1. (15 minutes) You are responsible for the safety of employees who work in and around a heavy ion collider. In order to assure their safety, you need to determine if the radiation weighting factor for high energy neutrons is appropriate for neutrons with an average energy of 100 MeV.
   a) Propose an experiment examining the physical characteristics of the ionization tracks that result from 100 MeV neutron beam irradiation.
   b) Propose a second experiment using a biological system that would provide you with the data you require to verify that the radiation weighting factor is correct.
   c) Discuss the strengths and weaknesses of your proposed experiments and how they would relate to the radiation weighting factor.

2. (15 minutes) A number of cell cultures are exposed to a range of doses of 250 kVp X rays or a beam of 3-MeV alpha particles. On a single diagram show what a typical survival curve for each of these types of radiation would look like. Be sure to label each axis completely in reasonable units and indicate the $D_0$ for each radiation. Then determine an RBE for the alpha particles based on your curves. State any assumptions.

3. (15 minutes) Consider monitoring the dose rate around a low-energy neutron source. Assume that you have a 10-mm diameter spherical tissue-equivalent ion chamber, filled with tissue-equivalent gas with density 0.0008 g/cc, the neutron energy is 50 keV, the range of a 50 keV proton is 1.2 mm in the gas, and the dose rate is 5 μGy per hour. How long would you have to integrate the current from this chamber to confirm the dose rate with a precision (standard deviation) of 2%?

4. (10 minutes) Several research groups are currently exploring the use of isotope-labeled antibodies against cancer cells to increase the specificity of radiation therapy. When only a fraction of the cancer cells will bind the antibody, the treatment can be made effective by using a gamma-emitting radioisotope that emits a gamma ray with a mean free path that is several times the diameter of the typical cell. It is extremely difficult to measure the dose to individual cancer cells in this situation. The photon fluence at the target cell location times the energy absorption coefficient for the photons in the cellular material is usually calculated. Do the conditions described meet the requirements for the calculated quantity to be equal to the dose? What is the primary requirement? List at least two of the characteristics of the situation that have to be met to satisfy that requirement.
5. (20 minutes) Students receive calibrated LiF TLDs that are 3.2 mm square x 0.9 mm thick. When exposed to the Vet school's $^{60}$Co source at an equivalent tissue depth of 1 cm, all results agree with calibration data from the manufacturer to within experimental error. Next the students perform a series of experiments and have puzzling results. Explain in detail the reasons for the results described below:

   a. When exposed to unfiltered 250 kV$_{p}$ X rays, their results are roughly 20% high compared to the exposure measured by a carbon-walled ion chamber.
   b. When exposed “free in air” to a low scatter $^{137}$Cs beam, the results are 10% or more low.
   c. When exposed to a PTB Sr/Y-90 source, the chips read 30% low compared to documentation given by PTB (the German bureau of standards) and measurements done with an extrapolation chamber.
   d. When exposed to thermal neutrons, the results are 10% or less of the dose calculated from measurements taken with activation foils at the same time that the chips were exposed.

6. (10 minutes) Using a NaI(Tl) detector the resolutions of the $^{137}$Cs 662-keV photopeak and the 1332-keV $^{60}$Co photopeak are measured. Calculate the expected ratio of resolutions of these two peaks based on the statistics of ion-pair formation?

7. (10 minutes) An air sample taken in the work area provided the following results:

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Air concentration ($\mu$Ci/mL)</th>
<th>Derived air concentration ($\mu$Ci/mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-35</td>
<td>1.0 x 10$^{-6}$</td>
<td>7.0 x 10$^{-6}$</td>
</tr>
<tr>
<td>Co-60</td>
<td>4.0 x 10$^{-8}$</td>
<td>7.0 x 10$^{-8}$</td>
</tr>
<tr>
<td>Zn-65</td>
<td>2.0 x 10$^{-8}$</td>
<td>1.0 x 10$^{-7}$</td>
</tr>
</tbody>
</table>

If the external dose rate in the area is 150 mrem/h, estimate the total effective dose equivalent for an individual working in this area for two hours without wearing respiratory protection. State all assumptions.

