NPRE 441

Principles of Radiation Protection

Number	Date Assigned	Date Due	Description
1	Jan. 18	Jan. 25	Obtain the Neumann series solution of the Transport Equation in terms of the outgoing collision density as: $\chi = S + (CT)\chi$ Compare the solution to that for the ingoing collision density: $\psi = S_c + (TC)\psi, \quad S_c = TS$.
2	Jan. 20	Jan. 27	Calculate the energy in eV of photons of electromagnetic radiation of: a) X-rays, b) Gamma rays, c) Visible light, d) Ultra violet light, e) Infrared. Start from an appropriate value of the wave length, and use: $E = h\nu$, $\nu = \frac{c}{\lambda}, c =$ speed of light, h = Planck's constant, λ = radiation wave length
3	Jan. 23	Jan 30	Consider the isotope Ra^{226}. Using Avogadro's law, calculate its activity and discuss its relationship to the Curie unit of activity. You can obtain the half life of the $Radium^{226}$ isotope from the Table of the Nuclides.
4	Jan. 25	Feb. 1	TThe production of $Carbon^{14}$ with a half life of 5730 years is an ongoing nuclear transformation from the neutrons originating from cosmic rays bombarding $Nitrogen^{14}$ in the Earth's atmosphere: ${}_0n^1 + {}_7N^{14} \rightarrow {}_1H^1 + {}_6C^{14}$ ${}_6C^{14} \rightarrow {}_{-1}e^0 + {}_7N^{14}$ --------------- ${}_0n^1 \rightarrow {}_{-1}e^0 + {}_1H^1$ Where $Nitrogen^{14}$ and $Carbon^{14}$ appear as catalysts in the overall reaction leading to the disintegration of a neutron into a proton and an electron. The atmospheric radiocarbon exists as $C^{14}O_2$ and is inhaled by all fauna and flora. Because only living plants continue to incorporate C^{14}, and stop incorporating it after death, it is possible to determine the age of organic archaeological artifacts by measuring the activity of the carbon present. Two grams of carbon from a piece of wood found in an ancient temple are analyzed and found to have an activity of 15 disintegrations per minute. Estimate the approximate age of the wood, if it is assumed that the current equilibrium specific activity of C^{14} in carbon has been constant at 13.56 disintegrations per minute per gram.
5	Jan. 27	Feb. 3	The naturally occurring isotope K^{40} is widely spread in the environment. In fact, the average concentration of potassium in the crustal rocks is 27 [g/kg] and in the oceans is 380 [mg/liter]. K^{40} occurs in plants and animals, has a half-life of 1.3 billion years

