SOLUTIONS AND ANSWERS TO 2000 ABHP EXAM

QUESTION 1

GIVEN: criticality accident at a nuclear fuel reprocessing plant.

SOLUTIONS AND ANSWERS(•) TO PARTS A THROUGH E:

A. Three primary considerations in developing a recommendation for rescuing a worker who is in the vicinity of the criticality accident include: 1. whether or not rescue operations might cause a secondary criticality, 2. whether or not the primary criticality accident might have caused the release of highly active fission and activation products from any spent fuel that was being processed and whether or not such release could present lethal radiation fields to the rescue team, and 3. whether or not nuclear criticality information suggests that the accident victim already received a radiation dose significantly above a lethal dose.

B. Primary exposure pathways and radiation sources include for specified individuals:
   1. Workers in the room at the time of the accident: external radiation from the neutrons and gamma rays emitted during the prompt criticality phase of the accident.
   2. Rescue workers after criticality stopped: external radiation from beta and gamma radiation emitted by neutron activation and fission products released during the accident.
   3. Other individuals within 0.1 km to 1 km at the time and following the incident: 1 and 2 above, depending on distance and shielding and details on any released radionuclides, and internal exposure from inhaled radioactive aerosols.
      Comment: More specific information would have to be given for this case 3 to more specifically state the "primary" exposure pathways.

C. A method used to "quick sort" persons potentially exposed during a criticality accident includes the detection of neutron activation products, e.g., 15 h half-life Na-24, in the body by detecting the gamma radiation emitted from the body with a GM survey meter.
   Comment: It is assumed that the question refers only to persons directly involved and exposed to fission neutrons emitted during the prompt critical phase of the accident.

D. Two medical interventions that could change the health outcome for an individual exposed to 750 rad include: 1. blood transfusions and 2. bone marrow transplants.

E. The unit "rad" is correctly used for an acute radiation dose from a criticality accident because it more closely relates to the threshold, non-stochastic effects of cell death and organ or tissue functions. The unit "rem" is reserved primarily for chronic occupational exposures, and it is used to estimate the risk of stochastic effects of cancer and hereditary disease.

SOLUTIONS AND ANSWERS TO 2000 ABHP EXAM

QUESTION 2

GIVEN: an open-air, cylindrical ion chamber calibrated to give correct response at temperature $\mathbf{T_1}$ of 20 ˚C or **293 ˚K** and pressure $\mathbf{P_1}$ of **760 mm Hg** is used to perform surveys at a food irradiation facility that uses a 100 Ci ^{137}Cs source:

V ≡ active volume of chamber = **235.5 cm^3**;
R ≡ radius of chamber = **5 cm**;
H ≡ height of chamber = **3 cm**; and
ρ_{air} ≡ density of air at STP (0 ˚C and 760 mm Hg) = 1.29 kg m^{-3} = **0.00129 g cm^{-3}**.

Comment: The given value for the density ρ_{air} is recognized as the value at *standard temperature and pressure* or STP (0 ˚C and 760 mm Hg); although, this was not stated as given information in the question. *Normal temperature and pressure* or NTP are respectively 20 ˚C and 760 mm Hg, which are the stated calibration values for the ion chamber. The failure of this ABHP question to specify the temperature/pressure conditions for the given value of ρ_{air} should be considered in grading solutions to this question.

SOLUTIONS AND ANSWERS(•) TO PARTS A THROUGH C:

A. The current **I** in **A** for an exposure rate $\dot{\mathbf{X}}$ of **1 R h^{-1}** based on the assumption of NTP conditions not stated in this part of the question is calculated:

• $$I = \left(1\ \frac{R}{h}\right)\left(2.58x10^{-7}\ \frac{coul\ g^{-1}}{R}\right)\left(\frac{1\ h}{3{,}600\ s}\right)(235.5\ cm^3)(0.00129\ g\ cm^{-3})\left(\frac{273\ ^\circ K}{293\ ^\circ K}\right)\left(\frac{1\ A}{coul\ s^{-1}}\right) = 2.03x10^{-11}\ A.$$

Comment: The temperature pressure conditions should have been stated in the question, and this omission should be considered in grading solutions to this part of the question.

B. A measurement $\dot{\mathbf{X}}$ of **12.6 R h^{-1}** is made at a pressure **P** of **740 mm Hg** and a temperature **T** of 35 ˚C or **308 ˚K**. The corrected or true exposure rate $\dot{\mathbf{X}}_c$ is calculated:

• $$\dot{X}_c = \dot{X}\left(\frac{T}{T_1}\right)\left(\frac{P_1}{P}\right) = 12.6\ \frac{R}{h}\left(\frac{308}{293}\right)\left(\frac{760}{740}\right) = 13.6\ \frac{R}{h}.$$

C. A measurement $\dot{\mathbf{X}}$ of **20 mR h^{-1}** is made under NTP conditions in a beam from a crack in a shield having a width **W** of **1 cm**. Under the assumption that the axis of the ion chamber is

parallel to the surface of the shield and perpendicular to the length of the crack and that the length of the crack exceeds the diameter, 2 R, of the ion chamber, the corrected exposure rate $\dot{\mathbf{X}}_c$ in the exit beam is then calculated:

- $$\dot{X}_c = \dot{X}\left(\frac{\pi R^2 H}{\pi R^2 W}\right) = \dot{X}\left(\frac{H}{W}\right) = \left(20\ \frac{mR}{h}\right)\left(\frac{3\ cm}{1\ cm}\right) = 60\ \frac{mR}{h}.$$

Comment: Under the assumption that the axis of the ion chamber is directly over the midpoint of the crack and is either parallel or perpendicular to the length of the crack and shield surface and that the length of the crack exceeds the diameter, 2R, and height, H, of the ion chamber, the corrected exposure rate $\dot{\mathbf{X}}_c$ in the exit beam is then approximated by:

- $$\dot{X}_c = \dot{X}\left(\frac{\pi R^2 H}{2 R W H}\right) = \dot{X}\left(\frac{\pi R}{2 W}\right) = \left(20\ \frac{mR}{h}\right)\left(\frac{(\pi)\ (5\ cm)}{(2)(1\ cm)}\right) = 157\ \frac{mR}{h}.$$

QUESTION 3

GIVEN: neutron activation of manganese:

σ ≡ Mn-55 activation cross section for reaction, Mn-55(n,γ)Mn-56 = **13.3×10^{-24} cm^2 at^{-1}**;
A_{wt} ≡ atomic weight of manganese and of Mn-55 for 100% abundance = **55 g mole^{-1}**;
$T_{1/2}$ ≡ half-life of Mn-56 = **2.58 h** = ; so
λ ≡ decay constant of Mn-56 = (ln 2)/($T_{1/2}$) = **7.46×10^{-5} s^{-1}**;
ρ ≡ density of air at STP = 0.00129 g cm^{-3}; and
Energies E_i and fractional yields Y_i of the Mn-56 associated decay gamma photons, i = 1 to 3: **E_1 = 0.847 MeV** and **Y_1 = 1**; **E_2 = 1.81 MeV** and **Y_2 = 0.27**; and **E_3 = 2.11 MeV** and **Y_3 = 0.14**, which yield a total photon energy E per disintegration: **E = Σ E_i Y_i = 1.63 MeV per decay**.

