SOLUTIONS AND ANSWERS TO 1999 ABHP EXAM

QUESTION 1

GIVEN: decay schemes, β_1 and γ_1 energies, and gamma spectra for ^{95}Nb and ^{28}Al.

SOLUTIONS AND ANSWERS(•):

- A. Origin of features 1-3 for ^{95}Nb spectrum 1 and features 4-7 for ^{28}Al spectrum 2 are described respectively as follows where the term *photopeak* in the question has been replaced by the term *total absorption peak* abbreviated by the acronym TAP:

- 1. This feature is the TAP for γ_1 of 0.766 keV, which is incorrectly labeled in spectrum 1 as 788 (keV). Counts within the TAP occur when the full energy of γ_1 is deposited in the detector.
- 2. This feature is the Compton edge for γ_1, which corresponds to the maximum energy of the Compton scattered electron produced when γ_1 undergoes a 180° backscatter in the detector and the backscattered photon escapes from the detector.
- 3. This feature is the backscatter peak for γ_1, which results when γ_1 undergoes a 180°Compton backscatter interaction in the surrounding shield, for example, and the backscattered photon then deposits all of its energy in the detector.
- 4. This 1,268 keV peak is the single escape peak for γ_1 of 1,779 keV, which results when γ_1 undergoes a pair production interaction in the detector, the positron after losing all of its kinetic energy in the detector undergoes annihilation with an electron, and then one 511 keV annihilation photon escapes from the detector while the other deposits all of its 511 keV energy in the detector along with the 757 keV total initial kinetic energy of the positron/negatron pair.
- 5. This 757 keV peak is the double escape peak for γ_1 of 1,779 keV similar to that described in 4 except both 511 keV annihilation photons escape from the detector.
- 6. This 511 keV peak is the TAP of the annihilation photon, which results when γ_1 undergoes a pair production interaction in the surrounding shield, for example, and one of the resulting 511 keV annihilation photon then deposits all of its energy in the detector.
- 7. This is the pulse height distribution from bremsstrahlung photons resulting from radiative energy losses by β_1 in the source holder or 345 mg/cm^2 Be absorber.

- B. If the HPGe detector were to be increased in size, then the height of the TAP relative to the height of the Compton edge would increase because in the larger detector more full energy deposition events would occur, e.g., more Compton scattered photons produced in the larger detector would have a higher probability of interacting by the photoelectric process instead of escaping from the detector. The original Compton electron’s kinetic energy and the Compton photon’s energy then sum to the original photon’s energy thereby leading to a pulse and count in the TAP.

- C. The FWHM is the full width of the TAP at half the maximum peak height. The FWHM in energy units for a HPGe detector is smaller than that of a NaI(Tl) detector/PMT because of the better resolution of the HPGe detector, which, for the same energy deposition, is a result of the larger number of electron-hole pairs in the HPGe detector compared to the number of electrons released from the photocathode surface of the PMT used with the NaI(Tl) detector.

- D. Escape peaks are generally more prominent in HPGe detectors than in NaI(Tl) detectors because typical HPGe detectors have lower intrinsic photon detection efficiencies than typical NaI(Tl) detectors for primary as well as secondary photons. For example, secondary X-ray photons following photoelectric interactions and secondary annihilation photons following pair production interactions of primary photons in either detector may escape from the detector.

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QUESTION 2

GIVEN: whole body counts of a worker at various times $\mathbf{t_i}$ in **days**, body activity $\mathbf{q(t_i)}$ in **µCi**, and $\mathbf{IRF(t_i)}$ values for class W and class Y inhalation intakes of 1 µm AMAD aerosols of ^{60}Co:

S-ALI$_W$ ≡ class W stochastic effect-based ALI = **200 µCi**; and
S-ALI$_Y$ ≡ class Y stochastic effect-based ALI = 30 µCi.

SOLUTIONS AND ANSWERS(•):

• A. An intake is the total activity taken into the body. For an inhalation intake it includes the total activity inhaled, part of which is exhaled. An uptake is the activity entering the systemic circulation.

• B. The activity ratio, **q(200 days)/q(0.1 day)**, of 0.**0372** compares to a class W inhalation IRF ratio, $\mathbf{IRF_W(200days)/IRF_W(0.1\ day)}$, of **0.0378** and to a class Y inhalation IRF ratio, $\mathbf{IRF_Y(200days)/IRF_Y(0.1\ day)}$, of **0.184**. Therefore, the whole body counting data are more consistent with a class W inhalation intake.

C. For an assumed inhalation intake of class W, 1 µm AMAD aerosols:

1. the worker's intake I is estimated based on the assumption that the variance associated with measurement i is proportional to its predicted measurement, (I)(IRF$_W$(t$_i$)):

•
$$\boldsymbol{I} = \frac{\sum_{i=1}^{i=9} q(t_i)}{\sum_{i=1}^{i=9} IRF_W(t_i)} = \frac{313.3\ \mu Ci}{2.313} = \mathbf{135\ \mu \boldsymbol{Ci}},\ and$$

Comment: An alternative equation for the intake, I = [Σ q(t$_i$)/IRF$_W$(t$_i$)]/n, also gives 135 µCi for I. This equation for I is based upon the average slope of the plot of q(t$_i$) versus IRF$_W$(t$_i$) for the n = 9 measurements; therefore, it is often called the "slopes" method for obtaining the estimated intake. The slopes intake equation inherently assumes that the variance associated with a measurement i is proportional to the predicted measurement squared, or by the expression k [(I)(IRF$_W$(t$_i$)]^2, where the proportionality constant k is set equal to the value of the reduced Chi-square statistic obtained when the proportionality constant is set equal to the expected value of unity for the reduced Chi-square statistic. The intake estimate obtained by the slopes equation puts undue weight on the later measurements, but when the actual measurements are close to their predicted measurements, either intake equation gives approximately the same intake estimate.

2. the worker's *committed effective dose equivalent* (CEDE) is estimated:

- $$\boldsymbol{CEDE} = I\left(\frac{5\ rem}{S\text{-}ALI_W}\right) = 135\ \mu Ci\left(\frac{5\ rem}{200\ \mu Ci}\right) = \mathbf{3.38}\ \boldsymbol{rem}.$$

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QUESTION 3

GIVEN: to aid in the diagnosis, a physician wants to give a ten week pregnant woman experiencing extreme chronic hip pain an x-ray that is expected to result in a dose of about 2 rem to her abdominal area.

SOLUTIONS AND ANSWERS(•):

A. Reasons for and against use of x-ray by physician trying to weigh risk versus benefit of x-ray procedure include:

• 1. Two reasons that support decision to conduct the x-ray exam include: (a) radiation induced malformations to the fetus are not likely after 10 weeks of pregnancy, and (b) risks from cancer in later life are minimal for a dose of 2 rem in the abdominal area.

• 2. Two reasons that support decision not to conduct x-ray exam include: (a) other diagnostic tests might provide the desired diagnostic information, and (b) the diagnostic information will not likely aid in the medical treatment of the woman for her pregnancy.

• B. I would recommend the x-ray because the risks to the fetus are minimal and the diagnostic information may be needed for the treatment of the woman and the ultimate safe delivery of her child.

C. Counsel given to patient regarding effects on the fetus include:

• 1. Three possible effects on the fetus at ten weeks of pregnancy include: (a) cancer in later life, (b) mental retardation, (c) congenital malformations. None of these effects would be expected at this dose level.

• 2. I would not recommend a therapeutic abortion because the risks to the fetus are minimal.

• D. The NCRP recommends limiting the dose to 500 mrem to the fetus of a pregnant radiation worker. This dose limit is not pertinent in this case. The NCRP recommends consideration of a therapeutic abortion if the dose level is high; the doses associated with diagnostic x-rays would rarely justify this consideration.

SOLUTIONS AND ANSWERS TO 1999 ABHP EXAM

QUESTION 4

GIVEN: a health physicist required to give information regarding the production of ^{24}Na:

$T_{1/2}$ = 14.96 h; so,
λ = $1.29\text{x}10^{-5}$ s^{-1};
E(γ_1) = **1.4 MeV** and **Y(γ_1) = 1.0**;
E(γ_2) = **2.8 MeV** and **Y(γ_2) = 1.0**;
σ_c = 0.534 b = **$5.34\text{x}10^{-25}$ cm^2 $atom^{-1}$;**
f ≡ grams of ^{23}Na per gram of Na = **0.2**;
μ_{en}/ρ = **0.03 cm^2 g^{-1}** for air;
μ/ρ = **0.046 cm^2 g^{-1}**, and ρ = **11.3 g cm^{-3}** for lead; so
μ = **0.520 cm^{-1}** for lead.

