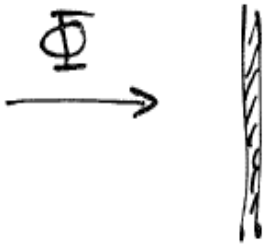
7.)
Dosimetry (Lilley chap.7)

Including biological effects of radiation and radiation protection

Basic principles

Definition of dose: $D = \lim_{V \to 0} \frac{\bar{\varepsilon}}{\rho V}$ $[Gy = \frac{J}{kg}]$

Charged particles(Directly ionizing radiation)



Dose: $D = \Phi(\frac{S_{col}}{\rho})$

Where S_{col} is the collision stopping power and Φ is the particle fluence.

For photons (Indirectly ionizing radiation)

Total linear attenuation coeff: $\mu = \tau + \sigma + \kappa$

Where τ represents the photo electric effect, σ the Compton effect and κ is pair production. These quantities are as already discussed, additive.

Mass energy transfer coeff.: $\frac{\mu_{tr}}{\rho} = \frac{\tau}{\rho}\left[1 - \frac{\delta}{h\nu}\right] + \frac{\sigma}{\rho}\left[1 - \frac{h\nu'}{h\nu}\right] + \frac{\kappa}{\rho}\left[1 - \frac{2mc^2}{h\nu}\right]$

Where the terms from left to right are corrections for X-ray radiation, compton scattering and radiation due to annihilation.

KERMA (Kinetic Energy Released per Mass)

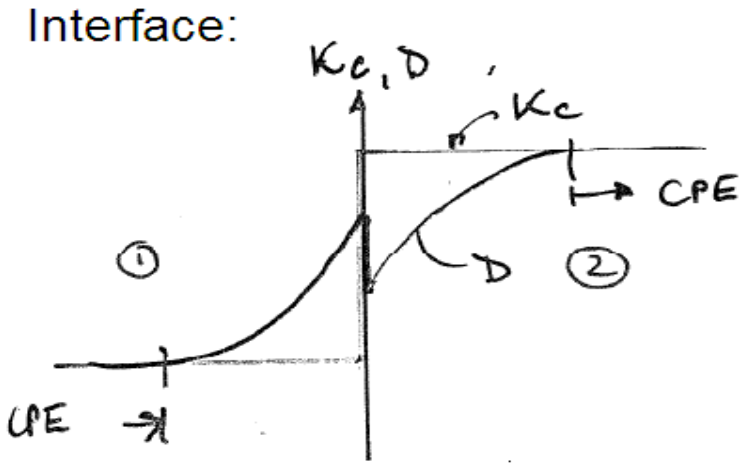
Definition of KERMA: $K \equiv \Psi(\frac{\mu_{tr}}{\rho})$ $[\frac{J}{kg} = Gy]$

Mass energy absorption coeff.: $\frac{\mu_{en}}{\rho} = \left(\frac{\mu_{tr}}{\rho}\right)(1-g)$

Where g is the correction factor for bremsstrahlung.

Collision KERMA: $D \overset{CPE}{=} K_c \equiv \Psi\left(\frac{\mu_{en}}{\rho}\right)$

CPE stands for Charged Particle Equilibrium (electron equilibrium).



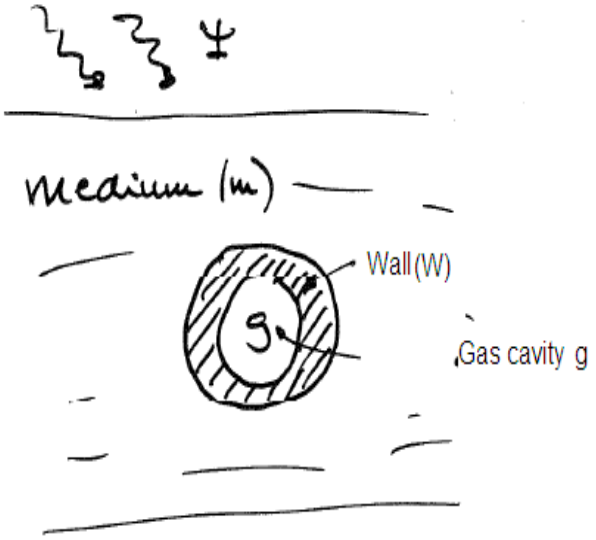
Illustrated cases:

$$\left(\frac{\mu_{en}}{\rho}\right)_1 < \left(\frac{\mu_{en}}{\rho}\right)_2$$

$$\left(\frac{S_c}{\rho}\right)_1 > \left(\frac{S_c}{\rho}\right)_2$$

Continuous fluence of secondary electrons at the boundary: $\frac{D_2}{D_1} = \frac{(\frac{S_c}{\rho})_2}{(\frac{S_c}{\rho})_1}$

