SOLUTIONS AND ANSWERS TO 1997 ABHP EXAM

QUESTION 1

GIVEN: You are the health physicist responsible for setting up an air sampling system in an exhaust vent of a nuclear facility which emits both particulates and radioiodine.

SOLUTIONS AND ANSWERS(*):

*   A. Isokinetic sampling in a vent, stack, or duct is used to assure that a representative sample of contaminant aerosols is collected, and it is achieved when the velocity V_S of air entering the sampling probe is the same as the velocity V_E of the exhaust gases at the sampling location in the exhaust. Anisokinetic conditions exist when $V_S \neq V_E$, and a representative sample generally will not be obtained.

*   B. Two factors leading to non-representative samples include (See answer to A.):

    1. When $V_S > V_E$, the sample will contain a deficit of larger particles.
    2. When $V_S < V_E$, the sample will contain an excess of larger particles.

*   C. Five factors leading to sample line losses include:

    1. diffusion deposition of particles on walls of sampling system,
    2. chemical reaction of contaminant aerosols, e.g. radioiodine, with walls,
    3. impaction of particles at bends,
    4. condensation of contaminant on walls, and
    5. electrostatic attraction of contaminant ions to charged wall surfaces.

*   D. The major effect is for sampling line losses of radioiodine which will react chemically with copper.

*   E. A cascade impactor is used to obtain the particle size distribution of contaminant aerosols, which is important in the design of the sampling system for those aerosols.

SOLUTIONS AND ANSWERS TO 1997 ABHP EXAM

QUESTION 2

GIVEN: whole body count of a worker who had an inhalation intake of class Y ^{60}Co and class D ^{131}I. Data for ^{60}Co are summarized (See comment below.):

$T_{1/2}$ ≡ physical half-life = **5.2 y**;
ALI ≡ stochastic annual limit on intake for class Y, 1 μm AMAD aerosols = **30 μCi**;
$<H_L/I>$ ≡ lung dose per unit intake = 3.4×10^{-7} Sv Bq^{-1} = **1.26 rem μCi^{-1}**;
(f_{NP}, f_{T-B}, f_P) ≡ **fractions** of lung dose due respectively to depositions in NP, T-B, and P regions of respiratory tract for 1 μm AMAD aerosols = **(0, 0, 1)**;
IRF ≡ fraction shown in given table of intake present in whole body;
W_T ≡ tissue weighting factor shown in table;
D_{NP}, D_{T-B}, D_P ≡ intake deposition fractions in table; and
H_{50}(AMAD)/H_{50}(1 μm) equation.

SOLUTIONS AND ANSWERS(*):

A. The ^{60}Co value of **(I/ALI)100%** is calculated given **q_{WB} = 21 μCi** and **IRF = 0.63** from the given table at an elapsed time of zero days for 1 μm AMAD aerosols:

*
$$\left(\frac{I}{ALI} \right) 100\% \; = \; \left(\frac{\left(\frac{q_{WB}}{IRF} \right)}{ALI} \right) 100\% \; = \; \mathbf{111\%}.$$

Comment: The given IRF values actually apply to a log-normal particle size distribution and not a single particle size as stated in the given table. The log-normal particle size distribution is characterized by its *activity median aerodynamic diameter* (AMAD) and geometric standard deviation.

B. The **CEDE** is calculated for a ^{60}Co intake **I** of **25 μCi** of 1 μm AMAD, class Y aerosols:

*
$$CEDE \; = \; I \left(\frac{5 \; rem}{ALI} \right) \; = \; \mathbf{4.17 \; rem}.$$

3

C. The **TEDE** is calculated given that the $\textbf{CEDE}_{\textbf{Co-60}}$ = **50 mrem**; the $\textbf{CDE}_{\textbf{I-131}}$ = **600 mrem** and $\mathbf{w_T}$ = **0.03** for the thyroid; and the external dose $\mathbf{H_{ext}}$ = **250 mrem**:

* $$\textbf{\textit{TEDE}} \ = \ CEDE_{Co-60} \ + \ w_T \ CDE_{I-131} \ + \ H_{ext} \ = \ \textbf{318 \textit{mrem}}.$$

D. The **CDE** to the lungs is calculated for an intake **I** of **30 μCi** of **10 μm** AMAD, class Y ^{60}Co aerosols:

$$\frac{\mathbf{H_{50}(10 \ \mu \textit{m})}}{\mathbf{H_{50}(1 \ \mu \textit{m})}} \ = \ 0 \ + \ 0 \ + \ f_P \left(\frac{D_P(10 \ \mu \textit{m})}{D_P(1 \ \mu \textit{m})} \right) \ = (1) \left(\frac{0.05}{0.25} \right) \ = \ \mathbf{0.2}; \ so$$

* $$\textbf{\textit{CDE}} \ = \ (I) \left\langle \frac{H_L}{I} \right\rangle \left(\frac{H_{50}(10 \ \mu \textit{m})}{H_{50}(1 \ \mu \textit{m})} \right) \ = \ (30 \ \mu Ci)(1.26 \ rem \ \mu Ci^{-1})(0.2) \ = \ \textbf{7.56 \textit{rem}}.$$

Comment: The following expression is given by the ABHP in the general information for this question: (f_{N-P}, f_{T-B}, f_P) = (0, 0, 100), which actually represent the percentages of the committed dose equivalent to the lungs due to depositions respectively in the N-P, T-B, and P regions of the respiratory tract and **not** as stated in the question: "where f_{N-P}, f_{T-B}, and f_P are the fractional contributions of the CDE to the reference tissue from initial depositions in the nasal passages, tracheo-bronchial, and pulmonary regions respectively." In the given equation for the ratio, $H_{50}(AMAD)/H_{50}(1 \ \mu m)$, the same symbols f_{N-P}, f_{T-B}, f_P represent fractions, which therefore are expressed as fractions in the list of given data summarized in our solution above.

QUESTION 3

GIVEN: the number **I** of induced genetic defects per generation when both parents are exposed:

$$I = 0.05 \frac{S \, d}{D_g},$$

where I must be corrected by a factor 0.5 if only one parent is exposed, and where

S ≡ spontaneous occurrence of genetic defects per generation;
d ≡ dose equivalent received by exposed population, **mSv**;
D$_g$ ≡ genetic doubling dose, which I assume must be received by exposed population every year to cause at equilibrium an induced rate I equal to S = **250 mSv**;
**R** ≡ relative risk = **(S + I)/S**; and
DDREF ≡ Dose and Dose Rate Effectiveness Factor for cancer induction = 2.

SOLUTIONS AND ANSWERS(*):

A. Given *linear-no-threshold* (LNT) model to describe dose response for cancer induction:

* 1. Two other models and their dose response curves are:

   a. Linear-threshold response Y: Y = A + B d, where A is a negative constant, B is a positive constant, d is the dose equivalent, and d ≥ - A/B when hormesis is not considered possible:

d, Dose Equivalent

5
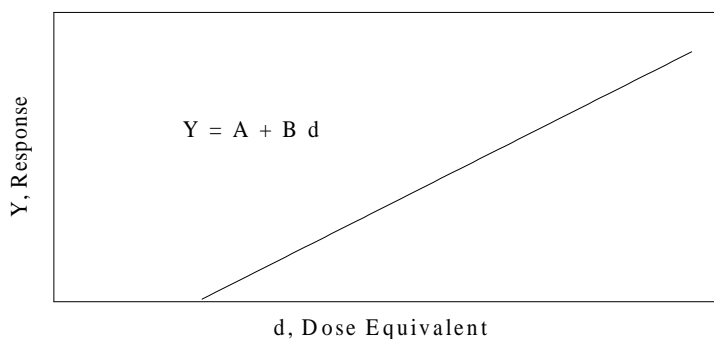
b. Linear-quadratic response Y: $Y = A\,d + B\,d^2$, where A and B are positive constants:
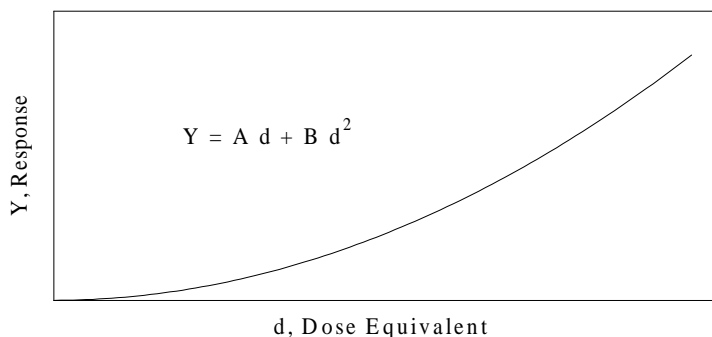
*   2. Characteristics of the LNT model that makes it useful for radiation protection: The response or risk of cancer is a simple function of the total dose regardless of when it is received and regardless of the dose rate. Therefore, to limit the risk in any control period, only the total dose need be limited. The assumption of no threshold is used to justify the ALARA principle.

*   B. The most likely effects of a 30 rem dose to the fetus at the following days after conception are as follows when *no effect*, which would be the most likely effect in all cases, is not considered:

    1. 3 days: death,
    2. 3 weeks: teratogenic effects, and
    3. 3 months: cancer.

    C. Regarding genetic effects:

*   1. The genetic doubling dose is that dose delivered to a population that doubles the spontaneous rate. The *mega-mouse* and *fruit fly* experiments were used to estimate the doubling dose.
    2. The relative risk **R** per generation caused by a dose **d** of **4 mSv** to a population of 40,000 men is calculated:

$$I = \frac{0.05}{2}\left(\frac{S\,d}{D_g}\right) = \frac{0.05}{2}\left(\frac{S\,(4\ mSv)}{250\ mSv}\right) = \mathbf{4x10^{-4}}\ \mathbf{S;}\ so$$

*

$$R = \frac{S + I}{S} = \frac{S + 4x10^{-4}\,S}{S} = \mathbf{1.0004.}$$

*   D. Regarding the harm from a collective dose delivered to a given population:

1. The dose response is assumed to be linear without threshold.
2. The respective population is assumed to be homogeneous in its response, i.e., the same risk per unit dose applies on average to each member of the population.

E. The excess number **N** of cancer deaths is calculated given:

P $\equiv$ number of persons in population = **40,000**;
d $\equiv$ dose delivered to each member of population = 4 mSv = **0.4 rem**; and
<R$_P$/d> $\equiv$ my assumed average risk from ICRP Publication 60 for a member of the general population = **5x10^{-4} rem^{-1}**.

*

$$N \;=\; P\; d\; \left\langle \frac{R_P}{d} \right\rangle \;=\; \mathbf{8}.$$

QUESTION 4

GIVEN: Ion chamber survey instrument used for general survey of area contaminated with mixed fission products and other data:

V	≡	volume of ion chamber and of contained air at ambient conditions = 200 cm^3;
X_s	≡	phenolic sliding shield thickness = **0.34 cm**;
X_w	≡	aluminized Mylar window thickness = 7 mg cm^{-2};
X_{wall}	≡	phenolic wall thickness = 0.16 cm;
V_c	≡	voltage = 50 volts;
ρ	≡	densities in table, **g cm^{-3}**;
μ/ρ	≡	mass attenuation coefficients in table, cm^2 g^{-1};
X_eρ	≡	wall thickness in table to establish electronic equilibrium, **g cm^{-2}**;
$E_{γmax}$	≡	maximum gamma energy for X_eρ wall thickness in table, **MeV**;
T	≡	beta particle kinetic energy in figure, **MeV**;
R	≡	beta particle range in figure corresponding to **T** in figure, **g cm^{-2}**; and various constants.

