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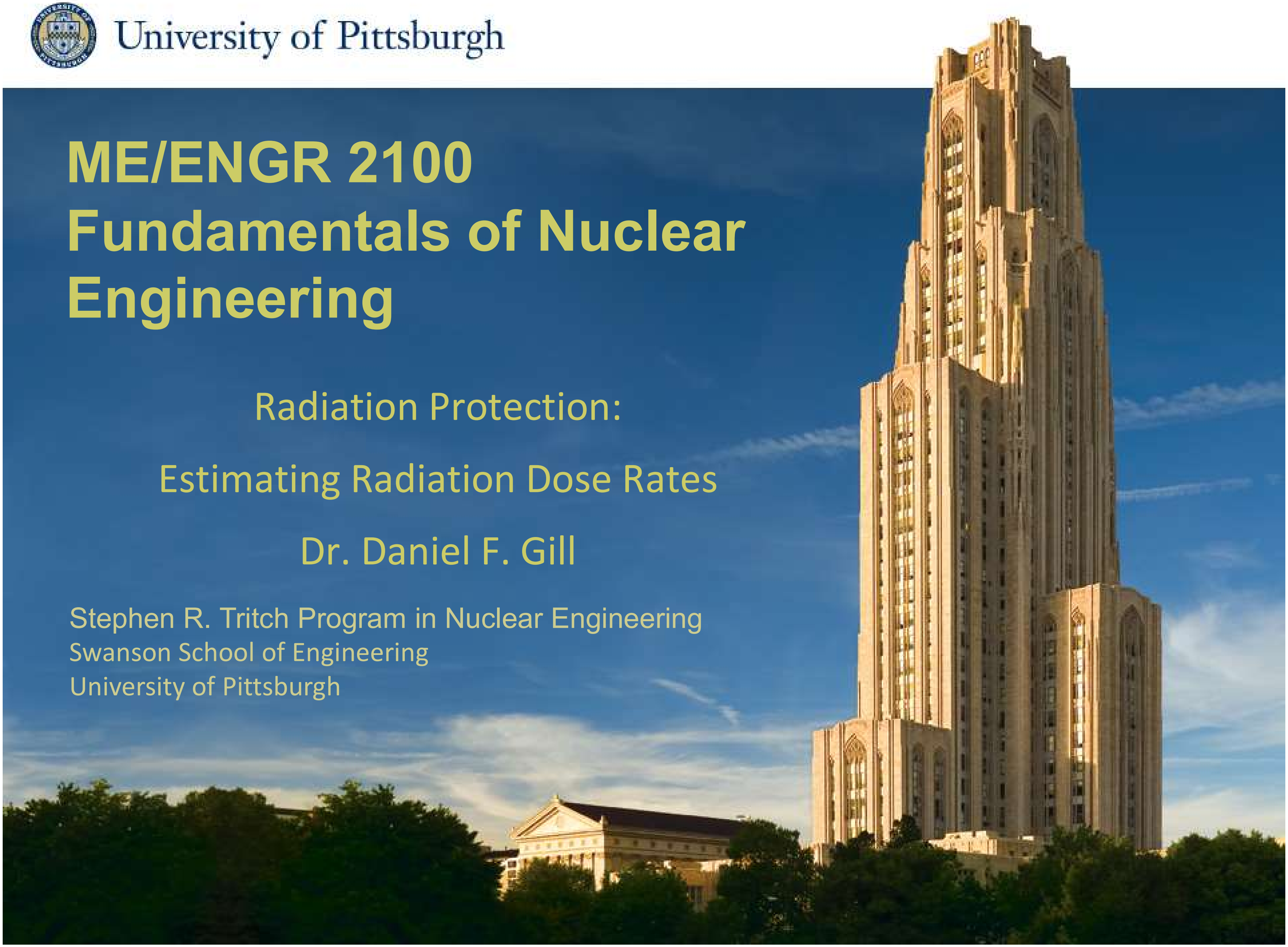

ME/ENGR 2100 Fundamentals of Nuclear Engineering

Radiation Protection:

Estimating Radiation Dose Rates

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Learning Objectives

- Estimate radiation dose and dose rate from specified alpha, beta, and gamma sources.

Dose Estimates

- Charged particles (α and β radiations):
  - Remember, we are calculating energy deposited per unit mass (of tissue)

$$\boxed{\begin{gathered} R_p(t) = \frac{Q(t)\,E'}{m} \\ Q(t) = Q_0 e^{-\lambda t} \end{gathered}}$$

Ref: Knief, Eq 3-5

- R_p = Dose Rate from Charged Particle
- Q = Activity (decays/unit time)
- E′ = Effective Energy (energy deposited)
  - α particles: $E' = E_\alpha$
  - β particles: $E' \approx 1/3\, E_{max}$ (due to antineutrino energy sharing in β-decay)
- λ = Decay Constant
- m = Mass (of Organ or Material)
- Then it’s just about getting the units right!