Bragg-Gray cavity theory



For a gas-filled dosimeter, which is constructed to measure the dose deposited in a medium:

Bragg-Gray cavity:

The cavity is so small compared to the range of the secondary electrons, that the ionisation that takes place in the dosimeter's gas is due to secondary electrons from the walls and the medium. If one assumes that the fluence of secondary electrons is approximately continuous over the boundary between the gas and the wall:

At the boundary: $\frac{D_{wall}}{D_{gas}} = \frac{(\frac{S_c}{\rho})_{wall}}{(\frac{S_c}{\rho})_{gas}}$

In this case, S_c represents the mean collision stopping power for the actual energy spectrum of the secondary electrons. Furtheron, if one assumes that the walls are so thick that CPE is reached inside the wall:

Inside the wall: $\frac{D_{medium}}{D_{wall}} = \frac{(\frac{\mu_{en}}{\rho})_{medium}}{(\frac{\mu_{en}}{\rho})_{wall}}$

$$\Rightarrow \quad D_{medium} = \frac{(\frac{\mu_{en}}{\rho})_{medium}}{(\frac{\mu_{en}}{\rho})_{wall}} \cdot \frac{(\frac{S_c}{\rho})_{wall}}{(\frac{S_c}{\rho})_{gas}} \cdot \underbrace{D_{gas}}_{measured}$$

Special case:

1.) Homogeneous dosimeter: $\left(\frac{S_c}{\rho}\right)_{wall} = \left(\frac{S_c}{\rho}\right)_{gas}$ (gas cavity does not need to be small)

2.) Tissue equivalent wall: $\left(\frac{\mu_{en}}{\rho}\right)_{medium} = \left(\frac{\mu_{en}}{\rho}\right)_{wall}$ (chamber walls do not need to be thick)

Micro dosimetry

Stochastic energy deposited in a small volume of gas, equivalent to the energy deposited in a microscopic tissue volume.

Specific energy: $z = \frac{\epsilon}{\rho \Delta V}$

This is a stochastic quantity for a fixed micro-volume.

Equivalent volumes:

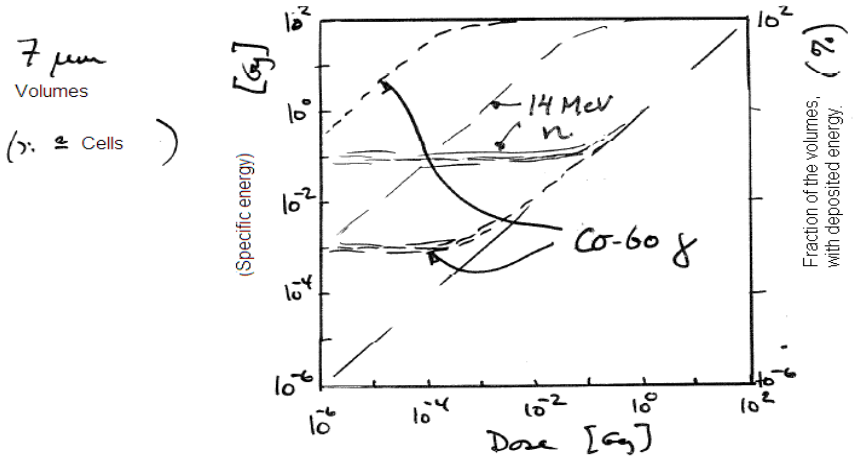
Equivalent energy deposition along a particle-track through the two volumes:

$$\delta\epsilon = \left(-\frac{dE}{dx}\right)_{gas} \cdot l_{gas} = \left(-\frac{dE}{dx}_{medium}\right) \cdot l_{medium}$$

$$\Rightarrow l_{gas} = \frac{(\frac{S_c}{\rho})_{medium}}{(\frac{S_c}{\rho})_{gas}} \cdot \frac{\rho_{medium}}{\rho_{gas}} \cdot l_{medium}$$

If we choose l_{gas} of the order of 10mm, the detector will be equivalent to a cell diameter l_{medium} around 10 μm, since $\frac{(\frac{S_c}{\rho})_{medium}}{(\frac{S_c}{\rho})_{gas}}$ is about 1, and $\frac{\rho_{medium}}{\rho_{gas}}$ around 10^3.