SOLUTIONS AND ANSWERS(*):

* A. Dose rates are determined:

1. gamma with shield in place, and
2. beta from difference of reading without shield and reading with the shield in place, multiplied by an appropriate correction factor.

* B. Three parameters that affect the correction factor needed to correct the meter reading (assumed to be gross reading without the shield in place) to obtain the beta dose rate include:

1. gamma dose rate response parameter without the shield in place,
2. energies of beta particles, and
3. density of air in ion chamber.

C. The maximum gamma and beta energies are obtained respectively:

* 1. **$E_{γmax}$ = 1 MeV** from X_eρ table value of **0.43 g cm^{-2}** corresponding to X_sρ calculated:

$$X_s\rho = (0.34\ cm)(1.25\ g\ cm^{-3}) = 0.425\ g\ cm^{-2} = \mathbf{0.43\ g\ cm^{-2}}.$$

*   2. $\mathbf{T}_{\boldsymbol{\beta}\mathbf{max}} = \mathbf{E}_{\boldsymbol{\gamma}\mathbf{max}} = \mathbf{1\ MeV}$ as also verified from given figure for **T** versus **R**, which actually applies to aluminum.

*   D.   Regarding electronic equilibrium:

       1.   Electronic equilibrium is a condition achieved when the number, direction, and energies of charged particles entering a small volume element of material are equal to the respective values for charged particles leaving that volume element.

       2.   If an instrument previously calibrated under electronic equilibrium conditions at one photon energy is used to measure a higher energy photon radiation field and electronic equilibrium is not established for the higher energy photons, the measured dose rate will be less than the actual dose rate.

QUESTION 5

GIVEN: A worker who expressed concerns of exposure from handling and inspecting depleted uranium plates over a 3 year period without any dosimetry:

ρ_{air} ≡   air density = 0.001293 g cm^{-3} = **1.293 mg cm^{-3}**;
ρ_w ≡   water density = 1 g cm^{-3} = **1,000 mg cm^{-3}**;
S   ≡   specific activity of plates = 3.6x10^{-7} Ci g^{-1};
m   ≡   mass of gloves = 200 g = **200,000 mg**; and
a   ≡   surface area of gloves = **400 cm^2**;

graphs of dose rate $\dot{\mathbf{D}}$ in **mGy h^{-1}** versus thickness **xρ** in **mg cm^{-2}**, which are assumed to apply to dose rates at the surface of semi-infinite sources; and table of radiation emissions.

  Comment: The emissions shown for Pa-234 are actually those for the isomer, Pa-234m.

SOLUTIONS AND ANSWERS(*):

A. Dose rates are obtained assuming a conservative epidermis thickness of **7 mg cm^{-2}**:

* $\dot{D}(7\ mg\ cm^{-2}) = 2\ mGy\ h^{-1}$ *for no gloves from expansion of Fig*.1.

  The total thickness **xρ** of absorbing material is calculated when gloves are worn:

$$x\ \rho\ =\ \frac{m}{a}\ +\ 7\ mg\ cm^{-2}\ =\ 507\ mg\ cm^{-2}\ when\ gloves\ are\ worn;\ so$$

* $\dot{D}(507\ mg\ cm^{-2}) = 0.12\ mGy\ h^{-1}$ *for gloves from Fig*.1.

*   Gloves should be worn under stated conditions to substantially reduce the dose and to prevent contamination of the hands.

B. The dose rate $\dot{\mathbf{D}}$ to the live skin at a distance **d** of 1 meter or **100 cm** is determined as follows by assuming a conservative epidermis of **7 mg cm^{-2}**, semi-infinite sources, and no significant change in the dose rate at 1 meter compared to the given surface dose rate, except for the added attenuation of the one meter of air (See comment below.). The total thickness **xρ** of absorbing material is calculated:

$$x \, \rho = (100 \; cm)(1.293 \; mg \; cm^{-3}) + 7 \; mg \; cm^{-2} = \mathbf{136 \; mg \; cm^{-2}}; \; so$$

* $$\dot{D}(\mathbf{136 \; mg \; cm^{-2}}) = \mathbf{0.9 \; mGy \; h^{-1}} \; from \; Fig.1.$$

Comment: This comment also applies to part C below. The dose rates shown in the figure are assumed to represent the surface dose rates when the uranium plates are covered with a varying thickness of attenuating material. The assumption that the dose rate does not depend on the distance **d**, except for the added attenuation of the one meter of air is not obvious from the stated given information. In fact, the dose rate would be expected to decrease less rapidly with distance than the decrease calculated for attenuation alone; although, this is not obvious without a careful evaluation of the effects of geometry and attenuation. To obtain a solution, the candidate must assume that the surface dose rates corrected for attenuation alone can be used to predict the dose rate out to a distance of 1 meter from the plates.

C.   The annual eye dose equivalent **H** in rem is calculated given:

t $\equiv$ annual exposure time = $(2.5 \; h \; day^{-1})(250 \; days) = \mathbf{625 \; h}$;
d $\equiv$ distance from plates = **30 cm**; and
$\mathbf{x_e \rho_w}$ $\equiv$ assumed tissue mass density thickness over lens of eyes = **300 mg cm⁻²** for assumed linear thickness $\mathbf{x_e}$ of **0.3 cm** and given $\mathbf{\rho_w}$ of **1,000 mg cm⁻³**. The total thickness **xρ** of absorbing material is calculated:

$$x \, \rho = (30 \; cm)(1.293 \; mg \; cm^{-3}) + 300 \; mg \; cm^{-2} = \mathbf{339 \; mg \; cm^{-2}}; \; so$$

$$\dot{H} = \dot{D}(339 \; mg \; cm^{-2}) = 0.3 \; mSv \; h^{-1} \; from \; Fig.1 = \mathbf{0.03 \; rem \; h^{-1}}.$$

* $$H = \dot{H} \, t = \mathbf{18.8 \; rem},$$

which exceeds the 15 rem NRC annual eye dose limit.

*   D. Five recommended safety practices include:

1. cover surface of stored plates with sufficient plastic to stop the ^{234m}Pa beta particle.
2. wear gloves when handling plates,
3. wear protective eye goggles,
4. have workers check gloves, clothing, and skin for contamination, and
5. have workers wear TLDs to monitor dose to the exposed skin, eyes, and fingers.

*   E. The three distinct slopes result primarily:

11

SOLUTIONS AND ANSWERS TO 1997 ABHP EXAM

1. Region A: absorption of alpha particles and low energy beta particles,
2. Region B: absorption principally of the high energy beta particles emitted by ^{234m}Pa, and
3. Region C: attenuation of x-ray, bremsstrahlung, and gamma photons.

QUESTION 6

GIVEN: A lead shield is to be added to a point source of ^{60}Co surrounded by an iron shield :

x_{Fe}	$\equiv$	thickness of iron shield = **2.5 cm**;
A	$\equiv$	activity of point source = **15 Ci**;
Γ	$\equiv$	gamma constant = 1.32 R h^{-1} Ci^{-1} m^2 = **1.32 x10^4 R h^{-1} Ci^{-1} cm^2**;
μ_{Pb}	$\equiv$	lead gamma attenuation coefficient = **0.679 cm^{-1}**;
μ_{Fe}	$\equiv$	iron gamma attenuation coefficient = **0.35 cm^{-1}**;
B_{Pb}	$\equiv$	lead buildup factor = **1 + μx/3** where μ and x apply to lead; and
B_{Fe}	$\equiv$	iron buildup factor = **1 + μx** where μ and x apply to iron.

SOLUTIONS AND ANSWERS(*):

A. Lead thickness x_{Pb} required for an exposure rate $\dot{X}$ of **2.5x10^{-3} R h^{-1}** on surface of added lead shield when buildup is neglected:

$$\dot{X} = \frac{A\ \Gamma}{(x_{Fe} + x_{Pb})^2}\ e^{-\mu_{Fe}\,x_{Fe}}\ e^{-\mu_{Pb}\,x_{Pb}},$$

which yields x_{Pb} by use of the *SOLVER* application on HP 42S calculator:

* $$x_{Pb} = \textbf{16.8 } cm.$$

Comment: Because the given dose rate is stated to apply to the surface of the added lead shield, the solution for the lead shield thickness requires a manual iterative solution or the use of a *SOLVER* application like the one on the HP 42S calculator. A manual iterative solution could require a considerable amount of time. A more reasonable question could have asked for the shield thickness that yields the required exposure rate at a distance of 1 meter from the source.

B. The exposure rate $\dot{X}$ outside the shield is obtained given a total thickness **x** of **22 cm**; an exposure rate $\dot{X}'$ of **2.5 mR h^{-1}** without buildup (i.e., from primary photons only), and that "the energy spectrum is not significantly degraded as it [photons] penetrates the iron shield":

$x_{Pb} + x_{Fe} = \textbf{x} = \textbf{22 cm}$; so $x_{Pb} = 22 - 2.5 = \textbf{19.5 cm}$;

SOLUTIONS AND ANSWERS TO 1997 ABHP EXAM

* $$\dot{X} = \dot{X}' \left(1 + \frac{\mu_{Pb} x_{Pb}}{3} \right) = \mathbf{13.5\ \textit{mR}\ \textit{h}^{-1}}.$$

Comment: The directive, "Assume the energy spectrum is not significantly degraded as it penetrates the iron shield.", is not realistic because almost 50% of the exposure rate outside the iron shield is due to Compton scattered photons, which would be considerably degraded in energy below that of the source photons and which could be assumed to be completely absorbed by the lead shield. If this interpretation is made of the ABHP directive, then only primary photons able to penetrate the iron shield need to be considered, and the above answer would be obtained. However, if the stated assumption in Part B is interpreted to mean that the buildup factor for iron still applies along with the buildup factor of lead for the primary photons, then a non-sensible, solution of **25.4 mR h⁻¹** for the exposure rate outside the lead shield could be calculated. If it is assumed that the energy spectrum does not change in either the iron or lead, then this means that only uncollided photons contribute to the exposure rate outside the shield. Therefore, the buildup factors would be unity, and the exposure rate outside the lead shield would be the given exposure rate of **2.5 mR h⁻¹** without buildup, which of course is contrary to the actual facts. A better question would be to direct the candidate:

"Assume that Compton scattered photons emerging from the iron shield are completely absorbed by the added lead shield, i.e., only account for primary photons emerging from the iron shield in calculating the exposure rate at the surface of the lead shield. Briefly explain why this assumption might be valid."

Another acceptable way of calculating the exposure rate outside laminated shields where the higher Z component is on the outside is to assume a buildup factor of unity for the lower Z shield. The buildup factor for the higher Z shield is then calculated from the total number of relaxation lengths for both shields. In this case, the total number of relaxation lengths is calculated as [(0.695)(19.5) + (0.35)(2.5)] or 14.1, which yields a lead buildup factor of 5.70 and an exposure rate of **14.3 mR h⁻¹** at the surface of the lead shield, which is somewhat larger than the value of 13.5 mR h⁻¹ shown as our answer in the equation above.

14

QUESTION 7

GIVEN: Data for a general purpose x-ray machine:

Conditions for table top survey with x-ray beam normal to table:

d_1 ≡ source to image distance (SID) = **34 inches**;
d_2 ≡ source to ion chamber distance = 34 - 7 = **27 inches**;
d_3 ≡ source to table top distance = 34 - 3 = **31 inches**;
t I ≡ product of exposure time and current = **10 mAs**; and
table of measured exposure X_m in **mR** versus voltage **V** in **kVp**.