8. (10 minutes) A 27 mCi Co-60 source is lost. At what distance can the lost source be detected with a survey instrument whose sensitivity is 0.013 $\mu$C/kg per hour (0.05 mR/h) above background?

$$\Gamma_{Co-60} = 1.32 \, R \, m^2 \, Ci^{-1} \, h^{-1}$$
9. (15 minutes) The emission rate of thorium-containing particles at the location of a ground-level thorium excavation operation is $10^8$ Bq/s and is comprised of $6 \times 10^7$ Bq/s of 100 µm radius particles, $3 \times 10^7$ Bq/s of 1 µm radius particles, and $1 \times 10^7$ Bq/s of 0.1 µm radius particles. A sampling site is located 40 km directly downwind from the excavation. The wind speed is 3 m/s or less during nighttime hours when the sky is overcast. What is the air concentration of thorium-containing particles at the sampling site?

The Gaussian plume, or Sutton's equation, model for atmospheric transport and dispersion is

$$\chi(x,y) = \frac{Q}{\pi \sigma_y \sigma_z \bar{u}} \times \exp \left[ -\frac{h^2}{2 \sigma_z^2} - \frac{y^2}{2 \sigma_y^2} \right]$$

and its use is facilitated by the attached tables and graphs. Here, $Q$ is the source strength, $\bar{u}$ is the mean wind speed in the $x$ direction, $h$ is the effective stack (or emission) height, and $y$ is the cross-wind distance. $\sigma_y$ and $\sigma_z$ are the crosswind and vertical standard deviations.

### Relation of Turbulence Types to Weather Conditions

<table>
<thead>
<tr>
<th>Surface wind speed (m s$^{-1}$)</th>
<th>Daytime insolation</th>
<th>Nighttime conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strong</td>
<td>Moderate</td>
</tr>
<tr>
<td>$&lt;2$</td>
<td>A</td>
<td>A-B</td>
</tr>
<tr>
<td>2-3</td>
<td>A-B</td>
<td>B</td>
</tr>
<tr>
<td>4/3-5</td>
<td>B</td>
<td>B-C</td>
</tr>
<tr>
<td>6/5-6</td>
<td>C</td>
<td>C-D</td>
</tr>
<tr>
<td>&gt;6</td>
<td>C</td>
<td>D</td>
</tr>
</tbody>
</table>

$^a$From Gifford (1968).

$^b$Conditions: A, extremely unstable; B, moderately unstable; C, slightly unstable; D, neutral (applicable to heavy overcast, day or night); E, slightly stable; F, moderately stable.

$^c$The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon that is covered by clouds.
FIGURE 4-6 Lateral diffusion ($\sigma_y$) versus downwind distance from source for various turbulence types. [From Gifford (1968).]
FIGURE 4-7 Vertical diffusion ($\sigma_z$) versus downwind distance from source for various turbulence types. [From Gifford (1968).]
1. (10 minutes) A worker stands directly under a 10-m length of pipe containing a radioactive liquid. If the pipe contains 100 Ci of a radionuclide with a specific gamma-ray constant of 1.5 R m² Ci⁻¹ h⁻¹, what is the exposure rate to the worker's head? Assume no attenuation by the 2.0-inch diameter pipe. The pipe is 1.0 m above the worker's head and she is standing at the midpoint of the pipe length. State all assumptions.

2. (15 minutes) Draw a diagram depicting the change of quality factor with LET and then discuss the reasons why the curve takes the shape that you drew.

3. (15 minutes) Compare and contrast the ICRP 30 Respiratory Tract Model to the ICRP 30 Bone Model.

