SOLUTIONS

Examination
Co-ordinating Radiation Protection Expert

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Problem 1 Radium Girls

Question 1.1

Estimate the ^{226}Ra activity still present on the hands of this alarm clock. You can assume that the dose rate is solely caused by ^{226}Ra (including its daughters).

The geometry of the measurement is such that the point source approach may be applied.

$$\dot{H}^* = \frac{h \cdot A}{r^2}. \quad \text{Result:} \quad 0.4\left[\frac{\mu Sv}{h}\right] = \frac{0.26\left[\frac{\mu\text{Sv}}{\text{h}} \cdot \frac{\text{m}^2}{\text{MBq}}\right] \times \text{A [MBq]}}{0.05^2\ [m^2]}$$

$$\text{A} = \frac{0.4 \times 0.05^2}{0.26} = 3{,}8 \cdot 10^{-3}\ \text{MBq} = 4\ \text{kBq}$$

Question 1.2

Assume that Casie ingested 1/104th of the total activity each working week. Calculate the committed effective dose ingested by Casie during one working week. Assume this was the only dose she ingested.

E(50) = A × e(50)

A_{total} = 603.7 µCi

Weekly dose: $603.7 \cdot 10^{-6}$ (Ci): 104 (weeks) × $37 \cdot 10^{9}$ (Bq/Ci) = $214.8 \cdot 10^{3}$ Bq

E(50) (Sv) = $214.8 \cdot 10^{3}$ (Bq) × $2.8 \cdot 10^{-7}$ (Sv/Bq) = 0.060 Sv

Question 1.3

Suppose that 603.7 µCi of ^{226}Ra is in equilibrium with all its daughters and dissolved in a tightly-sealed container holding 70 litres of water. Calculate the absorbed dose for this container during one year. Only the energy of the alpha radiation is required for this calculation.

Annual dose: 603.7 µCi = 22.34 MBq

The reduction in activity due to decay of ^{226}Ra (T½ = 1600 years) does not have to be taken into account.

The total number of disintegrations for 22.34 MBq ^{226}Ra in 1 year = $22.34 \cdot 10^{6}$(disintegrations/s) × 3600 (s/h) × 24 (h/day) × 365.25 (days/year) = $7.05 \cdot 10^{14}$ disintegrations/year.

The total α energy per disintegration =

4.784 + 5.490 + 6.003 + 7.687 + 5.297 MeV = 29.26 MeV/disintegrations

$7.05 \cdot 10^{14}$ disintegrations/year × 29.26 MeV/disintegration = $2.06 \cdot 10^{16}$ MeV

$2.06 \cdot 10^{16}$ MeV × $1.6 \cdot 10^{-13}$ J/MeV: 70 kg = 47.2 J/kg = 47.2 Gy

Question 1.4

Apply the calculation from Question 1.3a for a situation where the container with 70 litres of water is no longer tightly sealed and two thirds of the radon that is formed immediately escapes.

The total number of disintegrations for 22.34 MBq ^{226}Ra in 1 year remains unchanged at $7.05 \cdot 10^{14}$ disintegrations/year.

The total α energy per disintegration =
4.784 + 1/3 × (5.490 + 6.003 + 7.687 + 5.297) MeV = 4.784 + 8.159 =
12.94 MeV/disintegration

$7.05 \cdot 10^{14}$ disintegrations/year × 12.94 MeV/disintegration = $9.12 \cdot 10^{15}$ MeV

$9.12 \cdot 10^{15}$ MeV × $1.6 \cdot 10^{-13}$ J/MeV: 70 kg = 20.9 J/kg = 20.9 Gy

Scoring:

Problem 1	
Question	**Points**
1.1	3
1.2	4
1.3	5
1.4	3
Total	***15***

Problem 2. Liquid radioactive waste analysis

Question 2.1a

Why does only ^{32}P contribute in region C-B (the energy region between 167 and 2000 keV)?

^{32}P is the only nuclide in the waste with a maximum β energy of more than 167 keV and so contributes to the spectrum in the region between 167 and 2000 keV (region C-B).

Question 2.1b

Calculate the efficiency (cpm/dpm) of ^{32}P in region C-B.