Additional information:
d_{1AP} ≡ source to image distance (SID) for table top AP exam = **40 inches**; and
d_{1PA} ≡ source to image distance (SID) for chest PA exam = **72 inches**.

SOLUTIONS AND ANSWERS(*):

A. Entrance skin exposure, **ESE**, from AP abdominal exam given:

$(t\ I)_{AP}$ ≡ product of exposure time and current for AP exam = **60 mAs**;
V ≡ voltage for AP exam = **75 kVp**; so from table:
X_m ≡ measured exposure in survey = **112 mR** for **t I** of **10 mAs** and d_2 of **27 inches**;
x ≡ patient thickness = **10 inches**; so for d_{1AP} of **40 inches** and film **3 inches** below table top:
d_s ≡ distance from source to skin = (40 - 3 - 10) = **27 inches**.

$$* \qquad ESE\ =\ (X_m)\left(\frac{(t\ I)_{AP}}{t\ I}\right)\left(\frac{d_2}{d_s}\right)^2\ =\ (112\ mR)\left(\frac{60}{10}\right)\left(\frac{27}{27}\right)^2\ =\ \textbf{672}\ \textbf{\textit{mR}}.$$

B. Entrance skin exposure, **ESE**, from PA chest exam given:

$(t\ I)_{PA}$ ≡ product of exposure time and current for PA exam = **5 mAs**;
V ≡ voltage for PA exam = **115 kVp**; so from table:
X_m ≡ measured exposure in survey = **264 mR** for **t I** of **10 mAs** and d_2 of **27 inches**;
x ≡ patient thickness = **10 inches**; so for d_{1PA} of **72 inches** and film **0 inches** from the chest:
d_s ≡ distance from source to skin = (72 - 10) = **62 inches**.

* $$ESE = (X_m)\left(\frac{(t\ I)_{PA}}{t\ I}\right)\left(\frac{d_2}{d_s}\right)^2 = (264\ mR)\left(\frac{5}{10}\right)\left(\frac{27}{62}\right)^2 = \mathbf{25.0\ mR}.$$

* C. Two recommendations to lower the ESE include:

1. decrease mAs, which results in poorer image quality, and
2. increase film speed and/or use image intensifier screens, which result in better image quality.

D. Exposure **X** of technologist is calculated for an AP abdominal exam given:

ESE ≡ entrance skin exposure for patient calculated in part A = **672 mR**;
d ≡ distance of technologist from patient = **1 m**; and
R ≡ assumed ratio of 90 degree scattered exposure at 1 meter to ESE = **1x10⁻³ m²**.

* $$X = \frac{(ESE)(R)}{d^2} = \frac{(672\ mR)(1x10^{-3}\ m^2)}{(1\ m)^2} = \mathbf{0.672\ mR}.$$

* E. Three features to minimize exposure and dose of technologist in the control room include:

1. make distance from patient to control panel as large as practical,
2. provide shielding between control panel and x-ray source, and
3. make window for viewing patient of sufficient thickness.

* F. An exposure of 80 mrem in a month is high for this type of work because the low energy photons are easy to shield and the beam is not likely to expose the technologist.

* G. Three design characteristics of a general purpose x-ray system to minimize patient dose include: 1. film of sufficient speed, 2. collimation of beam, and 3. required inherent filtration to remove low energy photons.

SOLUTIONS AND ANSWERS TO 1997 ABHP EXAM

QUESTION 8

GIVEN: accidental ^{137}Cs release from a stack of a metal smelter:

t $\equiv$ release time interval = 8 h = **28,800 s**;
$\mathbf{D_s}$ $\equiv$ maximum deposition at 135 degrees and 2 km downwind = **14,000 pCi m^{-2}**;
u $\equiv$ wind speed from NW = **5 m s^{-1}**;
C $\equiv$ Pasquill atmospheric stability class;
$\mathbf{V_d}$ $\equiv$ deposition velocity = **0.002 m s^{-1}**;
H $\equiv$ effective stack height = **40 m**;
R $\equiv$ breathing rate = 0.8 m^3 h^{-1} = **2.22x10^{-4} m^3 s^{-1}**;
χ(x, 0, 0) $\equiv$ given equation for ground level concentration in air, **pCi m^{-3}**, where:
Q $\equiv$ release rate, **pCi s^{-1}**;
$\mathbf{\sigma_y}$ $\equiv$ cross wind dispersion coefficient in given figure, **m**; and
$\mathbf{\sigma_z}$ $\equiv$ vertical dispersion coefficient in given figure, **m**.

SOLUTIONS AND ANSWERS(*):

A. The intake **I** of a person remaining during **t** at point of maximum ground deposition:

$$D_s = \chi \ V_d \ t; \ so \ \chi \ t = \frac{D_s}{V_d}, \ and$$

* $$I = \chi \ t \ R = \frac{D_s}{V_d} R = \mathbf{1{,}550 \ pCi}.$$

B. Activity **Q t** of ^{137}Cs released from stack during **t** of **28,800 s** given also:

$\chi \equiv \chi$(2 km, 0, 0) = **300 pCi m^{-3}**; and
σ_y = **200 m**, and σ_z = **130 m** from given figures for Pasquill class C and 2 km distance.

$$\left(\frac{\chi}{Q}\right) = \frac{e^{-0.5\left(\frac{H}{\sigma_z}\right)^2}}{2 \ \pi \ \sigma_y \ \sigma_z \ u} = \mathbf{1.17x10^{-6} \ s \ m^{-3}}; \ so$$

* $$Q \ t = \frac{\chi}{\left(\frac{\chi}{Q}\right)} \ t = \mathbf{7.40x10^{12} \ pCi}.$$

17

*   C. Additional information useful in reducing the uncertainty in the release estimate is stack monitoring data including the analyses of stack filter samples and the stack gas exhaust flow rate.

*   D. Five routine tasks for assuring the quality of the counting system include:

1. checking all settings on the electronics prior to using counting system,
2. a chi-square test with a standard in a fixed position to evaluate the counter's operation,
3. a chi-square test with standard first removed and then placed in the standard position for each count to evaluate extra-Poisson variance associated with the sample changer, which should be made when the counting system is first assembled and then at least yearly,
4. background count of blank before each sample count and plot on control chart, and
5. standard source check of counter to confirm counting efficiency and plot of counting data on control chart.

E. Counts of a sample, blank, and a standard and calculations:

C_b $\equiv$ counts observed for blank = **123 c**;
T_b $\equiv$ counting interval for blank = **100 minutes**; so
R_b $\equiv$ blank counting rate = C_b/T_b = **1.23 cpm**, and
$\hat{\sigma}_b$ $\equiv$ estimated[1] standard deviation and standard error in $R_b = (R_b/T_b)^{1/2}$ = **0.111 cpm**;
C_{s+b} $\equiv$ sample gross count = **225 c**;
T_{s+b} $\equiv$ counting interval for sample = **50 minutes**; so
R_{s+b} $\equiv$ sample gross counting rate = C_{s+b}/T_{s+b} = **4.50 cpm**; so
$\hat{\sigma}_{s+b}$ $\equiv$ estimated standard deviation and standard error in $R_{s+b} = (R_{s+b}/T_{s+b})^{1/2}$ = **0.300 cpm**;
A_{std} $\equiv$ activity of standard and assumed standard error = **(89,570 ± 789) dpm** **(± 1 $\hat{\sigma}_{Astd}$)**;
C_i $\equiv$ standard gross count for measurement i (i = 1 to 5) = **9263, 9607, 9242, 9681, 9524**;
T $\equiv$ counting interval for each measurement of standard = **1 minute**; so

$\bar{R}_{std}$ $\equiv$ average gross counting rate of standard = $(\Sigma\, C_i)/(5\ T)$ = **9,463 cpm**; and

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[1]The overstrike hat symbol, $\wedge$, is used on $\hat{\sigma}_b$ to distinguish it from the population standard deviation σ_b in the blank counting rate. This hat symbol is used on estimates for other population statistics to distinguish them from the true population values. It is assumed that each observed count comes from an associated Poisson distribution whose mean μ and variance σ^2 are equal and that a single observed count or average count approximates its associated population mean.

$\hat{\sigma}_{\mathbf{std}}$ $\equiv$ estimated standard error^2 in mean rate $\bar{R}_{std}$ for standard $= (\bar{R}_{std}/5T)^{\frac{1}{2}} = \mathbf{43.5\ cpm}$.

The counter efficiency and sample activity and associated standard errors are calculated from the given data and quantities calculated as shown in the given data above:

1. Efficiency **E**:

* $$E = \frac{\bar{R}_{std} - R_b}{A_{std}} = \mathbf{0.106\ \textit{c\ d}^{-1}},\ \textit{and}$$

* $$\hat{\sigma}_E = \left(\frac{\hat{\sigma}_{std}^2 + \hat{\sigma}_b^2}{\left(\bar{R}_{std} - R_b\right)^2} + \frac{\hat{\sigma}_{A_{std}}^2}{A_{std}^2} \right)^{1/2} E = \mathbf{0.00105\ \textit{c\ d}^{-1}}.$$

2. Sample Activity **A**:

* $$A = \frac{R_{s+b} - R_b}{E} = \mathbf{30.8\ \textit{dpm}},\ \textit{and}$$

* $$\hat{\sigma}_A = \left(\frac{\hat{\sigma}_{s+b}^2 + \hat{\sigma}_b^2}{\left(R_{s+b} - R_b\right)^2} + \frac{\hat{\sigma}_E^2}{E^2} \right)^{1/2} A = \mathbf{3.03\ \textit{dpm}}.$$

Comment: It is not clear whether the candidate should use an experimental estimate of the standard error of 89.9 cpm, calculated from $[\Sigma(R_i - \bar{R}_{std})^2/n(n-1)]^{\frac{1}{2}}$ or the theoretical, propagated, Poisson standard error, $\hat{\sigma}_{std}$ of 43.5 cpm, which is calculated from $(\bar{R}_{std}/nT)^{\frac{1}{2}}$ as shown in the listed given data above and used in the solution shown to this part of the question for the $n = 5$ repetitive counts of the standard, each taken over a constant counting interval T of 1 minute. This comment includes guidance on the use of the chi-square statistic for the choice between the experimental and the theoretical, propagated, Poisson standard error estimate in this

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^{2}The standard error estimate in any sample mean $\bar{y}$ about the true population mean μ of a random variable Y is calculated from $\hat{\sigma}_y/n^{1/2}$, where $\hat{\sigma}_y$ is either an experimental or theoretical estimate of the population standard deviation σ for that random variable and n is the number of measurements. The value of $\hat{\sigma}_y$ for counting rates is calculated from the square root of the theoretical, propagated Poisson variance in the rate, which for the standard is given by $(\bar{R}_{std}/T)^{1/2}$.

ABHP question and in questions on other ABHP exams. The development of the equations for the chi-square statistic and their practical applications to counting data are given in a recent paper[3]. Their use for the 5 repetitive counts of the standard in this specific ABHP question is discussed as follows. To further help communicate the meaning of certain statistics, a glossary of symbols, definitions, and applicable equations is given at the end of this discussion.

