Theoretical HP

1. (10 min.) Multiply damaged sites in DNA are assumed to be biologically significant because they probably can not be repaired accurately by biological processes. Assume that the critical sites in DNA are spheres 10 nm in diameter. Recall that the average charged particle path length in a randomly irradiated sphere is 2/3 of the diameter.

A. Calculate the average energy per unit mass deposited in a 10 nm diameter sphere of tissue when an electron with stopping power of 1 keV/μm crosses the site.

B. Calculate the fraction of the 10 nm diameter sites in a tissue that will be hit by an electron if the tissue is exposed to 1 mGy

2. (10 min.) Assume you have an air filled tissue-equivalent plastic ion chamber that has been calibrated for tissue dose when exposed to $^{60}$Co gamma rays. You would like to use it to measure tissue dose for 1 MeV neutrons, but are concerned about the implications of cavity theory for these measurements. Explain why you can use charge produced in air to measure gamma ray dose in tissue, and describe the characteristics the detector must have for the same approach to work for neutrons.

3. (10 min.) The dose is equal to the kerma if there is charged particle equilibrium, CPE. Explain why you do not have CPE for the following cases:

   a. in muscle at the surface of bone exposed to 250 kVp x rays
   b. 0.5 mm from the surface of a 1mm diameter hot particle consisting primarily of $^{60}$Co
   c. in a 1 mm diameter tissue volume exposed to an external source of ultra soft x rays having a mean free path of 0.4 mm

4. (20 min.) A worker participating in a routine whole-body count was found to have an activity of 2.9 MBq of $^{137}$Cs in his body. No usual exposure or incident had been reported but a review of the records indicated that the exposure probably occurred by inhalation. The records also indicate that the last negative whole-body count (i.e., no activity measured) was obtained on this individual 180 days prior to the current whole-body count. Using the USNRC-recommended approach, answer the following questions:

   a.) What was the uptake for this exposure?
   b.) What was the intake for this exposure?
   c.) What was the committed effective dose equivalent for this exposure?
State all assumptions and show all your work necessary to answer these questions.

**Useful Data and Information:**

\[ f_l = 1.0 \quad T_R = 30 \text{ years} \quad \text{breathing rate} = 1.2 \text{ m}^3/\text{h} \]

\[ \text{total body mass} = 70,000 \text{ g} \quad \text{DAC} = 0.002 \text{ MBq/m}^3 \]

For stable cesium reaching the transfer compartment, a fraction, 0.1, is translocated to one compartment and retained there with a half-life of 2 days. The remainder is translocated to a second tissue compartment and retained there with a half-life of 110 days.

5. (20 minutes)
   (a) (15 min.) A 1000 particle/cm\(^3\) radioactive aerosol comprised of 10 \(\mu\text{m}\) diameter liquid particles is formed by an accident in a confined space. The half-life of the radioactive material in the liquid is 10 days. The initial activity concentration of the liquid is \(10^{12} \text{ Bq/cm}^3\). This aerosol has the property of producing new, ultrafine aerosol particles due to the decays: for every decay occurring in a 10 \(\mu\text{m}\) particle; 1 particle of 10 nm radius is ejected into the air.

   What is the activity of the 10 nm particles per cm\(^3\) of air one hour after the 10\(\mu\text{m}\) particles are formed? Assume none of the particles interact with each other and there are no removal mechanisms for the particles.

   (b) (5 min.) Discuss the consequences for internal exposure and air clean-up of this accident.

6. (10 min.) A beam of thermal neutrons strikes the front face of a large cylindrical BF\(_3\) tube 50 cm long. The diameter of the tube is 10 cm. The 2200 m/s fluence rate is \(10^6 \text{ n/cm}^2\cdot\text{s}\). The tube contains 600 mm of Hg partial pressure of \(^{10}\text{B}\)\(^{19}\text{F}_3\). What is the interaction rate in the tube? The \(\sigma_0\) cross section for \(^{10}\text{B}\) is 3838 barns. Assume ideal gas laws apply.

