ANSWERS

Exam
Radiation protection expert on the level of coordinating expert

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Question 1: Ingestion of uranium in drinking water

Question 1.1a (5 points)

Calculate the activity of ^{238}U in 1 μg natural uranium.

$$\lambda_{U-238} = \frac{ln2}{T_{\frac{1}{2},U-238}} = \frac{ln2}{4.47\cdot10^{9}[\mathrm{y}]\times365.25[\frac{\mathrm{d}}{\mathrm{y}}]\times24[\frac{\mathrm{h}}{\mathrm{d}}]\times3600[\frac{\mathrm{s}}{\mathrm{h}}]} = 4.91\cdot10^{-18}s^{-1}$$ [1 point]

$$N = \frac{m\times N_A}{M} = \frac{10^{-6}[\mathrm{g}]\times6.022\cdot10^{23}[\mathrm{mol}^{-1}]}{238.0[\frac{\mathrm{g}}{\mathrm{mol}}]}\times\frac{99.2742\%}{100\%} = 2.51\cdot10^{15}\mathrm{atomen}$$ [3 points]

$$A_{U-238} = \lambda\times N = 2.51\cdot10^{15}\times4.91\cdot10^{-18}[\mathrm{s}^{-1}] = 0.0123\,Bq$$ [1 point]

Question 1.1b (2 points)

Calculate the total activity of the three uranium-isotopes in 1 μg natural uranium.

U-238 delivers 49% of the total activity, the total activity is therefore:

$$A=\frac{100\%}{49\%}\times0.0123\,[\mathrm{Bq}] = 0.025\,\mathrm{Bq}$$

Question 1.2 (3 points)

Determine the committed effective dose caused by drinking water with an average uranium content of 92.42 $\mu g/L$ for one year.

$$A_{tot} = 0.025\left[\frac{\mathrm{Bq}}{\mu\mathrm{g}}\right]\times92.42\left[\frac{\mu\mathrm{g}}{L}\right]\times2.0\left[\frac{L}{day}\right]\times365.25\left[\frac{day}{year}\right] = 1.7\,k\mathrm{Bq}$$ [2 points*]

$$E(50) = A_{tot}\times e(50) = 1.7\cdot10^{3}\,[Bq]\times4.4\cdot10^{-8}\left[\frac{Sv}{Bq}\right] = 73.7\,\mu Sv$$ [1 point]

* 365 days is also correct

Question 1.3 (2 points)

Based on the linear no-threshold hypothesis (LNT-hypothesis), calculate the expected number of cancer-related deaths caused by the committed effective dose calculated in question 1.2.
If you were unable to answer question 1.2, use E(50)=100 μSv.

$$73.7 \cdot 10^{-6} \left[\frac{\text{Sv}}{\text{y}}\right] \times \frac{5\% \left[\text{Sv}^{-1}\right]}{100\%} = 3.7 \cdot 10^{-6}\ \text{y}^{-1}$$

For 12 million inhabitants that would result in 12 × 3.7 = 44 deaths [2 points]

Question 1.4 (1 point)

Is calculating the number of deaths in Bangalore based on the LNT-hypothesis in line with the recommendations of the ICRP?
Substantiate your answer.

No, due to biological and statistical uncertainties the ICRP strongly discourages calculating the hypothetical number of cancer cases or people with hereditary diseases based on low doses received by a large group of people over extended periods of time*.

**ICRP 103 pg. 51 lid 66*

Point rating:

Question 1	
Question	**Points**
1.1a	5
1.1b	2
1.2	3
1.3	2
1.4	1
Total	***13***

Question 2: Checking the level of enrichment

Question 2.1 (4 points)

Calculate the counting efficiency based on the measurement of the natural RbCl. Give the answer in tps/Bq.

1 g natural rubidium chloride contains 653 Bq (see given)
10 mg natural rubidium chloride will then contain 6.53 Bq

$$\varepsilon = \frac{R}{A} = \frac{\left(\frac{7520-1670}{1000}\right)[\text{tps}]}{6{,}53\ [\text{Bq}]} = \frac{5.85\ [\text{tps}]}{6.53\ [\text{Bq}]} = 0.896\ \text{tps/Bq}$$

Question 2.2 (4 points)

Calculate the relative standard deviation of the counting efficiency (calculated for question 2.1).

$$\sigma_{N_A - N_{\text{background}}} = \sqrt{\sigma_A{}^2 + \sigma_{\text{background}}{}^2} = \sqrt{N_A + N_{background}} = \sqrt{7520+1670} = 96\ \text{counts}$$

This is $\frac{96}{7520-1670} \times 100\% = 1.6\%$ of the net number of counts and therefore also 1.6% of the calculated counting efficiency.