SOLUTIONS AND ANSWERS(•):

A. Thermal neutron flux ϕ in n cm^{-2} s^{-1} required to produce a saturation activity **A(∞)** of **$3.7\text{x}10^{10}$ Bq** of ^{24}Na in a sodium target having a mass **m** of **5 grams**:

$$N \equiv \text{number of } {}^{23}_{11}Na \text{ atoms} = \left(\frac{m\ f}{\frac{23\ g}{g-atom}} \right) \left(\frac{6.023x10^{23}\ atoms}{g-atom} \right) = \mathbf{2.62x10^{22}\ atoms}.$$

•
$$\phi = \frac{A(\infty)}{N\ \sigma_c} = \mathbf{2.64x10^{12}\ n\ cm^{-2}\ s^{-1}}.$$

B. The unshielded dose rate $\dot{D}$ in rad h^{-1} in air at the surface of a shipping container having a radius **r** of **30 cm** containing a point source having an activity **A** of **$3.7\text{x}10^{10}$ Bq** is calculated:

•
$$\dot{D} = \frac{A\ (E(\gamma_1)\ +\ E(\gamma_2))}{4\ \pi\ r^2} \frac{\mu_{en}}{\rho} \left(1.6x10^{-6}\ \frac{erg}{MeV} \right) \left(\frac{1\ g-rad}{100\ erg} \right) \left(\frac{3{,}600\ s}{h} \right) = \mathbf{23.7\ rad\ h^{-1}}$$

C. Given an unshielded dose equivalent rate $\dot{\mathbf{H}}\mathbf{(0)}$ of **35 rem h^{-1}** at the surface of a shipping container, an addition of a lead shield having a thickness **x** of **10 cm** will not be sufficient for a Radioactive II label, which requires the shielded surface dose rate $\dot{\mathbf{H}}\mathbf{(x)}$ not to exceed **0.05 rem h^{-1}** and the dose equivalent rate $\dot{\mathbf{H}}\mathbf{(x, 1\ m)}$ at 1 meter not to exceed **0.001 rem h^{-1}**. The actual shielded surface dose equivalent rate $\dot{\mathbf{H}}\mathbf{(x)}$ exceeds the **0.05 rem h^{-1}** limit even when buildup is neglected:

- $$\dot{\boldsymbol{H}}\boldsymbol{(x)} = \dot{H}(0)\ e^{-\mu x} = 35\ rem\ h^{-1}\ e^{-5.2} = \mathbf{0.193}\ \boldsymbol{rem\ h^{-1}},$$

where $\mu\mathbf{x}$ = (0.52 cm^{-1})(10 cm) = **5.2**.

Comment: The above solution assumes that the added shield is contained withing the original shipping container.

QUESTION 5

GIVEN: a worker is exposed while transporting a Sr-90 thermoelectric generator the size of a baseball:

$\dot{D}_\beta(0)$	≡	contact beta reading for 7 mg cm^{-2} window = 800 rad h^{-1};
$\mathbf{\dot{D}_\beta(r)}$	≡	beta reading at distance r of 18 inches for 7 mg cm^{-2} window = **200 rad h^{-1}**;
$\dot{X}(0)$	≡	contact gamma reading for 300 mg cm^{-2} window = 3 R h^{-1};
$\mathbf{\dot{X}(r)}$	≡	gamma reading at distance r of 18 inches for 300 mg cm^{-2} window = **2 R h^{-1}**;
t	≡	exposure time = 2 minutes = **(2/60) h**;
r	≡	exposure distance assumed for lens of eyes = 18 inches;
x_1	≡	thickness of plastic bag for contact readings = 15 mg cm^{-2};
x_2	≡	thickness of two gloves = 78 mg cm^{-2};
$\mathbf{x_3}$	≡	thickness of coveralls = **29 mg cm^{-2}**;
$\mathbf{x_4}$	≡	thickness of respirator facepiece assumed to cover eyes = **250 mg cm^{-2}**; and

beta reduction factor $\mathbf{f_b}$ given for absorber thickness **x** in mg cm^{-2}:

$$f_b = e^{-0.00435\,(x)}.$$

SOLUTIONS AND ANSWERS(•):

A. Disregarding attenuation by air, the total dose **D** to the lens of the eyes is calculated from the sum of the beta and bremsstrahlung components:

$$D = \left[\dot{D}_\beta(r)\, e^{-0.00435(250 + 300 - 7)} \left(\frac{1.13\ rad_{tissue}}{rad_{air}}\right) + \dot{X}(r)\left(\frac{0.98\ rad}{R}\right)\right] t;$$

• $$\boldsymbol{D} = [21.3\ rad\ h^{-1} + 1.96\ rad\ h^{-1}]\left(\frac{2}{60}\ h\right) = \mathbf{0.775}\ \boldsymbol{rad},$$

which assumes: (1) the given gamma exposure rate reading $\mathbf{\dot{X}(r)}$ of **2 R h^{-1}** is from bremsstrahlung photons only, and thus it already has been corrected for the beta response from the ^{90}Sr/^{90}Y beta particles; (2) a tissue absorbed dose of **0.98 rad per R** of bremsstrahlung photons; (3) a tissue depth of **300 mg cm^{-2}** for the lens of the eyes; (4) the given air beta dose rate reading $\mathbf{\dot{D}_\beta(r)}$ of **200 rad h^{-1}** for a window thickness of **7 mg cm^{-2}** has been corrected for the contribution from bremsstrahlung photons; (5) a tissue absorbed dose of **1.13 rad relative to an air absorbed dose of 1 rad**, which accounts for the greater mass stopping power of tissue relative to air; and (6) attenuation of bremsstrahlung photons in the 250 mg cm^{-2} facepiece can be neglected.

If the second term in the bracket in the above equation, which represents the contribution of bremsstrahlung photons, is neglected, then the dose to the lens of the eyes is calculated for the beta component only:

$$D = \left[\dot{D}_\beta(r)\, e^{-0.00435(250 + 300 - 7)} \left(\frac{1.13\ rad_{tissue}}{rad_{air}} \right) \right] t;$$

- $$\boldsymbol{D} = [21.3\ rad\ h^{-1}] \left(\frac{2}{60}\ h \right) = \mathbf{0.710}\ \boldsymbol{rad},$$

Comment: The given information does not make clear whether or not the total window thickness for the gamma reading is for a total instrument window thickness of 300 mg cm^{-2} for the end cap only or for a total thickness of 307 mg cm^{-2}, which corresponds to the sum of the 300 mg cm^{-2} "End cap" and the 7 mg cm^{-2} "End window"; I assumed a total window thickness of 300 mg cm^{-2} as stated for the gamma readings. The actual "gamma readings" of the instrument would be dominated by the beta response from $^{90}Sr/^{90}Y$ beta particles, which is calculated at 18 inches from (200 rad h^{-1})($e^{-0.00453\ (300\ -\ 7)}$) or as 55.9 rad h^{-1}. If the given gamma reading $\dot{X}(r)$ of 2 R h^{-1} for the instrument is interpreted to represent the response from both beta particles and bremsstrahlung photons under a total window thickness of 300 mg cm^{-2}, then it could be used to directly calculate the dose rate to the lens of the eyes, which is at a tissue depth of 300 mg cm^{-2}. The calculated total dose rate then would be the value for the second term of 1.96 rad h^{-1} in the square bracket in the first equation above except for the fact that the beta component then would not be corrected for the attenuation in the 250 mg cm^{-2} facepiece. This total value of 1.96 rad h^{-1}, however, is much less than the value of 55.9 rad h^{-1} calculated above for the beta component of the instrument response not accounting for attenuation in the facepiece. In other words, the given gamma reading, under this assumption that it represents the effective response from both beta and bremsstrahlung photons, is found to be a fictitious, extraneous, and incorrect value when compared to the beta dose rate of 55.9 rad h^{-1} calculated at a tissue depth of 300 mg cm^{-2} from the instrument beta reading of 200 rad h^{-1} for a window thickness of 7 mg cm^{-2}. A gamma instrument with a window thickness of only 300 mg cm^{-2}, in fact, cannot be used to obtain the exposure from bremsstrahlung photons only because the high energy beta particles emitted by $^{90}Sr/^{90}Y$ weight the response of the instrument. This question contains a very large amount of extraneous information that requires a candidate to spend an undue amount of time to read and evaluate for possible use in obtaining a solution. I believe the gamma readings were given as extraneous (and incorrect) information that was not intended to be used in the calculation of the eye dose from a pure beta emitting source. The second answer for **D** of **0.710 rad** shown above is obtained when only the beta dose is considered. Such incorrect information as the gamma readings should never be given in a question whether or not such information is intended to test the ability of a candidate to select only that given information necessary to obtain the school solution. This question and the given information is extremely confusing.