SOLUTIONS AND ANSWERS(•) TO PARTS A AND B:

A. The neutron flux (i.e. fluence rate) ϕ in **n cm^{-2} s^{-1}** needed to produce a saturation activity **A** of 0.31 mCi of Mn-56 or **1.15×10^7 Bq** in a thin manganese target having a mass **m** of **1 g** is calculated:

The assumed constant number of target atoms **N** of Mn-55 is calculated:

$$N = \left(\frac{1\ g}{55\ g\ mole^{-1}} \right) (6.023 x 10^{23}\ atoms\ mole^{-1}) = 1.10 x 10^{22}\ atoms.$$

The saturation activity A is given by the product $\sigma\phi$N; so

• $$\phi = \frac{A}{\sigma N} = 7.86 x 10^{7}\ n\ cm^{-2}\ s^{-1}.$$

B. The exposure rate $\dot{\mathbf{X}}$ in **mR h^{-1}** at a time interval **t** of 1 h or **3,600 s** after irradiation ends is calculated for the Mn-56 source having an activity **A** of **0.31 mCi** at the end of irradiation for a distance **d** of 0.5 m or **1.64 feet** from the empirical relationship:

• $$\dot{X} = \frac{6\ A\ E}{d^2}\ e^{-\lambda t} = \frac{(6)(0.31)(1.63)}{1.64^2}\ e^{-(7.46 x 10^{-5})(3600)} = 0.862\ mR\ h^{-1}.$$

Comment: The question asks for the "gamma dose equivalent rate (in air) to a student", which is confusing because dose equivalent only applies to tissue and not air. The dose equivalent rate $\dot{\mathbf{H}}$ in mrem h^{-1} to the student is about (0.98) $\dot{\mathbf{X}}$ or **0.845 mrem h^{-1}**.

QUESTION 4

GIVEN: accidental release of ^{131}I in a laboratory and exposure of a worker:

A ≡ activity instantaneously vaporized at t = 0 and uniformly distributed = **15,000 μCi**;
V ≡ room air volume = **125 m^3**;
t ≡ exposure time interval for worker = **1 h**;
B ≡ breathing rate = **1.2 m^3 h^{-1}**;
F ≡ room ventilation = **100 m^3 h^{-1}**; so
K ≡ ventilation removal rate constant = F/V = **0.800 h^{-1}**;
F_{th} ≡ fraction of ^{131}I in blood that deposits in thyroid = **0.3**;
F_d ≡ fraction of ^{131}I inhaled that deposits in respiratory tract and reaches blood = **0.75**; and
D_u ≡ committed absorbed dose per unit activity uptake by thyroid = **5.5 rad μCi^{-1}**.

SOLUTIONS AND ANSWERS(•) TO PARTS A AND B:

A. The uptake **U** by the thyroid and the thyroid committed dose **D** are calculated:

When removal of ^{131}I from the room air volume is assumed to be dominated by ventilation and when decay of 8.05 day half-life ^{131}I is neglected, the uptake **U** and dose **D** are calculated:

- $$U = A\,(1 - e^{-Kt})\left(\frac{B}{F}\right) F_d\, F_{th} = 22.3\ \mu Ci.$$

and

- $$D = U\, D_u = (22.3\ \mu Ci)(5.5\ rad\ \mu Ci^{-1}) = 123\ rad.$$

B. If urinalysis and thyroid counting are assumed to comprise any bioassay of involved individuals, then five additional actions that should be taken include:

1. Report the incident to the appropriate regulatory authority.
2. Estimate the worker's thyroid dose from thyroid counting, and report this dose to the worker's supervisor and appropriate regulatory authorities.
3. Review the incident with the affected worker and the worker's supervisor including regulatory requirements and laboratory control procedures to limit contamination and exposures of personnel.
4. Require the worker to attend a training program commensurate with the exposure potential.
5. Require that all handling and processing of radioactive material, such as the evaporation of volatile radioactive material, take place in a fume hood.

SOLUTIONS AND ANSWERS TO 2000 ABHP EXAM

QUESTION 5

GIVEN: a 1.75 inch diameter GM instrument with a labeled efficiency **E** of **0.20 cpm/dpm** based on a calibration with a one inch diameter ^{137}Cs source in an aluminum planchet; table of radionuclides with radiations and intensities.

SOLUTIONS AND ANSWERS(•) TO PARTS A THROUGH D:

A. The expected counting rate **R** from a ^{99}Tc source having an activity **A** of **1 μCi** based on the given efficiency **E** of **0.2 cpm/dpm** for ^{137}Cs is calculated:

• $$R = \left(\frac{2.22x10^6\ dpm}{\mu Ci} \right) A\ E = 4.44x10^5\ cpm.$$

B. Four possible reasons why an observed counting rate of 3x10^5 cpm for ^{99}Tc is lower than the calculated counting rate based on the efficiency E for ^{137}Cs include: 1. The effective solid angle for detection for the larger ^{99}Tc source is smaller than that for the smaller ^{137}Cs source. 2. Back scatter of beta particles from the plastic backing of the ^{99}Tc source is smaller than that from the aluminum backing of the ^{137}Cs source. 3. Absorption of the lower energy beta particles from the ^{99}Tc source in the source itself, the intervening air, and the window of the GM detector is greater than that for the higher energy beta particles emitted from the ^{137}Cs source. 4. Gamma rays associated with the decay of ^{137}Cs also contribute to the response from the ^{137}Cs source while no gamma rays are associated with the ^{99}Tc source.

C. The ^{137}Cs **MDA** in **dpm** is calculated for a 95% confidence level (i.e., for a false negative probability $\beta = 0.05$ corresponding to the normal deviate $Z_\beta = 1.645$), for a sample counting interval $\mathbf{T_{s+b}}$ of **1 minute**, background rate $\mathbf{R_b}$ of **50 cpm**, an assumed background counting interval $\mathbf{T_b}$ of **1 minute**, and for an assumed lower limit of detection corresponding to a false positive probability α of 0.05 so that the normal deviate $Z_\alpha = Z_\beta = \mathbf{Z} = \mathbf{1.645}$, and for the assumption that the net counting rates are approximated by a normal distribution:

• $$MDA = \frac{1}{E}\left[\frac{Z^2}{T_{s+b}} + 2\ Z \left(\frac{R_b}{T_{s+b}} + \frac{R_b}{T_b} \right)^{1/2} \right] = \frac{1}{0.2}\ [2.71 + 32.9]\ dpm = 178\ dpm.$$