The experimental estimate, $\hat{\sigma}_{exp}$ (often called the sample standard deviation s), of the population standard deviation in the random counts is 201 as calculated from the expression, $[\Sigma(C_i - \bar{C})^2/(n-1)]^{1/2}$. The theoretical, Poisson estimated standard deviation, $\hat{\sigma}_p$, in the counts is only 97.3 as calculated from the square root, $(\bar{C})^{1/2}$, of the average count $\bar{C}$ of 9,463. Thus, the estimate of the reduced chi-square statistic, $\hat{\chi}_v^2$, is calculated from $\hat{\sigma}_{exp}^2/\hat{\sigma}_p^2$ as $(201)^2/(97.3)^2$ or 4.26, which indicates that the experimental variance estimate from the 5 repetitive counts is 4.26 times the theoretical, Poisson estimated variance in the counts for the population[4]. The estimated chi-square statistic, $\hat{\chi}^2$, is calculated from the product v $\hat{\chi}_v^2$ as (5-1)(4.26) or 17.0, where the number of degrees of freedom v is (n - 1) or 4. Based on the null hypothesis that the 5 repetitive counts of the standard show no more variance than the expected Poisson variance in the counts, a critical high chi-square high value, χ^2-high of 9.48, may be calculated for a significance level α of 5% and 4 degrees of freedom v. The probability, $P(\chi^2 > \hat{\chi}^2)$, of exceeding the calculated $\hat{\chi}^2$ value of 17.0 is only 0.20%. However, it is to be noted that a χ^2 value greater than the calculated value of 17.0 is expected to occur 0.20% of the time even when the actual counting data does not include any extra-Poisson variance. Candidates, however, could easily conclude that the repetitive counts of the standard show more variance than expected, i.e., unacceptable extra-Poisson variance. Therefore, they could chose to use the larger experimental standard error of 89.9 cpm rather than the theoretical Poisson standard error, $\hat{\sigma}_{std}$ of 43.5 cpm, for the mean rate $\bar{R}_{std}$ of 9,463 cpm calculated from the five measurements of the standard.

There are problems, however, associated with using the experimental standard error estimate in the average rate. Except for the five repetitive counts themselves, no other information is given to the candidate to evaluate any extra-Poisson variance in the counts of the standard. Certainly, a candidate could reasonably expect that the counter was working at the time

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[3]See paper, "Basic Applications of the Chi-Square Statistic Using Counting Data," by Mark Tries *et al* in Health Physics 77: 441-453, October, 1999. Symbols used in this paper differ somewhat from those used in the discussion here.

[4]This same conclusion that the experimental variance estimate is 4.26 times the Poisson variance estimate for the counts also applies to the calculated counting rates (See reference by Mark Tries above.).

and therefore justify the use of the theoretical Poisson standard error estimate in the average rate despite the high calculated $\hat{\chi}^2$ value of 17.0. Any significant extra-Poisson variance associated with the sample changer should have been eliminated when the counting system was first assembled (See answers to Part D.). All observations, including the blank count, the sample count, and the five counts of the standard exceed 30 counts; so it is reasonable to assume that the Poisson distributions for the counts can be approximated by normal distributions. However, if it is concluded that the experimental standard error estimate of 89.9 cpm should be used for the standard error in the average counting rate, $\bar{R}_{std}$ of 9,463 cpm, this standard error estimate cannot be combined, when it is determined with only 4 degrees of freedom ν, with other normal standard error estimates for the following reasons. Because it is not likely that observations of a normally distributed random variable Y will be more than a couple of standard deviations from the mean and because measurements nearer the mean have a higher probability density, an experimental standard deviation estimate $\hat{\sigma}_y$ and calculated experimental standard error $\hat{\sigma}_y/n^{1/2}$ in the sample mean $\bar{y}$ most likely will be underestimates for small samples n. The experimental standard error estimate, $\hat{\sigma}_y/n^{1/2}$, for the sample mean then must be multiplied by the t-statistic rather than the Z-score statistic to describe the confidence interval associated with the sample mean $\bar{y}$. The value of the t-statistic was not given in this ABHP question. Thus, the standard error in the background rate, $\hat{\sigma}_b$ of 0.111 cpm, and the standard error estimate for the activity of the standard, $\hat{\sigma}_{Astd}$ of 789 dpm , cannot be combined simply with the experimental standard error, of 89.9 cpm, for the average counting rate of the standard to obtain the propagated standard error in the counting efficiency.

      In addition to the problem of combining the experimental standard error estimate with other standard errors, it must be concluded that 5 repetitive counts of the standard are not sufficient to make any precise statement regarding extra-Poisson variance. The *per cent coefficient of variation* (%CV) in observations of any random variable having a mean μ and variance σ^2 is defined by its percent relative standard deviation or by the value of $(\sigma/\mu)100\%$. Thus, the %CV for a random variable gives a measure of the inherent variation of that random variable, which relates to how precise it can be estimated in repetitive measurements. Even when there is no extra-Poisson variance, the mean and variance of the χ^2 statistic are respectively ν and 2ν. Therefore, the %CV of the χ^2 statistic is $100\%(2/\nu)^{1/2}$ or 70.7% when ν equals (n - 1) or 4 for the n = 5 repetitive measurements of the standard in this ABHP question. For a Poisson distribution of counts, the mean μ and variance σ^2 in the counts are equal; so the %CV in the counts is simply $100\% \mu^{-1/2}$. For a population mean count μ equal to the sample mean of 9,463 counts for the 5 measurements of the standard, the %CV in the counts is only 1.03%. Thus, the Poisson calculated precision in the counts is considerably better than the precision in the χ^2 statistic for 5 measurements of the standard and only 4 degrees of freedom ν. Because the estimate $\hat{\chi}^2$ for the χ^2 statistic is used to decide if extra-Poisson variance might be present in repetitive counts of a source, at least 30 measurements are recommended. Thirty measurements

provide a %CV in the chi-square statistic of $(2/29)^{1/2}100\%$ or 26.3%, which still is quite large.

It also is informative to compare the %CV in the Poisson variance estimate, $\hat{\sigma}_p^2$, to the %CV in the experimental variance estimate, $\hat{\sigma}_{exp}^2$, for the five measurements (counts) of the standard. Each %CV can be obtained from its propagated relative variance (See referenced paper above by Mark Tries.). The %CVs in the two variance estimates for the counts are calculated as follows for a population having a mean count μ and variance σ^2 equal to the mean count $\bar{C}$ of 9,463 obtained for the $n = 5$ measurements of the standard in this ABHP question. It is assumed that repetitive counts of the standard are described by a Poisson distribution that can be approximated by a normal distribution. The %CVs for the two variances are calculated as follows for this assumed Poisson distribution of counts in which the expected reduced chi-square statistic, $< \chi_v^2 >$, is unity, i.e., it is assumed that there is no extra-Poisson variance in the counts.

Percent Coefficient of Variation of the Poisson Variance Estimate for the Counts:

$$\textbf{\%CV of } \hat{\sigma}_p^2 \equiv 100\% \left(\frac{\sigma \; of \; \hat{\sigma}_p^2}{\sigma_p^2} \right) = 100\% \left(\frac{\chi_v^2}{n \; \mu} \right)^{1/2} = 100\% \left(\frac{1}{(5)(9,463)} \right)^{1/2} = \textbf{0.460\%},$$

which is also the %CV for the calculated mean count $\bar{C}$ because $\hat{\sigma}_p^2$ is defined as $\bar{C}$.

Percent Coefficient of Variation of the Experimental Variance Estimate for the Counts:

$$\textbf{\%CV of } \hat{\sigma}_{exp}^2 \equiv 100\% \left(\frac{\sigma \; of \; \hat{\sigma}_{exp}^2}{\sigma_{exp}^2} \right) = 100\% \left[\frac{2}{v} \right]^{1/2} = 100\% \left[\frac{2}{4} \right]^{1/2} = \textbf{70.7\%},$$

where the expected experimental variance, σ_{exp}^2, is the population variance, σ^2, which in this case is the Poisson variance, σ_p^2, which equals the mean count μ of 9,463 for the assumed population. The relative variance, $2/v$, for the experimental variance estimate is the same as the relative variance for the reduced chi-square statistic. The coefficient of variation of the experimental variance estimate for the counts is $(70.7)/(0.460)$ or 154 times greater than that for the Poisson variance estimate. Thus, for any reasonable mean count μ, the Poisson variance estimate, $\hat{\sigma}_p^2$, has much better precision than the experimental variance estimate, $\hat{\sigma}_{exp}^2$, especially for a small number of measurements n. Even when the counting data actually reflect extra-Poisson variance and the calculated reduced chi-square statistic is no longer unity, the Poisson variance estimate still will have much better precision than the experimental variance estimate for the population variance. For example, when the expected reduced chi-square statistic has the value $\hat{\chi}_v^2$ of 4.26 calculated from the 5 measurements of the standard, the %CV for the experimental variance estimate in the population variance has the same value of 70.7 %, and the %CV for the Poisson

22

variance estimate is increased to the value of 0.949 % as calculated by the applicable equation above. The percent coefficient of variation of the experimental variance estimate for the counts is then (70.7)/(0.949) or 74.5 times greater than that for the Poisson variance estimate. Thus, the precision of the Poisson variance estimate is much better than the precision of the experimental variance estimate for the population variance even when repetitive counts of a source reflect extra-Poisson variance. However, if it is concluded, based on at least thirty repetitive measurements, that the measurements do in fact reflect extra-Poisson variance designated here by $\sigma^2_{\Delta p}$, then the experimental variance estimate, $\hat{\sigma}^2_{\exp}$, should be used as the best estimate for the population variance, σ^2, because it is represented now by the sum, $(\sigma^2_p + \sigma^2_{\Delta p})$, of the Poisson variance and the actual extra-Poisson variance (See referenced paper above by Mark Tries.). The estimate $\hat{\sigma}^2_{\Delta p}$ for any extra-Poisson variance is calculated from the difference of $\hat{\sigma}^2_{\exp}$ and $\hat{\sigma}^2_p$. Even though it may not have good precision for the small number of degrees of freedom ν of 4 in the five measurements of the standard, the estimate $\hat{\sigma}^2_{\Delta p}$ for the extra-Poisson variance is calculated from the five measurements of the standard in this ABHP question:

$$\sigma^2_{\Delta p} \approx \hat{\sigma}^2_{\Delta p} \equiv \hat{\sigma}^2_{\exp} - \hat{\sigma}^2_p = \left(\hat{\chi}^2_\nu - 1\right)\hat{\sigma}^2_p = (4.26 - 1)9{,}463 = 30{,}849,$$

which compares to the Poisson variance estimate $\hat{\sigma}^2_p$ of 9,463 and experimental variance estimate $\hat{\sigma}^2_{\exp}$ of 40,312 calculated from the product $\hat{\chi}^2_\nu\ \hat{\sigma}^2_p$. Thus, the total experimental variance is presumably dominated by extra-Poisson variance, and one might conclude that the experimental variance estimate $\hat{\sigma}^2_{\exp}$ is a better estimate of the population variance σ^2. Because of the very poor precision in $\hat{\chi}^2_\nu$, as reflected by its large %CV of 70.4%, not much confidence can be placed on the estimate of either $\hat{\sigma}^2_{\exp}$ or $\hat{\sigma}^2_{\Delta p}$. The percent coefficient of variation of $\hat{\sigma}^2_{\Delta p}$ is calculated using as population statistics the corresponding estimates obtained from the five repetitive measurements of the standard in this ABHP question:

$$\%\,CV\ of\ \hat{\sigma}^2_{\Delta p} \equiv 100\%\left(\frac{\sigma\ of\ \hat{\sigma}^2_{\Delta p}}{\sigma^2_{\Delta p}}\right) = 100\%\left[\frac{2}{\nu}\left(\frac{\chi^2_\nu}{\chi^2_\nu - 1}\right)^2 + \frac{\chi^2_\nu}{n\,\mu}\right]^{1/2},\ or$$

$$\%\,CV\ of\ \hat{\sigma}^2_{\Delta p} = 100\%\left[\frac{2}{4}\left(\frac{4.26}{4.26 - 1}\right)^2 + \frac{4.26}{(5)(9{,}493)}\right]^{1/2} = 92.4\%.$$

The actual extra-Poisson variance could just as well be zero with such a large value for its percent coefficient of variation. Thus, the solutions shown in this question use the theoretical, propagated, Poisson variance estimates for all observed counting data.