7. (20 min.) A radioactive gas decays by 100% alpha emission to a daughter that emits a gamma ray and then is stable. By trapping the gas in a small pressurized Ar-filled ion chamber, the gammas can be counted and the saturation current measured. The gamma activity is measured with a 6 inch diameter NaI(Tl) detector 18 inches from the ion chamber. The intrinsic efficiency of the NaI detector is 50% for the gamma of interest. Assume the gas sample is a point source and the NaI detector is an aperture detector. The measured count rate from the detector is 510 cps. Given
that $W$ is 26.3 eV/ion pair for Ar and the saturation current is 5.3 nA, calculate the energy of the emitted alphas?

8. (20 min.) Describe the factors, ranked in order of importance, that play a role in determining whether a cell will survive irradiation with ionizing radiation. Be sure to include all the most important physical, chemical and biological factors and justify the order in which you rank these.
Interactions, Measurements, Theory of Radiation

1. (10 minutes) A group of environmental activists have just discovered that they are getting exposed to ionizing radiation when they take a commercial airline flight across country to attend their national convention. They want to measure the neutron component of this radiation and have access to a nifty little high-pressure hydrogen detector that they have been using to monitor neutrons around nuclear power plants. Unfortunately they have not thought about the neutron energy spectrum. Neutrons with energy greater than 100 MeV are responsible for about half of the neutron dose at aircraft altitudes. Explain the errors that are likely to occur in the high-pressure proportional counter when the high-energy neutron events occur, and indicate whether you expect the instrument to over-estimate or under-estimate the dose.

2. (15 minutes) One finds significant discrepancies when comparing the measured spectrum of photons at a depth in tissue with the value calculated by a Monte Carlo program that includes only the Compton and coherent (Raleigh) scattering cross sections. If the incident photon energy is above 1.5 MeV, list three processes that modify the photon spectrum and indicate the change that each will make in the total photon spectrum.

3. (20 minutes) A 10-g capsule of a radioactive material is measured initially (when no $^{234}\text{U}$ has accumulated) to produce 100 W of thermal energy from the decay:

$$^{238}\text{Pu}\rightarrow^{234}\text{U} + \alpha.$$  

(a) (12 minutes) What is the initial activity per gram of the material?
(b) (3 minutes) Explain whether or not the ratio of activities of the $\text{Pu}$ to $\text{U}$ is accurately described by secular equilibrium 10 years after the material, containing no $\text{U}$, is sealed in the capsule.
(c) (5 minutes) How many $\text{U}$ atoms were produced during those 10 years?

Note: You may obtain necessary data from the Nuclide Chart.

4. (10 minutes) In thermal neutron-induced fission of $^{235}\text{U}$, suppose a $^{72}\text{Cu}$ nucleus is formed. If you assume the other nucleus produced has the same N/Z ratio as $^{72}\text{Cu}$, how many prompt neutrons were released by this fission event?
5. (20 minutes) Consider serial decay described by the equation:

\[ N_a \xrightarrow{\lambda_a} N_b \xrightarrow{\lambda_b} N_c \]

where \( N_a(0) = N_0; N_b(0) = 0 \). The \( N \)'s are the number of atoms in a sample.
For the case that \( \lambda_a = \lambda_b = \lambda \):

a. (15 minutes) derive the relation for the activity of the sample due to atoms of type b, i.e., \( A_b(t) \).

b. (5 minutes) derive the relation for the time, \( t_m \), at which \( A_b(t) \) is a maximum.

6. (20 minutes) Consider the \( ^9\text{Be}(p,\alpha) \) reaction. The Q-value is 2.126 MeV. The kinetic energy of the incident proton is \( T_p \); the kinetic energy of the alpha is \( T_\alpha \); the alpha emerges at an angle of 90 degrees with respect to the direction of the incident proton.

a. (18 minutes) Derive an equation for the kinetic energy of the recoil nucleus, \( T_R \).

b. (2 minutes) If \( T_p = 2 \) MeV, find \( T_R \).

7. (15 minutes) An engine wear test is to be carried out in which the mass of radioactive piston-ring particles in an oil sample is to be determined. A sample of the used oil gives 13,834 counts over a 3-minute period. A standard has been prepared using exactly 100 \( \mu \)g of the same activity material, which gives 91,396 counts over a 10-minute period. Background for the detector has been determined to be 281 counts/minute, measured over a very long counting time. Find the mass of the particles in the sample and its expected fractional standard deviation.