4. (15 minutes) After a minor earthquake, a subterranean fissure opens that provides a pathway for Rn-222 to diffuse into a rarely used, 500 m³ basement that is well sealed from the upper floors and generally has no air exchange. A week after the earthquake, you measure the radon activity at the EPA action level of 4 pCi/l. In order that you can design a ventilation system to divert the radon away from the house, you must know the rate of infiltration of the radon gas into the basement. What is the infiltration rate? Assume a constant infiltration rate that began at the time of the earthquake.

Recall that $^{222}Rn \xrightarrow{t_{1/2}=3.8d}^{218}Po$.

5. (10 minutes) From the perspective of respiratory insult by aerosols, "dirty" air in some ways is safer to breath than "clean" air. Why is this statement correct or incorrect? In your discussion you should mention respiratory compartments and aerosol properties.

6. (15 minutes) Radiation protection exposure limits are based on acceptable levels of risk and a relationship between risk and dose, currently assumed to be linear without a threshold. The risk is based on epidemiological data for responses to doses ranging from about 0.1 Gy to several Gray. Below this dose range the uncertainty in the data is too large to contribute to the estimation of risk. Recent radiation biology experiments suggest that the dose response relationship is not linear. Sketch at least two alternative dose response relationships and explain how the radiation protection limits might be altered if one of your alternatives could be proven to be correct for the risk of colon cancer.

7. (15 minutes) You are called by a physician working in an emergency room. A radiation worker has drunk 5 grams of triated water ($T_2O$) in an apparent suicide attempt. The physician has calmed the patient with sedatives but the patient is not isolated from medical personnel. He wants you to suggest treatment and what radiological precautions he might have to take. What do you tell the doctor? Tritium emits an 18.6 keV end-point energy beta, has a 12.3 year half-life, and a biological half-life of 9.4 days.
Reactor Theory and Experimentation

Spring 2005

1. **(10 minutes)** A fuel pin is operating at a certain fuel centerline temperature. However, it is desired to lower the centerline temperature in order to gain a greater margin between the operating temperature and the melting temperature. To do this, it is desired to introduce a power depression in the middle of the pin. However, the average fuel pin power and the fuel pin dimensions/geometrical configuration should be kept the same. How do you accomplish this?

2. **(25 minutes)** You are given a sample of a radioactive nuclide $Y$ that contains $N$ nuclei at some starting time.
   a. What is the expected number of $Y$ nuclei that remain after one half-life?
   b. What is the probability that all of the original $Y$-nuclei remain after one half-life?
   c. What is the probability that exactly one $Y$ nucleus remains after one half-life?
   d. In the case $N=2$, apply your results for parts b and c to confirm your result of part a.
   e. Discuss any limitations of neutron transport theory, in light of what the preceding parts of this problem say about actual population values compared to expected values.
   f. For what type or types of reactor(s) and what conditions will this limitation be particularly severe?

3. **(15 minutes)** You perform an experiment to measure the fuel temperature coefficient of reactivity for a small research reactor. You place the reactor at three different power levels and measure the fuel temperature at these power levels as well as note the reactivity change due to changes in the control rod positions. The data is shown in Table I.
   a. From this data, estimate the fuel temperature coefficient of reactivity for the core.
   b. Describe how the sign and magnitude of this coefficient of reactivity can affect the safe operation of the reactor.

<table>
<thead>
<tr>
<th>Power (kW)</th>
<th>Fuel Temperature (°F)</th>
<th>Total Rod Worth (cents)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>90.2</td>
<td>905</td>
</tr>
<tr>
<td>200</td>
<td>349.5</td>
<td>965</td>
</tr>
<tr>
<td>1000</td>
<td>694.9</td>
<td>1045</td>
</tr>
</tbody>
</table>