Glossary of Symbols, Definitions, and Applicable Equations for Comment on Question 8

Y	$\equiv$	normally distributed random variable, e.g., a count C or counting rate measurement R when population mean count $\mu \geq$ about 30 counts.
μ	$\equiv$	population mean of a general normally distributed random variable Y;
	$=$	$(\Sigma\, y_i)/n$, for $i = 1$ to n where $n \to \infty$.
σ^2	$\equiv$	population variance of a general normally distributed random variable Y;
	$=$	$(\Sigma\, (y_i - \mu)^2/n$, for $i = 1$ to n where $n \to \infty$;
	$=$	μ for a Poisson distribution of counts of the same radiation source over the same counting interval T.
%CV of Y	$\equiv$	% coefficient of variation of random variable $Y \equiv 100\%(\sigma/\mu)$.
$\bar{y}$	$\equiv$	sample mean and estimate of population mean $= (\Sigma\, y_i)/n$, for $i = 1$ to n and where:
n	$\equiv$	number of measurements of random variable Y.
$\hat{\sigma}^2_{exp}$	$\equiv$	experimental[5] estimate of population variance $= \Sigma\, (y_i - \bar{y})^2/(n-1)$, for $i = 1$ to n, where $(n-1)$ = number of degrees of freedom ν for calculated $\hat{\sigma}^2_{exp}$ statistic;
	$\equiv$	$\Sigma\, (C_i - \bar{C})^2/(n-1)$, for $i = 1$ to n count measurements each over a constant counting interval T; and
	$\equiv$	$\Sigma\, (R_i - \bar{R})^2/(n-1)$, for $i = 1$ to n rates R_i each determined over a constant counting interval T, where $R_i = C_i/T$ and $\bar{R} = \bar{C}/T$.
$\hat{\sigma}^2_p$	$\equiv$	Poisson estimate[6] of population variance in counts or counting rates:
	$\equiv$	$\bar{C}$ for n repetitive counts each over a constant counting interval T.
	$\equiv$	$\bar{R}/T$ for n calculated rates R_i each over a constant counting interval T.
Z_i	$\equiv$	Z-score for measurement y_i of random variable $Y = (y_i - \mu)/\sigma$.
$\hat{Z}_i$	$\equiv$	Z-score estimate for measurement i of a count C_i or rate R_i:

[5]The same symbol $\hat{\sigma}^2_{exp}$ is used to represent the experimental variance estimate in the counts and the experimental variance estimate in the counting rates.

[6]The same symbol $\hat{\sigma}^2_p$ is used to represent the Poisson variance estimate in the counts and the propagated, Poisson variance estimate in the counting rates.

$$= (C_i - \bar{C})/\hat{\sigma}_p = (C_i - \bar{C})/\bar{C}^{1/2} \text{ for count measurement } C_i, \text{ which equals } \hat{Z}_i \text{ for } R_i:$$

$$= (R_i - \bar{R})/\hat{\sigma}_p = (R_i - \bar{R})/(\bar{R}/T)^{1/2} \text{ for counting rate measurement } R_i.$$

$\chi^2 \quad \equiv \quad$ chi-square statistic $\equiv \Sigma (Z_i)^2 = \Sigma (y_i - \mu)^2/\sigma^2$, $i = 1$ to n;.

$<\chi^2> \quad \equiv \quad$ mean or expected value of $\chi^2 = v$, where

$v \quad \equiv \quad$ number of degrees of freedom $= n$ when μ and σ^2 are known.

$V(\chi^2) \quad \equiv \quad$ variance of $\chi^2 = 2\,v$.

%CV of $\chi^2 \quad \equiv \quad$ % coefficient of variation of $\chi^2 = 100\%(2/v)^{1/2}$.

$\chi^2_v \quad \equiv \quad$ reduced chi-square statistic $\equiv \chi^2/v$.

$<\chi^2_v> \quad \equiv \quad$ expected value of $\chi^2_v = 1$.

$V(\chi^2_v) \quad \equiv \quad$ variance of $\chi^2_v = (2/v)$.

%CV of $\chi^2_v \quad \equiv \quad$ % coefficient of variation of $\chi^2_v = 100\%(2/v)^{1/2}$, which equals %CV of χ^2.

$\hat{\chi}^2 \quad \equiv \quad$ estimated chi-statistic from count or counting rate data:

$$= \Sigma(C_i - \bar{C})^2/\hat{\sigma}_p^2 = \Sigma(C_i - \bar{C})^2/\bar{C} \text{ for } i = 1 \text{ to n count measurements, which equals:}$$

$$= \Sigma(R_i - \bar{R})^2/\hat{\sigma}_p^2 = \Sigma(R_i - \bar{R})^2/(\bar{R}/T) \text{ for counting rate measurements.}$$

$\hat{\chi}^2_v \quad \equiv \quad$ estimated reduced chi-square statistic for count or counting rate data:

$$= \hat{\chi}^2/v = \hat{\chi}^2/(n - 1) = \hat{\sigma}^2_{exp}/\hat{\sigma}^2_p, \text{ where } v = (n - 1) \text{ because } \bar{C} \text{ or } \bar{R} \text{ are estimated from}$$

the data.

$\sigma^2_{\Delta p} \quad \equiv \quad$ extra-Poisson variance in count or counting rate data $= \sigma^2 - \sigma^2_p$.

$\hat{\sigma}^2_{\Delta p} \quad \equiv \quad$ estimate of extra-Poisson variance in count or counting rate data $= \hat{\sigma}^2_{exp} - \hat{\sigma}^2_p$;

$$= (\hat{\chi}^2_v - 1)\hat{\sigma}^2_p.$$

%CV of $\hat{\sigma}^2_p \quad \equiv \quad$ % coefficient of variation of $\hat{\sigma}^2_p \equiv 100\%$ (σ of $\hat{\sigma}^2_p)/\sigma^2_p = 100\% \,[\chi^2_v/n\,\mu\,]^{1/2}$.

%CV of $\hat{\sigma}^2_{exp} \quad \equiv \quad$ % coefficient of variation of $\hat{\sigma}^2_{exp} \equiv 100\%$ (σ of $\hat{\sigma}^2_{exp})/\sigma^2_{exp}$;

$$= 100\% \,[(2/v)\,]^{1/2}, \text{ which is the %CV for the } \chi^2 \text{ statistic itself.}$$

%CV of $\hat{\sigma}^2_{\Delta p} \quad \equiv \quad$ % coefficient of variation of $\hat{\sigma}^2_{\Delta p} \equiv 100\%$ (σ of $\hat{\sigma}^2_{\Delta p})/\sigma^2_{\Delta p}$;

$$= 100\% \,[\,(2/v)(\chi^2_v/(\chi^2_v - 1))^2 + (\chi^2_v/n\,\mu)\,]^{1/2}.$$

QUESTION 9

GIVEN: A 100 MeV He^{+2} accelerator and reactions: X(^{4}He, n)A and X(^{4}He, 2n)B which are stated to have equal cross sections and data:

T$_{1/2}$ of A	=	1 day = **86,400 s**; so
λ_A	≡	decay constant of A = (ln2)/(T$_{1/2}$ of A) = **8.02x10^{-6} s^{-1}**;
Γ_A	≡	gamma constant for A = **0.5 R h^{-1} Ci^{-1} m^2**;
ρ_A	≡	density for A = 7.8 g cm^{-3};
T$_{1/2}$ of B	=	5 day = **432,000 s**; so
λ_B	≡	decay constant of B = (ln2)/(T$_{1/2}$ of B) = **1.60x10^{-6} s^{-1}**;
Γ_B	≡	gamma constant for B = **1 R h^{-1} Ci^{-1} m^2**;
ρ_B	≡	density for B = 3.3 g cm^{-3};
$\dot{N}_e$/I	=	**6.2x10^{12} e s^{-1} μA^{-1}**;
V	≡	cell volume = **100 m^3**;
F	≡	ventilation flow rate = **7 m^3 s^{-1}**; so
K$_V$	≡	ventilation removal constant = F/V = **0.07 s^{-1}**.

SOLUTIONS AND ANSWERS(*):

A. Ratio of exposure rates, $\dot{X}_A/\dot{X}_B$, for various operating times **t** and shutdown times τ:

1. **t** = 1 day = **86,400 s** and τ = **0**:

*
$$\frac{\dot{X}_A}{\dot{X}_B} = \left(\frac{1 - e^{-\lambda_A t}}{1 - e^{-\lambda_B t}} \right) \left(\frac{\Gamma_A}{\Gamma_B} \right) = \mathbf{1.94}.$$

2. **t** = 2 months ≈ ∞ and τ = **0**:

*
$$\frac{\dot{X}_A}{\dot{X}_B} = \left(\frac{\Gamma_A}{\Gamma_B} \right) = \mathbf{0.5}.$$

3. $t = 2$ months $\approx \infty$ and $\tau = 2$ days = **172,800 s**:

*
$$\frac{\dot{X}_A}{\dot{X}_B} = \left(\frac{e^{-\lambda_A \tau}}{e^{-\lambda_B \tau}} \right) \left(\frac{\Gamma_A}{\Gamma_B} \right) = \textbf{0.165}.$$

B. The number $\dot{N}$ of He^{+2} ions striking target per second is calculated from given and calculated data partially used here and in discussion for part D below:

F ≡ duty factor or fraction of time accelerator is pulsed = **0.001**;
W ≡ pulse width = 1 μs = **1x10^{-6} s**; so
t_p ≡ time between midpoint of pulses = W/F = 0.001 s = **1,000 μs**;
$\dot{N}_p$ ≡ number of pulses per second = F/W = **1,000 s^{-1}**; and
I_p ≡ peak beam current = 1 mA = **1,000 μA**.

*
$$\dot{N} = I_P F \left(\frac{6.2x10^{12} \ e \ s^{-1}}{\mu A} \right) \left(\frac{1 \ He^{+2}}{2 \ e} \right) = \textbf{3.10x10}^{12} \ \textbf{\textit{He}}^{+2} \ \textbf{\textit{s}}^{-1}.$$

C. Delay time **t** after shutdown for concentration to reach a safe level **C(t)** given:

$\bar{t}_c$ ≡ assumed mean life of O_3 molecules due to chemical reaction only = **2,000 s**; so
K_c ≡ rate constant describing chemical removal of O_3 = $1/\bar{t}_c$ = **5x10^{-4} s^{-1}**;
K_V ≡ ventilation removal rate constant = F/V = **0.07 s^{-1}**; so
k ≡ total removal rate constant = $K_c + K_V$ = **0.0705 s^{-1}**;
$C(0)$ ≡ initial O_3 concentration = **10 ppm**; and
$C(t)$ ≡ final safe O_3 concentration = **0.1 ppm**.

$$C(t) = C(0)e^{-kt}; \ so$$

*
$$t = \frac{1}{k} \ln\left(\frac{C(0)}{C(t)} \right) = \textbf{65.3} \ s.$$

Comment: The candidate is directed: "Assume that the mean life of O_3 is 2000 sec". This directive easily could be interpreted to account for all removal mechanisms including ventilation and chemical reactions of ozone. As shown by the calculation for the ventilation removal rate constant in our solution, the given statement only applies to removal by chemical reactions. The directive should have been stated: "Assume that the mean life of O_3

is 2000 sec as a result of removal by chemical reactions only."