- B. Annual dose limits are: (1) 50 rem for the skin, (2) 15 rem for the lens of the eyes, (3) 5 rem for the whole body, and (4) 50 rem for an extremity.

- C. Skin dose is evaluated at a tissue depth of 0.007 cm (7 mg cm^{-2}).

- D. The deep dose equivalent is evaluated at a tissue depth of 1 cm (1,000 mg cm^{-2}).

- E. Four factors to consider when interpreting the response of a TLD with filters for skin and eye dose when worn on the chest under coveralls during this incident include: (1) a correction of the TLD skin dose response by the factor $e^{+0.00435\,(29)}$ to account for attenuation of beta particles in the coveralls assuming the TLD has been calibrated for dose to live skin, (2) a correction of the TLD eye dose response by the factor $e^{+0.00435\,(29\,-\,250)}$ to account for attenuation of beta particles in the coveralls and in the facepiece assuming the TLD has been calibrated for dose to the lens of the eyes, (3) a correction of the TLD skin dose response by the factor $(d_{TLD}/d_{skin})^2$ where d_{TLD} is the distance from the source to the TLD and d_{skin} is the smallest distance from the source to any point on unprotected skin, and (4) a correction of the TLD eye dose response by the factor $(d_{TLD}/d_{eye})^2$ where d_{TLD} is the distance from the source to the TLD and d_{eye} is the distance from the source to the lens of the eyes.

QUESTION 6

GIVEN: Radiation Safety Manager determines work controls for radiological work by pregnant staff workers, none of whom are minors:

$T_{\beta max}$ = 1.7 MeV for P-32;
$T_{\beta max}$ = 0.606 MeV, and Γ = 0.21 R-m^2/hr-Ci for I-131;
Given work control recommendations are defined in our answers by letters:
(a) ≡ prohibits work;
(b) ≡ allows work to continue with stated additional specific work controls; and
(c) ≡ allows work to continue without additional work controls.

• In the stated work descriptions for parts A through E of this question, recommendation (a), (b) with stated specific additional controls, or (c) will be selected and the technical basis will be given, including any assumptions in addition to those stated here. Because information regarding the costs for radiation protection is not given in this subjective question, radiation protection optimization and ALARA are not considered. Only the dose limits applicable to the exposure of the pregnant female or her fetus are considered in choosing (a), (b), or (c). These limits are given: (1) 5 rem to the whole body, 50 rem to any organ, the skin, or extremity, and 15 rem to the lens of the eyes of the pregnant worker in any control year of practice and (2) 0.5 rem for the fetus during the entire gestation period, with the additional recommendation to limit the monthly dose to 50 mrem. The *technical basis*, shown by the acronym TB, for selecting (a), (b), or (c) are based upon concerns for assuring that the dose limits for (1) or (2) are not exceeded from either internal or external exposure. The technical basis will be shown, for example:
TB = (1), internal for I-131. However, concerns for litigation regarding alleged health effects on the fetus are also considered in the answers below.

SOLUTIONS AND ANSWERS(•):

• A. Recommendation = (b) with addition of extremity and other personnel dosimetry to monitor extremity, skin, and eye dose of pregnant worker; required contamination control checks particularly after dilution operation; and monthly urinalysis. TB = (1), dose limits from combined external and internal exposures, which will prevent limit (2) for fetus being exceeded if limits in (1) for pregnant worker are adequately controlled.

• B. Recommendation = (c). TB: neither limits for (1) or (2) are likely to be exceeded. The highest monthly TLD reading of 0.230 rem in August is reduced by the lead apron to 0.0575 rem; so the fetus would not likely receive 0.05 rem even for this highest monthly reading. However, for concerns for potential litigation and possible concerns by the pregnant worker, it is recommended that a TLD be placed under the lead apron to more accurately monitor the entrance skin dose over the abdomen of the pregnant worker.

- C. Recommendation = (a). TB = (2), internal plus external.
- D. Recommendation = (a). TB = (2) external.
- E. Recommendation = (c). TB: doses are negligible compared to the limits in (1) for the pregnant worker and the limit (2) for the fetus provided the worker does not violate the interlocks and the specified operating procedures.

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QUESTION 7

GIVEN: five accident scenarios as stated in the question and designated by numbers (1) through (5) respectively in answers below.

SOLUTIONS AND ANSWERS(•):

A. Five actions listed by highest priority 1 through lowest priority 5 in response to a radiological accident involving personal injury are summarized:

• 1. Provide first aid needed for survival of injured person if radiation field and other environmental conditions permit it; otherwise, remove injured person first from any life threatening environment.

• 2. Call for needed emergency medical, fire, and other support personnel according to emergency plan. This should have almost as high a priority as 1, and if possible other people present in the area might initiate these calls at the same time 1 is initiated.

• 3. Monitor victim for contamination, and with the aid of emergency medical personnel wash wounds of any radioactive contamination and remove contaminated clothing from accident victim; save all washings and clothing for later detailed analyses of the activity of all radionuclides.

• 4. With the aid of emergency medical personnel, provide diuretics, blocking agents, or chelation agents to enhance excretion of radionuclides if the condition of the accident victim allows and if the magnitude of the estimated intake warrants such medical interventions.

• 5. Remove and evaluate dosimeters to estimate the victims dose for future medical guidance.

B. The preferred bioassay procedure for each specified accident 1 through 5 is given and justified:

• 1. Urinalysis for Pu-239 because of direct uptake into the blood from the wound and the lack of significant photons associated with the decay of Pu-239.

• 2. Urinalysis for H-3 because of direct uptake into the blood through the skin and the lack of significant photons associated with the decay of H-3.

• 3. Whole body count for high yield 0.662 MeV gamma photons following external decontamination because all inhaled Cs-137 is assumed to be in the relatively transportable compound class D and essentially all ingested Cs-137 is taken directly up into the blood and rapidly distributed throughout all soft tissue in the body.

• 4. Urinalysis for S-35 because of direct uptake into the blood from the small intestine and the lack of significant photons associated with the decay of S-35.

• 5. Thyroid counting of emitted gamma photons because all inhaled I-131 is assumed to be in the relatively transportable compound class D, and it is rapidly taken up into the blood and deposited in the thyroid gland.

C. Four medical intervention techniques that are used to minimize internal dose include:

- 1. Removal of contamination to prevent internal contamination by washing of skin and wounds and possibly excision of contaminated tissue to prevent uptake into the blood.
- 2. Enhance excretion of contaminated body fluids to reduce deposition of radionuclides in systemic tissues. An example is the use of diuretics, e.g., increasing the intake of water to enhance the excretion of tritiated water from the body.
- 3. Use of blocking agents in the form of stable isotopes that compete for deposition sites in systemic tissues with the radioactive contaminant, e.g. KI to increase the deposition of stable iodine in the thyroid thereby blocking the deposition of radioactive I-131 and enhancing its excretion in the urine.
- 4. Use of chemical agents that form compounds with the radioactive contaminant that are excreted from the body, including chelation agents, e.g. calcium or zinc DPTA which form a complex with Pu-239 in the blood before the Pu-239 has a chance to deposit in the liver or bone. The chelated Pu-239 is then rapidly eliminated from the body with the urine.