8. (10 minutes) The half-value layer (HVL) for iron, i.e., the thickness required to reduce the exposure rate by 1/2, is 1.47 cm for 1 MeV photons. The exposure rate at the surface of an iron slab is 800 mR/h. Stating all your assumptions, calculate the following:

a. the photon linear attenuation coefficient (\( \mu \));

b. the thickness of iron necessary to reduce the source exposure rate to 200 mR/h; and

c. the thickness of iron required to reduce the source exposure rate to 150 mR/h.
Fall 2004 Applied Health Physics Ph.D. Qualification Exam

1. (10 minutes) Over the years there have been a number of approaches taken for the measurement of personnel exposure to neutron radiation. One popular approach has been to use thermoluminescence dosimeters (TLDs) in a personnel-monitoring badge.

Please answer the following questions.

a.) What TLD materials typically are used in such a badge?
b.) Explain how these materials are used to detect neutrons?
c.) Is it possible to use TLDs to measure the fast and thermal neutron doses? Explain how this is done.
d.) What are some of the pitfalls in the use of these types of TLDs in a mixed neutron and gamma radiation environment?

2. (10 minutes) There is interest in understanding radiation exposures to passengers flying on commercial aircraft. The radiation includes a significant dose due to neutrons produced by interaction of cosmic rays in the atmosphere. Some scientists want to express the results of measurements on aircraft in terms of dose equivalent, while others argue that it should be done in terms of absorbed dose. Explain the difference and why you favor one approach or the other for assessment of the given exposure scenario.

3. (15 minutes) Answer the following questions regarding the new 10CFR20 regulations on occupational radiation exposure:

a.) What is the annual exposure limit (stochastic) for an occupationally exposed individual? If this limit should be exceeded, how is this excess exposure recorded?
b.) What is a planned special exposure and what annual exposure limits apply to this situation? What is the lifetime limit for planned special exposures?
c.) How are medical exposures (i.e., diagnostic or therapeutic) accounted for in keeping up with the exposure history of an individual, if the exposed individual is also an occupationally exposed worker?
d.) What is a “declared pregnant female” and what is the radiation exposure limit for the embryo/fetus?
e.) If the limit set for the embryo/fetus already has been exceeded at the time of the declaration of pregnancy, what responsibility does the licensee have for additional exposure?
4. (15 minutes) A certain gas-filled detector uses the isotope $^3$He with sufficient purity to make it an acceptable proportional counting gas, and a popular engineering solution for slow neutron detection via an (n, p) reaction.

a.) Describe what it means to operate in the “proportional” region.
b.) Discuss any advantages or disadvantages of $^3$He as compared to $^{10}$B when used as a proportional counter material for slow neutron detection, and
c.) For such a detector exposed to thermal neutrons, sketch the pulse-height spectrum (relative number of counts vs. energy) when*

i. The dimensions and pressure in the detector tube are sufficient to collect the majority of charged particle reactions products, and
ii. The dimensions and other parameters are not sufficient to prevent wall effects.

*The numbers you place on the abscissa of each graph must accurately depict recoil particle energies.

5. (10 minutes) Current knowledge of the lifetime risk of fatal cancer attributable to ionizing radiation is based largely on Japanese A-bomb survivor data. ICRP risk coefficients (Publication 60) have been increased from a nominal fatality probability coefficient of $1.25 \times 10^{-2} \text{ Sv}^{-1}$ to $4 \times 10^{-2} \text{ Sv}^{-1}$ for a worker population and to $5 \times 10^{-2} \text{ Sv}^{-1}$ for members of the general public.

a.) List three reasons for this increase in the risk coefficient.
b.) List three factors that significantly contribute to the uncertainty of a specific risk calculation based on the current values.

6. (10 minutes) Consider three different accident cases (below) that liberate long half-life airborne radionuclides into a very clean room. Without the facilities for airtight sealing of the room, various pathways exist that allow dispersal of the radioactivity outside the room via heating/air conditioning ductwork and leakage around windows and doors. For the purposes of this question, assume the fans driving the ventilation through the ductwork stop operating as soon as the accident occurs, no dampers are present in the ducts and windows and doors are shut immediately.