			and an abundance of 0.0119 atomic percent. Potassium's concentration in humans is 1.7 [g/kg]. In urine, potassium's concentration is 1.5 [g/liter]. 1) Calculate the specific activity of K^{40} in Becquerels per gram and in Curies/gm of K^{40} alone. 2) Calculate the specific activity of K^{40} in Becquerels per gram and in Curies per gm of overall potassium. 3) Calculate the specific activity of K^{40} in urine in [Bq/liter]. 4. A beta activity above 200 transformations (disintegrations) per minute per liter of urine following accidental exposure to fission products is indicative of an internal deposition in the body, and requires intervention. How does this "body burden" criterion compare to the activity caused by the one due to the naturally occurring potassium?
6	Jan. 30	Feb. 6	Identify the particles appearing in cosmic ray showers together with their properties such as masses, charges, energies and half lives.
7	Feb. 1	Feb. 8	Estimate the degree of ionization in air caused by an exposure rate of 1 mRoetgen/min from x or gamma rays.
8	Feb. 3	Feb. 10	In a possibly future matter/antimatter reactor, use the mass to energy equivalence relationship to calculate the energy release in ergs, Joules and MeV from the complete annihilation of: a. An electron/positron pair. b. An antiproton/proton pair. Consider the following masses: $m_{\text{electron}} = m_{\text{positron}} = 9.10956 \times 10^{-28}$ gram, $m_{\text{proton}} = m_{\text{antiproton}} = 1.67261 \times 10^{-24}$ gram.
9	Feb. 6	Feb 13	Data mine for the decay diagrams, half lives, types and energies of radiation emitted, for the two isotopes: 1. Sr^{90}, 2. Cs^{137}, resulting from the weapons testing in the atmosphere in the 1950s.
10	Feb. 8	Feb. 15	Data mine for the decay diagrams, half lives, types and energies of radiation emitted, for the following isotopes appearing in the $Radon^{222}$ decay chain: Rn^{222}, Po^{218}, Pb^{214}, Bi^{214}, Po^{214}, Pb^{210}, Bi^{210}, Po^{210}. Identify the ones that are particularly radio toxic.
11	Feb. 10	Feb. 17	$Radon^{222}$ as a daughter in the decay chain of uranium is gaseous at room temperature. It is an inert or noble gas that does not interact chemically in the body. However it decays into Pb^{210} which attaches itself to vegetation such as tobacco leaves as a solid and subsequently decays into Po^{210} which emits an energetic alpha particle with 5.3 MeV of energy. The inhalation of these two isotopes in the particulate matter of cigarettes smoke delivers to the average smoker 8 rems per year to the basal cells of the bronchial tissue. The “population cancer effective dose” is the total radiation effective dose that if spread through a population would cause one additional cancer death and is considered to be approximately 2,000 cSv or rems. Calculate the ensuing radiological risk in units of cancer deaths per year in a population of 28 million smokers.
12	Feb. 13	Feb. 20	Calculate the masses in metric tonnes of the radioactive elements in the world oceans from the data about their activity densities. If consuming 1.25 gm of U^{235} per day produces 1 MWth of power, calculate the amount of energy that can be produced from the uranium in the world oceans.
13	Feb. 15	Feb. 22	Data mine for the decay diagrams, half lives, types and energies of radiation emitted, for the following isotopes used in food irradiation and the sterilization of medical

			products: Cs^{137}, Co^{60}.
14	Feb. 17	Feb. 24	1. Using the chart of the nuclides, generate the decay chains for U^{238} and Th^{232}. 2. Identify the two gaseous radon isotopes in the chain and find their decay graphs. 3. Identify the solid products of the radon chain that are of particular health interest, and show their decay diagrams, decay products, half lives, and decay energies.
15	Feb. 22	Mar. 1	a) Express the recommended Action Level (AL) for radon gas in units of Bq/m^3 of air, and pCi/Liter of air. d) Express the Working Level (WL) for radon gas in units of Bq/m^3 of air, and pCi/Liter of air.
16	Mar. 1	Mar. 8	The following two equations may be derived between the lead isotopes abundance ratios at times 0 and t, and the present ratio of uranium to lead $(U/Pb)_t$: $$\left(\frac{Pb^{206}}{Pb^{204}}\right)_t = \left(\frac{Pb^{206}}{Pb^{204}}\right)_0 + \frac{(U^{238}/U)_t}{(Pb^{204}/Pb)_t}\left(\frac{U}{Pb}\right)_t (e^{\lambda_{238}t} - 1)$$ $$\left(\frac{Pb^{207}}{Pb^{204}}\right)_t = \left(\frac{Pb^{207}}{Pb^{204}}\right)_0 + \frac{(U^{235}/U)_t}{(Pb^{204}/Pb)_t}\left(\frac{U}{Pb}\right)_t (e^{\lambda_{235}t} - 1)$$ The half lives are: $T^{238}_{1/2} = 4.5x10^9\ years, T^{235}_{1/2} = 7.1x10^8\ years$ The isotopic abundances are measured as: $\left(\frac{U^{235}}{U}\right)_t = 0.0072, \left(\frac{U^{238}}{U}\right)_t = 0.9927, \left(\frac{Pb^{204}}{Pb}\right)_t = 0.0148$ The present abundances of lead in ordinary lead are: $\left(\frac{Pb^{206}}{Pb^{204}}\right)_t = 16.0, \left(\frac{Pb^{207}}{Pb^{204}}\right)_t = 15.3$ The primeval abundances ratios of lead are considered to be the ones existing in iron meteorites with low uranium content so that the radiogenic lead is negligible are: $\left(\frac{Pb^{206}}{Pb^{204}}\right)_0 = 9.4, \left(\frac{Pb^{207}}{Pb^{204}}\right)_0 = 10.3$ Calculate an estimate for the age of the earth by solving the two equations in the two unknowns $(U/Pb)_t$ and the time t.
17	Mar. 3	Mar. 13	For a narrow beam configuration, compare the thicknesses of H_2O, Fe, Al, concrete and Pb that will reduce the intensities of the gamma photons from Co^{60} to 1 percent of their initial intensity.
18	Mar. 8	Mar. 15	Obtain the decay diagram for Co^{60} from the Chart of the Nuclides. Identify all the energies and intensities of its beta and gamma decays. For a Co^{60} source, calculate the specific heating power in MeV/(gm.sec) and in (Watt?(gm.sec). Assume that all the beta particles energy, and only 5 percent of its gamma emissions are absorbed in the source.
19	Mar. 13	Mar. 31	For a wide beam configuration, accounting for the build up factor, compare the thicknesses of H_2O, concrete and Fe that will reduce the doses from the gamma photons from Co^{60} to 1 percent of their initial intensity. Compare to the results obtained from the narrow beam approximation.
20	Mar. 15	Mar. 31	Compare the thicknesses of the following different materials that would attenuate a narrow beam of 1 MeV gamma rays in "good geometry" to one millionth of its initial strength, given their linear attenuation coefficients in cm^{-1}:

<table>
<tr><td></td><td></td><td></td><td>
<table>
<tr><td>Material</td><td>Density
[gm/cm^3]</td><td>Linear attenuation
coefficient,
at 1 MeV, [cm^{-1}]</td></tr>
<tr><td>Pb</td><td>11.3</td><td>0.771</td></tr>
<tr><td>H_2O</td><td>1</td><td>0.071</td></tr>
<tr><td>Concrete</td><td>2.35</td><td>0.149</td></tr>
</table>
</td></tr>
<tr><td>21</td><td>Mar. 17</td><td>Mar. 31</td><td>
1. Compare the thicknesses of concrete and water that would attenuate a narrow beam of 1 MeV gamma rays in “good geometry” to 10^{-6} (one millionth) of its initial strength, given their linear attenuation coefficients in cm^{-1}:
<table>
<tr><td>Material</td><td>Density
[gm/cm^3]</td><td>Linear attenuation
coefficient,
at 1 MeV,[cm^{-1}]</td></tr>
<tr><td>H_2O</td><td>1</td><td>0.071</td></tr>
<tr><td>Concrete</td><td>2.35</td><td>0.149</td></tr>
</table>
2. If you use the practical wide uncollimated beam geometry, what would be the corresponding thicknesses, using the data from the following table:

Table: Linear equation coefficients b, for dose buildup factors for a gamma ray isotropic point source.
<table>
<tr><th rowspan="2"></th><th rowspan="2">(μx)</th><th colspan="7">Gamma ray energy [MeV]</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>6</th><th>8</th><th>10</th></tr>
<tr><td rowspan="7">H_2O</td><td>1</td><td>2.13</td><td>1.83</td><td>1.69</td><td>1.58</td><td>1.46</td><td>1.38</td><td>1.33</td></tr>
<tr><td>2</td><td>3.17</td><td>2.77</td><td>2.42</td><td>2.17</td><td>1.91</td><td>1.74</td><td>1.63</td></tr>
<tr><td>4</td><td>7.68</td><td>4.88</td><td>3.91</td><td>3.34</td><td>2.76</td><td>2.40</td><td>2.19</td></tr>
<tr><td>7</td><td>16.2</td><td>8.46</td><td>6.23</td><td>5.13</td><td>3.99</td><td>3.34</td><td>2.97</td></tr>
<tr><td>10</td><td>27.1</td><td>12.4</td><td>8.63</td><td>6.94</td><td>5.18</td><td>4.25</td><td>3.72</td></tr>
<tr><td>15</td><td>50.4</td><td>19.5</td><td>12.8</td><td>9.97</td><td>7.09</td><td>5.66</td><td>4.90</td></tr>
<tr><td>20</td><td>82.2</td><td>27.7</td><td>17.0</td><td>12.9</td><td>8.85</td><td>6.95</td><td>5.98</td></tr>
<tr><td rowspan="7">Concrete
2.35
[gm/cm^3]</td><td>1</td><td>2.2</td><td>1.7</td><td>1.65</td><td>1.6</td><td>1.55</td><td>1.4</td><td>1.35</td></tr>
<tr><td>2</td><td>3.6</td><td>2.8</td><td>2.4</td><td>2.25</td><td>1.95</td><td>1.75</td><td>1.65</td></tr>
<tr><td>4</td><td>7.8</td><td>4.9</td><td>3.8</td><td>3.3</td><td>2.75</td><td>2.4</td><td>2.2</td></tr>
<tr><td>7</td><td>15.0</td><td>8.4</td><td>6.2</td><td>5.0</td><td>4.0</td><td>3.3</td><td>3.0</td></tr>
<tr><td>10</td><td>24</td><td>12.3</td><td>8.6</td><td>6.8</td><td>5.2</td><td>4.3</td><td>3.8</td></tr>
<tr><td>15</td><td>43</td><td>19</td><td>12.6</td><td>9.9</td><td>7.1</td><td>5.7</td><td>5.1</td></tr>
<tr><td>20</td><td>70</td><td>27</td><td>17</td><td>13</td><td>9.1</td><td>7.3</td><td>6.3</td></tr>
</table>
The table gives the coefficient “b” for the buildup up factor “B” in the linear form:
$$B(\mu x, E) = 1 + b(\mu x)$$
Iterate if necessary.
</td></tr>
<tr><td>22</td><td>Mar. 29</td><td>Apr. 5</td><td>
Carry out the detailed derivation proving that, for elements other than hydrogen, the mean value of the cosine of the scattering angle for neutron collisions is given by:
$$\overline{\mu_0} = \overline{\cos\theta_L} = \frac{\int_0^{4\pi} \cos\theta_L \, d\Omega}{\int_0^{4\pi} d\Omega} = \frac{2}{3A}.$$
</td></tr>
<tr><td>23</td><td>Mar. 31</td><td>Apr. 7</td><td>
For thermal neutrons, calculate the values for the average logarithmic energy decrement ξ, the moderating ratio, and the slowing down power for:
1. Ordinary water, H_2O.
</td></tr>
</table>