D. Regarding physician's recommendations:

- 1. I agree with the recommendation for chelation therapy following an inhalation intake of 5 ALI of Am-241 because all compound forms of americium are assumed to be in the intermediate transportable class W compound form, which is cleared from certain lung compartments with a half-life of 50 days or less to the blood. The committed bone dose of 250 rem thus can be lowered with very little risk from side effects of the chelation agent.
- 2. I agree with the lung lavage for 1 lung at a time following an inhalation intake of 10 ALI of mixed fission products provided the physician can state that the risk of the procedure is considerably less than the stochastic cancer mortality risk of about a 2.5% chance from a committed effective dose equivalent of 50 rem and provided the procedure is estimated to substantially reduce the radiation risk.

E. Specific medical interventions warranted by the estimated intakes of the radionuclides in each accident scenario 1 through 5 and any associated special concern and/or precaution are given respectively:

- 1. Washing of Pu-239 contaminated wound and excision of contaminated tissue: Concerns include disfigurement or enhanced uptake by using a poor procedure or technique, and precautions include monitoring of wound with a wound counter and the collection and radioactivity analysis of all washings and excised tissue to monitor the effectiveness of the procedure. Urine bioassay should be used to estimate the total uptake and internal radiation dose for future medical guidance.

- 2. Increased fluid intake and physical activity to enhance excretion of tritiated water: Concern includes not to have such a high fluid intake that it could cause a significant electrolyte imbalance, and precaution includes daily sampling and analysis of urine samples to monitor the effectiveness of the procedure and to more accurately determine the total effective dose equivalent for future medical guidance.

- 3. Blocking agent such as Prussian blue (ferric ferrocyanide or one of its modifications) to limit the uptake of Cs-137 from the small intestine where it would otherwise have a fractional absorption (f_1) of unity: Concern includes the toxic effect of the blocking agent and precaution includes limiting the amount of the agent to limit its toxic effect. Once the upper respiratory tract and the GI tract have been cleared of Cs-137, the agent should no longer be used. Whole body counts should be obtained to estimate the internal radiation dose for future medical guidance.
- 4. Induce vomiting: Concern includes the need for its early implementation to limit uptake into the blood from the small intestine and precaution includes the collection and analysis of the vomit and of urine samples to determine its effectiveness and to estimate the internal radiation dose for future medical guidance.
- 5. Use of blocking agent KI (See C, 3 above.): Concern includes the early administration of the agent for it to be effective and precaution includes limiting the amount of the agent to amounts not likely to cause a toxic effect. Thyroid and whole body counts should be obtained to estimate the thyroid and whole body doses for future medical guidance.

QUESTION 8

GIVEN: Professor using $Hg(CH_3)_2$ tagged with radioactive Hg-203 in an experiment:

C ≡ steady state $Hg(CH_3)_2$ airborne concentration = **0.005 mg m^{-3}**;
S_A ≡ specific activity of $Hg(CH_3)_2$ = **5 µCi mg^{-1}**;
DAC ≡ derived air concentration for Hg-203 = $7x10^{-5}$ µCi cm^{-3} = **70 µCi m^{-3}**;
PEL ≡ permissible exposure concentration limit for $Hg(CH_3)_2$ = **0.01 mg m^{-3}**;
A_{Hg} = **200.6 g per mole** of Hg;
A_C = **12 g per mole** of C;
A_H = **1 g per mole** of H;
$T_{1/2}$ = **47 day**; so
λ ≡ decay constant for Hg-203 = $(\ln 2)/T_{1/2}$ = 0.0147 day^{-1} = **$1.71x10^{-7}$ s^{-1}**.

SOLUTIONS AND ANSWERS(•):

A. The fraction **F** of Hg atoms that are tagged is calculated:

$$\boldsymbol{A_{Hg(CH_3)_2}} = A_{Hg} + 2(A_C + 3\ A_H) = 230.6\ g\ per\ mole = \mathbf{230{,}600}\ \boldsymbol{mg\ per\ mole\ of\ Hg(CH_3)_2}.$$

• $$\boldsymbol{F} \equiv \frac{N_{Hg-203}}{N_{Hg}} = \frac{\dfrac{S_A\ (37{,}000\ s^{-1}\ \mu Ci^{-1})}{\lambda}}{\dfrac{(6.023x10^{23}\ Hg\ atoms\ per\ mole\ of\ Hg(CH_3)_2)}{(230{,}600\ mg\ per\ mole\ of\ Hg(CH_3)_2)}} = \mathbf{4.14}\boldsymbol{X10^{-7}}.$$

B. The activity concentration **U** of Hg-203 corresponding to the PEL is calculated and compared to the DAC of 70 µCi m^{-3}:

• $$\boldsymbol{U} = (PEL)(S_A) = (0.01\ mg\ m^{-3})(5\,\mu Ci\ mg^{-1}) = \mathbf{0.05}\ \boldsymbol{\mu Ci\ m^{-3}},$$

which is only 0.0714% of the DAC of 70 µCi m^{-3}.

Comment: The above calculation assumes that the PEL, as given, refers to the mass of the compound per cubic meter rather than the mass of mercury in the compound per cubic meter.

C. The highest specific activity $\mathbf{S_{A\text{-}max}}$ of the tagged compound that can be used to assure compliance with the OSHA requirement, f(DAC) + f(PEL) $\leq$ 1, that the sum of the concentrations relative to their respective limits be less than or equal to unity is calculated:

$$\frac{C\ S_{A-\max}}{DAC} + \frac{C}{PEL} = 1;\ so$$

- $$\boldsymbol{S_{A-\max}} = \left(1 - \frac{C}{PEL}\right)\left(\frac{DAC}{C}\right) = \left(1 - \frac{0.005}{0.01}\right)\left(\frac{70\ \mu Ci\ m^{-3}}{0.005\ mg\ m^{-3}}\right) = \mathbf{7{,}000}\ \boldsymbol{uCi\ mg^{-1}}.$$

QUESTION 9

GIVEN: demineralizer in a PWR *reactor coolant system* (RCS) contains only ^{60}Co after a continuous operating period and stated assumptions in the question:

t ≡ operating period = 200 days = **288,000 minutes**;
r ≡ radius of demineralizer = **2 feet** = **0.610 meters**;
F ≡ flow rate of RCS through demineralizer = 480 lpm = **$4.8 x 10^5$ mL min^{-1}**;
E ≡ efficiency of demineralizer = **1**;
U ≡ concentration of ^{60}Co in RCS = **$8 x 10^{-5}$ μCi mL^{-1}**;
Γ = **1.3 R m^2 h^{-1} Ci^{-1}**;
λ ≡ decay constant = (ln 2)/(5.26)(365)(24)(60) = **$2.51 x 10^{-7}$ min^{-1}**;
gamma and beta energies and yields;
1 rad in air = 1 rad (or 1 rem) in tissue; and
lead attenuation coefficients and buildup factors for an "Isotropic Point Source."

> **Comment**: an exposure of 1 R equals 0.876 rad to air, which is about 0.98 rad or 1 rem to tissue. However, the stated assumption in the question requires the candidate to assume 1 R is equivalent to 0.876 rem to tissue. I believe it was intended for the candidate to assume that 1 R is equivalent to 1 rem, but the solutions below follow the stated assumption in the question where 1 R is then assumed to equal 0.876 rem.