Case 1: the accident is the open boiling (i.e. no excess pressure develops) of a radioactive liquid.
Case 2: the accident is the grinding or crushing of a solid block of radioactive material.
Case 3: the accident is the formation of a crack in a high pressure pipe resulting in the “dry” spraying of a volatile fluid containing a dissolved radioactive salt.

a.) In terms relevant to the migration of the activity, characterize the species carrying the radioactivity in each of the three cases.
b.) In each of the three cases, what would be the pathways for migration of the radioactivity out from the room, i.e., via ductwork, via leakage around windows and doors, both, neither.
7. (15 minutes – see below) In processing radioactive material with an activity of 0.01 Ci/gm and a half-life that is long with respect to measuring times, a fraction of this material becomes airborne within the workplace. Assume that you have at your disposal for collecting the airborne material a single-stage impactor designed to operate at a flow rate of 10 liter/min with 50% collection efficiency at 2 μm diameter. The impactor stage is followed by an after-filter.

a.) (6 min) Suppose you sample the air in this workplace for 10 minutes. You find that a total of $10^{-5}$ gram of material is collected on the impactor stage and the after-filter. The total activity of this sample is $5 \times 10^{-10}$ Ci. What is the mass per liter of inactive aerosol material in this workplace?

b.) (9 min) Further, assume $4 \times 10^{-10}$ Ci is collected on the impactor stage. Estimate the total respiratory exposure of a worker during a 7.5 hour workday in this workplace. State your assumptions.

8. (20 minutes) You are responsible for the safety of employees that 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 energy of 100 MeV.

Propose an experiment examining the physical characteristics of the ionization tracks that result from 100 MeV neutron beam irradiation and 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. Discuss the strengths and weaknesses of your proposed measurements and how they would relate to the radiation weighting factor.

9. (15 minutes) A new cancer treatment technique based on attaching atoms of a radionuclide to an antibody molecule. If the antibody binds preferentially to a cancer cell, the dose should be concentrated on the cells you want to kill. To confirm the effectiveness of the technique, a dosimeter using a 1 micrometer thick plastic scintillator is devised that could be placed near the surface of the tumor. It works fine as a dosimeter. However, the desire is now to use it to measure the stopping power of the electrons reaching the plane of the detector.

To determine the instruments effectiveness for such a purpose, calculate the resolution of the detector in keV (full width-half maximum).

Assume that:
- The stopping power of the electrons is about 1 keV/μm,
- The radiation yield in the scintillator is 0.075,
- The scintillator efficiency is 40 eV per photon,
- The optical coupling of the scintillator to the photomultiplier is 30%, and
- The photocathode efficiency for the photons produced by this scintillator is 20%.
1) (15 minutes) **Consider** the typical BWR and PWR plant systems shown in Fig. 1. For each system there is a throttle valve preceding the turbine. Assume that both systems are operating at 75% of full power. A larger load is applied to the turbine causing the turbine governor to open the throttle valve (i.e., call for more steam).

a) Describe the thermal and neutronic feedback effects that opening the throttle valve will have on the reactor power for the BWR plant.

b) Describe the thermal and neutronic feedback effects that opening the throttle valve will have on the reactor power for the PWR plant.

c) Give an example of how you might modify these plants (if necessary) in order to make them load-following (i.e., when the throttle valve is opened the reactor power passively increases to adjust to the increased load).

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Fig. 1. Typical (a) BWR and (b) PWR plant systems.
2. (30 minutes) You are asked to do a preliminary evaluation of the required enrichment (as a function of the reactor's diameter) of a proposed spherical, UO$_2$-fueled, water-cooled reactor that will produce 3,800 MWt.

The following design characteristics are specified: fuel-to-coolant volume ratio equals 0.27; average coolant temperature equals 300 °C; and peak neutron flux is 1.8E14 n/cm$^2$-sec. You may use the following data: UO$_2$ density = 10 gm/cm$^3$; U-235 thermal fission cross section at 20°C = 500 barns; 1 watt = 6.24E12 Mev/sec.

a) (5 minutes) State all your assumptions.

b) (25 minutes) Solve for the enrichment as a function of the reactor's diameter showing all equations, defining all terms in your solution, and showing the units in your answer.

3. (25 minutes) A light water reactor fuel pin is operating at a linear power of 8 kW/ft. The fuel pellet diameter is 0.9 cm and the fuel pin diameter is 1.2 cm. The bulk coolant temperature is 290 °C. The heat transfer coefficient to the coolant is 1.9 W/cm$^2$°C. The fuel-to-clad gap conductance is 1.1 W/cm$^2$°C. The fuel conductivity is 0.025 W/cm°C, and the clad conductivity is 2.0 W/cm°C.