Comparing the graphs of specific energy z versus dose D for gamma and neutron irradiation, we see that energy deposition by neutrons typically occurs in "packages" 100 times larger than by gamma.



External dosimetry (γ-radiation)

From a point source of activity A:

Dose deposited in air, at distance r from the point source:

Dose rate: $\dot{D}_{air} \overset{CPE}{=} \dot{K}_{c,air} = \frac{A}{r^2}\Gamma_{air}$

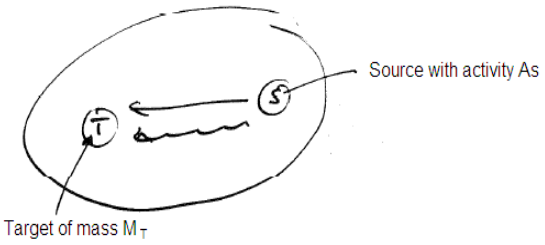
Specific gamma radiation constant: $\Gamma = \frac{1}{4\pi}\sum_{\gamma i} k_i E_{\gamma i}\left(\frac{\mu_{en}}{\rho}\right)_{air,E_{\gamma i}} \quad \left[\frac{Gym^2}{sBq}\right]$

Sometimes, Γ is given relative to the exposition rate $[\frac{Coulomb}{kg \cdot s}]$

Specific gamma exposition constant: $\Gamma_{Exp} = \frac{\Gamma_{Dose}}{\frac{W}{e}}$

Where $\frac{W}{e}$ is the average amount of energy required to generate an ion pair in air (34 $\frac{eV}{ip}$).

Internal dosimetry



Dose rate in target organ: $\dot{D}_T = \sum_S A_S \cdot SEE(S \leftarrow T)$

Specific effective energy: $SEE(T \leftarrow S) = \frac{1}{M_T} \sum_i k_i E_i \phi_i (T \leftarrow S)$

Where M_T is the mass of the target organ, and the sum goes over the different types of radiation i, k_i is the yield of radiation of type i per disintegration, E_i is the mean quantum of energy of radiation type i, and ϕ_i is the fraction of this type of energy which is absorbed.

Absorbed fraction: $\phi_i(T \leftarrow S) = \begin{cases} 1 & \text{if } S \equiv T, \text{ for } \alpha, \beta \\ 0 & \text{if } S \neq T, \text{ for } \alpha, \beta \\ \textit{Must be measured} & \text{for } \gamma \end{cases}$

Dose: $D = \sum_S \tilde{A} \cdot SEE(T \leftarrow S), \quad \tilde{A} = \int_0^t A(t)dt$

A biokinetic model for $A(t)$ is required to calculate $\tilde{A}$.

$$\lambda_{tot} = \underbrace{\lambda_R}_{Radiological} + \underbrace{\lambda_B}_{Biological}$$

Biological effects of radiation

Indirect effects of ionising radiation

Radiation of water→ Water radicals → Possible biological damage

$$H_2O + \text{ionising radiation} \rightarrow \begin{cases} H_2O^* \\ H_2O + e^- \rightarrow H_2O^- \\ H_2O^+ \end{cases}$$

$$H_2O^+ \rightarrow H^+ + OH'$$
$$H_2O^- \rightarrow H' + OH^-$$

Where OH' and H' are radicals. Effect of radicals on biomolecules:

$$RH + OH' \rightarrow R' + H_2O$$
$$RH + H' \rightarrow R' + H_2$$

Where R' represents a potentially lethal damage. Fixation of a possible damage in presence of oxygen:

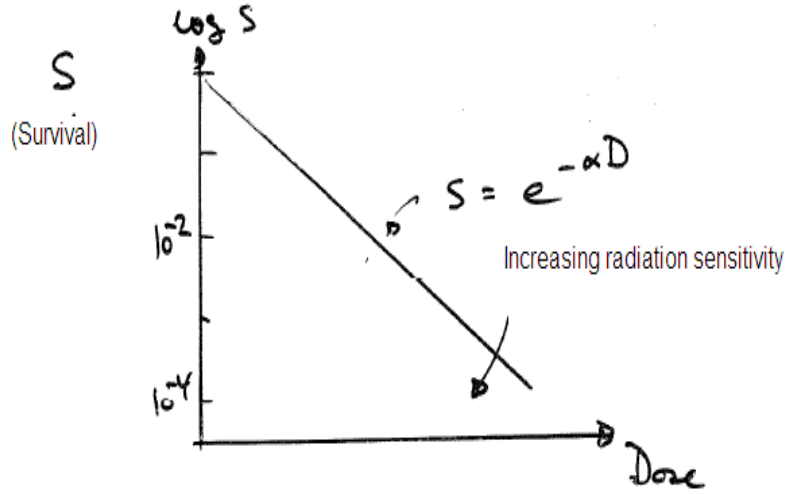
$$R' + O_2 \rightarrow RO_2'$$

$$RO_2' + RH \rightarrow RO_2H + R'$$

Where RO_2H is a biomolecule with a fixed damage.

Radiative effects are combinations of direct and indirect effects, i.e. direct hits in biomolecules and generation of radicals through radiolysis of water).

Irradiation of biological cells decreases the colony forming ability of cells



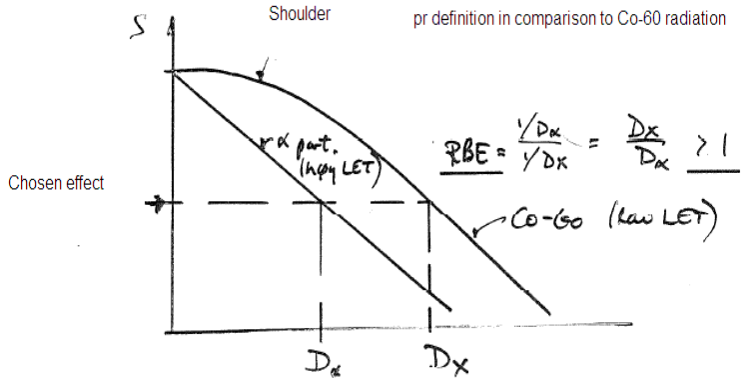
Single hit, single target theory:

Probability of survival: $P(survival) = P(no\ hits) = P(n = 0) = \left(\frac{\mu^n e^{-\mu}}{n!}\right)_{n=0} = e^{-\mu} = e^{-\frac{D}{D_0}}$

Where n is the Poisson distributed variable for the number of hits, D_0 is the average dose corresponding to one lethal hit, and μ is the average number of hits at dose D, i.e. $\mu = D/D_0$.

Relative biological effect (RBE) for different types of radiation

RBE is per definition a comparison with Co-60 radiation.



Chadwick and Leenhouts (1973)

$$S = e^{-(\alpha D + \beta D^2)}$$

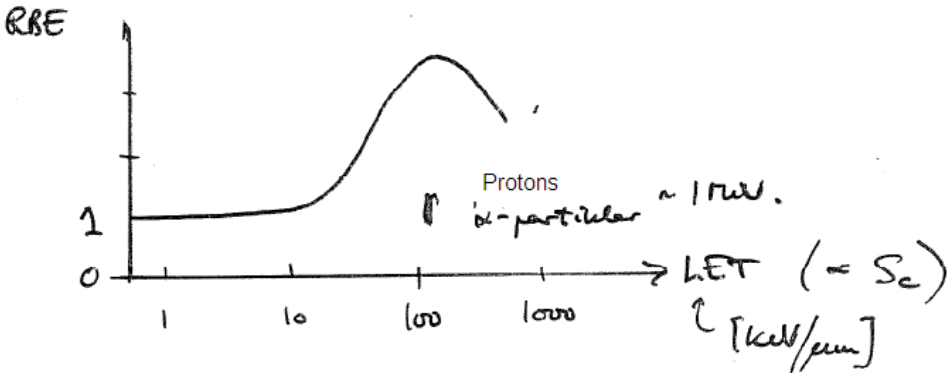
For small doses: $P(damage) = 1 - S \simeq \underbrace{\alpha D}_{HighLET} + \underbrace{\beta D^2}_{LowLET}$

1.) The critical molecule is DNA.

2.) Double strand damage is the critical event.

