22.05 Reactor Physics - Part Eight – Supplemental

Why Radiation Is Dangerous

1. **Background**: Nuclear engineers and radiation workers all recognize that exposure to radiation can be dangerous. But surprisingly few can explain why. A brief, mostly qualitative, explanation is provided here.

2. **Quantification:** One of the difficulties in explaining radiation, be it nuclear power or nuclear medicine, to the public is that few people are cognizant of the units that are employed to measure radiation. Instead, the assumption is often that there are only two levels: 1) none which implies safety and 2) any which implies lethal. We note here the actual units, of which there are three:

a) Exposure: This is what a radiation detector measures. Radiation may consist of either charged (alpha, beta, protons, fission products) or neutral (gamma, neutron) particles. For charged particles, a detector directs the beam onto a gas. Each particle ionizes the gas to create an electron/ion pair. An electric field is imposed across the gas and that field causes the electron and ion to move in opposite directions to the anode and cathode where they are registered as a signal. Neutral particles are similarly detected except that they first interact with the detector wall thereby creating charged particles that move into the gas.

The SI unit of exposure is the X-unit (not yet named after a person). It is equal to one Coulomb per kilogram (1C/kg) and is a measure of the amount of ionization that is created.

b) Absorbed Dose: This is the amount of energy deposited in tissue as a result of the radiation that is incident on the tissue. Its SI unit is the Gray which equals one joule per kilogram. It should be noted that energy released is not necessarily equal to energy absorbed. When radiation passes through tissue, it interacts. For example, a photon may undergo a Compton scatter to produce an electron and a lower energy photon. Energy has been lost by the incident photon. But it may not be deposited locally unless both the scattered electron and the newly emitted low energy photon attenuate locally.

To relate exposure to absorbed dose one needs to know the energy needed to create an ion pair. In tissue, it is 25 eV. In air, it is 34 eV. Thus, for air:

$$1 \text{ X unit} = \left(\frac{1\text{C}}{\text{kg air}}\right)\left(\frac{1 \text{ ion}}{1.6 \times 10^{-19} \text{ C}}\right)\left(\frac{34 \text{ eV}}{\text{ion}}\right)\left(\frac{1.6 \times 10^{-19} \text{ J}}{1 \text{ eV}}\right)\left(\frac{1 \text{ Gy}}{1 \text{J/kg}}\right)$$

$$= 34 \text{ Gray}$$

c. Dose Equivalent: This is the amount of biological damage done by the radiation. It is related to the absorbed dose by the relation:

$$H=QD.$$

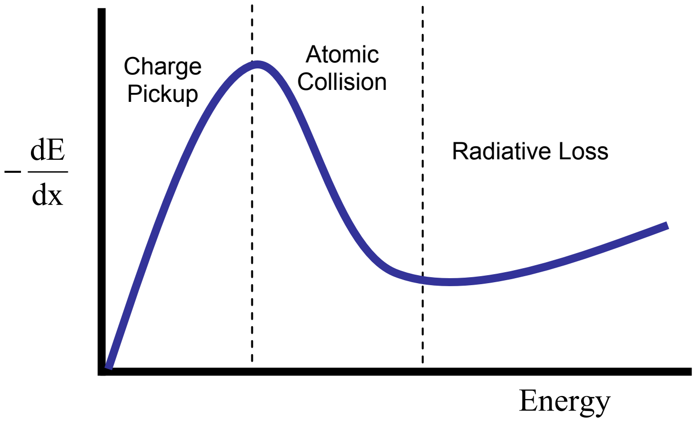
Where H is the dose equivalent, Q is the quality factor, and D is the absorbed dose. The quality factor allows for the LET (linear energy transfer) of the radiation. Photons, which interact sparsely, have a LET of unity. Protons, which interact densely (i.e., many nearby interactions as they slow down) have a LET of ten.

The SI unit of the dose equivalent is the Sievert. It is also equal to a joule/kilogram because quality factor is dimensionless.

4. **Lethal Dose:** The LD 50/30 is the dose that is lethal to 50% of the population in 30 days. It is usually cited as 4.5 Sv.

5. **Energy Equivalent to a Lethal Dose:** Assume (for ease of arithmetic) that a typical person has a mass of 100 kg. So, the energy equivalent to a lethal dose is 450 joules. 1 J equals 1 Watt-second. So, the lethal dose is 450 Watt-seconds. In other words, if light from a typical reading lamp (100 W bulb) were ionizing radiation, you would receive a lethal dose after 4.5 seconds. The amount of energy involved in a lethal dose is vanishingly small. Why then is radiation so harmful?

6. **Interaction Mechanisms:** Neutral particles generate charged particles as they attenuate. For example, photons produces electrons via pair production, Compton scattering, or the photoelectric effect while neutrons knock hydrogen nuclei (protons) loose. So, we need to consider how charged particles slow down. The energy lost per unit distance of travel is the stopping power. The figure below shows it as a function of particle energy:



There are three mechanisms for energy loss. At very high (relativistic) energies, the particle radiates energy as Bremsstrahlung. At energies that are typically encountered in most nuclear applications (1-10 MeV), the dominant mechanism is collisions with atomic electrons. At low energies (keV and below) charge pickup occurs – the particle becomes neutral.

How much energy can be transferred in an atomic collision? For a head-on interaction, it is:

$$Q_{max} = \frac{4\ mM}{(m+M)^2}\ E$$

Where

Q_{max} is the energy transferred,
m is the electron mass,
M is the mass of the incident particle, and
E is the energy of the incident particle.

Consider a 1 MeV proton that strikes an electron. In this case, $m \ll M$, and we obtain

$$Q \cong \frac{4m}{M} E$$
$$\cong 50\ \text{eV}$$

So, only 50 eV is lost per collision. Hence, for a single 1MeV proton to attenuate, 20,000 collisions are required. This is one reason why ionizing radiation is so dangerous. The amplification factor is enormous. There is another, equally important reason though. The energy lost per collision is on the order of 50 eV. The energy required to ionize an electron, which is the process whereby chemical bonds in molecule, such as DNA are broken, is 25 eV. Thus, the energy lost in each of the 20000 collisions that it takes to slow down one proton is almost exactly that needed to break a chemical bond.

7. **Effect of Other Types of Energy Sources:** It remains to note why other energy (visible light, heat) do not have a lethal effect. The energy associated with visible light is typically a few eV – less than that required to break a chemical bond. Similarly, the energy distribution associated with a high temperature is the quantity kT where k is Boltzmann's constant.

8. **Summary:** To summarize, the reason that ionizing radiation is lethal if absorbed even in seemingly small quantities is that: 1) neutral particles generate charged ones; 2) many thousands of atomic collisions are required to slow down each charged particle; and 3) the energy released per atomic collision is almost exactly that needed to ionize an electron in tissue.