It has been determined that by including an additive in the fuel fabrication, it will be possible to increase the fuel conductivity. It is desired to reduce the fuel centerline temperature by 100 °C. By what percentage must the fuel conductivity be increased to achieve this fuel centerline reduction?
4. (30 minutes) This problem deals with the core design of a conventional PWR. You may assume all the usual characteristics such as water coolant, pressure, turbulent flow, square fuel assembly geometry, etc.

The fuel assemblies are to be redesigned from a 15 X 15 array to a 17 X 17 array by reducing the fuel pin diameter and pitch.

You are the engineer studying the steady-state convective heat transfer from the cladding to the coolant. $\Delta T$ film is the temperature rise from the bulk coolant temperature to the clad surface as given by the usual heat transfer relationship:

$$q'' = h_{cb} \Delta T$$

where $h_{cb}$ is the Dittus-Boelter heat transfer coefficient.

Derive the relationship between film temperature rise, $\Delta T$, as a function of pin radius for the two cases; i.e. derive:

$$\Delta T_{17}/\Delta T_{15} = F \left( \frac{r_{17}}{r_{15}} \right)$$

The following characteristics are identical for the two cases:

- a) core power
- b) core flow
- c) core $\Delta T$
- d) core height and diameter

Neglect water holes, instrument tubes, and control rod positions.
5. (20 minutes) A long thin cylindrical reactor vessel is in the center of a cylindrical containment building. The reactor vessel surface is uniformly at temperature $T_1$ and the containment inner wall is at uniform temperature $T_2$. Gas is heated by the reactor vessel, cooled by the outer wall, and circulates by natural convection as shown. The gas circulates under laminar flow conditions.

Derive the gas temperature distribution as a function of the given radii and temperatures, neglecting end effects i.e. the gas temperature is a function of radial position only.

You may find the equation given below useful.

\[
\rho C_p \left( \frac{\partial T}{\partial t} + v_r \frac{\partial T}{\partial r} + \frac{v_\theta}{r} \frac{\partial T}{\partial \theta} + v_z \frac{\partial T}{\partial z} \right) = k \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2} \right] \\
+ 2\mu \left[ \left( \frac{\partial v_r}{\partial r} \right)^2 + \left[ \frac{1}{r} \left( \frac{\partial v_\theta}{\partial \theta} + v_r \right) \right]^2 + \left( \frac{\partial v_z}{\partial z} \right)^2 \right] + \mu \left[ \left( \frac{\partial v_\theta}{\partial \theta} + \frac{1}{r} \frac{\partial v_z}{\partial z} \right)^2 \right] \\
+ \left( \frac{\partial v_z}{\partial r} + \frac{\partial v_r}{\partial z} \right)^2 + \left[ \frac{1}{r} \frac{\partial v_r}{\partial \theta} + r \frac{\partial}{\partial r} \left( \frac{v_\theta}{r} \right) \right]^2
\]

**Cylindrical coordinates:**
Ph.D Qualifying Examination  
Reactor Theory and Experimentation

1. (5 min). How many mean free paths thick must a shield be designed in order to attenuate incident neutron beam by a factor of 1000, assuming that the only significant interaction in the shield is radiative capture?

b) (10 min). Suppose you could mix a neutron-scattering material into this shield without reducing the number density of the neutron-capturing material. Now how many mean-free paths thick must the shield be to attenuate by a factor of 1000 – thicker, thinner, or the same thickness as the answer to part (a)? You will receive zero points for just giving an answer; for credit, you must explain your reasoning.

2. (15 min).

a) Sketch the energy spectrum of neutrons in a typical commercial light-water reactor.

b) Identify the dominant features qualitatively giving reasons for the shape of the spectrum in different energy regions, and any other significant features.

c) Why is the energy spectrum of neutrons important in reactor analysis?