The activity can be calculated based on the count rate in region C, however you first need to know what the detection efficiency is in this energy region. The total efficiency in region C for ^{32}P = 0.95 cpm/dpm. The activity can be calculated based on the test of the pure ^{32}P sample.

	R(C) cpm	ε(C) cpm/dpm	A dpm	A Bq
^{32}P	11576	0.95	*12185*	*203*

The results of the pure ^{32}P sample can be used to calculate how much of the spectrum is measured in the region above 167 keV (region C-B).

	R(C-B) cpm	ε(C-B) cpm/dpm
^{32}P	11576 - 3524 = 8052	8052/12185 = 0.66

Alternatively:

the efficiency of region C-B is a fraction of the efficiency of C:

$$\varepsilon_{C-B} = \frac{R_{C-B}}{R_C} \times \varepsilon_C = \frac{11576\ (cpm) - 3524\ (cpm)}{11576\ (cpm)} \times 0.95\ \left(\frac{cpm}{dpm}\right) = \frac{8052}{11576} \times 0.95 \left(\frac{cpm}{dpm}\right)$$

$$= 0.66\ \left(\frac{cpm}{dpm}\right) = 0.66\ \left(\frac{cps}{Bq}\right)$$

Question 2.2

Calculate the activity of ^{32}P in the 10-litre barrel.

The count rate in region C-B of the waste sample is:

639540 (cpm) - 272400 (cpm) = 367140 cpm.

The ^{32}P activity in the waste sample is 367140 (cpm)/0.66 (cpm/dpm) = $5.56 \cdot 10^5$ (dpm) = 9.26 kBq ^{32}P in 10 ml.

The ^{32}P activity in the 10-litre barrel filled to 90% is 9,000 [ml]/10 [ml] × 9.26 [kBq] = $8.33 \cdot 10^6$ Bq = 8.3 MBq ^{32}P.

Alternatively:

$R_{C\text{-}B}$ = 6119 cps; $A_{sample} = R_{C\text{-}B} / \varepsilon_{C\text{-}B}$ = 6119 (cps) / 0.66 (cps / Bq) = 9.26 kBq.

Question 2.3

Calculate the activity of ^{35}S in the 10-litre barrel.

^{35}S is measured in region C, but the spectrum of ^{32}P is also measured in this region. First we calculate the contribution of ^{32}P.

The efficiency of ^{32}P in region C is 0.95 [cpm/dpm]. The activity of ^{32}P in the waste sample is 556273 dpm. The count rate in region C caused by ^{32}P is then 0.95 (cpm/dpm) × 556273 (dpm ^{32}P) = 528459 cpm.

In region C, the waste sample produces 639540 cpm; 528459 cpm of this is produced by ^{32}P and so 639540 (cpm) - 528459 (cpm) = 111081 cpm is produced by ^{35}S.

The efficiency of ^{35}S in region C is 0.90 [cpm/dpm].

The ^{35}S activity in the waste sample is 111081 (cpm)/0.90 (cpm/dpm) = $123 \cdot 10^3$ (dpm) = $2.0 \cdot 10^3$Bq ^{35}S.

The ^{35}S activity in the 10-litre barrel (90% full) is 9,000 (ml)/10 (ml) × $2.0 \cdot 10^3$ (Bq) = $1.9 \cdot 10^6$ (Bq) = 1.9 MBq ^{35}S.

Question 2.4

Calculate the fraction of the secondary dose level for discharges to water caused by the discharge of the contents of the 10-litre barrel.

The maximum emission to water is

[maximum possible discharge per year/Re_{ing}]$_{P\text{-}32}$ + [maximum possible discharge per year/Re_{ing}]$_{S\text{-}35}$ =

$[A_{P\text{-}32} \times CR_{P\text{-}32}/Re_{P\text{-}32}] + [A_{S\text{-}35} \times CR_{S\text{-}35}/Re_{S\text{-}35}]$ =

$[8.3 \cdot 10^6 \text{ Bq} \times 0.1/4.2 \cdot 10^8] + [1.9 \cdot 10^6 \times 1/7.1 \cdot 10^9]$= 0.00224 Re per discharge.

This is 10 discharges per year = 0.0224 Re
Secondary dose level = 100 Re
The fraction of the secondary dose level = 0.0224/100 = 0.00022.

