22.01 Fall 2015, Problem Set 9 (Normal Version)

Due: December 2, 11:59PM on Stellar

August 26, 2015

Complete all the assigned problems, and do make sure to show your intermediate work. Please upload your full problem set in PDF form on the Stellar site. Make sure to upload your work at least 15 minutes early, to account for computer/network issues.

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1 Conceptual Questions

1. Define the major short-term biological effects due to intense gamma radiation exposure, and explain their origins.
2. Starting from the entry of a quantum of ionizing radiation into the body, explain, step by step, the most likely mechanism to induce mutations in a cell.
3. List some of the other, non-radioactive sources of the free radicals responsible for DNA damage and eventual cell mutations. Where do they come from?
4. You are given four cookies containing dangerous levels of a high-activity isotope. Each has the same half life, the same concentration, therefore the same activity. One emits alpha particles, one emits beta particles, one emits gamma rays, and one emits neutrons, all at the same energies. You may put one in your pocket, hold one in your hand, eat one, and give one to a "friend." What do you do, and why? Use your knowledge of stopping power, range, and relative biological effectiveness (RBE) to answer the question.
5. Explain why cancerous tumors are relatively resistant to radiation compared to normal cells, making radiation therapy more difficult.

2 Analytical Questions

For these questions, read the following article on The Demon Core accident, and this article detailing the resulting radiation effects suffered by the two workers exposed.

1. Explain, step by step, what caused the high exposure to radiation.
2. Calculate or find the total energy, dose, and equivalent dose absorbed by Daghlian and Hemmerly in the following units:
   (a) Roentgen
   (b) Rad
   (c) Rem
   (d) Sieverts
   (e) Gray
3. If the men's equivalent doses had been due to fast neutrons instead of gamma and x-rays, what would the energy absorbed in Roentgens been for each person?

3 Radiation Resistance, G-Values, and Fevers

For these questions, you will calculate a few parameters related to radiation resistance and sensitivity by changing someone's body temperature. We will focus on two free radicals produced by radiation: hydrogen peroxide (H_2O_2) and the uncharged hydroxide group (OH). The first liberates free oxygen in water, while the other tears electrons from other molecules to form the more stable OH^- hydroxide ion.

1. Standard diffusion of species in liquids and solids follows the well known Arrhenius law:

$$D(T) = D_0 e^{\frac{-E_A}{kT}} \tag{1}$$

   where $D(T)$ is the diffusion coefficient in $\left[\frac{m^2}{sec}\right]$, D_0 is the diffusion prefactor, E_A is the activation energy in eV for the species to move, k is Boltzmann's constant, and T is the temperature in Kelvin. Using the data for hydrogen peroxide from this article (see p. 558) and this article for hydroxide ion data (see Table 1), find the values of D_0 and E_A for each molecule's diffusion.

2. Calculate the distance that one of each molecule will travel in 10^{-6} seconds at body temperature ($37C$), or about the time that intracascade reactions stop.

3. Suppose that someone has ingested al alpha emitter, perhaps by smoking, which releases 4MeV alpha particles. Which of the two molecules do you expect to do more damage to DNA? You should consider both the amount of each produced, as well as how far they can travel. Develop an expression for the "damage effectiveness" of each of these ions, based on your calculations.

4. Graph this "damage effectiveness" as a function of temperature from 32-42C (the range of body temperatures that won't ensure death). Does your answer to (3.3) change with changing temperature? What does this say about your susceptibility to radiation damage if you have a fever of 40C?

5. Suppose now that cryogenic freezing actually works, and that people can be stored at liquid nitrogen temperatures for thousands of years (see Figure 1). Compare the expected amount of DNA damage to a given cell in this person during 1,000 years of freezing, compared to 100 years of life.

Figure 1: Cryogenic freezing of humans. Image source:
https://legendoflaura.wordpress.com/2013/09/09/futurama-series-finale-2013/ accessed on 2015-08/26.