SOLUTIONS AND ANSWERS(•):

A. The gamma dose equivalent rate $\dot{\mathbf{H}}$ at a distance d of **1 foot** above the centerline of the surface immediately after the 200 day operating period is calculated based on stated assumptions:

The total activity **A(t)** assumed to be spread uniformly over the top surface is calculated:

$$\boldsymbol{A(t)} = \frac{U\ F\ E}{\lambda}\left(1 - e^{-\lambda t}\right) = 1.07 x 10^{7}\ \mu Ci = \mathbf{10.7\ \boldsymbol{Ci}}.$$

The activity per unit area, $\mathbf{C_a}$, is calculated:

$$\boldsymbol{C_a} = \frac{A(t)}{\pi\ r^2} = \frac{10.7\ Ci}{\pi\ (0.610\ m^2)} = \mathbf{9.15\ \boldsymbol{Ci\ m^{-2}}}.$$

The dose equivalent rate $\dot{\mathbf{H}}$ at a distance **d** of **1 foot** above the center of a disk source having a radius **r** of **2 feet** and activity per unit area $\mathbf{C}_a$ of **10.7 Ci m^{-2}** is obtained from the disk source equation for the exposure rate $\dot{\mathbf{X}}$**(d)** given in the list of "Useful Equations and Constants":

- $$\dot{H} = \dot{X}(d)\left(\frac{0.876\ rem}{R}\right) = \pi\ \Gamma\ C_a\ \ln\left(\frac{r^2 + d^2}{d^2}\right)\left(\frac{0.876\ rem}{R}\right) = \mathbf{52.7\ rem\ h^{-1}}.$$

B. The dose equivalent **H** of the worker is calculated to determine whether the lead shielding on top of the demineralizer is sufficient to prevent a dose greater than worker's remaining annual administrative limit given the stated assumptions, other assumptions stated here, and given information:

$\mathbf{H_L}$	≡	remaining allowed dose equivalent = **0.3 rem**;
A(0)	≡	initial ^{60}Co activity = **60 Ci**;
T	≡	elapsed time = **0.5 years**; so
A(T)	≡	A(0) exp(-(0.5)(ln 2)/(5.26)) = **56.2 Ci**; and so
$\mathbf{C_a}$	≡	A(T)/π r^2 = **48.1 Ci m^{-2}**;
$\mathbf{t_W}$	≡	worker's exposure time = **0.5 h**;
x	≡	lead shield thickness = 2 inches = **5.08 cm**;
r	≡	radius of disk source = **2 feet** = **0.610 meters**; and
d	≡	distance above center of disk source = **9 feet = 2.74 meters**.

- Other assumptions: At a distance **d** of **9 feet** from a disk source having a radius **r** of **2 feet**, much of the scattered radiation in the shield will not reach the dose point of the worker. Because buildup data are given, however, I will assume buildup is effective. Even though the buildup data are for a point isotropic source, I will use the buildup data for a disk source because the distance d is 4.5 times the radius r of the disk, which could be approximated as point source. To simplify the calculation, I assume that all primary photons traverse a fixed shield thickness of 2 inches. This is reasonable because the longest path for the stated geometry is 2.05 inches. Therefore, the transmission **T(μx)** through the shield can be approximated:

$$\boldsymbol{T(\mu x)} = B(\mu x)\ e^{-\mu x} = 2.11\ e^{-3.30} = \mathbf{0.0778},$$

where by interpolation between values in the given tables for the average photon energy of 1.25 MeV: **μx** = (0.65 cm^{-1})(5.08 cm) = **3.30**, and the buildup factor **B(μx)** = **2.11**. The shielded dose equivalent **H** is then calculated:

- $$\boldsymbol{H} = \dot{X}(d)\left(\frac{0.876\ rem}{R}\right) T(\mu x)\ t_W = \pi\ \Gamma\ C_a\ \ln\left(\frac{r^2 + d^2}{d^2}\right)\left(\frac{0.876\ rem}{R}\right) T(\mu x)\, t_W = \mathbf{0.323}\ \boldsymbol{rem},$$

which exceeds the worker's limit $\mathbf{H_L}$ of **0.3 rem**.

For the assumption that the disk source can be approximated by a point source, the dose equivalent **H** is calculated:

- $$\boldsymbol{H} = \dot{X}(d)\left(\frac{0.876\ rem}{R}\right) T(\mu x)\ t_W = \left(\frac{A(T)\ \Gamma}{d^2}\right)\left(\frac{0.876\ rem}{R}\right) T(\mu x)\, t_W = \mathbf{0.332}\ \boldsymbol{rem},$$

which is only 3% larger than the value calculated from the disk source equation and which also exceeds the worker's limit $\mathbf{H_L}$ of **0.3 rem**.

QUESTION 10

GIVEN: a CW neon gas laser in the center of a 20 meter square room with the beam directed towards a diffuse reflector at the center of one wall:

ρ_λ ≡ reflectivity = **0.9**;
Φ ≡ power = 20 W = **20,000 mW** ;
$\mathbf{d_{1/e}}$ ≡ beam diameter (where irradiance is 1/e of the central beam value) = 2 mm = **0.2 cm**; so by equation in the ABHP attached table of Useful Equations and Constants:
$\mathbf{d_{1/e^2}}$ ≡ $2^{1/2}\, d_{1/e}$ = **0.283 cm**, which yields a beam area corresponding to the average beam irradiance for a Gaussian beam profile rather than the central beam value;
ϕ ≡ beam divergence = **0.001 radians**;
λ ≡ wavelength = **540 nm**;
table of MPEs in energy fluence units.

SOLUTIONS AND ANSWERS(•):

A. Answers are matched to the following radiometric quantities:

- • 1. Radiant energy: c. J
- • 2. Radiant power: f. W
- • 3. Radiant intensity: a. W cm^{-2}
- • 4. Radiance: d. W sr^{-1} cm^{-2}
- • 5. Radiant exposure: e. J cm^{-2}

B. The following terms are defined and described in terms of their appropriateness:

- • 1. The *nominal hazard zone* (NHZ) is the area within which radiation levels from direct or scattered radiation exceed the *maximum permissible exposure* (MPE).
- • 2. The *nominal ocular hazard distance* (NOHD) is the distance measured along the beam axis from the laser to the human eye within which the exposure is expected to exceed the MPE.

• The specification of the NHZ is more appropriate than the NOHD for indoor laboratories because the laser is more likely to be used in a fixed area/location compared to outdoor use, and the presence of scatterers/reflectors is more likely to be constant, thus making it easier to define a fixed NHZ.

C. The NHZ for this laser laboratory is estimated by assuming the MPE applies to viewing of diffuse reflection from the wall target and assuming as stated in the question that the intrabeam MPE applies. The equation below for the NHZ distance is that in the ABHP attached table, "Useful Equations and Constants"(See comment below.).

I shall assume an exposure time **t** of **0.25 seconds**, which is the blink aversion time as recommended in ANSI Z136.1. The intrabeam MPE in the table provided in this question is given in energy fluence units while the equation for the NHZ distance in the attached table of Useful Equations and Constants uses the MPE in energy fluence rate units. The MPE in energy fluence rate units is obtained by dividing the given equation, 1.8 $t^{3/4}$ x10^{-3} J cm^{-2} for a wavelength λ of 540 nm, by the blink aversion time t, which gives the following expression, **1.8 $t^{-1/4}$ x 10^{-3} J cm^{-2} s^{-1}**, as the **MPE** in energy fluence rate units. Thus, the **MPE** is calculated as 2.55x10^{-3} J cm^{-2} s^{-1} or **2.55 mW cm^{-2}**. The NHZ is then calculated from this MPE using the attached NHZ equation and other given bolded data above:

- $$\boldsymbol{NHZ} = \left(\frac{\rho_\lambda \ \Phi \ \cos\theta_v}{\pi \ MPE} \right)^{\frac{1}{2}} = 47.4 \ cm = \mathbf{0.474} \ \boldsymbol{m},$$

where the angle of reflection θ_v is conservatively taken as **0 degrees**.

Comment: The stated assumption in this part to the question: "Assume the intrabeam MPE applies." is confusing when it was intended that the NHZ equation in the attached table for diffuse reflection be used instead of an appropriate equation for intrabeam viewing, which was not given in the ABHP attached table. Also confusing is the use of the same symbol MPE for energy fluence, which corresponds more directly to the exposure limit in the table provided in the question, and for energy fluence rate, which is used in the equation for the NHZ in the attached table and which corresponds more directly to an exposure rate limit.

D. The minimal **OD** of the protective eyewear to reduce the irradiance below the intrabeam **MPE** of **2.55 mW cm^{-2}** calculated in part C for a viewing time **t** of **0.25 s** is obtained for the beam diameter **d_{1/e^2}** of **0.283 cm** calculated in the given data above from the equation in the table, "Useful Equations and Constants", which was attached to the exam. The radiant intensity **I** is calculated for the beam diameter **d_{1/e^2}** of **0.283 cm**, which is less than a nominal pupil size of 0.7 cm:

$$\boldsymbol{I} = \frac{\Phi}{\pi \left(\frac{d_{1/e^2}}{2} \right)^2} = \frac{20{,}000 \ mW}{\pi \left(\frac{0.283 \ cm}{2} \right)^2} = \mathbf{3.18x10^5 \ mW \ cm^{-2}}, \ \textit{and}$$

- $$\boldsymbol{OD} = \log_{10}\left(\frac{I}{MPE} \right) = \log_{10}\left(\frac{3.18x10^5}{2.55} \right) = \mathbf{5.10}.$$

Comment: The question should have stated the location for intrabeam viewing or the beam diameter itself.