*   D.   Problems that the following instruments could experience in surveys near target with beam on:

     1.   Geiger-Mueller pulse detector, which I assume has a dead time of about 50 to 100 μs: The reading on the GM instrument will simply correspond to the pulse rate $\dot{\mathbf{N}}_\mathbf{p}$ of **1,000 s$^{\mathbf{-1}}$** of the accelerator when the pulse width **W** of **1 μs** is much less than the GM dead time and when the time interval between pulses, $\mathbf{t_p}$ of **1,000 μs**, is significantly greater than the GM dead time (See the calculations with the given data in part B above.).

     2.   Ion chamber whose mean current is assumed to be measured to yield the exposure rate: Recombination of ions within the ion chamber will occur if the instantaneous dose rate within the 1 μs pulse width for the accelerator is very high, and this recombination will give an erroneous reading below the actual average exposure rate.

*   E.   The neutron radiation field will die off essentially instantaneously when the machine is turned off (Note: sufficient information is not given to calculate an actual half-life, and the concept of half-life might not actually apply in this case.).

     Comment: A specific quantity like half-life should not been asked when it is not expected for the candidate to calculate a specific half-life. It is confusing and causes candidates to spend valuable time trying to find information provided in the question that will help them calculate a half-life. No such information is provided; so this question really does not have a numerical answer. The question should have directed: "Describe qualitatively how the neutron radiation field changes with time after the beam is turned off."

*   F.   Five sources of industrial hazards associated with this type of accelerator facility include:

     1.   electrical shock;
     2.   noxious gases (e.g., ozone and NO_x),
     3.   cryogenic hazards (e.g., liquid nitrogen),
     4.   RF/microwave hazards from RF sources used to supply energy to beam particles, and
     5.   all radiation sources (e.g., neutron and gamma radiation from beam particle reactions in target and beam line components and radiations emitted by radionuclides produced through beam particle reactions and indirectly through neutron activation.

*   G.   Five ionizing radiations produced during operation of the accelerator include: 1. neutrons, 2. gamma photons, 3. characteristic x-rays, 4. bremsstrahlung photons, and 5. beta particles, e.g., from neutron activation reactions.

SOLUTIONS AND ANSWERS TO 1997 ABHP EXAM

QUESTION 10

GIVEN: Termination urine sample containing ^{137}Cs resulting from inhalation exposure event:

t ≡ time after exposure when 24 h urine sample is completed = **20 days**;
T ≡ exposure time interval = 30 minutes = **0.5 h**;

$\bar{t}_v$ ≡ average time for one air change in room = **2 h**; so
K_V ≡ ventilation removal constant = $1/\bar{t}_v$ = **0.5 h^{-1}**; so
k ≡ total rate constant for removal of ^{137}Cs from room air = $\lambda + K_V \cong K_V$ = **0.5 h^{-1}**;
F ≡ breathing rate for Reference Man = **1.2 m^3 h^{-1}**;
V_u ≡ total volume of urine in 24 h sample = **1,500 mL**;
V_s ≡ volume of urine analyzed = **500 mL**;
A_s ≡ activity in analyzed urine = **0.43 μCi**; and
IRF ≡ fraction of intake expected to be present in 24 h urine sample shown in given table.

SOLUTIONS AND ANSWERS(*):

A. The intake **I** is calculated:

*
$$I = \frac{A_{24\,h}}{IRF} = \frac{A_s \left(\dfrac{V_u}{V_s} \right)}{IRF} = \textbf{498 } \boldsymbol{\mu Ci},$$

where **IRF = 2.59 x10^{-3}** as shown in table for **t = 20 days**.

B. The initial airborne concentration C(0) to which the worker was exposed is estimated given in addition:

I ≡ worker's intake = 1.5 mCi = **1,500 μCi**.

$$I = \int_0^T C(0)\, e^{-kt}\, F\, dt = C(0)\, F \left(\frac{1 - e^{-kT}}{k} \right); \; so$$

*
$$C(0) = \frac{k\, I}{F\, (1 - e^{-kT})} = 2,830\ \mu Ci\ m^{-3} = \textbf{0.00283 } \boldsymbol{\mu Ci\ cm}^{-3}.$$

SOLUTIONS AND ANSWERS TO 1997 ABHP EXAM

*   C. Answer is 3.

*   D. Answer is 4.

*   E. Answers are: 1. (b), 2. (d), 3. (a), and 4. (c).

*   F. An instrument routinely used to detect uranium contamination on personnel as they leave contaminated areas is a thin window (about 2 mg cm^{-2}), pancake type GM detector and rate meter. Advantages include its low cost, durability, and sensitivity to the beta and alpha radiation associated with the decay of uranium and progeny. Disadvantages include the relatively high background, the fact that the window easily can be punctured, and the lack of discrimination between alpha, beta, and gamma radiation, which limits its use for checking for alpha emitting contamination in external radiation fields.

QUESTION 11

GIVEN: Information on radon and its short lived progeny, including table of principle
radiations, energies, and half-lives.

SOLUTIONS AND ANSWERS(*):

* A. A *working level* **(WL)** is that concentration of short lived radon progeny that has a potential
alpha energy emission of **1.3×10^5 MeV L^{-1}**.

B. The working level concentration **C_{Po-218}** from ^{218}Po only is calculated given:

U_{Po-218} ≡ activity concentration of ^{218}Po = 600 Bq m^{-3} = **0.6 Bq L^{-1}**;
λ_{Po-218} ≡ decay constant of ^{218}Po = (ln 2)/(3.1)(60 s) = **3.73×10^{-3} s^{-1}**; and
E_{Po-218} ≡ potential alpha energy emission of ^{218}Po = 6 + 7.7 = **13.7 MeV**.

*
$$C_{Po-218} = \frac{U_{Po-218}}{\lambda_{Po-218}} E_{Po218} \left(\frac{1 \ WL}{1.3x10^5 \ MeV \ L^{-1}} \right) = \mathbf{0.0170 \ WL}.$$

C. The exposure **E** in working level months **(WLM)** is calculated given:

C ≡ WL concentration of short lived progeny = **0.02 WL**;
t ≡ exposure time = (14 h day^{-1})(30 weeks)(7 days week^{-1}) = **2,940 h**; and
M ≡ assumed occupational month = **170 h**.

*
$$E = C \ t \left(\frac{1 \ M}{170 \ h} \right) = \mathbf{0.346 \ WLM},$$

where differences in breathing rate in a home and a mine need not be considered.

* D. The dose delivered by Rn/Rn progeny depends on properties:

1. Two Rn/Rn progeny aerosol properties include:
    a. radon is a chemically inert gas which therefore is primarily exhaled when present in the
    tidal air volume of the lungs, and
    b. the progeny exist as solid aerosol particles comprised of ions, atoms, or atoms attached to
    condensation nuclei, which influences their diffusion and deposition on surfaces within
    various regions of the respiratory tract when inhaled.

    2. Three important characteristics of the respiratory tract include:
       a. thickness of the mucous sheet;
       b. action of cilia on the flow of the mucous sheet in clearing particles; and
       c. thickness and mass of critical target tissue, e.g., the basal cells of the bronchial epithelium.

*   E. Answer is 5.

    F. Regarding radon and radon progeny measurements:

*   1. Definitions for measurement types are given:
       a. Grab: a measurement of a sample taken over a relatively short time.
       b. Integrated: a measurement proportional to the integrated exposure.
       c. Continuous: a measurement that can be related to essentially the instantaneous concentrations or short term average concentrations over an extended monitoring period.

*   2. Examples of the measurement types include:
       a. Grab: radon concentration in air collected in a ZnS(Ag) scintillation cell and concentrations of short lived progeny from 3 counts of a 5 minute air filter sample.
       b. Integrated: radon exposure from measurement of alpha tracks in a plastic detector exposed over an extended period of time, and radon progeny from integrated TLD response from radiation emitted by progeny collected on a filter paper in a continuous air sampler.
       c. Continuous: radon concentration of sampled air that continuously passes through a ZnS(Ag) scintillation cell and radon progeny from alpha counts of a filter in a constant air particulate monitor.

QUESTION 12

GIVEN: Assessment of hazards from non-ionizing radiation sources:

λ_1 $\equiv$ peak wavelength of UV light box = **300 nm**;
λ_2 $\equiv$ peak wavelength of BSC cabinet = **280 nm**;
T_1 $\equiv$ exposure time per day with UV light box = 20 minutes = **1,200 s**;
T_2 $\equiv$ exposure time per day with BSC = 30 minutes = **1,800 s**;
TLV $\equiv$ threshold limit values in table, **J m^{-2}**; and
S_λ $\equiv$ relative spectral effectiveness in table.

SOLUTIONS AND ANSWERS(*):

A. Operating manuals give irradiances **I** assumed to represent personnel exposure situations at the stated distances from the two sources:

I_1 $\equiv$ irradiance from UV light box at 2 feet = 1 μW cm^{-2} = **0.01 J s^{-1} m^{-2}**; and
I_2 $\equiv$ irradiance from BSC at 6 inches = 0.6 μW cm^{-2} = **0.006 J s^{-1} m^{-2}**.

*   1. The exposure **E** in an 8 hour work day from each source is calculated relative to its respective TLV, which also applies to an 8 hour work day and when the same tissue is exposed from each source. These relative exposures are then summed:

*
$$\frac{E_1}{TLV_1} + \frac{E_2}{TLV_2} = \frac{I_1\,T_1}{TLV_1} + \frac{I_2\,T_2}{TLV_2} = \mathbf{0.438},$$

where: **TLV$_1$ = 100 J m^{-2}**, and **TLV$_2$ = 34 J m^{-2}**. Therefore, the total exposure is within the allowed limit.

*   2. The assumption that the irradiances are at their respective peak wavelengths is incorrect because both sources emit a spectrum of wavelengths.

*   3. A better method of assessing exposures to an individual would be to make actual measurements. Exposures to individuals could be well established using TLDs prepared and calibrated for use as UV detectors, which could be affixed to various exposed areas, e.g., head, hands, etc. to obtain reasonably accurate integrated exposures.

*   B. Tissues at risk to UV include:

1. the eye especially superficial tissue of the eye; conjunctivitis is a common response of the eye, and

   2. exposed skin; erythema from short term exposures and skin cancer from chronic exposures are possible responses.

* C. Two steps to lower exposures to UV light in the lab include:

   1. use protective clothing to cover exposed skin and UV-absorbing safety glasses to limit the exposure of the eyes, and
   2. use UV opaque shielding material where possible.