4. **(10 minutes)** Starting with the 6-factor formula, obtain the expression for the maximum value of the multiplication factor that can be attained in any conceivable reactor configuration. To get credit, you must clearly show all your assumptions leading to the maximum value of the multiplication factor.
5. **(15 minutes)** After shutdown from equilibrium high-power operation, the time-dependent behavior of $^{135}$I and $^{135}$Xe is given by:

$$N_I(t) = \frac{\phi_0 \sum f y_{Te}}{\lambda_i} e^{-\lambda_i(t-t_0)}$$

$$N_{Xe}(t) = \frac{\phi_0 \sum f (y_{Te} + y_{Xe})}{\lambda_{Xe} + \phi_0 \sigma_{a,x}} e^{-\lambda_{Xe}(t-t_0)} + \frac{\phi_0 \sum f y_{Te}}{\lambda_i - \lambda_{Xe}} \left[ e^{-\lambda_{Xe}(t-t_0)} - e^{-\lambda_i(t-t_0)} \right],$$

where $\phi_0$ is the neutron flux level prior to shutdown. Demonstrate that there will be no buildup of $^{135}$Xe following shutdown unless the flux prior to shutdown obeys the following relationship:

$$\phi_0 > \frac{y_{Xe} \lambda_{Xe}}{y_{Te} \sigma_{a,x}}.$$  

where $y_{Xe}$ is the $^{135}$Xe fission product yield, $y_{Te}$ is the $^{135}$Te fission product yield, $\lambda_{Xe}$ is the decay constant for $^{135}$Xe, and $\sigma_{a,x}$ is the one-group microscopic absorption cross section for $^{135}$Xe.

Provide a physical explanation of this result.

**Hint:** The decay of $^{135}$Te is rapid enough that it is justifiable to assume that $^{135}$I is formed directly from fission with a yield $y_{Te}$.

6. **(20 minutes)** You are part of a team designing a liquid-fueled, spherical-shaped reactor. The reactor will be composed of a mixture of uranyl nitrate and heavy water. This will simultaneously serve as the nuclear fuel, moderator, coolant, and working fluid. The reactor will consist of a spherical chamber in which the mixture will be allowed to reach a critical configuration. Assume that one-group diffusion theory is valid.

a. The nuclear data team has calculated the following one-group cross section values for the fuel mixture that you may use in designing the core:

$$\nu = 2.4205 \text{ neutrons/fission}$$

$$\Sigma_t = 0.01155 \text{ cm}^{-1}$$

$$\Sigma_a = 0.02451 \text{ cm}^{-1}$$

$$\Sigma_{ir} = 0.08156 \text{ cm}^{-1}$$

Using these values determine the critical radius of a reactor composed of this fuel.

b. Shutdown control for the reactor will be provided by chemically adding a strong absorber to the fuel mixture in process. The nuclear data team has calculated that when the maximum amount of absorber is added the one-group cross sections for the mixture will be as follows:

$$\nu = 2.4205 \text{ neutrons/fission}$$

$$\Sigma_t = 0.01155 \text{ cm}^{-1}$$

$$\Sigma_a = 0.02678 \text{ cm}^{-1}$$

$$\Sigma_{ir} = 0.08156 \text{ cm}^{-1}$$

Set the radius of the reactor equal to the radius you determined in part a. Now calculate the criticality ($k_{eff}$) of the reactor with the absorber added. Also, calculate the reactivity worth of this absorber.
7. **(25 minutes)** The following is an open source report of a nuclear terrorism incident:

“December 24, 2004, 3:16 AM. A PWR in NY state is at steady state, critical (with no extraneous source) at hot zero power (HZP), ready to resume full power operation. It is attacked by a group of terrorists. They successfully place explosives on the primary loop system and take control of the control room. At time $t=0$, they withdraw all control rods from the core and detonate the explosives. Minutes later, CNN announces that a nuclear power plant has been sabotaged and used as a nuclear weapon.”