- E. The eyewear best to use in this laser lab for an OD of 5 is given as follows:

The laser emits at 540 nm. I would select Brand X with an OD of 5, which provides the required level of protection around this wavelength in the green part of spectrum. The human eye is very sensitive and dependent for vision at this wavelength. If the higher optical density (e.g. the OD of 7 for Brand Y) were to be used, then an increased reduction by a factor of 100 would result in transmission at this wavelength, thereby resulting in a marked reduction in visibility for the wearer. This situation would discourage its use and/or present other hazards from poor visibility.

F. Answers are matched to the following FDA laser classes:

- 1. Class I: b. not an ocular hazard.
- 2. Class II: c. 0.25 second exposure threshold.
- 3. Class III: d. momentary intrabeam viewing is hazardous.
- 4. Class IV: a. can damage skin or eye from diffuse reflection.

QUESTION 11

GIVEN: a cylinder of enriched UF_6 is punctured:

m ≡ net mass of UF_6 in cylinder = **$9.071x10^6$ g**;
F_{235} ≡ mass of ^{235}U relative to mass of U = **0.05**;
h ≡ stack height = **25 meter**;
V ≡ building air volume = 10^6 cubic feet = **28,300 m^3**;
F ≡ stack flow rate = 10^4 cfm = **4.72 m^3 s^{-1}**; so
K ≡ ventilation constant = F/V = **$1.67x10^{-4}$ s^{-1}**;
λ_{234} ≡ ^{234}U decay constant = (ln 2)/($3.154x10^7$ s y^{-1})$T_{1/2}$ ^{234}U = **$8.79x10^{-14}$ s^{-1}**;
λ_{235} ≡ ^{235}U decay constant = (ln 2)/($3.154x10^7$ s y^{-1})$T_{1/2}$ ^{235}U = **$3.10x10^{-17}$ s^{-1}**;
λ_{238} ≡ ^{238}U decay constant = (ln 2)/($3.154x10^7$ s y^{-1})$T_{1/2}$ ^{238}U = **$4.88x10^{-18}$ s^{-1}**;
F_{234} ≡ mass of ^{234}U relative to mass of U = (0.01)F_{235} = **0.0005**;
F_{238} ≡ mass of ^{238}U relative to mass of U = 1 - F_{234} - F_{235} = **0.9495**;
A_F ≡ atomic mass of fluorine = **19 amu**; and
Graphs of σ_y and σ_z in **meters**.

SOLUTIONS AND ANSWERS(•):

A. The specific activity S_A of the UF_6 is calculated:

The average atomic mass A_U of the U in UF_6 can be shown to essentially equal that for ^{238}U:

$$A_U = (234\ F_{234} + 235\ F_{235} + 238\ F_{238})\ amu = \mathbf{238\ amu}.$$

The molecular weight, **MW**, of UF_6 is therefore (238 + 6(19)) amu or **352 g $mole^{-1}$** and each mole of UF_6 contains Avogadro's number N_A of **$6.023x10^{23}$ atoms of U $mole^{-1}$**. The specific activity S_A of the UF_6 is calculated:

$$S_A = \frac{\left(N_A \frac{A_U}{MW}\right)\left(\frac{\lambda_{234}\ F_{234}}{234\ g\ mole^{-1}} + \frac{\lambda_{235}\ F_{235}}{235\ g\ mole^{-1}} + \frac{\lambda_{238}\ F_{238}}{238\ g\ mole^{-1}}\right)}{3.7x10^{10}\ Bq\ Ci^{-1}},\ or$$

$$S_A = \frac{2.07x10^{-6}\ Ci\ of\ U-234}{g_{UF_6}} + \frac{7.26x10^{-8}\ Ci\ of\ U-235}{g_{UF_6}} + \frac{2.14x10^{-7}\ Ci\ of\ U-238}{g_{UF_6}},\ or$$

- $$S_A = \frac{2.35x10^{-6}\ Ci\ of\ total\ U}{g_{UF_6}}.$$

B. The initial release rate **Q** for a UF_6 specific activity $\mathbf{S_A}$ of $\mathbf{10^{-5}}$ **Ci** $\mathbf{g^{-1}}$ and the stated assumptions is calculated:

- $$Q = m\ S_A\ K = (9.071x10^6\ g)(10^{-5}\ Ci\ g^{-1})(1.67x10^{-4}\ s^{-1}) = \mathbf{0.0151\ Ci\ s^{-1}}.$$

C. The ground level activity concentration $\mathbf{U_{Total}}$ on the plume centerline at a downwind distance of **500 meters** for a constant release rate **Q** of $\mathbf{3.32x10^{-4}}$ **Ci** $\mathbf{s^{-1}}$, wind speed **u** of **5 m** $\mathbf{s^{-1}}$, and **class D** stability conditions is calculated:

- $$U_{Total} = \frac{Q}{\pi\ u\ \sigma_y\ \sigma_z}\ e^{-\frac{1}{2}\left(\frac{h}{\sigma_z}\right)^2} = \mathbf{1.23x10^{-8}\ Ci\ m^{-3}},$$

where σ_y of **38 m** and σ_z of **19 m** were obtained from the given graphs at 500 meters for class D stability.

- D. Five control measures used to preclude accidental criticality include: 1. limit the mass of fissile material at any one location below the quantity necessary for criticality; 2. use of safe geometry vessels for storing liquid solutions, e.g., tall narrow cylinders; 3. maintain a sub-critical spacing and geometry, e.g. planar areas of stored fuel rods with sufficient separation to prevent criticality; 4. add neutron absorbing material to storage facilities, e.g. cadmium in fuel storage racks; and 5. limit the presence of neutron moderators, e.g. water, and reflectors, e.g., the human body.

- E. Three reasons why stack effluent monitoring shows the apparent UF_6 release to be lower than predicted include: 1. condensation of UF_6 and chemical reactions on surfaces including duct work and the stack itself; 2. the building ventilation is likely to be filtered; and 3. chemical reaction of UF_6 with constituents in the air and the formation of particles that settle to surfaces especially during the relatively long mean residence time of 1/K or 1.66 hours in the building.

SOLUTIONS AND ANSWERS TO 1999 ABHP EXAM

QUESTION 12

GIVEN: electron linear accelerator used to produce neutrons from a tantalum target from a beam of electrons having an energy **E** of **120 MeV** and power **P** of **50 kW**.

SOLUTIONS AND ANSWERS(•):

• A. Researchers and operators receive low levels of β/γ exposures from activated components and prompt neutron and gamma radiation leakage through shielding or direct radiation from the target only when the machine is operating. Maintenance workers, who normally would not be present during operation, only receive β/γ exposures from activated components while performing maintenance operations near the target and surrounding material.

• B. Based upon a requirement for 96 hours of operation, 8 hours for maintenance, and an assumed 24 hour per day schedule with no activities on Saturday and Sunday, I would recommend the following schedule. Operation would take place 24 hours per day Tuesday through Friday for a total operation time of 96 hours, which would allow a reasonable cool-down period for decay of short-lived activation products prior to maintenance work on Monday, thereby reducing the dose to maintenance workers.

• C. The photon energy threshold for neutron production in most materials by the reaction ${}^{A}X(\gamma, n){}^{A-1}X$ is about 8 MeV, which corresponds essentially to the binding energy of the "last" neutron in the formation of the nucleus of the atom X of mass number A. The threshold kinetic energy of the electron, which undergoes radiative energy losses producing bremsstrahlung photons with energies up to its kinetic energy, is the same as the photon energy threshold for the reaction. Neutron yields and energies increase significantly at higher electron/photon energies, which puts greater demands on neutron shielding.