Question 2.3 (4 points)

Does the level of enrichment of the supplied RbCl correspond to what was ordered? Support your answer with a calculation.

Quick estimation:
Abundance enriched material = 27.83% x (12110-1670/7520-1670) = 49.7%
49.7% << 99%

Alternative method:
1 gram natural RbCl contains 27.83% radioactive Rb and is 653 Bq
99%/27.83% × 653 Bq = 2323 Bq = $2.3 \cdot 10^3$ Bq

Based on this calculation the 10 mg 99% enriched RbCl should contain 23 Bq.
The activity in this sample is actually, based on the measurement with the liquid scintillation counter:

$$R_{netto} = \frac{12110-1670}{1000} = 10.44\ \text{tps}$$

The activity of 10 mg 99% enriched RbCl is:

$$A = \frac{R}{\varepsilon} = \frac{10.44}{0.896} = 11.7\ \text{Bq}$$

The activity present is about half the promised activity. The discrepancy between the measured value and promised value is much larger than the standard deviation of the measurement, and it has therefore been established that the supplied rubidium chloride is less than 99% enriched.

Question 2.4 (3 points)

Explain why in this case the liquid scintillation measurement is a better detection method than a contamination monitor.

LSC gives the highest counting efficiency. Combined with the low activity of the sample, any other method using a contamination monitor would yield results with very large uncertainties.

Point rating:

Question 2	
Question	**Points**
2.1	4
2.2	4
2.3	4
2.4	3
Total	***15***

Question 3: ^{99m}Tc-generators

Question 3.1 (4 points)

Show through a calculation that the dose at the surface of the collo is practically exclusively caused by the 740 keV and 778 keV photons of ^{99}Mo. Do this by calculating the transmission of the 181 keV and 740 keV photons through the lead shielding.

181 keV:

d= 2.5 cm lead
μ/ρ= 1.415 cm^2/g [interpolation of correct estimation based on table D]
ρ lead = 11.34 g/cm^3
μ= 1.415 cm^2/g × 11.34 g/cm^3 =16.05 cm^{-1}
μd = 16.05 cm^{-1} × 2.5 cm= 40
B = 2

T= $e^{-\mu d}$ × B = e^{-40} × 2 = $8.5 \cdot 10^{-18}$ = nil

740 keV:

d= 2.5 cm lead
μ/ρ= 0.0995 cm^2/g
ρ lead = 11.34 g/cm^3
μ= 0.0995 cm^2/g × 11.34 g/cm^3 =1.128 cm^{-1}
μd = 1.128 cm^{-1} × 2.5 cm= 2.8
B = 1.7

T= $e^{-\mu d}$ × B = $e^{-2.8}$ × 1.7 = 0.1 (10%)

Conclusion: the contribution of the 181-keV photons is negligible compared to the 740-keV photons

Question 3.2 (5 points)

Calculate the ambient dose equivalent rate (caused by the 740 keV and 778 keV photons of ^{99}Mo) at the surface of a collo when leaving the airport.

For a radionuclide emitting a number of different photon energies, where the shielding ensures a near complete shielding of the lower photon energies, a H*(10) calculation using the ambient dose equivalent rate constant (h) will yield an overestimation. It is more accurate to do an H*(10) calculation based solely on the 740 keV and 778 keV photons. This is possible using the rule of thumb for air kerma (attachment pg. 5) where air kerma can be calculated per photon energy. The transmission can also be determined per photon energy.

740 keV:

$$\dot{K} = \frac{\Gamma \times A}{r^2} \times T$$

$\Gamma = \frac{1}{8}(E_\gamma \times y) = \frac{1}{8} \times (0.74 \times 0.123) = 0.0113$ μGy m² MBq^{-1} h^{-1}

A = 10 000 MBq

d=2.5 cm

r= 0.195 m

T (740 keV) through 2.5 cm lead = 0.1 (see question 1)

$$\dot{K} = \frac{0.0113 \times 10000\ [MBq]}{0.195^2} \times 0.1 = 300\ \mu Gy \cdot h^{-1}$$ (1 pt)

778 keV:

$$\dot{K} = \frac{\Gamma \times A}{r^2} \times e^{-\mu d} \times B$$

$\Gamma = \frac{1}{8}(E_\gamma \times y) = \frac{1}{8} \times (0.778 \times 0.043) = 0.0042$ μGy m² MBq^{-1} h^{-1}