Question 2.5

Calculate the relative statistical inaccuracy in the calculation of the activity of ^{32}P based on 1 sigma.

We use (10.9) in Bos to calculate the sigma of region C and B based on the calibration measurement of ^{32}P (Figure 2):

$$\sigma_R = \frac{1}{t}\,\sigma_N = \frac{1}{t}\sqrt{N} = \sqrt{\frac{R}{t}}$$

$$\sigma_{R_C} = \sqrt{\frac{R_C}{t}} = \sqrt{\frac{11576\ (cpm)}{0.5\ (m)}} = 152\ cpm$$

$$\sigma_{R_B} = \sqrt{\frac{R_B}{t}} = \sqrt{\frac{3524\ (cpm)}{0.5\ (m)}} = 84\ cpm$$

The sigma of the count rate of ^{32}P based on Bos (10.11) is:

$$\sigma_{R_{32_P}} = \sqrt{{\sigma_{R_C}}^2 + {\sigma_{R_B}}^2} = \sqrt{152^2\ (cpm)^2 + 84^2 (cpm)^2} = \sqrt{30200}\ (cpm) = 174\ cpm$$

The sigma of the activity can be calculated using the efficiency of ^{32}P:

$$\sigma_{A_{32_P}} = \frac{\sigma_{R_{32_P}}}{\varepsilon_{32_P}} = \frac{174\ (cpm)}{0.66\ (\frac{cpm}{dpm})} = 263\ (dpm) = \frac{263\ (dpm)}{60\ (\frac{dpm}{Bq})} = 4.4\ Bq$$

The relative inaccuracy is then:

$$\sigma_{A_{32_P,rel}} = \frac{\sigma_{A_{32_P}}}{A_{32_P}} = \frac{4.4\ (Bq)}{203\ (Bq)} = 0.0216 = 2.2\%$$

Alternatively:

$$\sigma_{R_C} = \sqrt{\frac{R_C}{t}} = \sqrt{\frac{193\ (cps)}{30\ (s)}} = 2.5\ cps$$

$$\sigma_{R_B} = \sqrt{\frac{R_B}{t}} = \sqrt{\frac{59\ (cps)}{30\ (s)}} = 1.4\ cps$$

The sigma of the count rate of ^{32}P based on Bos (10.11) is:

$$\sigma_{R_{32_P}} = \sqrt{{\sigma_{R_C}}^2 + {\sigma_{R_B}}^2} = \sqrt{2.5^2\ (cps)^2 + 1.4^2 (cps)^2} = \sqrt{8.4}\ (cps) = 2.9\ cps$$

The sigma of the activity can be calculated using the efficiency of ^{32}P:

$$\sigma_{A_{32_P}} = \frac{\sigma_{R_{32_P}}}{\varepsilon_{32_P}} = \frac{2.9\ (cps)}{0.66\ (\frac{cps}{Bq})} = 4.4\ Bq$$

Scoring:

Problem 2	
Question	**Points**
2.1a	2
2.1b	3
2.2	3
2.3	3
2.4	3
2.5	3
Total	17

Problem 3. Abou's travels

Question 3.1

Use a calculation to demonstrate that the effective dose received by Abou from a single scan in the luggage scanner is equivalent to a few μSv. You may disregard the shielding provided by the conveyor belt and the suitcase for this question. Use the exposure at the level of the conveyor belt to calculate the effective dose.

Find the amount in appendix 1 <u>at 150 kV</u>: K_a = 18.3 mGy per mA min at 1 m

exposure = 0.2 (mA) × 20×10^{-3} s/60 (s/min) = 6.7×10^{-5} mA min
distance = 63.5 cm = 0.635 m
kerma = 18.3 (mGy per mA min) × 6.7×10^{-5} (mA min) × (1 m/0.635 m)^2
= 3.0 × 10^{-3} mGy = 3.0 μGy

Find the amount in appendix 2 at 100 kV: E (AP)/K_a = 1.3 Sv/Gy
→ E (AP) = 3.0 (μGy) × 1.3 (Sv/Gy) = 3.9 μSv/scan.