D. The true counting rate $\mathbf{R_T}$ is calculated for an observed counting rate $\mathbf{R_O}$ of **100,000 cpm** and a GM dead time τ of 50 μs or **8.33x10^{-7} minutes per count**:

• $$R_T = \frac{R_O}{1 - R_O\ \tau} = 109{,}000\ cpm.$$

QUESTION 6

GIVEN: data for preparing a special incident report for a male worker of age **N = 27 years**: quarterly external deep dose equivalents $\mathbf{H_i}$ of **0.7 rem**, **1.2 rem**, **1.8 rem**, and **0.3 rem** respectively in the i = 1st to 4th quarter, which sum to a total external deep dose equivalent $\mathbf{H_{total}}$ of **4 rem** for the year; inhalation intakes I_j (j = 1 to j = 2) in the first quarter: $\mathbf{I_1}$ = **80 μCi of ^{137}Cs** and $\mathbf{I_2}$ = **19.5 μCi of ^{131}I**, whose inhalation, *stochastic-effect-based annual limit on intakes* (SALIs) are equal: $\mathbf{SALI_1} = \mathbf{SALI_2}$ = **200 μCi**. The inhalation, *non-stochastic-effect-based annual limit on intake* (NALI) is the limiting ALI for I-131: $\mathbf{NALI_2}$ = **50 μCi of ^{131}I**.

SOLUTIONS AND ANSWERS(•) TO PARTS A THROUGH C:

A. The *committed dose equivalent* (**CDE**) to the thyroid from the ^{131}I intake is calculated:

- $$CDE = I_2 \left(\frac{50\ rem}{NALI_2} \right) = 19.5\ \mu Ci \left(\frac{50\ rem}{50\ \mu Ci} \right) = 19.5\ rem.$$

B. The *committed effective dose equivalent* (**CEDE**) from all intakes is calculated based on the assumption that an intake of 1 SALI of any radionuclide corresponds to a CEDE of 5 rem:

- $$CEDE = 5\ rem \sum_{j=1}^{j=2} \frac{I_j}{SALI_j} = 5\ rem \left(\frac{80\ \mu Ci}{200\ \mu Ci} + \frac{19.5\ \mu Ci}{200\ \mu Ci} \right) = 2.49\ rem.$$

C. The *total effective dose equivalent* (**TEDE**) is calculated as follows from the sum of the annual total deep dose equivalent $\mathbf{H_{total}}$ of **4 rem** calculated from the sum of the given quarterly values shown in the given information to this question and assumed to apply to this part and from the **CEDE** of **1.2 rem** "from radionuclide intake" stated in this part. This given CEDE is assumed to include the contribution of 0.780 rem calculated from the product of the stated CDE of 26 rem to the thyroid and an assumed stochastic-effect-based thyroid weighting factor w_T of 0.03; so the **TEDE** is calculated:

- $$TEDE = CEDE + H_{total} = 1.2\ rem + 4\ rem = 5.2\ rem,$$

which does exceed the TEDE limit of 5 rem recommended by the NCRP from exposures in any control year of practice and the limit of 1 rem per year if this worker's lifetime occupational dose happens to exceed a TEDE of N rem or 27 rem. Information is not

provided to evaluate this latter lower limit of 1 rem (See comment below.).
Comment: This part to the question does not make it clear to the candidate what given information in the question should be included in the calculation of the CEDE and then the TEDE, and this lack of clarity should be considered in grading this part to the question. It is not clear whether or not the given CEDE of 1.2 rem includes the contribution of 0.780 rem from the stated CDE of 26 rem to the thyroid. The word “intake” in the statement, “Assume you have calculated a CEDE from radionuclide intake of 1.2 rem...”, is a singular word, which might lead the candidate to add the calculated 0.780 rem CEDE contribution from the stated 26 rem CDE to the thyroid. The word “intake” should be replaced by “all intakes” or at least “intakes” to make the meaning clear. A candidate should not be required to guess at the ABHP meaning in statements of given information. Because part B already requires a candidate to calculate a CEDE from all relevant intake data, there is no point in using obtuse wording in this part to test a candidate’s knowledge on this point again.

QUESTION 7

GIVEN: An intake **I** of **5 ALI** (non-stochastic, based on bone surface limit) at a company designated by index 1 employing Pu-239; an intake **I** of **5 ALI** (non-stochastic, based on thyroid limit) at another company designated by index 2 employing I-131; and a tissue stochastic-effect-based weighting factor $\mathbf{w_T}$ of **0.03** in either case.

SOLUTIONS AND ANSWERS(•) TO PARTS A THROUGH E:

A. The *committed dose equivalent* (**CDE**) to the bone surface for the worker at company 1 and to the thyroid for the worker at company 2 are recognized to be the same value calculated:

- $$CDE = 50\ rem \left(\frac{I}{ALI} \right) = 50\ rem \left(\frac{5\ ALI}{ALI} \right) = 250\ rem.$$

Their individual contributions to the *committed effective dose equivalents* (**CEDE**) are the same value calculated for either worker at company 1 and company 2:

- $$CEDE = CDE\ w_T = (250\ rem)(0.03) = 7.5\ rem.$$

B. Removal of the thyroid to preclude the likelihood of thyroid cancer is not justified because the cancer mortality risk is small and approximately given by the product of the CEDE and the ICRP 26 risk factor of $1x10^{-4}$ rem^{-1} or $(7.5)(1x10^{-4})$ or $7.5x10^{-4}$(0.075% chance). Also, thyroid cancer is an easily diagnosed and treatable cancer.

C. Three arguments against the argument that tumors were caused 1 year later in both workers by their intakes of 5 ALI include: 1. The ALIs are designed to prevent non-stochastic effects that might cause the impairment of the functions of the respective tissues, and these limits are less than the stochastic-effect-based ALIs. 2. The risk of cancer mortality in either case is small, about a 0.0.08% chance during the remaining lifetime. 3. In either case, the latent period following irradiation for the observation of the cancer greatly exceeds the time for the observation of tumors 1 year after the intake, and for the case of the worker at company 1 who had an intake of Pu-239, most of the committed dose will not even have occurred because of the relatively long effective half-life of 50 years for Pu-239.

D. With respect to the administration of the chelating agent DPTA to the worker at company 1:

1. It is appropriate for Pu-239 because the DPTA combines with Pu-239 in the blood , and it is then excreted in the urine with the Pu-239 thereby preventing the deposition of Pu-239 in bone and liver. The DPTA does not affect the I-131 in the blood. Also, most of the I-131intake is rapidly taken up into the blood and rapidly deposited in the thyroid before a

blocking agent, e.g., KI, or any chelating agent could be administered.

