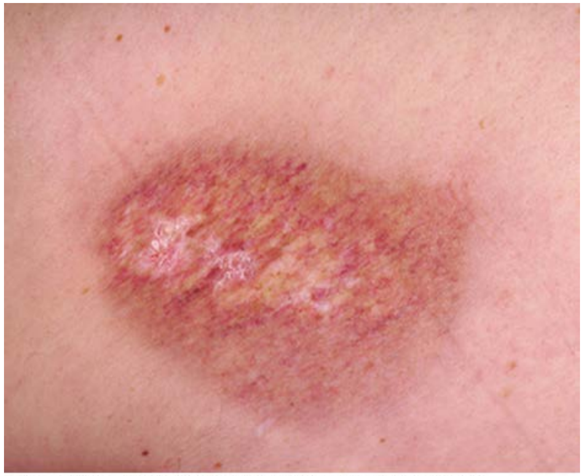
- Radiation scares people more than, for example, a car accident.

- 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

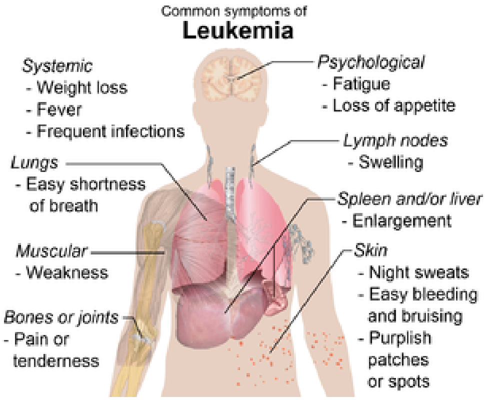
- Stress associated with dislocating most people, especially the elderly, from their homes had greater health effect than the radiation exposure

Radiation Damage

– Radiation burns
  - deeper
  - heal much more slowly



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



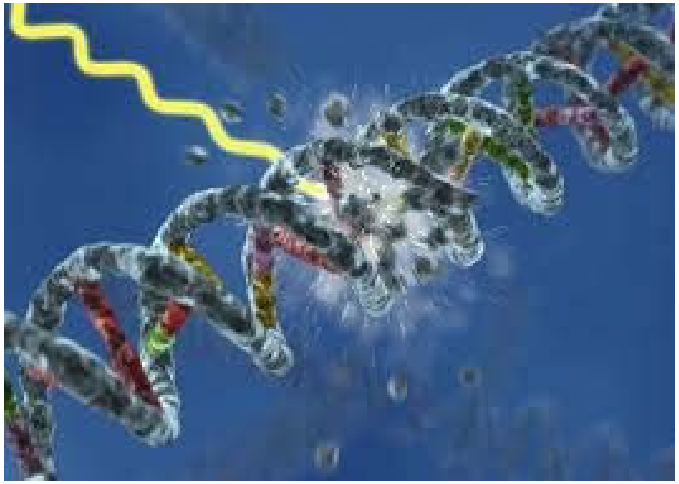
– Radiation Detection
  - more difficult to detect by normal senses
  - Even for fatal exposures – minimally felt.

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
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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

Roentgen is a measure of exposure with dimensions of charge/kg

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

Effects of absorbed Doses

Organ/Tissue	Endpoint	D_{50} (Gy)	$D_{th}(Gy)$
skin	erythema	6 ± 1	3 ± 1
	moist desquamation	30 ± 6	10 ± 2
ovary	permanent ovulation supression	3 ± 1	0.6 ± 0.4
testes	sperm count supressed for 2 y	0.6 ± 0.1	0.3 ± 0.1
eye lens	cataract	3.1 ± 0.9	0.5 ± 0.5
lung	death[a]	70 ± 30	40 ± 20
GI system	vomiting	2 ± 0.5	0.5
	diarrhea	3 ± 0.8	1
	death	10 ± 5	8
bone marrow	death	3.8 ± 0.6	1.8 ± 0.3

[a] dose rate 0.5 Gy/h.

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 $\left(\boldsymbol{\frac{\mu_{en}}{\rho}}\right)_{\boldsymbol{air}} = \mathbf{0.02931}$

Eq. 9.9

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

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

$$= 12.1 \mu R/h$$

Kerma rate in air

Linearly interpolate the interaction data for air in Ap. C for E=0.662 MeV to get

$$\left(\frac{\boldsymbol{\mu_{tr}}}{\boldsymbol{\rho}}\right)_{\boldsymbol{air}} = \mathbf{0.02937}$$

Eq. 9.5

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

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

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

Equivalent Dose Rate

Assume charged particle equilibrium so kerma rate is the same as absorbed dose rate, $\dot{\boldsymbol{K}} = \dot{\boldsymbol{D}}$. 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 $\boldsymbol{\left(\frac{\mu_{tr}}{\rho}\right)_{water} = 0.03260}$

Eq. 9.5 & 9.10

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

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

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