   D. A microwave transmitter is to be used in a health effects study:

   ν $\equiv$ frequency $= 1\text{x}10^{10}$ Hz $= \mathbf{1\text{x}10^{10}\ s^{-1}}$;
   $\mathbf{P_p}$ $\equiv$ peak power $= \mathbf{2\text{x}10^{6}\ mW}$;
   $\mathbf{W}$ $\equiv$ pulse width $= \mathbf{1\text{x}10^{-3}\ s}$;
   $\mathbf{R}$ $\equiv$ pulse rep rate $= \mathbf{200\ s^{-1}}$;
   $\mathbf{G}$ $\equiv$ antenna gain $= \mathbf{16\ dB}$; and
   $\mathbf{D}$ $\equiv$ maximum horn antenna dimension $= \mathbf{20\ cm}$.

* 1. Two precautions to prevent harm to technician include:
   a. provide interlock to shut down transmitter if persons enter the control area, and
   b. use microwave absorbing materials on walls/surfaces to reduce exposure from scattered radiation.
   2. The maximum free space power density **I** in mW cm^{-2} is calculate for the stated assumptions and distance **d** of **300 cm**:

$$\bar{P} \equiv \textit{ave. power} = P_p\ R\ W = \mathbf{4.00x10^{5}\ mW}.$$

$$10\ \log_{10}\left(\frac{P_{beam}}{\bar{P}}\right) \equiv G = 16;\ so$$

$$\mathbf{P_{beam}} = 10^{1.6}\ \bar{P} = \mathbf{1.59x10^{7}\ mW}.$$

* $$I = \frac{P_{beam}}{4\ \pi\ d^{2}} = \mathbf{14.1\ mW\ cm^{-2}}.$$

* 3. A lab technician spends 2 minutes in a room with an average free space power density of 25 mW cm^{-2}. The worker was not exposed above the ANSI microwave recommended limit of 10 mW cm^{-2} because the ANSI recommendations allow averaging over a 6 minute interval, which gives an average value of 8.33 mW cm^{-2}.

SOLUTIONS AND ANSWERS TO 1997 ABHP EXAM

E. Given concerns for hazards from a microwave device operating at 2,400 MHZ or frequency ν of **2.4x10⁹ s⁻¹**:

* 1. This device cannot cause ionization and damage to DNA because the photon energy **E** is much less than the ionization potential for all materials as shown:

$$E = h\ \nu = (6.6262x10^{-34}\ J\ s)\ (2.4x10^9\ s^{-1})(6.24x10^{18}\ eV\ J^{-1}) = 9.92x10^{-6}\ eV.$$

* 2. The primary effect of microwave radiation on tissue results from the heating caused by the enhanced motion of polar molecules (e.g., H_2O) as they attempt to orient themselves with the oscillating electric component of the microwave radiation field.

* F. The ALARA principle is applied to ionizing radiation to limit the risks of stochastic effects such as cancer and hereditary disease, which are **assumed** to have a zero threshold dose. For microwave and other non-ionizing radiation, the deterministic effects of concern exhibit a threshold power density or total exposure that must be exceeded for detrimental effects to manifest themselves. Thus, TLVs can be used to prevent detrimental deterministic effects associated with non-ionizing radiation sources. The stochastic effect of cancer associated with ionizing radiation may, in fact, have a practical threshold dose that must be exceeded. If such a practical threshold dose could be established and accepted by the radiation protection community, then TLVs could be established for ionizing radiation and the ALARA principle no longer would be justified.

QUESTION 13

GIVEN: ^{60}Co and ^{137}Cs data, symbols, and buildup factors as shown.

Comment: In the given table of Exposure Buildup Factors for Point Source at 1 MeV, the column labeled as R(mfp)* is confusing. The column should have been labeled as μx and designated by a footnote: "number of relaxation lengths" or "number of mean free paths." A candidate could easily be confused by the symbols, R(mfp)*, which would normally be interpreted as a variable R expressed as a function of mfp. If candidates were to search for the meaning of an assumed variable R, they would not find any additional information in the question that would provide any insight into the meaning of R. The footnote, "* mean free paths", does not necessarily clarify the meaning of an assumed variable R, which itself represents, in reality, the number of mean free paths, i.e., R is not a function of mfp but rather R represents the number of mean free paths. The correct notation for this quantity is given by the symbol for the quantity followed by a comma and then its units, for example, R, mfp.

SOLUTIONS AND ANSWERS(*):

A. Dose rate $\dot{\mathbf{D}}$ in the overhead crane when bucket containing ^{60}Co is at surface of water given:

$\dot{\mathbf{D}}_1$ ≡ dose rate under water from assumed point source of ^{60}Co in bucket = **3 rad h^{-1}**;
$\mathbf{d}_1$ ≡ distance under water from ^{60}Co to point of measurement = **1 m**;
$\mathbf{d}_2$ ≡ distance in air from water surface or from ^{60}Co source to crane = **10 m**; and

I assume ^{60}Co in bucket can be treated as a point source; no water remains in bucket when at surface of water; and attenuation of photons in air can be neglected.

Let $\dot{\mathbf{D}}_1(0)$ ≡ dose rate at 1 meter in air, which can be related to $\dot{\mathbf{D}}_1$ in water:

$$\dot{D}_1 = \dot{D}_1(0)\ B\ e^{-\mu x},\ or$$

$$\dot{D}_1(0) = \frac{\dot{D}_1}{B\ e^{-\mu x}} = \textbf{223 rad h}^{-1},\ where:$$

μx ≡ number of relaxation lengths in water = $(0.0707\ \text{cm}^{-1})(100\ \text{cm})$ = **7.07**; so
B ≡ buildup factor from table = **15.8**.

$$* \qquad \dot{D} = \dot{D}_1(0)\left(\frac{1\ m}{d_2}\right)^2 = (223\ rad\ h^{-1})\left(\frac{1\ m}{10\ m}\right)^2 = \mathbf{2.23\ \mathit{rad\ h^{-1}}}.$$

B. The activity **A** in Bq of ^{137}Cs is calculated for a point source in air given:

$\dot{\mathbf{D}}$ $\equiv$ dose rate assumed in water target volume when source is in air = **0.1 Gy h⁻¹**;

d $\equiv$ distance from source = **30 cm**;

$\mathbf{E}_\gamma$ $\equiv$ gamma photon energy = **0.662 MeV**;

$\mathbf{Y}_\gamma$ $\equiv$ gamma photon yield = **0.898 (Bq s)⁻¹**, which is actually 0.850 (Bq s)⁻¹, but given value will be used;

$\boldsymbol{\mu}_{\mathbf{enCs\text{-}137}}$ $\equiv$ water photon energy absorption coefficient = **0.0327 cm⁻¹**; so

$(\boldsymbol{\mu}_{\mathbf{enCs\text{-}137}})/\boldsymbol{\rho}$ $\equiv$ water mass energy absorption coefficient = **0.0327 cm² g⁻¹**.

$$\dot{D} = \frac{A\ E_\gamma\ Y_\gamma\left(\dfrac{\mu_{enCs-137}}{\rho}\right)}{4\ \pi\ d^2}\left(\frac{1.6x10^{-13}\ J}{MeV}\right)\left(\frac{10^3\ g}{kg}\right)\left(\frac{1\ Gy}{J\ kg^{-1}}\right)\left(\frac{3,600\ s}{h}\right);$$

$$\dot{D} = 0.1\ Gy\ h^{-1} = 9.90x10^{-13}\ Gy\ h^{-1}\ Bq^{-1}\ A;\ so,$$

$$A = \mathbf{1.01x10^{11}\mathit{Bq}}.$$

C. The specific activity $\mathbf{S_L}$ in **MBq m⁻¹** of ^{60}Co in a **long** pipe is calculated given:

$\dot{\mathbf{D}}$ $\equiv$ measured dose rate = **0.9 rad h⁻¹**;

d $\equiv$ perpendicular distance from pipe to dose point, **1 m**;

$\boldsymbol{\Gamma}$ $\equiv$ gamma constant = 3.7x10⁻⁴ mSv h⁻¹ MBq⁻¹ m² = **3.7x10⁻⁵ rad h⁻¹ MBq⁻¹ m²**;

$\boldsymbol{\theta}$ $\equiv$ angle that the pipe subtends at the dose point = $\boldsymbol{\pi}$ **radians**; and

My assumptions: the pipe is very long and located in a scatter free air environment; there is no attenuation of photons in the pipe or in the air between segments of the pipe and the dose point, which is equivalent to assuming that the pipe is located in a vacuum. The dose point is opposite the midpoint of the pipe, which subtends essentially an angle $\boldsymbol{\theta}$ of $\boldsymbol{\pi}$ **radians** at the dose point (Most of the dose is from segments of the pipe closest to the dose point; therefore, the assumption of no attenuation nor buildup might be reasonable. See comment and calculations below). I also assume a dose of 100 rads = 100 rem = 1 Sv.

$$\dot{D} = \frac{S_L \, \Gamma}{d} \, \theta; \; so$$

* $$S_L = \frac{d \, \dot{D}}{\theta \, \Gamma} = \frac{(1 \; m)(0.9 \; rad \; h^{-1})}{\pi \; (3.7x10^{-5} \; rad \; h^{-1} \; MBq^{-1} \; m^2)} = \mathbf{7{,}740 \; MBq \; m^{-1}}.$$

Comment: Because data was provided in the given information, candidates might be convinced that less restrictive assumptions than those summarized above should be made. They also could wonder what is meant by "a long, thin-walled, 2.5 cm diameter pipe." They might spend a lot of time trying to decide how long is "long" as well as the location of the dose point with respect to one end of the pipe? They also might assume that the pipe is located in a water medium rather than air; the type of medium was not stated in this part of the question. Depending on the assumptions, candidates would be required to spend a lot more time in calculating the specific activity of the line source than the time taken in the solution shown above, especially if they did not have a calculator having numerical integration capability. To demonstrate the magnitude of the error in the simple solution shown above and the iterative procedure a candidate might have to use in obtaining a solution with less restrictive assumptions, calculations have been made of the dose rate $\dot{D}$ at 1 meter from the midpoint of line sources of various lengths. The specific activity S_L was chosen in each case to produce a limiting dose rate of 0.9 rad h⁻¹ for a very long pipe stated in this part of the question. Results are shown in Table 1 below. The angle θ each line subtends at the dose point also is shown in the table as a percent of π, which is the angle for an infinite line source. Dose rates have been calculated using the numerical integration application of the HP 42S calculator when the pipe is located in a vacuum, air, or water. For air and water, account was taken for the attenuation and buildup in these media. A power function for the buildup factor in air or water was obtained from the given table values by using the STAT application of the HP 42S calculator and fitting the values of (B-1) versus the number of relaxation lengths, µr shown in the given table (actually stated as R(mfp)*).

The dose rates $\dot{D}$ were obtained from a numerical integration of the following integral:

$$\dot{D} = 2 \int_{y=0}^{y=L/2} \frac{S_L \, dy \, \Gamma}{r^2} \, B e^{-\mu r},$$

where:

L ≡ length of line source, **m**;
B ≡ buildup factor = $1 + 1.06\ (\mu r)^{1.36}$ for air = $1 + 1.07\ (\mu r)^{1.37}$ for water; and
r ≡ distance from differential line segment dy to dose point = $(y^2 + d^2)^{1/2} = (y^2 + 1)^{1/2}$, **m**.