2. Three factors that most contribute to the effectiveness of the DPTA following the inhalation intake include: (a) the timeliness of the administration of the DPTA shortly after the intake to assure that Pu-239 in blood uptake, primarily from certain respiratory tract compartments, is chelated and excreted with the urine before it has a chance to deposit in the bone and liver; (b) the inhalation chemical compound class which affects the solubility and transportability of the Pu-239, thereby affecting the uptake of Pu-239 into the blood and the relative saving in dose to bone and liver; and (c) the type of DPTA (zinc or calcium) and whether or not the toxicity of the DPTA and the general health of the patient would allow especially extended treatment which could yield dose savings that would justify the toxicity risks.

E. Three changes in the ICRP 66 lung model relative to the ICRP 30 model include: 1. an increase in the default AMAD from 1 μm to 5 μm for evaluating occupational exposures and for deriving intake to dose conversion factors or ALIs, and DACs and a large extension in the applicable particle size range; 2. extension of the model's application from occupationally exposed adults to children, smokers versus non-smokers, and mouth breathers versus nose breathers; and 3. change from the inhalation chemical compound classes of D, W, and Y, which did not specifically relate to mechanical and dissolution clearance pathways, to the classifications F, M, and S (fast, moderate, and slow clearance), which treat mechanical and dissolution clearance pathways specifically.

QUESTION 8

GIVEN: electron accelerator for which shielding is required:

E ≡ electron energy = **20 MeV**;
I ≡ peak current = 1 A = **1,000 mA**;
L ≡ pulse length =1 μs = $\mathbf{10^{-6}}$ **s**;
F ≡ pulse frequency = 10 Hz = $\mathbf{10\ s^{-1}}$;
Z_W ≡ tungsten atomic number = 74;
Z_{Cu} ≡ copper atomic number = 29, and
five figures from NCRP 51.

SOLUTIONS AND ANSWERS (•) TO PARTS A THROUGH E:

A. The concrete wall thickness (density = 2.35 g cm^{-3}) to yield **0.5 mrem** $\mathbf{h^{-1}}$ when the dose point is at 90° from the beam direction and **5 meters** from the target is calculated:

The average beam current $\mathbf{I_{avg}}$ is calculated:

$$\mathbf{I_{avg}} = (I)(L)(F) = (1000\ mA)(10^{-6}\ s)(10\ s^{-1}) = \mathbf{10^{-2}\ mA}.$$

The output $\mathbf{\dot{D}_{I_0}\ I^{-1}}$ of **2000 rads** $\mathbf{m^2\ mA^{-1}\ min^{-1}}$ at 90° for 20 MeV is read from Fig. E.1. The dose rate at **5 meters** in the 90° degree direction is then obtained:

$$\mathbf{D_{5m}} = (I_{avg})(2000\ rads\ m^2\ mA^{-1}\ min^{-1})(1/5\ m)^2 = \mathbf{0.800\ rads\ min^{-1}},$$

which is equivalent to 0.800 rem min^{-1} or **800 mrem** $\mathbf{min^{-1}}$ since the quality factor for bremsstrahlung is unity.

The required transmission, **T**, is then calculated:

$$\mathbf{T} = (0.5\ mrem\ h^{-1})/((800\ mrem\ min^{-1})(60\ min\ h^{-1})) = \mathbf{1.04x10^{-5}.}$$

The bremsstrahlung at 90° has a lower effective energy than that in the beam direction, and Fig. E.6 may be used to incorporate the difference by finding an equivalent electron energy that would yield the desired photon energy distribution. From the figure, the equivalent electron energy is slightly above 10 MeV for the given 20 MeV incident electron energy. I shall assume 10 MeV. From Fig. E.8, using the **10 MeV curve**, we may read the required concrete thickness (density = 2.35 g cm^{-3}) as **190 cm** for the required transmission value **T** of $\mathbf{1.04x10^{-5}}$:

- **required thickness = 190 cm**.

B. If the required transmission **T** is $\mathbf{10^{-4}}$ and the existing concrete wall thickness $\mathbf{x_1}$ is **30 inches**, the required additional lead thickness $\mathbf{x_2}$ is calculated:

From the approach used in part A, a thickness $\mathbf{x_1}$ of **30 inches** of concrete yields a transmission $\mathbf{T_1 = 10^{-2}}$ for photons produced by **10 MeV** electrons. Thus, the additional transmission $\mathbf{T_2}$ required of the lead is calculated:

$$\mathbf{T_2} = T/T_1 = 10^{-4}/10^{-2} = \mathbf{10^{-2}},$$

and this additional transmission may be obtained by adding **two tenth value layers** of lead. From Fig. E.14 (solid curve), at an electron energy of **10 MeV**, **1 TVL = 2.2 in**. Thus,

- **The required added thickness is (2)(2.2 in) = 4.4 in = 11.2 cm of lead.**

C. Five parameters important to the estimation of the emission of radiation from an accelerator are described: 1. **Average beam current**: Radiation output varies linearly with average beam current. 2. **Beam particle energy**: As energy increases, radiation yields from the target typically increase, and nuclear reactions not possible at low energies become important. 3. **Beam particle type**: Electrons will produce bremsstrahlung radiation as they strike the target, and at energies $\gtrsim$ 8 MeV, which corresponds approximately to the binding energies of nucleons, photoneutron production becomes increasingly important. In positive ion accelerators, positive ions most notably produce neutrons from direct nuclear interactions of beam particles with nuclei within the target. 4. **Atomic number of target nuclei**: Typical bremsstrahlung yields increase for electron machines as atomic number increases. Radiation yields from positive ion accelerators markedly increase once the kinetic energy of the positive ion exceeds the coulomb potential barrier of target nuclei, which varies as the square of the atomic number of the target nuclei. 5. **Target thickness**: Radiation yields vary with target thickness, typically reaching a peak at a specific thickness.

D. Five considerations for selecting shielding materials for an accelerator include: 1. Type(s) of radiation; 2. Energies of radiation; 3. Atomic number; 4. Mass density; and 5. Hydrogen content as it relates to neutron shielding.

E. For the specified beam particles and energies, two principle radiations of concern for occupied areas are listed for each type of accelerator a through e: a. **Potential drop with protons/deuterons of 1-10 MeV**:1. neutrons and 2. bremsstrahlung from back-streaming electrons; b. **Electron linear with electrons 1-10 MeV**: 1. bremsstrahlung and 2. neutrons if

selected target used, e.g., Be at E > 1.62 MeV or high Z targets at E $\gtrsim$ 8 MeV; otherwise, direct or scattered electrons; c. **electron linear with electrons > 10 MeV**: 1. bremsstrahlung and 2. neutrons; d. **Cyclotron with protons/deuterons 10-50 MeV**: 1. neutrons and 2. gamma rays; and e. **Betatron with electrons 1-50 MeV**: 1. bremsstrahlung and 2. neutrons.

QUESTION 9

GIVEN: laser information including **limiting aperture** of **7 mm**, transmission and absorption graphs, and figure depicting anatomy of the eye.