You are asked to analyze to the best of your knowledge the above text. Consider the reactor feedback effects and the effects of destroying the primary loop. Assume that the power level reached in the sabotaged reactor was 10,000% nominal power for a duration of about 2 seconds. Do you concur with CNN’s claim that the power plant was used as a nuclear weapon? You may assume that 1 kiloton of TNT equivalent is equal to $4.18 \times 10^{12}$ J.
Fission Engineering  
Spring 2005

1) (25 minutes) A light water reactor fuel pin is operating at a linear power of 8 kW/ft. The fuel pellet radius is $R_i = 0.45$ cm and the fuel pin radius is $R_o = 0.6$ cm. The clad surface temperature is 320 °C. The fuel conductivity is 0.025 W/cm °C, and the clad conductivity is 2.0 W/cm °C.

In case 1, the fuel pin has a flat heat source profile across the pin.

In case 2, due to a flux depression in the center of the pin, the heat source profile is given as:

$$q'' (r) = A [1 + a (r / R_i)^2]$$  
where $a = 0.6$

The linear power is the same in both cases. There is no gap between the fuel and clad.

(a) (10 minutes) Which case has a higher fuel centerline temperature?  
(b) (15 minutes) What is the difference in centerline temperature for the two cases?

2) (30 minutes) A BWR6 controls reactor power by controlling core flow in the power and flow range from 60% to 100%.

A. List and describe the three principal reactivity effects which govern this power to flow relationship. Be sure to state whether the effect is positive or negative.

B. A BWR6 in steady state at 60% power and flow increases its power to 100% by increasing core flow to 100%. Assume that no control rod movements occur and neglect reactivity effects other than those you listed in Part A.

   Qualitatively describe the sequence of reactivity effect changes that take place during this transient.

C. Derive the energy balance relationship among $Q_{Rx}$ (reactor power), $m_{ci}$ (core coolant flow), and $X_{quality}$ (core exit, average thermodynamic equilibrium quality). List your assumptions.

D. Show how core average exit quality varies with power using the expression you derived in Part C.
3) (20 minutes) Discuss the advantages and disadvantages between sodium-cooled fast reactors and pressurized water reactors including consideration of knowledge of nuclear cross sections, nuclear data, neutron fluxes, the physics of nuclear fission, and/or thermo-physics of fluids.

4) (30 minutes) Derive the linear heat generation rate $q'(z)$ that would yield a uniform (constant) axial fuel temperature distribution $T_f(z) = \text{const.}$ in the cylindrical bare homogeneous reactor. State all your assumptions. How would you load your fuel to achieve this linear heat generation rate $q'(z)$? Describe how this can be done.

5) (15 minutes) In selecting coolants for nuclear power reactors, what are the desirable coolant characteristics? List at least 8 characteristics.
Interactions, Measurements, Theory of Radiation
Spring 2005

1. (10 min.) Consider the proton-induced and alpha-induced reactions $p(U,\nu)Y$ and $\alpha(U,\nu)Z$. Assume the Q values for these reactions are both positive. If the proton is moving at an initial, nonrelativistic, velocity, $v_p$, and its energy is just sufficient to produce $w$ and $Y$, estimate the $\alpha$ velocity, $v_\alpha$, that is just sufficient to produce $\gamma$ and $Z$. Assume the radii of the incident particles are equal.

2. (10 min.) Calculate the activity per cm$^3$ of newly-synthesized, 60% tritiated, nonane. The chemical formula for the non-tritiated molecule is C$_9$H$_{20}$. You should assume for the purposes of this problem that its formula weight is 128.0, and its density is 0.715 gm/cm$^3$. The half-life of tritium is 12.3 years.

3. (20 min.) A 1-mm thick, 10-cm diameter gold disk is irradiated in a $10^8$ n/cm$^2$-s (2200 m/s) thermal neutron beam, with the beam perpendicular to the face of the disk. After 2 hours of irradiation, the disk is removed from the beam. Consider the 411.8 keV photons at a point 1 cm away from the face of the center of the disk. Neglect the interaction of the gamma rays with the disk.
   
a) Calculate the Au-198 activity
   
b) Calculate the gamma dose rate (in tissue in mrad/hr)

The following information may be useful:
Density of gold: 19.3 g/cm$^3$

The 411.8-keV photon yield for Au$^{198}$ is 95.58%.