      As can be seen from values in Table 1 below for either a vacuum or air, the line source must have a length L approaching several kilometers before essentially a constant dose rate of 0.9 rad h^{-1} is obtained at a distance d of 1 meter from the midpoint of the line source. Such a length would seem to be unrealistic for the pipe. The specific activity S_L is calculated as 7,787 Mq m^{-1} when air is considered the medium and account is taken of the attenuation and buildup in air. This value is only slightly larger than the value of 7,740 MBq m^{-1} calculated for a vacuum in the simple solution shown above, which neglects attenuation and buildup in air. For a water medium, the line source need only have a length of about 4 meters or more before a constant dose rate of 0.9 rad h^{-1} is obtained. For the pipe located in a water medium, it must have a specific activity S_L of 1.824×10^6 MBq m^{-1} to produce the given dose rate of 0.9 rad h^{-1}.

D. The minimum number **N** of lead-wool blankets required to shield a small valve is calculated from the information given here and in the general data for this question:

m ≡ mass of 1 lead blanket = 10.4 kg = **10,400 g**;
$\mathbf{x_b}$ ≡ thickness of 1 lead blanket = **2.5 cm**;
$\mathbf{V_b}$ ≡ volume of 1 lead blanket = 31 cm x 62 cm x 2.5 cm = **4,805 cm^3**; so
$\boldsymbol{\rho_b}$ ≡ density of blanket = m/V_b = **2.16 g cm^{-3}**;
A ≡ surface area of 1 lead blanket = 31 cm x 62 cm = **1,922 cm^2**; so
$\mathbf{x_b\,\rho_b}$ ≡ mass density thickness of one lead blanket = m/A = **5.41 g cm^{-2}**;
$\boldsymbol{\mu/\rho}$ ≡ mass attenuation coefficient of lead = (0.679 cm^{-1})/(11.4 g cm^{-3}) = **0.0596 cm^2 g^{-1}**;
$\mathbf{\mu_b x_b}$ ≡ no. of mfp corresponding to 1 blanket = $(x_b\,\rho_b)(\mu/\rho)$ = **0.322**;
$\boldsymbol{\mu_b}$ ≡ linear attenuation coefficient of blanket = $\mu_b x_b / x_b$ = **0.129 cm^{-1}**;
$\dot{\mathbf{H}}\mathbf{(0)}$ ≡ unshielded dose equivalent rate at d_1 = **150 mrem h^{-1}**, where:
$\mathbf{d_1}$ ≡ distance from valve = **100 cm**;

$\dot{\mathbf{H}}\mathbf{(x)}$ ≡ dose rate defining a high radiation area = **100 mrem h^{-1}** at
$\mathbf{d_2}$ ≡ distance from surface of valve and assumed center = **30 cm**; and

SOLUTIONS AND ANSWERS TO 1997 ABHP EXAM

Table 1. *Dose Rates $\dot{D}$ Opposite Mid-point of ^{60}Co Line Sources in a Vacuum, Air, and Water.*

L, m	θ, % of π	$\dot{D}_{vac}$, rad h^{-1} for μ = 0 m^{-1} S_L = 7740 Mbq^{-1}	$\dot{D}_{air}$, rad h^{-1} for μ = 7.75E-3 m^{-1} S_L = 7887 Mbq^{-1}	$\dot{D}_{water}$, rad h^{-1} for μ = 7.07 m^{-1} S_L = 1.824E6 Mbq^{-1}
1	29.5	0.266	0.269	0.722
2	50.0	0.450	0.455	0.886
3	62.6	0.563	0.569	0.899
4	70.5	0.634	0.641	0.900
5	75.8	0.682	0.689	0.900
10	87.4	0.787	0.794	0.900
20	93.7	0.843	0.849	0.900
40	96.8	0.871	0.876	0.900
80	98.4	0.885	0.889	0.900
100	98.7	0.888	0.892	0.900
1000	99.9	0.899	0.900	0.900
2000	99.9	0.899	0.900	0.900
10000	100	0.900	0.900	HP 42S gives 0.

*   As defined in 10 CFR 20, "*High radiation area* means an area, accessible to individuals, in which radiation levels could result in an individual receiving a dose equivalent in excess of 0.1 rem (1 mSV) in 1 hour at 30 centimeters from the radiation source or from any surface that the radiation penetrates."

SOLUTIONS AND ANSWERS TO 1997 ABHP EXAM

1. Solution for number N of lead-wool blankets based on distance d_2 of 30 cm measured from the center of the valve:

   My assumptions: I assume the valve can be considered as an unshielded point source that produces a dose equivalent rate $\dot{\mathbf{H}}(0)$ of **150 mrem h⁻¹** at a distance $\mathbf{d_1}$ of **100 cm** from the source without any attenuation in the air and a shielded dose equivalent rate $\dot{\mathbf{H}}(\mathbf{x})$ of **100 mrem h⁻¹** at a distance $\mathbf{d_2}$ of **30 cm** from the source.

   Calculation of required number, μx, of mean free paths, i.e., relaxation lengths:

   $$\dot{H}(x) = \dot{H}(0) \left(\frac{d_1}{d_2}\right)^2 B(\mu x) \ e^{-\mu x};$$

   so the required transmission T defined by $B(ux)\ e^{-\mu x}$ is calculated:

   $$T \equiv B(\mu x) \ e^{-\mu x} = \left(\frac{\dot{H}(x)}{\dot{H}(0)}\right) \left(\frac{d_2}{d_1}\right)^2 = \mathbf{0.0600}.$$

   An underestimate μx_1 of 3 and an overestimate μx_2 of 4 for the required μx value yield two values, T_1 and T_2 respectively, for the transmission when the respective buildup factors of 1.95 and 2.19 from the given table are used in the calculations:

   $$T_1 = B(3)e^{-3} = (1.95)e^{-3} = \mathbf{0.0971}, \ and$$

   $$T_2 = B(4)e^{-4} = (2.19)e^{-4} = \mathbf{0.0401}.$$

   An exponential fit of T versus μx for these two points yields from the STAT application of the HP 42S calculator the μx value for the required transmission T of 0.0600:

   $$\mu x = \mathbf{3.54} \ relaxation \ lengths.$$

   The required number **N** of blankets is obtained from the required **μx** value of **3.54** and the $\mathbf{\mu_b x_b}$ value of **0.322** for 1 blanket:

*
$$N = \frac{\mu x}{\mu_b x_b} = \frac{3.54}{0.322} = 11.0 = \mathbf{11 \ blankets}.$$

This number N corresponds to a thickness N x_b of 27.5 cm of blanket material. Therefore, the maximum radius of the valve is (30 - 27.5) cm or 2.5 cm.

2. Alternative solution for number N of lead-wool blankets based upon the distance d_2 of 30 cm measured from the outer surface of the blankets:

   Based on the definition shown above for a high radiation area, an alternative solution for **N** is obtained if the distance $\mathbf{d_2}$ of **30 cm** is measured from the outer surface of the shield of wool blankets. For this alternative interpretation, the required exposure rate $\mathbf{\dot{H}(x)}$ of **100 mrem h^{-1}** is expressed:

$$\dot{H}(x) = \dot{H}(0) \left(\frac{d_1}{d_2 + Nx_b} \right)^2 B(\mu_b \, Nx_b) \ e^{-\mu_b Nx_b},$$

where $B(\mu_b \, N \, x_b)$ is a linear buildup factor function for the required thickness N x_b of blanket material. The buildup factor function was obtained from a linear fit of buildup factors B versus the number of relaxation lengths up to the value of 5 shown in the given table by using the STAT application on the HP 42S calculator:

$$B(\mu_b \, N \, x_b) = 1.05 + 0.271 \, (\mu_b \, N \, x_b).$$

The SOLVER application was used to solve for N in the expression for $\dot{H}(x)$, which gives the alternative solution for the minimum number N of lead-wool blankets:

*
$$N = 7.39 = \mathbf{8 \ blankets}.$$

QUESTION 14

GIVEN: A cyclotron produces large quantities of ^{11}C, ^{13}N, ^{15}O, and ^{18}F. The plastic transfer line is broken and a constant release rate of ^{15}O occurs in a room where instant and complete mixing of ^{15}O can be assumed:

F ≡ room exhaust flow rate = 30 m³ min^{-1} = **0.500 m³ s⁻¹**;

V ≡ room volume = 6 m x 6 m x 3 m = **108 m³**; so

$\mathbf{K_V}$ ≡ ^{15}O room ventilation removal rate constant = F/V = **4.63x10⁻³ s⁻¹**;

P ≡ ^{15}O atom release rate = **2.6x10⁹ at s⁻¹**;

$\mathbf{T_{1/2}}$ ≡ half-life of ^{15}O = **12.2 s**, which is incorrect. The correct value is **122 s**, which also will be used in alternative solutions below; so

λ ≡ decay constant of ^{15}O = **5.68x10⁻² s⁻¹** and **5.68x10⁻³ s⁻¹** for respectively the given incorrect half-life and the correct half-life; and so

k ≡ total rate constant describing removal of ^{15}O from the room = $K_V + λ$ = **6.14x10⁻² s⁻¹** and **1.03x10⁻² s⁻¹** for respectively the given incorrect half-life and the correct half-life;

SOLUTIONS AND ANSWERS(*):

* A. For either the incorrect or correct half-life of ^{15}O, decay is more dominant than ventilation because in either case the decay constant λ exceeds the ventilation constant K_V.

B. The activity concentration **U(t)** of ^{15}O at a time **t** of 4 minutes or **240 s** after the onset of the release is calculated for the incorrect and correct half-life respectively:

The total removal rate, k N(t), of ^{15}O atoms from the room at any time t is given by

$$k \ N(t) \ = \ P \left(1 \ - \ e^{-kt}\right); \ so$$

$$U(t \ ) \ \equiv \ \frac{\lambda \ N(t)}{V} \ = \ \left(\frac{\lambda}{k}\right)\left(\frac{P}{V}\right)\left(1 \ - \ e^{-kt}\right), \ which \ gives:$$

*
$$U(t) \ = \ \mathbf{2.23x10^7} \ \textbf{\textit{Bq m}}^{-3} \ \textit{for the incorrect half-life}, \ and$$

$$U(t) \ = \ \mathbf{1.22x10^7} \ \textbf{\textit{Bq m}}^{-3} \ \textit{for the correct half-life}.$$

*   C. Exceeding the DAC of ^{15}O for a short time like 6 minutes does not necessarily mean an overexposure will have occurred for the following two reasons:

1. The exposure **E** in DAC-h is the product of the average concentration $\bar{\mathbf{C}}$ in multiples of the DAC and the actual exposure time **t** in hours. This calculated exposure could be significantly less than the exposure limit of 2,000 DAC-h when no other external or internal exposures occur in the 2,000 hour period applicable to the given control year. For an exposure time of only 6 minutes, the average concentration $\bar{\mathbf{C}}$ could be as high as 20,000 times the DAC.
2. The concentration will decrease rapidly due to decay and ventilation; so the average concentration $\bar{\mathbf{C}}$ will be much less than the peak concentration.

*   D. Posting of the hood is required because a technician may occasionally place his or her head inside the hood where the concentration is stated to exceed the DAC.

*   E The radionuclides listed in the given premise to this question decay by either positron emission or electron capture; therefore, they emit neutrinos and positrons. Characteristic x-rays and any gamma rays are associated with the decay respectively of the atomic and nuclear excited states of the product atoms. Annihilation photons having an energy of 0.511 MeV are produced in the surrounding materials when the emitted positrons combine with electrons and undergo positron-negatron pair annihilation.

*   F. Two health physics concerns associated with the use of plastic transfer lines include:

1. Radiation damage may cause cracking of the lines and release of radionuclides into the room.
2. Radioactive species such as ^{18}F may react with the plastic, and the lines could present an external radiation hazard regardless.

*   G. The answer is 1.