SOLUTIONS AND ANSWERS(•) TO PARTS A THROUGH E:

A. For the specified four types of lasers, the anatomical structures that are most sensitive to damage include, for the following stated reasons: 1. **Far infrared, CO_2 (10.6 μm)**: **Cornea** because this wavelength is strongly absorbed by most organic molecules, including those in corneal tissue, which is located on the outer eye structure; 2. **Visible, gold vapor laser (0.628 μm)**: **Retina** because this wavelength is transmitted to the retina and largely absorbed in the pigmented retinal epithelium, thereby causing thermal effects and damage; 3. **UV-A, nitrogen laser (0.337 μm)**: **Lens** because this longer wavelength UV-A radiation can be absorbed in the lens producing photochemical effects leading to possible cataracts; 4. **UV-C, krypton fluoride excimer laser (0.248 μm)**: **Cornea** because this shorter wavelength UV-C radiation is strongly absorbed superficially in corneal tissues thereby producing effects such as conjunctivitis and possibly corneal clouding.

B. MPEs vary considerably between wavelengths of 0.647 μm(red) and 0.530 μm (green) because the retinal tissue is the major tissue at risk, and the first pathology occurs in the *pigmented retinal epithelium* (PRE). The damage to the retinal tissue varies with wavelength because: 1. the percentage of light transmitted to the retina and PRE varies with wavelength; 2. the energies of the photons, and the consequent thermal energy produced by absorption, vary inversely with wavelength; and 3. the efficiency of absorption of photons by melanin in the PRE varies somewhat with wavelength.

C. Skin effects associated with the following UV bands include: 1. **UV-A**: This band is reflected to a significant extent and unless the individual is unusually photosensitive, e.g., through the use of certain chemical sensitizers, significant adverse skin effects would not be expected. Skin tanning and short-duration erythema are possible minor effects. 2. **UV-B** and 3.**UV-C**: Both of these bands could be expected, at significant exposures, to produce erythema, skin tanning, premature skin aging, and possibly skin cancer at a future time. Melanoma seems to be most strongly associated with UV-B exposure.

D. The maximum allowable laser power output **P** in **mW** is calculated based on stated assumptions and pertinent given data:

MPE ≡ maximum permissible exposure = **0.01 J cm^{-2}**;
d ≡ beam diameter = 3.5 mm = **0.35 cm**; and

t ≡ maximum alignment time = **1.2 s**.

$$\frac{MPE}{t} = \frac{P}{\pi\ (0.5\ d)^2};\ so$$

- $P = \frac{MPE}{t}\ \pi\ (0.5\ d)^2 = \frac{0.01\ J\ cm^{-2}}{1.2\ s}\ \pi\ ((0.5)(0.35\ cm))^2 = 8.02x10^{-4}\ J\ s^{-1} = 0.802\ mW.$

E. The evaluation of whether or not the Q-switched laser equipment is appropriate to use in a show involving the scanning of the audience with a laser beam is made from the given pertinent data, calculated quantities, and assumed quantities:

P ≡ power, assumed in a single pulse = **40 W**;
W ≡ pulse width = 20 μs = **$2x10^{-5}$ s**;
F ≡ pulse frequency = 25 kHz = **$2.5x10^{4}$ s^{-1}**; so
$\bar{P}$ ≡ average power assumed to be delivered to an observer = P W F = **20 W**;
d_a ≡ beam diameter = 2 mm = **0.2 cm**;
r ≡ laser to audience distance = 25 m = **2,500 cm**;
ϕ ≡ beam divergence = 0.2 milliradians = **$2x10^{-4}$ radians**;
R ≡ assumed lateral scan rate of audience = **20,000 cm s^{-1}**;
d_p ≡ assumed maximum pupil diameter = 7 mm = **0.7 cm**; so
t ≡ maximum eye exposure time in scan of audience = d_p/R = **$3.50x10^{-5}$ s**; and
MPE ≡ maximum permissible exposure = **1.8 $t^{3/4}x10^{-3}$ J cm^{-2}**; so
MPE = **$8.19x10^{-7}$ J cm^{-2}**.

The energy Φ in **J** delivered to the eye of an observer is calculated from the product of the average delivered power **$\bar{P}$** of **20 W** and the maximum eye exposure time **t** of **$3.5\ x10^{-5}$ s**, which yields a value of **$7x10^{-4}$ J** for Φ. This value for Φ is used along with other given bolded quantities listed above and in the equation for the *nominal ocular hazard distance* (**NOHD**) given in the attached list of Useful Equations and Constants to evaluate the appropriateness of the laser:

- $$NOHD = \frac{1}{\phi}\left(\frac{1.27\ \Phi}{MPE} - d_a^2\right)^{1/2} = 1.65x10^5\ cm = 1{,}650\ m,$$

which greatly exceeds the listed distance **r** of **25 meter** from the laser. Therefore, this laser would not be appropriate for the proposed use.

QUESTION 10

GIVEN: air sampling data at a downwind location from a brush fire over land contaminated with plutonium:

F_a ≡ fraction of alpha particles not absorbed in filter = **0.4**;
R ≡ filter retention = **0.8**;
S_d ≡ detector active area = **60 cm^2**;
r_b ≡ background rate = **3 cpm**;
t_b ≡ background counting interval = **60 minutes**;
R_1 ≡ first gross sample counting rate = **50 cpm**;
t_g ≡ first sample counting interval = **10 minutes**;
R_2 ≡ second gross sample counting rate = **36 cpm**;
t_g ≡ second sample counting interval = **10 minutes**;
t ≡ time between start of first to start of second sample counting interval = **60 minutes**;
E ≡ alpha detection efficiency assumed uniform over S_d = **0.3 cpm/dpm**;
S_f ≡ active filter area with uniform activity distribution = **500 cm^2**;
B ≡ breathing rate = **1.2 m^3/h**;
$t_{1/2}$ ≡ effective half-life of Rn-222 progeny on filter = **30 minutes**;
<CEDE/I> ≡ ^{239}Pu CEDE per unit inhalation intake = **5x10^{-5} Sv/Bq**; and
LLD equation, which is in units of net counts and is expressed in terms of r_b, t_b, and t_g.

SOLUTIONS AND ANSWERS(•) TO PARTS A THROUGH E:

A. The ^{239}Pu airborne activity concentration **U** in **Bq m^{-3}** is calculated from the given data, stated assumptions, and a sample air volume **V** of **1 m^3**:

The initial counting rate **R_0** from radon progeny at the time of the first count of the filter is calculated:

$$R_0 = \frac{R_1 - R_2}{1 - e^{-\frac{\ln 2}{t_{1/2}} t}} = \frac{50\ cpm - 36\ cpm}{1 - 0.25} = 18.7\ cpm.$$

Thus, **U** is calculated from the first sample count and other given data:

• $$U = \frac{R_1 - r_b - R_0}{E\left(\frac{S_d}{S_f}\right) F_a\ R\ V} = 2{,}460\ dpm\ m^{-3} = 40.9\ Bq\ m^{-3}.$$

Comment: The simple correction for radon progeny in part A above is based on stated assumptions in the question. Such simple corrections may cause a gross error in calculated concentrations, and such inappropriate corrections should not be encouraged by the ABHP in their exams (See comments for part B below and for part A in question 13.).