			2. Heavy water, D_2O.
24	Apr. 5	Apr. 12	1. Modify the random number generation procedure in the notes to generate a pseudo random numbers sequence that has a short period and repeats itself after a short length. Consider the consecutive numbers as points on the unit square (or the unit cube) and plot their distribution. 2. Modify the procedure again with your own choice of the constants to generate a sequence with a long period, and display your generated points to show their uniform distribution.
25	Apr. 7	Apr. 14	Write a Monte Carlo procedure to simulate the transport kernel T for the one dimensional neutron diffusion in a homogeneous medium. Sample the distribution and display the ensuing probability density function for a medium with a macroscopic total cross section of 1 $[cm]^{-1}$. Plot the resulting continuous probability density function.
26	Apr. 10	Apr.17	Modify the procedure that simulates the dice throwing random variable to simulate the discrete probability density function of the collision kernel C, considering the following values of the rations of the macroscopic cross sections for the different reactions to the total cross section: $\frac{\Sigma_s}{\Sigma_t} = 0.1, \frac{\Sigma_f}{\Sigma_t} = 0.3, \frac{\Sigma_\gamma}{\Sigma_t} = 0.4, \frac{\Sigma_{n,2n}}{\Sigma_t} = 0.1, \frac{\Sigma_{n,3n}}{\Sigma_t} = 0.1.$ Plot the resulting discrete probability density function.
27	Apr. 12	Apr. 19	1. Write the expression for the probability density function, pdf. 2. Derive the expression for the cumulative distribution function, cdf. 3. Invert the cdf to determine the sampling process to simulate the two following physical phenomena: a) The distance traveled between two points in a one dimensional homogeneous medium with a total cross section Σ_t. b) The time to the next decay of a radioactive substance with a decay constant λ.
28	Apr. 14	Apr. 21	Write a rejection sampling procedure that would sample the Maxwellian distribution for particles energy, velocity or temperature. Check that you are using a normalized probability density function. Plot the sampled probability density function and cumulative distribution function.
29	Apr. 17	Apr. 24	Derive the probability density function, the cumulative distribution function and the sampling procedure to sample an isotropic radiation source in the upper positive quadrant.
31	Apr. 19	Apr. 26	Derive the probability density functions, cumulative distribution functions and the sampling formulae to sample the neutron flux distribution in a reactor in the form of a cube of side length 2a.
32	Apr. 21 Term paper (10 % of final grade)	Final Exam day	Choose only one of either project I or II. It is recommended that you pick the first project if you feel that you will benefit from learning to be an informed user of a widely used radiation transport code. Choose the second project if you feel you would benefit from learning the internal structure and source code of a typical Monte Carlo neutron diffusion methodology, in view of eventually writing and programming your own. **I. Fission neutrons and gamma rays transport shielding problem.** Consider a californium^{252} neutron source placed at the center of a water cylinder of 20 cms in radius and 40 cms in height. 1. Construct a Monte Carlo simulation model for the system to use with the MCNP5 code. 2. Estimate the following quantities for a neutron source strength of $S=10^{10}$ [neutrons/sec]:

			a) Neutron and gamma rays currents on the faces of the cylinder. b) Neutron and gamma rays average fluxes in the water cylinder using the track length estimator. c) The neutron and gamma rays energy fluxes. 3) Increment the number of histories and plot the estimates as well as their standard deviations as a function of the number of histories for the reference case. 4) Double then triple the dimensions of the cylinder, and plot the results for the different water cylinder sizes. 5) Estimate the attenuation factors at the surfaces of the cylinder. 6) Use the following shielding materials and compare the obtained results: a) H_2O (reference case input) b) D_2O, c) Graphite. Present copies of your input files, results and plots for the different cases in the form of a technical report, and include a comprehensive comparison and discussion of your results. **II. Fission neutrons diffusion and slowing down in a shield.** Consider a fission neutron source falling on the side of a homogeneous medium rectangular parallelepiped. 1. Estimate the following quantities for a neutron source strength of $S=10^{10}$ [neutrons/sec]: a) Neutron flux as a function of thickness, energy and scattering angle in the shield. b) Neutron reflections, absorptions and transmissions in different regions of the shield. c) The effective dose or dose equivalent that is transmitted through the shield. 3) Increment the number of histories and plot the estimates as well as their standard deviations as a function of the number of histories for the reference case. 4) Vary the shield thickness and calculate and plot the relevant parameters as a function of shield thickness. 5) Estimate the attenuation factors at the back of the shield. 6) Use the following shielding materials and compare the obtained results: a) Aluminum (Reference case input), b) H_2O. c) Sodium. Present copies of your input files, results and plots for the different cases in the form of a technical report, and include a comprehensive comparison and discussion of your results.

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Assignments Policy

Assignments will be turned in at the beginning of the class period, one week from the day they are assigned.
The first five minutes of the class period will be devoted for turning in, and returning graded assignments.
Late assignments will be assigned only a partial grade. Please try to submit them on time since once the assignments are graded and returned to the class, late assignments cannot be accepted any more.
If you are having difficulties with an assignment, you are encouraged to seek help from the teaching assistants during their office hours.
Questions may be emailed to the TA(s), but face-to-face interaction is preferred.
Although you are encouraged to consult with each other if you are having difficulties, you are kindly expected to submit work that shows your individual effort. Please do not submit a copy of another person's work as your own.
Copies of other people's assignments are not conducive to learning, and are unacceptable.
For further information, please read the assignments policy and assignments guidelines.