• D. Knowing the neutron spectrum in areas occupied by personnel is important in estimating neutron dose. If instrumental measurements are made of the neutron spectrum, proper fluence to dose conversion factors can be evaluated. In addition, the type and magnitude of the responses of neutron personnel dosimeters depend strongly on the neutron energy, e.g., calculation of the expected neutron albedo dosimeter response per unit of total neutron fluence requires knowledge of the neutron spectrum.

• E Three different ways for measuring the neutron spectrum include:

1. **Bonner spheres**-use of multiple polyethylene spheres of differing diameters with centered ${}^{6}LiF(Eu)$ scintillation detectors, which respond primarily to thermal neutrons: Measured counting rates differ for the varying sized spheres because of the varying moderation of the

incident neutron's energy. Measured counting rates from the spheres along with a known energy-efficiency matrix can be used to obtain the overall shape of the energy spectrum through an iterative process with a computer.

2. **^{3}He neutron spectrometer**: By evaluating the pulse height distribution from the proton and triton produced in the $^{3}He(n,p)^{3}H$ exothermic reaction (Q = 0.764 MeV), it is possible to unfold the neutron energy distribution. When neutrons above about 2 MeV are present, the confounding influence of the pulses from ^{3}He recoils produced though elastic scattering reactions with neutrons may have to be dealt with through pulse shape discrimination.
3. **Threshold activation foils**-irradiation of various target nuclides that exhibit energy thresholds for the production of a radioactive product, e.g., $^{32}S(n,p)^{32}P$, which has a neutron threshold energy of about 3 MeV: By selecting a variety of different target nuclides in foils with different neutron energy thresholds and known effective cross sections and by measuring the amount of radioactive products formed, one can infer, usually from a computer program, the shape of the neutron energy distribution.

F. Two types of routine personnel dosimeters useful for accelerator produced neutrons include:

- 1. Track etch detectors such as polycarbonate plastic (CR-39): Recoil nuclei from fast neutron interactions produce damage tracks that become visible after development of the thin plastic film in strong caustic solution. They are used as fast neutron detectors and are most useful above an energy of about 500 keV.
- 2. Thermoluminescent albedo dosimeters such as paired ^{6}LiF and ^{7}LiF elements shielded against direct thermal neutrons with cadmium: The body is used to thermalize fast neutrons and reflect them back to the dosimeters. The ^{6}LiF element is sensitive to thermal neutrons and gamma rays, and the ^{7}LiF element is sensitive to only gamma rays. The net reading obtained from the difference of the ^{6}LiF and ^{7}LiF responses is a measure of the neutron dose. The devices are very energy dependent, and knowledge of the neutron spectrum is necessary in the determination of the appropriate calibration factor.

G. One radioactive and one non-radioactive contaminant produced in the air around the target area are described:

- 1. The 9.97 minute half-life radioactive product ^{13}N is produce by the reaction $^{14}N(\gamma, n)^{13}N$.
- 2. The non-radioactive product ozone (O_3) results from reactions of oxygen following ionization of the air by electrons or photons.

QUESTION 13

GIVEN: patient administered I-131 for a thyroid ablation is incontinent for urine and will be on a catheter with a urine collection bag:

A ≡ quantity of I-131 administered = 7,400 MBq = 200 mCi = 200,000 μCi;
F ≡ fraction of A removed from body in first 24 hours due to biological elimination and radioactive decay = 0.5;
λ ≡ decay constant = (ln2)/(8.04 day) = 8.62×10^{-2} day^{-1} = **3.59×10^{-3} h^{-1}**;
K ≡ biological removal rate constant = (ln2)/(138 day) = 5.02×10^{-3} day^{-1} = **2.09×10^{-4} h^{-1}**;
k ≡ total removal rate constant = λ + K = **3.80×10^{-3} h^{-1}**;
m ≡ mass of thyroid = 20 g;
Γ ≡ I-131 gamma constant = **2.2 R cm^2 h^{-1} mCi^{-1}**;
V ≡ volume of urine at 24 hour mark = 1 liter; and
a "Pancake" GM and thin window NaI(Tl) probe.

Comment: Other miscellaneous information, most of which is not used in the solution, is given including an **incorrect** value of 1.4×10^7 photons/s-cm^2 for the fluence rate of 364 keV photons corresponding to an exposure rate of 1 R h^{-1}. The actual value for 1 R h^{-1} is about 1.5×10^6 photons/s-cm^2.

SOLUTIONS AND ANSWERS(•):

A. The activity $\mathbf{A_u}$ of I-131 in the urine from an exposure rate $\dot{\mathbf{X}}$ of **0.047 R h^{-1}** at a distance **d** of **30.48 cm** is calculated:

• $$A_u = \frac{\dot{X}\, d^2}{\Gamma} = \frac{(0.047\ R\ h^{-1})(30.48\ cm)^2}{(2.2\ R\ cm^2\ h^{-1}\ mCi^{-1})} = \mathbf{19.8\ mCi}.$$

B. The pro and con for use of either instrument in performing a field screening of the nurse's thyroid to determine if the nurse had an uptake of I-131 are summarized:

• 1. GM: con: low efficiency for gamma rays emitted from thyroid and pro: high efficiency for detecting beta radiation emitted from contamination on the skin. Meausrements with and without an absorber sufficiently thick to stop the beta particles can be used to distinguish contamination on the skin from I-131 in the thyroid.

• 2. Thin window NaI(Tl): con: depending on thickness of window, it might not be able to detect the beta radiation from skin contamination and pro: high efficiency for detecting gamma rays emitted from the thyroid.

• 3. I would use the GM detector with and without absorber material for determining if significant skin contamination is present, and I would use the NaI(Tl) probe to estimate the activity of I-131 present in the thyroid.

C. The activity **A** in the nurse's thyroid at the time of the count is calculated:

$\mathbf{T_{s+b}}$ ≡ thyroid counting interval = **600 s**;
$\mathbf{C_{s+b}}$ ≡ gross count in 0.364 MeV peak = **1,800 counts**; so
$\mathbf{R_{s+b}}$ ≡ $(C_{s+b})/(T_{s+b})$ = $\mathbf{3.00\ s^{-1}}$
$\mathbf{E_\gamma}$ ≡ photon detection efficiency = $\mathbf{0.001\ c\ \gamma^{-1}}$;
$\mathbf{Y_\gamma}$ ≡ yield of photon = $\mathbf{0.82\ \gamma\ decay^{-1}}$; and
$\mathbf{R_b}$ ≡ background rate in photon's ROI = 80 cpm = $\mathbf{1.33\ s^{-1}}$.

• $$\boldsymbol{A} = \frac{R_{s+b} - R_b}{E_\gamma\ Y_\gamma\ (37\ Bq\ nCi^{-1})} = \mathbf{55.0}\ \boldsymbol{nCi}.$$

D. The doses following an activity deposition $\mathbf{A_d}$ of **100 μCi** in the thyroid of a janitor are calculated for a thyroid dose per unit cumulated activity or **S** factor of **0.022 rad per μCi-h**:

1. The *committed dose equivalent* (**CDE**) to the thyroid is calculated:

• $$\boldsymbol{CDE} = \left(\frac{A_d}{k}\right) S = \left(\frac{100\ \mu Ci}{0.00380\ h^{-1}}\right)\left(0.022\frac{rad}{\mu Ci - h}\right) = 579\ rad = \mathbf{579}\ \boldsymbol{rem}.$$

2. The *committed effective dose equivalent* (**CEDE**) to the whole body is calculated:

• $$\boldsymbol{CEDE} = w_T\ CDE = (0.03)(579\ rem) = \mathbf{17.4}\ \boldsymbol{rem},$$

where the thyroid is the only significantly irradiated tissue whose weighting factor $\mathbf{w_T}$ of **0.03** is used to convert the thyroid CDE to the CEDE for the whole body.

• 3. Intervention is not advisable because as stated in the problem the deposition of 100 μCi in the thyroid has already occurred, and the blocking agent KI would no longer be effective. In addition, a CEDE of 17.4 rem has a cancer mortality risk of less than 1%, and thyroid cancer is readily treated by ablation therapy.