B. The LLD in cpm is obtained from the given equation in units of net counts by dividing the given equation by the symbol t_g for the gross sample counting interval, which yields:

- $$LLD = 3.29\left(\frac{r_b}{t_g} + \frac{r_b}{t_b}\right)^{1/2} + \frac{3}{t_g} = 3.29\left(\frac{3}{10} + \frac{3}{60}\right)^{1/2} + \frac{3}{10} = 2.25\ cpm.$$

Comment: A given equation in any question or in the attached list of "Useful Equations and Constants" has very little meaning when symbols are not defined and the units for the algebraic quantities are not specified. The given equation for the "LLD" in this question is in units of net counts, but the units are not specified. This part B asks for the "LLD" in units of cpm. If the ABHP meant to confuse candidates, I believe that it has succeeded whether or not this confusion was intended or not. Obviously, the same symbol, "LLD", should not be used for two separate quantities, one in terms of net counts and the other in terms of net counting rate. The actual LLD also depends on interference from radon progeny, but this interference is not taken into account in the given equation. The above stated obtuseness should be considered by the ABHP panel in grading this part B of Question 10.

C. The *committed effective dose equivalent* (**CEDE)** is calculated from the given **<CEDE/I>** value of **$5x10^{-5}$ Sv Bq^{-1}** and for the given exposure to a concentration **U** of **20 Bq^{-3}** for a time interval **t** of **4 h** at a breathing rate **B** of **1.2 m^3 h^{-1}**:

- $$CEDE = U\ B\ t\left\langle\frac{CEDE}{I}\right\rangle = 4.80x10^{-3}\ Sv.$$

D. Five ways of improving the dose estimate for off-site individuals include: 1. determination of the particle size distribution and AMAD of collected ^{239}Pu aerosol particles on the filter; 2. correcting the calculated respiratory tract deposition for the actual AMAD; 3. correcting the <CEDE/I> factor for the actual AMAD; 4. determination of the inhalation compound classes for the ^{239}Pu aerosol particles and taking this information into consideration in calculating a revised <CEDE/I> factor; and 5. collecting and analyzing deposited plutonium aerosol particles at various downwind locations and relating this data and other data obtained in 1 through 4 above along with an estimate of the settling velocity of ^{239}Pu aerosols to the total exposures and calculated doses of individuals at these locations.

E. Five methods to reduce the potential long term dose to individuals from exposures in brush five events over contaminated land include: 1. limitation of the amount of brush over contaminated land through the use of defoliation agents; 2. establishment of fire breaks between contaminated land areas and other land areas with a significant amount of brush and fire potential; 3. decontamination of areas where the potential exists for resuspension of radioactive materials; 4. early warning of individuals in downwind locations to shelter themselves and close intake ventilation of homes if potential exposure and dose are not too high; and 5. early warning of individuals in downwind locations to evacuate area if potential exposures and corresponding doses would warrant such an evacuation.

Comment: I do not believe that contamination levels of sufficiently high specific activity exist in the United States that would have the potential of causing significant downwind airborne concentrations of concern despite the concerns expressed in the media about recent fires near Los Alamos. From this standpoint, the calculated airborne concentration is unrealistically high, especially when the dilution associated with the wind and large volumes of air needed to sustain a brush fire are considered.

QUESTION 11

GIVEN: radon flux measurements from soil and from concrete surface into a home along with other given data defined by symbols and units given in the question, except for the same symbols converted to different bolded units used in equations shown in the following solutions and in other expanded symbol definitions:

$\mathbf{F_{eq}}$ ≡ equilibrium factor ≡ $\mathbf{(C_{WL})(100\ pCi\ L^{-1}\ WL^{-1})/(U) = 0.4}$, where:
$\mathbf{C_{WL}}$ ≡ concentration of Rn-222 progeny in number of **WL**, and
U ≡ steady state radon concentration actually present, $\mathbf{pCi\ L^{-1}}$, and
$\mathbf{100\ pCi\ L^{-1}\ WL^{-1}}$ ≡ radon concentration needed to sustain 1 WL of progeny under secular equilibrium conditions, i.e., when there is no removal of radon or of each progeny from the air volume other than by radioactive decay therefore resulting in a steady state activity concentration of radon which equals that for each progeny.
$\mathbf{K_V} = 0.5\ h^{-1} = \mathbf{1.39x10^{-4}\ s^{-1}}$; and
λ ≡ decay constant for Rn-222 = $(\ln 2)/T_{1/2} = \mathbf{2.10x10^{-6}\ s^{-1}}$; so
k ≡ total removal rate constant for Rn-222 = $K_V + \lambda = \mathbf{1.41x10^{-4}\ s^{-1}}$.

SOLUTIONS AND ANSWERS(•) TO PARTS A THROUGH F:

A. The steady state indoor radon concentration **U** in $\mathbf{pCi\ L^{-1}}$ is calculated:

• $$U = \frac{J_i\ A}{k\ A\ H} = \frac{J_i}{k\ H} = 5{,}670\ pCi\ m^{-3} = 5.67\ pCi\ L^{-1}.$$

B. The annual exposure rate **E** in **WLM per year** for a radon concentration **U** of $\mathbf{14\ pCi\ L^{-1}}$ is calculated:

From the given value of **0.4** for $\mathbf{F_{eq}}$, the concentration $\mathbf{C_{WL}}$ of progeny is calculated:

$$C_{WL} = \frac{F_{eq}\ U}{100\ pCi\ L^{-1}\ WL^{-1}} = \frac{(0.4)(14\ pCi\ L^{-1})}{100\ pCi\ L^{-1}\ WL^{-1}} = 0.0560\ WL,$$

and so the exposure **E** is calculated for the given occupancy factor **F** of **0.7** and the definition of 170 h per occupational month:

• $$E = C_{WL}\left(\frac{8{,}760\ h\ y^{-1}}{170\ h\ M^{-1}}\right) F = 2.02\ WLM\ y^{-1}.$$

C. Four sources of uncertainty in the application of the results from epidemiological studies of underground miners to health effects in the general population include:

1. Miners were heavy smokers and their epidemiological data will most likely overestimate the risk to non-smoking occupants of a home especially if radon and smoke acted synergistically in causing the high incidence of lung cancers observed in miners.
2. Miners also may have been exposed to other carcinogens, e.g., diesel smoke and dusts including radioactive species such as uranium, thorium, and their progeny that are not present in a home but which might have been partially responsible for lung cancers observed in miners.
3. The unattached radon progeny cause most of the dose to the bronchial epithelium, and the fraction of progeny unattached to condensation nuclei and other aerosol particles in a mine differs from that in a home.
4. The breathing pattern of miners differs from that of occupants of homes.