Example Calculation

Alexander Litvinenko at University College Hospital

- Po-210 poisoning of Alexander Litvinenko (11/1/2006)
- Q = Activity (*10 micrograms or ≈50 mCi*)
- λ= Decay Constant (*0.693/(138 d)=6.25e-8 sec*$^{-1}$)

$$\frac{10x10^{-6}\,gms}{210\,gms/mole}\;x\;6.023x10^{23}\,atoms/mole = 2.87x10^{16}\,atoms$$

$$\lambda N = \left(\frac{0.693}{(138d)(24hr/d)(3600\sec/hr)}\right)\left(2.87x10^{16}\,atoms\right) = 1.79x10^{9}\,dps = \frac{1.79x10^{9}\,dps}{3.7x10^{7}\,{}^{dps}\!/_{mCi}} \approx 50\,mCi$$

- E′ = Effective Energy
  - α particles: E′ = E$_\alpha$ (5.407MeV *x 1.6e-6 ergs/MeV=8.65e-6 ergs*)
  - m = Mass (*say a 2,000 gm liver*)

$$R_p(t) = \frac{(50\,mCi)\left(3.7x10^{7}\,{}^{dps}\!/_{mCi}\right)(5.407\,{}^{MeV}\!/_{dis})\left(1.6x10^{-6}\,{}^{ergs}\!/_{MeV}\right)}{2,000\,gms}$$

$$R_p(t) = \frac{(8\,ergs/gm-\sec)}{(100\,ergs/gm-rad)} = 0.08\;rads/\sec \qquad (\textbf{\textit{Plus}}\;the\;times\;RBE = 20\;\;for\;\;\alpha's)$$

$$= 1.6\;\;Rem/sec$$

How long to get 1,000 Rem?

Dose Estimates

- Photons (γ and X-Ray radiation)
  - Attenuation

$$\boxed{\Phi(x) = \Phi(0)\, e^{-\mu x}}$$

    - μ – Total linear attenuation coefficient (like a total cross-section for photons)
  - Dose

$$\boxed{R_\gamma = \Phi(t)\; E\; \frac{\mu_a}{\rho}}$$

: the density converts energy per volume to per unit mass (i.e., dose), and the QF = 1

    - μ_a – Absorption linear attenuation coefficient
    - ρ – Density of target material