A = 10 000 MBq

d= 2.5 cm

r= 0.195 m

T (778 keV) = $e^{-\mu d} \times B = e^{-2,6} \times 1.7 = 0.126$

μ/ρ= 0.0926 cm²/g

ρ lead = 11.34 g/cm³

μ= 0.0926 cm²/g × 11.34 g/cm³ =1.05 cm^{-1}

μd = 1.05 cm^{-1} × 2.5 cm= 2.6

B = 1.7

$$\dot{K} = \frac{0.0042 \times 10000\ [MBq]}{0.195^2} \times 0.123 = 136\ \mu Gy \cdot h^{-1}$$ (1 pt)

$\dot{K}_{(740\ kev)} + \dot{K}_{(778\ keV)} = 300 + 139 = 436\ \mu Gy \cdot h^{-1}$

In attachment 3 the conversion factor from kerma to H*(10) can be found:

H*(10)/Ka = 1.18

1.15 – 1.2 is also correct. Use of rule of thumb H*(10)=1/7 y.E is correct

$\dot{H}$*(10) = $\dot{K}$ × 1.18 = 436 μGy· h^{-1} × 1.18 = 514 μSv/h = 0.5 mSv/h

1 pt for correct μ or d½ (T of 778 keV)

2 pt for determining kerma constant using rule of thumb or by reading x yield

1 pt for converting Γ → h, or K [Gy]→H*(10) [Sv]

1 pt for the correct final answer

Calculating using the ambient dose equivalent rate constant and transmission of 740 keV photons would result in 0.7 mSv/h: 2 pt instead of 5 pt.

Because the energies of 740 and 778 keV are close together, one can also choose to calculate the total kerma of $\frac{1}{8}\Sigma(E_\gamma \times y)$ combined with the transmission value of 778 keV

Question 3.3 (3 points)

Calculate the transportation index and indicate which danger label should be attached to each collo (see attachment, pg. 8). Motivate your answer.
If you were unable to find the answer to question 3.2 you can assume 600 µSv/h.

1 meter from the surface, so 1.195 meter from the point source:
514 µSv/h x $\left(\frac{0.195}{1.195}\right)^2$ = 13.7 µSv/h → T.I. = 1.4

For yellow-III applies:
at surface of collo: 500 – 2000 µSv/h
T.I.: 1-10

This collo: yellow-III.
Correct transport index 1 pt
Correct motivation and conclusion (dose at surface , T.I. and sticker type) 2 pt

Question 3.4 (4 points)

What is the effective dose the driver received in the first four weeks? The decay of ^{99}Mo can be neglected for this calculation.

H*(10) for 1 collo = 68.5 µSv/h (decay can be neglected)

Each Saturday:
First three hours (six colli), driver dose during transport:
3 [h] × 6 x 68.5 [µSv/h] = 1233 µSv

Second three hours (three colli), driver dose during transport:
3/6 colli x 1233 = 616.5 µSv
Or
3 hours x 3 colli x 68.5 µSv = 616.5 µSv
(2 pt for the correct calculation of the two different routes)

Exposure per Saturday:
6 colli for 3 hours (airport to A) and 3 colli for 3 hours (A to B)
1233 µSv + 616.5 µSv = 1849.5 µSv per week.

Exposure for the entire month:
4 Saturdays x 1849.5 µSv = 7.4 mSv
H*(10) = E (see given)

E = 7.4 mSv
(2 pt for adding to the correct final answer)

Point rating:

Question 3	
Question	**Points**
3.1	4
3.2	5
3.3	3
3.4	4
Total	***16***

Question 4: Positioning a CT scanner

Question 4.1 (4 points)

Calculate the effective yearly dose behind the lead containing wall at position P generated only by the C-arm. The kerma due to scattered radiation at 3 meters distance amounts to K_a = 0.6 µGy per Gy·cm^2 (read from attachment, pg. 12).

At 3 meter: 20 [Gy·cm^2] × 0.6 [µGy/Gy·cm^2] × 800 examinations per year = 9600 µGy/year

At 4 meter: 9600 [µGy/year] × $\left(\frac{3}{4}\right)^2$ = 5.4 mGy/year.