3. (15 min). Recall the in-hour formula given $K$ delayed-neutron groups:

$$\rho = \omega \left( \Lambda + \sum_{k=1}^{K} \frac{\beta_k}{\omega + \lambda_k} \right)$$

Let $\omega_b$ denote the largest root (algebraically largest, not largest in magnitude).

a) Assume $\rho$ is small and find an approximate expression for $\omega_b$. [Hint: if $\rho$ is small, $\omega_b$ must also be small.]

b) Assume $\rho$ is slightly greater than $\beta$ and find an approximate expression for $\omega_b$.

c) We are interested in a model with one delayed-neutron group that is equivalent (in some sense) to the model with $K$ groups. The in-hour equation for one group is

$$\rho = \omega \left( \Lambda + \frac{\beta}{\omega + \lambda} \right)$$

Derive expressions for $\beta$ and $\lambda$ such that the resulting $\omega_b$ is the same as the $K$-group $\omega_b$ in the two limits considered above, namely $\rho$ small and $\rho > \beta$.

4. (15 min). Consider a critical reactor operating in steady state at extremely low power. At $t=0$, a small amount of reactivity is introduced by withdrawing a control rod. At $t=T$, the control rod is returned to its original position. [Assume that $T \gg$ mean generation time.] Sketch the reactivity, the power level, and the total delayed-neutron precursor concentration as functions of time from $t=0$ to $t=T$. For maximum credit, describe the shapes (e.g., linear, cosine, exponential, etc.) of the curves in different time intervals.
(20 min). An approach-to-critical experiment is performed using an AGN-201 reactor. Considering the description, figure, and data given below, estimate the critical rod position, explain how you determined this position, and discuss why the data from the two detectors have different characteristics.

The reactor is initially subcritical with coarse and safety rods partially inserted. The fine control rod is initially at 0.0 cm (fully inserted). A neutron source is in an access port (see Figure). Two BF$_3$ tubes (Detectors A and B) are used to record counts in 1-minute time intervals after the population has settled following each rod movement.

![Diagram](image_url)

Fig. 1. Horizontal cross section showing positions of the core, source, and detectors.

The fine control rod is moved to various positions. At each position, the count rates are allowed to stabilize, and then 1-minute counts are taken from each detector. The table below gives the data.

<table>
<thead>
<tr>
<th>Fine Control Rod Position (cm)</th>
<th>Detector A</th>
<th>Detector B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>19300</td>
<td>6300</td>
</tr>
<tr>
<td>4</td>
<td>18899</td>
<td>6200</td>
</tr>
<tr>
<td>8</td>
<td>21700</td>
<td>6400</td>
</tr>
<tr>
<td>12</td>
<td>27000</td>
<td>6600</td>
</tr>
<tr>
<td>16</td>
<td>34500</td>
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<tr>
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<td>21.6</td>
<td>102000</td>
<td>9410</td>
</tr>
<tr>
<td>22.8</td>
<td>131000</td>
<td>10800</td>
</tr>
</tbody>
</table>

Table I. Counts in 1-minute intervals for detectors A and B for each rod position.
6. **(20 min)**. Consider the one-group diffusion model for a bare homogeneous finite cylindrical reactor. Find the radius and height of the reactor, as functions of the material buckling, such that the mass of the critical reactor is a minimum. [Your answers should be of the form $R = \_/_/B_m$ and $H = \_/_/B_m$, where $B_m^2$ is the materials buckling. Find the numbers that go in the blanks.]

7. **(10 min)**. A spherical balloon is filled with a uniform mixture of UF₆ and helium, forming a gaseous reactor. It is surrounded by non-reflecting materials. When the balloon has radius $R = R_c$, the system is critical. If the balloon were compressed (without changing its temperature) to radius $R = R_c/2$, would the system be critical, subcritical, or supercritical? You will receive zero points for just giving an answer; for credit, you must explain your reasoning. [Hint: What happens to the geometric buckling and the materials buckling?]

8. **(10 min)**. An infinite medium of He-4 contains a uniformly distributed isotropic source emitting $10^6$ n/cm²-s. All source neutrons are emitted with energy 10 keV. The helium density is $10^{18}$ atoms per cm³. The microscopic scattering cross section for helium is approximately 4 barns for neutron energies between 0.1 eV and 20 keV. The absorption cross section is negligibly small.

What is the energy-dependent scalar flux of once-collided neutrons? That is, what is $\phi_1(E)$ [neutrons / (cm²-s-keV)], the scalar flux of neutrons that have had exactly one collision since they were emitted? Give $\phi_1(E)$ for all energies $E$. Your answers should be numbers with units, not just symbols.