DOSE ESTIMATES

- GAMMA
  - Attenuation

$$\Phi\ (x) = \Phi(0)\ e^{-\mu\ x}$$

μ = Linear Attenuation Coefficient

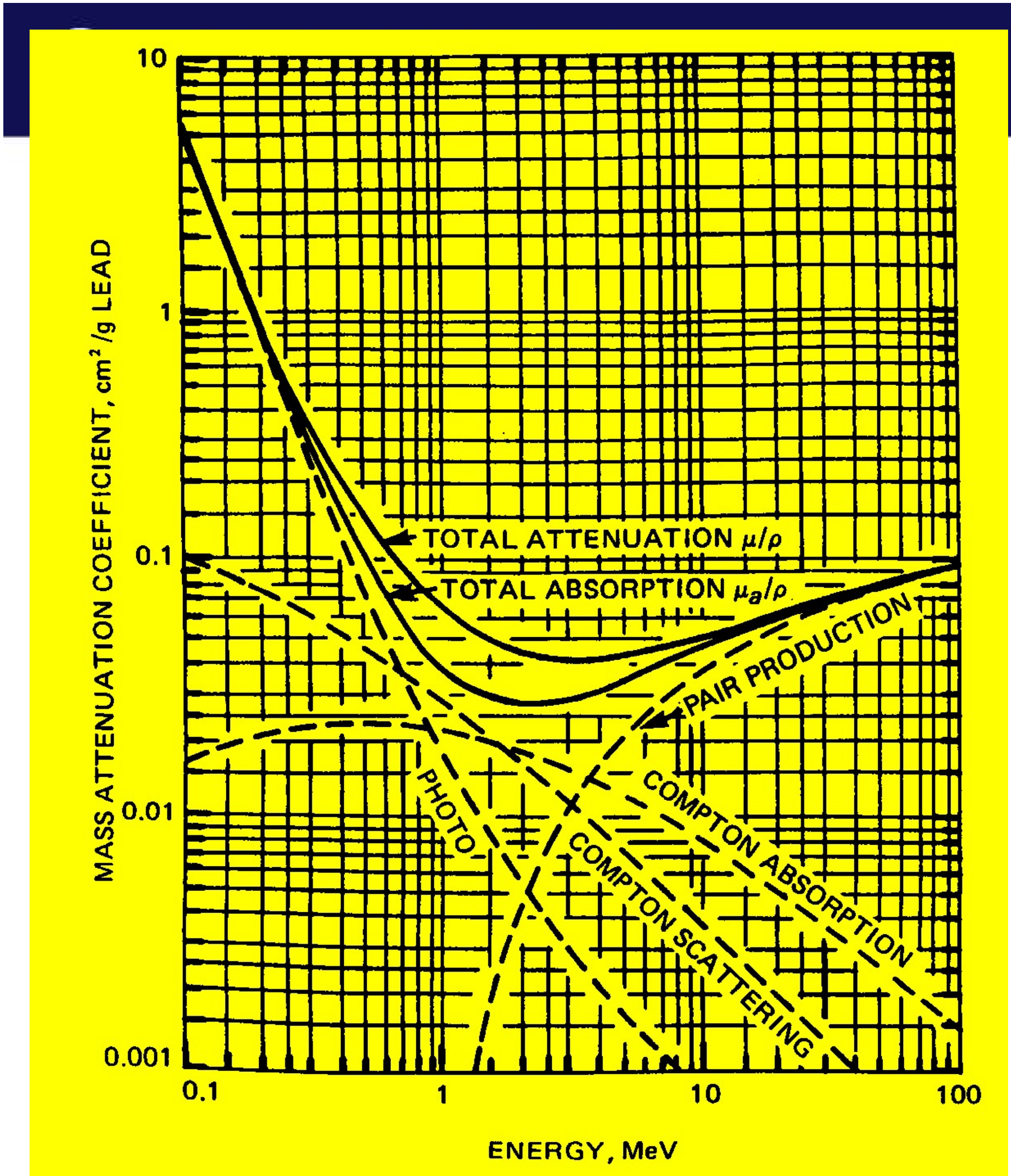
$$\Phi(x) = \Phi(0)\ e^{-\ (\mu/\rho)\ (\rho\ x)}$$

μ/ρ = Mass Attenuation Coefficient [cm^2-gm]

Note that “thickness” now becomes areal density, ρx

(effectively the number/unit area you would see looking end on)

  - Processes
    - Photoelectric
    - Compton
    - Pair Production



Mass Attenuation Coefficient for Lead

From Knief, Fig. 3-4

Example Problem 1 (Knief, pg 83)

- Consider gamma energy of 1 MeV and a flux of 10^8 photons/cm^2-sec
- For 1 MeV photons in water (similar to human tissue), ρ=1 gm/cm^3 and μ_a=0.03 cm^{-1}

Dose rate from

$$\boxed{R_\gamma = \Phi(t)\ E\ \frac{\mu_a}{\rho}}$$

$$R_\gamma = \frac{\left(10^8\ \gamma / cm^2 - \sec\right)\left(1\ MeV\right)\left(0.03 cm^{-1}\right)}{1\ gm / cm^3}\, x\, \frac{1.6x10^{-13} J}{MeV}\, x\, \frac{1\ Gy}{1\ J/kg}\, x\, \frac{1000\, gm}{kg} = 0.48\ mGy/\sec$$

$$OR\ \left(0.48\ mGy/\sec\right) x \frac{100\ rad}{Gy}\, x\, \frac{1\ Gy}{100\ mGy}\, x\, \frac{100\ mrad}{rad} = 48\ mrad/\sec$$

With QF=1 for gamma radiation

$$R_\gamma\ in\ Rem = R_\gamma\ in\ Rad\ x\ (QF = 1)\ so\ the\ dose\ is\ 48\ mrem/sec$$

Dose Estimates

- Neutrons
  - Fast Neutrons

$$\boxed{R_{fn}(t) = \frac{\Phi(t)\ E\ \Sigma_s\ f}{\rho} = \frac{\Phi(t)\ E\ \Sigma_s}{\rho}\frac{2A}{(A+1)^2}}$$

Ref: Knief, Eq 3-9

Σ_s = Macroscopic scattering cross section

f = Fractional energy transfer per collision (note approximation above)

A = Atomic mass number of atoms in material

  - Thermal Neutrons
    - Absorption
    - Activation / Induced Radiation

Example Problem (Knief pg 83)