$\mu_{\text{en}}/\rho$ (tissue) for 411.8 keV is 0.0325 cm$^2$/g.

4. (15 min.) Neglecting scattered photons, calculate the positron production rate per cm$^2$ of target material (positrons/cm$^2$-sec) produced by a 2-MeV gamma-ray beam having an initial intensity of $10^6$ photons/cm$^2$-sec as the beam traverses 5 cm of Pb. The attenuation coefficients for pair production, photoelectric absorption, and Compton scattering are: $\mu_{\text{pp}} = 0.40$ cm$^{-1}$; $\mu_{\text{ph}} = 0.10$ cm$^{-1}$; $\mu_{\text{c}} = 0.32$ cm$^{-1}$, respectively.
5. **(20 min.)** An infinite slab of thickness $t$ has a uniform surface source of monoenergetic photons on one face emitting $2S_a\eta^3/\pi$ photons/cm$^2$-s-sr into the slab, where $\eta$ is the cosine of the angle between $\hat{\Omega}$ and the inward normal, and $S_a$, the total emission rate per cm$^2$ into $2\pi$ sr is constant. The slab has a linear attenuation coefficient of $\mu$ cm$^{-1}$ and is surrounded by vacuum. Using the Transport Equation find at the opposite face of the slab:

a) (15 min.) The uncollided angular flux.

b) (5 min.) The uncollided scalar flux. Express your result for the scalar flux in terms of the Exponential Integrals. Recall:

\[
\eta \frac{\partial \Psi}{\partial Z} + \mu \Psi(z, \hat{\Omega}) = S(z, \hat{\Omega}),
\]

\[
E_n(x) = \int_0^1 w^{\eta-2} e^{-x/w} dw.
\]

6. **(20 min.)**

a) (10 min.) Why are there resonances in the neutron-absorption cross section for many nuclei? That is, why is a neutron with a certain energy much, much more likely to be absorbed than a neutron with a slightly different energy? Sketch an energy-level diagram of a nucleus and use it to help with your explanation.

b) (5 min.) Uranium-238 exhibits resonances in its cross section. What isotope’s energy levels are responsible for this? Is it U-237, U-238, or U-239? Briefly explain.

c) (5 min.) Why is the absorption cross section of He-3 so much larger than that of He-4?

7. **(10 min.)** An M.D. wants to use an alpha emitting nuclide, attached to an antibody molecule, to treat cancer. For the specific type of cancer he is dealing with he needs a low-energy alpha particle (4 MeV or less), and to avoid irradiating other organs, he needs a short half life (2 or 3 days would be ideal).

a) How would you explain to him that you would not expect such a radionuclide to exist?

b) He suggests looking for a decay chain that will deliver the needed low-energy alpha particles for the short time he wants. Explain how you would do this, or why it would not work.
8. (15 min.)

a) A BF$_3$ detector is used to monitor the neutron flux in the AGN, but we use a fission chamber instead at the NSC. Why can’t we use a BF$_3$ tube at the NSC? [Hint: it’s not the difference in sensitivity.]

b) Why are escape peaks more prominent in HPGe detectors than for NaI detectors, for the same size detectors?

c) After dropping a NaI(Tl) detector and cracking the crystal, someone suggests that it be dissolved in water and used as a liquid detector as is done with anthracene dissolved in benzene. Would this work? Explain your answer.

d) A Geiger counter is used to count a source of known isotopic content and the dose rate is calculated from the measurement. The dose is also measured with a large-volume ion chamber. Under what circumstances would the Geiger counter measurement be a better choice (that is, give the better assessment of dose rate)?

e) An alpha emitter is collected on a piece of filter paper along with other radioisotopes. Name 3 ways to measure the alpha emission rate while discriminating against beta- and gamma-emitters.