D. Four sources of uncertainty in the dosimetric model for the respiratory tract as applied to risk estimates from radon exposures include:

1. The fraction of radon progeny unattached to condensation nuclei and other aerosol particles can greatly alter the deposition and dose to the critical bronchial epithelium tissue.
2. The thickness of the mucous sheet can greatly influence the dose to the underlying critical basal cells and this thickness may vary with smokers and non-smokers and the degree of any respiratory disease.
3. The deposition of radon progeny in various regions of the respiratory tract can vary with the breathing pattern, e.g., nose versus mouth breathing, and this deposition can vary in individuals from values assumed in the dosimetric model.
4. The rate of clearance of deposited radon progeny aerosols from various regions of the respiratory tract may vary considerably from individual to individual and from the default values used in the dosimetric model.

E. Four methods to reduce radon entry into a home or building include: 1. seal cracks in foundation; 2. ventilate crawl spaces with outdoor air; 3. maintain a positive pressure in the basement relative to that of soil gas, e.g., by using outdoor air for combustion of fuel in the furnace and/or pressuring basement with a fan; 4. strip high levels of radon from well water or absorb radon on charcoal filters before well water is used in a house.

F. The answer for the factor reduction of radon in water in pCi L^{-1} to radon in air in pCi L^{-1} is D. 10,000 to 1 reduction.

SOLUTIONS AND ANSWERS TO 2000 ABHP EXAM

QUESTION 12

GIVEN: patient administered ^{131}I for Graves' disease and pertinent data:

F ≡ fractional uptake by patient's thyroid = **0.60**;
T_e ≡ effective half-life in patient, which I assume to include decay = **5 d**; so
k ≡ effective removal rate constant = $(\ln 2)/T_e$ = 0.139 d^{-1} = **1.60×10^{-6} s^{-1}**; and
S ≡ dose per unit cumulated activity = **1.57×10^{-3} mGy MBq^{-1} s^{-1}**.

SOLUTIONS AND ANSWERS(•) TO PARTS A THROUGH D:

A. The administered ^{131}I activity **A** in **MBq** needed for a dose **D** of 70 Gy or **70,000 mGy** is calculated:

- $$A = \frac{k\,D}{F\,S} = 119\ MBq.$$

B. The external dose **H** to the spouse is calculated for an administered activity **A** of **1480 MBq**, distance **d** of **1 meter**, exposure time **t** of **8 h** over a period of 24 h; and gamma constant Γ of **7.647×10^{-5} mSv h^{-1} MBq^{-1} m^2** when decay and biological elimination are neglected:

- $$H = \frac{A\,\Gamma}{d^2}\,t = 0.905\ mSv.$$

C. Given that the dose equivalent to the patient's spouse is 2.5 mSv or 0.25 rem if the patient is released immediately after administration, the licensee is in compliance with requirements of 10CFR35 which allows release if it is not likely that any individual coming in contact with the patient will receive a dose greater than 0.5 rem.

D. Four general precautionary measures that should be suggested to the patient for perhaps a month include: 1. not to nurse an infant until sufficient clearance of ^{131}I has taken place; 2. not to hold an infant or child for an extended period of time; 3. to maintain distance between self and other persons and to limit contact with persons; and 4. the tongue-in-cheek precaution of limiting sexual contact with others, especially nuclear power plant radiation workers, e.g. health physics technicians, who may be mistakenly thought to have had an occupational exposure to I-131 and/or who may contaminate samples used in the evaluation of their workplace.

QUESTION 13

GIVEN: use of CAM beginning at 0800 hours to monitor airborne beta emitting radionuclides at a power reactor facility and data relating to an airborne release:

F ≡ monitor flow rate = 1 ft^3 min^{-1} = **$2.83x10^4$ cm^3 min^{-1}**;
R ≡ filter retention = **0.9**;
E ≡ counting efficiency = **0.3 c d^{-1}**;
R_b ≡ background rate excluding collected radon progeny on filter = **70 c min^{-1}**;
$T_{1/2}$ ≡ effective half-life of radon progeny = **30 minutes**; so
λ ≡ effective decay constant for radon progeny = $(\ln 2)/T_{1/2}$ = 0.0231 min^{-1}; and
Table of **ALIs** in **μCi** and **DACs** in **μCi cm^{-3}** for Co-60, I-131, and Cs-137.

SOLUTIONS AND ANSWERS(•) TO PARTS A THROUGH E:

A. A radon progeny "beta concentration" **U_1** of **$3x10^{-10}$ μCi cm^{-3}** is present with an "effective half-life of 27 minutes". At 0900 hours or for a sampling interval **t_1** of **60 minutes**, the gross counting rate **R_g** that should be observed on the monitor is calculated:

Comment and assumptions: It is not clear what is meant by the given phrase, "...beta concentration of $3x10^{-10}$ μCi cm^{-3} with an effective half-life of approximately 27 minutes." How does the "concentration" have an effective half-life? I assume that the stated effective half-life refers to the activity of radon progeny on the filter sample and not that associated with the airborne concentration of progeny. The beta activities of the radon progeny, 27 minute half-life Pb-214 and its daughter 20 minute half-life Bi-214, would not exist on the filter under transient equilibrium conditions at any significant activity level; so a 27 minute effective half-life is not likely. The apparent or "effective half-life" would vary with the sampling time, the relative airborne concentrations of radon progeny, and the time after the end of sampling. The effective half-life after the end of sampling would vary from a value of about 45 minutes at 20 minutes after the end of sampling to a value corresponding to the transient equilibrium value of 27 minutes at about 600 minutes after the end of sampling. An approximate "effective half-life" of about 35 minutes might be observed at 60 minutes after the end of sampling. The radon progeny effective half-life stated in this part of the question differs from that given above; so the radon progeny effective decay constant is calculated now: λ = (ln 2)/(27 min) = **0.0257 min^{-1}**, which with other given data gives **R_g** if it assumed incorrectly that the given radon progeny concentration U_1 can be considered as representing a single radionuclide having the values specified for λ, R, F, and E above:

- $$R_g = R_b + (2.22x10^6\ dmin^{-1}\ \mu Ci^{-1})\ \frac{U_1\ R\ F\ E}{\lambda}\ (1 - e^{-\lambda t_1}) = (70 + 156)\ c\ min^{-1} = 226\ \ c\ min^{-1}.$$

B. From the observation of a net counting rate increase $\mathbf{R_s}$ of **40,000 c min^{-1}** over a sampling interval **t** of **10 minutes**, the airborne concentration **U** of beta emitters with half-lives much greater than 10 minutes is calculated on the assumption that no significant decay is associated with radionuclides causing R_s:

- $$U = \frac{R_s}{E\ R\ F\ t}\left(\frac{1\ \mu Ci}{2.22x10^6\ d\ \mathrm{min}^{-1}}\right) = 2.36x10^{-7}\ \mu Ci\ cm^{-3}.$$

C. Four advantages of a whole body count over urine bioassay for detecting suspect inhalation intakes of ^{137}Cs and ^{60}Co include: 1. Both radionuclides are easily detected by high intensity gamma rays associated with their decay. 2 Whole body counting provides a rapid evaluation of whether significant intakes took place, while urine bioassay generally requires a longer time for the collection of 24 hour samples and the separate chemical processing and counting of the samples. 3 Whole body counting provides a direct measurement of the body burden, which can be directly related to the internal dose rate while urine bioassay requires the use of an assumed biokinetic model for first the estimation of an intake from the urine data and then an estimate of the committed dose from an intake to committed dose conversion factor based upon the assumed biokinetic model. 4. Repetitive whole body counts provide a measure of the clearance rate and the cumulated activity, which can be directly related to the internal dose over the time of measurements while urine bioassay only indicates what has been excreted with the urine and not the activity remaining in the body nor the activity that also may have been excreted by other excretion pathways, e.g. by the fecal pathway.