Question 3.2

Calculate the average ambient dose equivalent rate (in μSv/h) at 10 cm above the top of the luggage scanner (A, Figure 1). You may disregard the shielding provided by the conveyor belt, the suitcase and the wall of the scanner for this question.

Find the amount in appendix 2 at 100 kV: H*(10)/K_a = 1.65 Sv/Gy

→ H* (10) = 3.0 (μGy) × 1.65 (Sv Gy) = 5.0 μSv/scan at 63.5 cm height

number of scans per hour = 10 (per min) × 60 (min/h) = 600 per hour

distance = 63.5 (cm) + 47 (cm) + 10 (cm) = 120.5 cm

→ H* (10) = 600 (per hour) × 5.0 (μSv) × (63.5 cm/120.5 cm)^2
= 8.3 × 10^2 μSv/h.

Question 3.3

Lead shielding is placed on the top of the scanner (B, Figure 1). Calculate the minimum required lead thickness to meet the legal requirement for radiation leakage for inherently safe devices. Round the result off to the nearest 0.5 mm.

limit = 1 μSv/h
required transmission = 1 (μSv/h)/8.3×10^2 (μSv/h) = 0.0012
Find in Figure 1 for 150 kV and 0.0012 × 18.3 (mGy) = 0.022 mGy
→ 0.17 cm = 1.7 mm lead
→ rounds off to 2.0 mm lead.

Question 3.4a

Calculate the maximum possible effective annual dose of the customs official caused by scattered radiation. You can assume that the area of the scattering surface is the same as the surface area of a suitcase with the maximum allowable dimensions, measured at point C (Figure 1), and with a scattering angle of 90°.

Primary kerma $K_{a,primary}$ = 3.0 µGy per scan
Number of scans per year = 600 (per hour) × 2000 (h/yr) = 1.2×10^{6} per year
Scattering surface area = 55 (cm) × 35 (cm) = 1925 cm^2
Linear interpolation in Table 1 at 90°
→ scattering coefficient = (0.05% + 0.14%)/2 = 0.095%
= 0.00095 per 400 cm^2 at 1 m

Scattered radiation $K_{a,scatter}$ = 3.0 µGy × 1.2×10^{6} (yr^{-1}) × 0.00095 × (1925 cm^2/400 cm^2) × (1 m/1.5 m)^2
= 7.3×10^{3} µGy/yr = 7.3 mGy/yr
→ E(AP) = 7.3 (mGy/yr) × 1.3 (Sv/Gy) = 9.5 mSv/yr.

Note: it is permitted to deviate from the linear interpolation if you can justify this.

Question 3.4b

Name at least one practically feasible measure that could reduce the radiation exposure of customs officials.

- fit flexible lead strips in the opening of the luggage scanner
- fit a transparent lead glass screen; a thickness of 1 to 2 mm lead equivalents should be sufficient (see Question 3.3)
- half a point will be deducted if only personal protective equipment is given as an answer, because this is not a practically feasible solution and it is not in keeping with the occupational hygiene strategy.

Assessment suggestions:

Problem 3	
Question	**Points**
3.1	4
3.2	3
3.3	4
3.4a	5
3.4b	1
Total	**17**

Problem 4. Production of 18F

Question 4.1

Calculate the activity of the ^{18}F that is produced if the water target enriched with ^{18}O is irradiated for two hours (= 120 minutes).

$A_t = \dot{P} \times (1 - e^{-\lambda t})$ and $\dot{P} = f \cdot \frac{m \cdot N_A}{M} \cdot \sigma \cdot \varphi$ and $m = \rho \cdot V$

$\dot{P} = f \times (m \cdot N_A/M) \times \sigma \times (I/q) = 0.97 \times (1.11\ (g/cm^3) \cdot 4.0\ (ml) \times 6.022 \cdot 10^{23}\ (mol^{-1})/20\ (g/mol)) \times 0.011 \cdot 10^{-24}\ (cm^2) \times (120 \cdot 10^{-6}\ (C \cdot s^{-1} \cdot cm^{-2})\ /1.60 \cdot 10^{-19}\ (C))$

$\dot{P} = 0.97 \times 1.34 \cdot 10^{23} \times 1.1 \cdot 10^{-26} \times 7.49 \cdot 10^{14}\ s^{-1} = 1.07 \cdot 10^{12}\ s^{-1}$

$A_t = \dot{P} \times (1 - e^{-\lambda t}) = \dot{P} \times (1 - e^{-\ln(2) \times t/T_{1/2}}) = \dot{P} \times (1 - e^{-\ln(2) \times 120\ (minutes)/109.7\ (minutes)})$

$A_t = 1.07 \cdot 10^{12}\ (s^{-1}) \times 0.5315 = 5.68 \cdot 10^{11}$ Bq = 0.57 TBq

Question 4.2

Calculate the minimum irradiation time(in number of whole half-lives) required to reach at least 95% saturation activity (maximum activity).