The conversion factor E(AP)/Ka = 1.4 Sv/Gy, so

E(AP) = 5400 [µGy/year] × 1.4 [Sv/Gy]= 7560 µSv/year = 7.6 mSv/year

Shielded by 1 mm lead:

T read from 1.0 mm: T= 0.004

7.6 [mSv/year] x 0.004 = 30 µSv/year

1 pt for correct distance correction

1 pt for including DAP and number of examinations

1 pt for correct use of the conversion factor

1 pt for correct shielding

Question 4.2 (5 points)

Calculate the required thickness of the lead glass in mms if the total effective dose in P is not allowed to exceed 50 µSv/year.

From the scattering diagram of the CT-scanner: 1 µGy at 200 mAs at a distance of approximately 2.6 meter.

Per year at 2.6 meter: $\frac{51850000}{200} \times$ 1 [µGy] = 26·10^4 µGy/year

K_a at 5 meters distance (point P): 26·10^4 [µGy/year] × $\left(\frac{2.6}{5}\right)^2$ = 70304 µGy/year

The conversion factor E(AP)/K_a = 1.4 Sv/Gy, so

E(AP) = 70304 [µGy/year] × 1.4 [Sv/Gy]= 98426 µSv/year

The C-arm already contributes 30 μSv/year. The total dose as a result of the CT scanner and the C-arm is not allowed to exceed 50 μSv/year, and the contribution of the CT scanner is thus not allowed to exceed 20 μSv/year.

$$T = \frac{20\ [\mu Sv/year]}{98426\ [\mu Sv/year]} = 2 \cdot 10^{-4}$$

According to the attachment on pg. 9, this corresponds to 1.9 mm lead equivalent. The table of the attachment on pg. 10 gives for 90 kV and 1.9 mm lead equivalent a lead glass thickness of 5.7 mm. When rounding this to the nearest mm, this corresponds to 6 mm lead glass.

Question 4.3 (4 points)

Determine whether the contribution of the CT scanner to the effective dose on the site boundary is lower than the secondary level.

From the scattering diagram of the CT scanner at 2.3 meter at the rear: 1 μGy per 200 mAs

Per year this is $K_a = 1\ [\mu Gy] \times \frac{51850000}{200}$ = 259250 μGy/year

The conversion factor $E(AP)/K_a$ = 1.4 Sv/Gy, so without shieling the effective dose comes down to

E(AP) = 259250 [μGy/year] × 1.4 [Sv/Gy]= 363 mSv/year

The ratio of the specific weight of normal concrete compared to aerated concrete: 2400/600 = 4 times lower specific weight. This means that 10 cm aerated concrete corresponds to 2.5 cm normal concrete. A wall thickness of 20 cm concrete and 10 cm aerated concrete therefore corresponds to a thickness of 225 mm of normal concrete.

The transmission of X-rays through concrete as found in the transmission graph yields for 90 kV: T = ± 0.00006 (1 pt for values between 0.00005 and 0.00007)

So E = 363 [mSv/year] × 0.00006 = 22 μSv/year

This exceeds 10 μSv/year (the secondary level for external radiation).

Question 4.4 (4 points)

Calculate, using the iso kerma map of the C-arm (attachment, pg. 12), whether the equivalent dose limit of the eye lens of the radiologist is exceeded.

In the attachment on pg. 12 can be found that at 100 cm: ± 4 $\mu Gy/Gy \cdot cm^2$

At 80 cm this is $(100/80)^2 \times 4$ [$\mu Gy/Gy \cdot cm^2$] = 6.25 $\mu Gy/Gy \cdot cm^2$

Kerma at 80 cm: DAP × K_A/DAP =

20 [$Gy \cdot cm^2$] × 6.25 [$\mu Gy/Gy \cdot cm^2$] = 125 µGy per examination

K_a =125 µGy per examination × 200 examinations per year = 25 mGy/year

$D_{eye\ lens}$ = K_a × $D_{eye\ lens}$ /K_a = 25 [mGy/year] × 1.9 [Gy/Gy] = 47.5 mGy/year

$H_{eye\ lens}$ (Sv) = $D_{eye\ lens}$ [Gy] × 1 [Sv/Gy] = 47.5 mSv/year

This exceeds the limit of 20 mSv/year.

2 pt for correctly reading the iso kerma map and distance correction

1 pt for converting per year (multiplying with DAP value, 200 examinations per year per radiologist)

Converting K_a-D and $D_{eye\ lens}$ – $H_{eye\ lens}$ (correct unit) together 1 pt

Point rating:

Question 4	
Question	**Points**
4.1	4
4.2	5
4.3	4
4.4	4
Total	***17***