D. For an air concentration **U** of **2x10^{-6} µCi cm^{-3}** comprised of **25% ^{60}Co** and **75% ^{137}Cs**, the **CEDE** for an exposure time **t** of **1 h** is calculated since both DACs are based upon the stochastic-effect-based limit of **5 rem** for an exposure of **2000 DAC-h**:

- $$CEDE = \left(\frac{0.25\ U}{DAC_{Co}} + \frac{0.75\ U}{DAC_{Cs}}\right) t\left(\frac{5\ rem}{2000\ DAC-h}\right) = 0.188\ rem.$$

E. The **CDE** to the thyroid and the **CEDE** for an intake of **2 ALI of ^{131}I** and an intake of **0.5 ALI of ^{137}Cs** are calculated for a thyroid stochastic risk weighting factor $\mathbf{w_T}$ of **0.03**:

- $$CDE = 2\ ALI\left(\frac{50\ rem}{ALI}\right) = 100\ rem,$$

and

- $$CEDE = 0.5\ ALI\left(\frac{5\ rem}{ALI}\right) + w_T\ CDE = 2.5\ rem + 3\ rem = 5.5\ rem.$$

QUESTION 14

GIVEN: A researcher reported a spill in a laboratory where ^{32}P, ^{35}S, and ^{14}C are used, and subsequent investigations indicate that wide spread contamination in a corridor with three outside entrances and 12 attached rooms had occurred from a spill 24 hours ago. Data for ^{35}S include values given and calculated:

$\mathbf{E_{max}}$ ≡ maximum beta energy = 167.4 keV = **0.1674 MeV**; so
ϵ ≡ average energy, which is assumed to be absorbed in body = $E_{max}/3$ = **0.0558 MeV**;
$\mathbf{T_b}$ ≡ biological half-life = 9.3 h = **0.388 day**; and
$\mathbf{T_r}$ ≡ physical half-life = **87.2 d**; so
λ_e ≡ effective rate constant for removal of ^{35}S from body = $(\ln 2)/T_b + (\ln 2)/T_r$ = **1.79 d^{-1}**.

SOLUTIONS AND ANSWERS(•) TO PARTS A THROUGH E:

A. Four actions to ensure the extent of the spill is determined and contaminated areas properly isolated include: 1. Except for members of a survey team, prevent personnel access to all potentially contaminated areas. 2. Monitor for contamination those persons who had access within the last 24 hours to potentially contaminated areas, especially their shoe bottoms, and remove contaminated clothing and shoes. 3. Interview all persons who had access to contaminated areas within the past 24 hours with respect to where they have been, and identify on and off-site locations that will require surveying. 4. Perform contamination surveys using wipes and portable instruments, e.g., thin window GM detector, to determine the extent of contamination and the need for decontamination.

B. Three items that should be taken to the scene to assess and control the spill include: 1. thin window pancake GM detector used in conjunction with rate meter having an audible output for monitoring individuals and surfaces for beta activity; 2. absorbent paper to cover and confine surface contamination, especially on floors; and 3. floor tape, yellow rope and stanchions, and signs to demarcate and prevent access to contaminated areas.

C. Given a worker's urine sample contains a concentration of 1500 dpm mL^{-1} and that it may be assumed this value "reflects the average ^{35}S concentration in the body" or a calculated mass concentration **C** of **$6.76x10^{-4}$ μCi g^{-1}** and that the intake by the worker took place at a time interval **t** 48 hours or **2 days** ago, the **CEDE** in rem is calculated from this data and other given bolded quantities listed in the given information above:

• $$CEDE = 51.1 \frac{C \epsilon}{\lambda_e} e^{\lambda_e t} = 3.86x10^{-3}\ rem = 3.86\ mrem.$$

Comment: The stated assumption in this part to the question shown in quotes above is a

gross oversimplification. The assumption would apply to HTO in body water, but even then the urine concentration should be corrected by the fraction of (42 kg/62 kg) or by 0.677 to obtain the concentration in soft tissue. For ^{35}S and other internal emitters that are retained in certain body compartments with much longer half-lives, the calculated residence time could be much longer than that implied by the given biological half-life of 9.3 h for ^{35}S in this question. The activity concentration of ^{35}S in the body would not be uniform. This instruction by the ABHP is not justified, and it may encourage candidates to perform such overly simplified internal dose calculations in their practice, thereby causing gross under estimates of internal radiation doses.

D. Radionuclides present in the spill could be determined as follows. The most direct way would be to ask the researcher what radionuclides he was working with when the spill occurred. If this is not effective, it is relatively easy to distinguish ^{35}S and ^{14}C together from ^{32}P by a two channel liquid scintillation counting system, where the lower energy beta particles from ^{35}S and ^{14}C produce pulses in the lower energy channel and the much higher energy beta particles from ^{32}P produce pulses mostly in the higher energy channel. If it is necessary to distinguish ^{35}S from ^{14}C, this differentiation can be made by placing some of the spilled contaminants in aqueous solution, converting sulphur to the sulphate ion, adding stable sulphate ions to the solution, precipitating the sulphate ion with excess barium ions, and filtering the precipitate. The filtrate will contain ^{14}C and ^{32}P if present. If liquid scintillation counting of the filtrate shows activity in the ^{14}C channel, but if such activity is less than what would be calculated by scintillation counting prior to the precipitation, it can be concluded that ^{35}S was also present along with ^{14}C in the spill. If no activity is found in the ^{14}C channel, then ^{14}C was not present in the spill.

E. The following four items are evaluated with respect to (a) violation of federal/agreement state regulations, (b) good work practices, or (c) not of concern:

1. personnel use radioactive materials before completing radiation safety training: **(a)** if not done under direct supervision of an authorized user as part of the training program and **(b)**.
2. a centrifuge contaminated to 1500 dpm/100 cm^2: **(b)** but may be **(c)** if users are aware of it and if the level of contamination is expected.
3. one millicurie of ^{14}C was used in un-posted rooms: **(b)**.