$1 - e^{-\ln(2) \cdot t/109.7} = 0.95$

$e^{-\ln(2) \cdot t/109.7} = 0.05$

$-\ln(2) \cdot t/109.7 = \ln(0.05)$

$t = 109.7 \cdot \ln(0.05)/(-\ln(2)) = 474$ min

the number of half-lives is 474/109.7 = 4.32 -> at least 5 half-lives

alternatively:

$1 - e^{-\ln(2) \cdot (t/T_{1/2})} = 0.95$

$e^{-\ln(2) \cdot (t/T_{1/2})} = 0.05$

$-\ln(2) \cdot t/T_{1/2} = \ln(0.05)$

$t = -\ln(0.05)/\ln(2) \times T_{1/2} = 4.32\ T_{1/2}$ -> at least 5 half-lives

Question 4.3

Calculate the length of the ^{18}F bolus and argue why the bolus in the described situation cannot be considered a point source.

Data: the source volume is 4.0 ml, the inside diameter of the pipe is 1.0 mm.

The length (L) of the bolus is: $L = volume/\pi \cdot r^2 = 4.0 / \pi \cdot (0.050)^2 = 509$ cm = 5.1 m

The source cannot be considered a point source because the distance to the source is much smaller (a factor of 20) than five times the largest dimension of the source.

Question 4.4

Calculate the ambient dose equivalent rate that the operator reads on the monitor (assume the amount of ^{18}F activity calculated in Question 4.1).

The formula for the irradiation rate of a shielded line source is described by:

$\dot{H}^*(10) = (h \cdot A \cdot \theta / r \cdot l)\, (1/\theta \cdot \mu d)^{½} \cdot B \cdot e^{-\mu d}$

Find $\mu_{concrete}$ in Appendix 2: $(\mu/\rho)_{concrete}$ (E = 0.5 MeV) = 0.0892 (cm^2/g), $\mu_{concrete} = (\mu/\rho)_{concrete} \times \rho_{concrete} = 0.0892\ (cm^2/g) \times 2.35\ (g/cm^3) = 0.210\ cm^{-1}$, $\mu_{concrete} \cdot d = 0.21\ (cm^{-1}) \cdot 25.0\ (cm) = 5.24 = 5.2$

Calculate the exposure build-up factor using Appendix 3:

B (E = 0.5 MeV and μd = 5.0) = 12.2
B (E = 0.5 MeV and μd = 6.0) = 15.9
using interpolation, it follows that B (E = 0.5 MeV and μd = 5.2) = 13.1

Calculate the angle (θ):

$\tan(\theta)$ is $5.1/1.25 = 4.08 \rightarrow \theta = 76.2^0$. Converted to radians, this is 1.33 rad

Calculate the ambient dose equivalent rate:

$\dot{H}^*(10) = (h \cdot A \cdot \theta / r \cdot l)\, (1/\theta \cdot \mu d)^{½} \cdot B \cdot e^{-\mu d} =$

$(0.166\ (\mu Sv \cdot m^2 \cdot h^{-1} \cdot MBq^{-1}) \cdot 568000\ (MBq) \cdot 1.33 / 1.25\ (m) \cdot 5.1\ (m)) \cdot (1 /$

$1.33 \cdot 5.2)^{½} \cdot 13.1 \cdot e^{-5,2} = 543\ \mu Sv/h = 0.54\ mSv/h$.

Using 0.5 TBq, the answer is then: 0.472 mSv/h = 0.47 mSv/h.

Scoring:

Problem 4	
Question	**Points**
4.1	3
4.2	3
4.3	3
4.4	7
Total	***15***