Consider dose from a 1 MeV neutron flux of 10^8 neutrons/cm^2-sec

- For 1 MeV neutrons in water (similar to human tissue), $\rho=1$ gm/cm^3 and assume $\Sigma_s = 0.1$ cm^{-1}

$$\boxed{R_{fn}(t) = \frac{\Phi(t)\ E\ \Sigma_s\ f}{\rho} = \frac{\Phi(t)\ E\ \Sigma_s}{\rho}\ \frac{2A}{(A+1)^2}}$$

Fast neutrons react mostly with the hydrogen atoms with A = 1, so $\frac{2A}{(A+1)^2} = 0.5$

$$R_\gamma = \frac{\left(10^8\ neutrons \big/ cm^2 - \sec\right)\left(1\ MeV\right)\left(0.1 cm^{-1}\right)\left(0.5\right)}{1\ gm \big/ cm^3}\ x\ \frac{1.6x10^{-13} J}{MeV}\ x\ \frac{1\ Gy}{1\ J \big/ kg}\ x\ \frac{1000\, gm}{kg} = 0.8\ mGy \big/ \sec$$

$$OR\ \left(0.8\ mGy \big/ \sec\right) x\ \frac{100\ rad}{Gy}\ x\ \frac{1\ Gy}{100\ mGy}\ x\ \frac{100\ mrad}{rad} = 80\ mrad / \sec$$

With QF=10 for fast neutrons

$$R_\gamma\ \ in\ Rem = R_\gamma\ \ in\ Rad\ x\ (QF = 10)\ so\ the\ dose\ \ is\ 800\ mrem \big/ sec$$

Internal Exposure

- External radiation limits are intended for deeply-penetrating ionizing photon and neutron radiation.
- Charged particles have a much shorter range and external sources of these radiation types are not a health hazard.
  - The layer of dead skin on the outside of our bodies provides sufficient shielding for alpha and some beta radiations.
- However, if charged particle radiation sources are ingested or inhaled the high LET radiation will deposit all of its energy in the body.

Internal Exposure Pathways

- Ingesting or inhaling radioactive nuclides is referred to as radiation **intake**. In this phase the nuclides remain outside of the biological barrier in the GI track, lungs or sinuses.
- **Uptake** occurs when radionuclides cross the biological barrier and enter the body. Uptake rates are very dependent on the elemental properties of the nuclide.
- Once in the body, some elements are rapidly incorporated into tissues and organs. Radioisotopes of these elements can be very hard to flush out of the body.

Effective Half-Life for isotopes taken internally

- Once a radionuclide has crossed the biological boundary, it will continue to emit radiation and damage nearby tissue until it is removed from the body.
- Two main removal mechanisms:
  - Radioactive decay
    - Eventually all atoms of the radioisotope will decay away.
  - Biological removal
    - The body can flush elements out of the body through normal excretion processes (sweat, tears, urine, feces).

So $\lambda^{eff} = \lambda^{rad} + \lambda^{biol}$; or equivalently:
Half-life: $1/T^{eff} = 1/T^{rad} + 1/T^{biol}$; or
Mean lifetime: $1/T_{1/2}^{eff} = 1/T_{1/2}^{rad} + 1/T_{1/2}^{biol}$

$$N(t) = N_0 e^{-\lambda r t} e^{-\lambda b t} = N_0 e^{-(\lambda r + \lambda b)t}$$

Example Problem (Knief Problem 3-16)

- Given for Strontium-90

$$T_{1/2} = 28yr$$

$$T_{1/2}^{biol} = 11yr$$

$$Critical\ \ organ = Bone$$

Compute the effective half-life of Sr-90 in the human body.

$$\frac{1}{T_{1/2}^{eff}} = \frac{1}{T_{1/2}} + \frac{1}{T_{1/2}^{biol}} = \frac{1}{28} + \frac{1}{11} = 0.1266\ \ or\ \ T_{1/2}^{eff} = \frac{1}{.1266} = 7.9yrs$$

Internal Radiation

- Total radiation dose accumulated over the time that any radionuclide remains in the body is referred to as **committed dose**.
- Treatment for internal dose:
  - Limit uptake / promote excretion
    - Patients are given supplements to prevent the body from absorbing the offending element (e.g. iodine pills to protect thyroid from uptaking radioactive iodine isotopes) .
    - Additional supplements can bind to elements in the body, creating a more soluble form that can be flushed away.
    - Effectiveness is highly dependent on the element(s) involved.
  - Monitor (internal dosimetry / bioassay)
    - Urine Samples
    - Lung / Whole body count