3.) Single strand damage can be repaired.

4.) A high density of single strand damage($\propto \beta D^2$) can result in double strand damage.



Modifying effects

Dose rate

Fractionation

Cell cycle

Oxygen

Radiation protection

This formalism is meant to be used to estimate low doses of ionizing radiation (up to 100 mGy) that may induce stochastic effects such as cancer development and/or genetic mutations.

Formalism

Equivalent dose (for organ T): $H_T = \sum_R \omega_R \cdot D_{T,R}, \qquad [Sv]$

Radiation weighting factor : $\omega_R \ [\frac{Sv}{Gy}]$

Tissue weighting factors: $\sum_T \omega_T = 1$

$$\omega_R = \begin{cases} 1 & \text{for } \gamma,\ \beta \\ 2 & \text{for protons} \\ 20 & \text{for } \alpha\text{-particles, heavy ions, and fission fragments} \\ 2.5 & \text{for neutrons below 10 keV, increasing to} \\ 20 & \text{for neutrons around 1 MeV, decreasing to} \\ 2.5 & \text{for neutrons above 1000 MeV} \end{cases}$$

$$\omega_T = \begin{cases} 0.12 & \text{for bone marrow, colon, lung, stomach, breast, remainder tissue} \\ 0.08 & \text{for gonads} \\ 0.04 & \text{for bladder, oesophagus, liver, thyroid} \\ 0.01 & \text{for bone surface, brain, salivary glands, skin} \end{cases}$$

Effective dose for the entire body: $E = \sum_T \omega_T H_T = \sum_T \omega_T \sum_R \omega_R D_{T,R} \qquad [Sv]$

The sums are over radiation doses to target tissue T from different types R of ionizing radiation that hit the target tissue (i.e. alpha, beta, gamma, or neutron irradiation). The radiation weighting factor ω_R indicates the biological effectiveness of each type of radiation, and the tissue weighting factors ω_T represent the health risk associated with irradiation of tissue or organ T. Notice that values for the radiation weighting factors and tissue weighting factors recently were revised (ICRP Publication 103, 2007), and therefore are different from previously published ones (ICRP 60, and Lilley 2001).

For internal radiation after inhalation or ingestion of radioactivity:

Committed effective dose: $E(50) = \underbrace{\int_0^{50} \dot{E(t)} dt}_{Bio-kinetic\ model}$

For radiation protection: $SEE(T \leftarrow S) = \sum_R \omega_R \cdot SEE_R(T \leftarrow S)$

i.e. SEE in $\left[\frac{Sv}{dis.}\right]$

Effective dose coefficients for inhalation and ingestion (ICRP 68, 1994): $e_{inh} = \frac{E(50)}{A_{inh}}$

$e_{ing} = \frac{E(50)}{A_{ing}}$

Annual limit on intake (inh. or ing.): $ALI = \frac{E_{lim}}{e_{50}} = \frac{E_{lim}}{\frac{E(50)}{A_{intake}}}$

Where E_{lim} represents a specific limit (20 mSv for workers).

The total sum:

$$\sum_{sources} \frac{A_{intake,inh}}{ALI_{inh}} + \sum_{sources} \frac{A_{intake,ing}}{ALI_{ing}} + \sum_{sources} \frac{E_{external}}{E_{lim}} \leq 1.0$$

Risk coefficients (ICRP 103, 2007):

Fatal cancer development	5.5% pr.Sv.
Heritable (genetic) damage	0.2% pr.Sv.
	5.7 % pr.Sv.

Dose limits (for effective dose)= $\begin{cases} 20\frac{mSv}{year} & \text{for worker in a radiation related profession} \\ 1\frac{mSV}{year} & \text{for the public} \end{cases}$

Radiation protection guide lines

1.) Every dose counts

2.) "Practice" is a will-fully chosen use of radiation.

Radiation protection principles that apply (only) for "practices":

- The reasons for use of radiation should be well-founded and properly stated.
- The dose should be ALARA (As Low As Reasonably Achievable)
- The usage of radiation ("practice") should not exceed any accepted dose limits. (20mSv/year for employees, 1mSv/year for the public)

3.) Intervention to reduce or eliminate radiation dose should have a net beneficial effect.

NB! Dose limits apply only to "practices", i.e dose contributions from natural background radiation do not count (around 3mSv/year in Norway).