- E. A simple ratio of the I-131 activity A(t) detected within the thyroid to the non-stochastic inhalation ALI will not provide a reasonable accurate estimate of the CEDE for the following reasons. To use the ALI, the activity A(t) at some time t after the intake first must be converted to an estimated intake I calculated by dividing the activity A(t) by the applicable thyroid *intake retention fraction* (IRF) estimated for class D, 1 μm AMAD aerosols for an acute intake from $(0.63)(0.3)e^{-kt}$, where 0.63 is the fraction of an inhalation intake that deposits in the respiratory tract and is rapidly absorbed into the blood, 0.3 is the fraction of the uptake in the blood that is deposited in the thyroid, k is the effective removal rate constant for I-131 in the thyroid, and t is the time since the acute intake. For organic vapor forms of I-131, the fraction of the intake deposited in the respiratory tract is unity; therefore, the IRF value is estimated from $(0.3)e^{-kt}$, and the ingestion ALI then should be used to estimate the CDE. The CDE in either case can be estimated from the expression, (A(t)/IRF)(50 rem/ALI), and the CEDE then can be estimated from the product of w_T CDE.

  Comment: The ALI given in this question is incorrectly stated as 50 mCi; the actual value for the ALI is 50 μCi.

QUESTION 14

GIVEN: questions pertaining to environmental monitoring principles:

1 gallon = **3.785 liters**; and the **correct** equation from HPS N13.30-1996:

$$MDA = \frac{4.65\ s_b}{K} + \frac{3}{K\ T},$$

where:

s_b ≡ Poisson propagated standard deviation in background rate = $(R_b/T)^{½}$; counts min^{-1};
T ≡ sample or background counting interval, minutes; and
K ≡ calibration constant, which in this question is the counting efficiency, counts $decay^{-1}$.

Comment: The equation given in the ABHP exam is wrong, and the definition given for K also is wrong. I will use the correct equation above.

SOLUTIONS AND ANSWERS(•):

A. Given the Gaussian dispersion model, the ground level centerline concentration $\chi(x, 0, 0)$, which is measured at distance x of 1 km downwind, crosswind distance y of zero, and distance z of zero above the ground, is expected to change for the following conditions:

The answers shown below are justified by how factors in the dispersion equation influence the calculated value of $\chi(x, 0, 0)$:

$$\chi(x,\ 0,\ 0) = \frac{Q}{\pi\ u\ \sigma_y\ \sigma_z}\ e^{-\frac{1}{2}\left(\frac{h}{\sigma_z}\right)^2},$$

where I assume an elevated release from a stack and where quantities are defined:

Q ≡ release rate, Ci s^{-1};
h ≡ effective stack height, m;
u ≡ wind speed, m s^{-1};
σ_y ≡ dispersion coefficient measured in meters in the crosswind direction from the centerline of the plume, which increases with downwind distance x and which is greater the greater the instability of the atmosphere, i.e., the more the environmental lapse rate exceeds the

process or dry adiabatic lapse rate for a parcel of dry air as it rises, expands, and cools adiabatically in its surrounding air environment. This process, **positive**, lapse rate relates to a parcel of air released from the stack, and it corresponds to a **decrease** in temperature of 1°centigrade for each 100 meters rise; and

σ_z ≡ dispersion coefficient measured in meters in the vertical direction from the centerline of the plume, which also increases with downwind distance x and which is greater the greater the instability of the atmosphere.

Answers are obtained with reference to the factors in the above equation:

- 1. As h increases, $\chi(x, 0, 0)$ decreases as $\exp[-½(h/\sigma_z)^2]$ decreases.
- 2. As u increases, $\chi(x, 0, 0)$ decreases as 1/u decreases.
- 3. As the environmental lapse rate goes from a (super-adiabatic) positive lapse rate (unstable condition) to a negative lapse rate (very stable condition, temperature inversion, temperature increases with height), σ_y and σ_z will decrease. The value of $\chi(x, 0, 0)$ will generally decrease provided the value of x of 1 km for both lapse rates happens to correspond to a distance downwind that is less than the distance where the maximum ground concentration occurs, which depends upon the effective stack height h for isotropic dispersion: $\chi_{max} = (0.234)/(u\ h^2)$ when $\sigma_z = h/2^{1/2}$. Because the stack height h and dispersion coefficients were not given, a definitive answer cannot be given. For isotropic dispersion, the answer depends on the magnitude of the decreasing factor $\exp[-½(h/\sigma_z)^2]$ relative to the increasing factor $(1/\sigma_z)^2$ as σ_z becomes smaller in going from a positive to a negative lapse rate.
- 4. In this case the effective stack height h increases; therefore, $\chi(x, 0, 0)$ decreases as $\exp[-½(h/\sigma_z)^2]$ decreases.

B. For release through a pipe at the bottom and middle of a wide shallow and straight river, the downstream centerline concentration C (assumed at the center of the river) is expected to change with the stated conditions:

- 1. The centerline concentration is expected to increase as the temperature of the discharge is increased because the density of the discharged water is less.
- 2. If the release rate Q in Ci s^{-1} increases with increased velocity of discharge, assuming the released concentration does not change, then the concentration everywhere in the river will increase.
- 3. If the river current F in $m^3\ s^{-1}$ increases, then the average concentration $\bar{C}$ in the river will decrease.
- 4. As time t increases, the activity concentration C(t) in sediment on the river bottom will decrease with depth in the sediment if the activity release rate Q and sedimentation rate do

not change with time t. The reason for this conclusion is that radioactivity in sediment at greater depths has a longer period for decay.

C. For the stated conditions, the actual **MDA** is calculated:

K ≡ counting efficiency = **0.2 c d^{-1}**;
R_b ≡ background rate = **85 cpm**;
MDA_d ≡ desired MDA = (0.1 pCi g^{-1})(500 g) = 50 pCi = **111 dpm** for
m ≡ sample mass = 500 g; and
T ≡ sample or background counting interval = **4 minutes**; so
s_b ≡ $(R_b/T)^{½}$ = **4.61 cpm**.

- $$MDA = \frac{4.65\ s_b}{K} + \frac{3}{K\ T} = \frac{(4.65)(4.61)}{(0.2)} + \frac{3}{(0.2)(4)} = \mathbf{111\ dpm},$$

which meets the desired **MDA_d** of **111 dpm**.

D. The *committed effective dose equivalent* (**CEDE**) for an individual consuming fish from a contaminated stream is calculated:

V ≡ volume of contaminated water = 15,000 gallons = **5.68x10^7 mL**;
T ≡ release time = 2 days = **1.728x10^5 s**; so
F_R ≡ V/T = **329 mL s^{-1}**;
C_R ≡ Cs-137 concentration in released effluent = 8.81x10^3 pCi mL^{-1} = **0.00881 μCi mL^{-1}**;
F_S ≡ stream flow rate = 200 cfs = **5.66x10^6 mL s^{-1}**;
B ≡ bioaccumulation factor for fish = **2,000**;
m ≡ mass of consumed fish = **250 g;**
ALI ≡ stochastic annual limit on intake = **100 μCi**.

A solution for the stated information is obtained:

- $$CEDE = \left(\frac{\frac{V\ C_R}{T}}{F_R + F_S} \right) (B\ m) \left(\frac{5,000\ mrem}{ALI} \right) = \mathbf{12.8\ mrem}.$$

Comment: The ALI of 100 mCi given in the exam has been replaced by the correct value of 100 μCi in ICRP Publication 30. This question assumes incorrectly that a steady state bioaccumulation factor B of 2,000 applies to fish swimming in water over a two day period. Of course we could assume that the fish swim along with the slug of contaminated water until they reach a steady state activity, but such an assumption would not be realistic.

Comments Applicable to Questions on the 1999 ABHP Exam

The given information provided in some parts to Question 14 as well as some other questions on this 1999 ABHP exam is poorly stated, often obtuse or even wrong, and needlessly redundant and extraneous to the solutions. We have changed the wording of some of the given information to make clear our answers. For Question 14, there is no definitive answer to Part A, 3. Members of the ABHP and the Part II panel are encouraged to evaluate and improve their peer review process, including the **writing** of their solutions using the **actual given** information on the final draft printed version of the exam. By using a peer review process that requires the writing of solutions using the actual given information (e.g., the given MDA equation in Question 14 which is wrong and gives the wrong units and the ALI for Cs-137 which is 1,000 times the actual value), most of the errors in a question should be easily identified and corrected before the exam is actually given to candidates. The final corrected printed version given to candidates should be printed using the same printer as the final draft version of the exam.