Problem 1. The route of a ^{99m}Tc cow

Question 1.1a

When (date and time) was the generator dispatched by the manufacturer according to the information on the transport label?

The calibration information is Friday 28 April, 6.00, 25.8 GBq ^{99}Mo.
The generator was sent with a maximum activity of 88.25 GBq.
The isotope that determines the decay rate in the generator is ^{99}Mo.

$$A_t = A_0 \times 0{,}5^{t/T½}$$

$$25{,}8\ [\text{GBq}] = 88{,}25\ [\text{GBq}] \cdot 0{,}5^{t\ [\text{uur}]/65{,}94\ [\text{uur}]}$$

$$\log \frac{25{,}8\ [\text{GBq}]}{88{,}25\ [\text{GBq}]} = t\ [\text{uur}]/65{,}94\ [\text{hour}] \times \log 0{,}5$$

$$-0.534 = t/65.94 \times -0.301$$

t = 117 hours = 4 days and 21 hours.
The generator may be dispatched as of Sunday (23 April), 9.00 a.m.

Question 1.1b

Calculate the transmission of the total package of the generator based on the information entered by the manufacturer on the label.

$$\dot{H}^*(10) = 13\ \mu\text{Sv}\cdot\text{h}^{-1} = \frac{0{,}026\ [\mu\text{Sv}\cdot\text{MBq}^{-1}\cdot\text{m}^2] \times 88{,}25\cdot 10^3 [\text{MBq}]}{1{,}195^2 [\text{m}^2]} \times T$$

$T = 8.1\cdot 10^{-3}$ (= 0.0081 = 0.81%)

Question 1.2

Estimate the highest ambient dose equivalent rate at a distance of 1 metre from the packaged generator for Monday 15 May and also determine the TI for the same date.

88.25 GBq results in a transport index (TI) of 1.3.

This means that the ambient dose equivalent rate is approximately 13 µSv/hour at a distance of 1 metre.
The ambient dose equivalent rate is ‘proportionate’ to the activity with the same package.

$$\dot{H}^*(10) = 13\ [\mu Sv \cdot h^{-1}] \times \frac{340\ [MBq]}{88{,}25 \cdot 10^3 [MBq]} = 0{,}050\ \mu Sv/uur$$

Alternative: The calculation of 1.1b can also be repeated with the activity on 15 May and the calculated transmission.

$$\dot{H}^*(10) = \frac{0{,}026\ [\mu Sv \cdot MBq^{-1} \cdot m^2] \times 340\ [MBq]}{1{,}195^2 [m^2]} \times 8{,}1 \cdot 10^{-3} = 0{,}050\ \mu Sv/uur$$

0.050 $\mu Sv \cdot h^{-1}$ divided by 10 results in TI = 0.005
After rounding off to 1 decimal and rounding off upwards, TI = 0

Question 1.3

Based on the assumptions of the anticipated unintended event, calculate the ambient dose equivalent in the area of the hands of the person cleaning up the puddle. For the sake of simplicity, the puddle of 10 ml may be regarded as a point source.

$$A_t = A_0 \times 0{,}5^{t/T½}$$

$$A_t = 1500\ [MBq] \cdot 0{,}5^{3\ (uur)/6\ (uur)} = 1{,}061\ MBq$$

5% of this amount = 53.0 MBq of ^{99m}Tc

Hands:

$$H^*(10) = \frac{0{,}023\ [\mu Sv\ h^{-1} MBq^{-1} m^2] \times 53{,}0\ [MBq]}{0{,}01^2 [m^2]} \times \frac{1}{60}\ [h] = 203\ \mu Sv = 0{,}20\ mSv$$

Question 1.4

Calculate the activity of ^{99}Tc in the ground.

The administered activity of ^{99m}Tc is, cumulative over 40 years (without decay):

$(100 \times 1.50 \cdot 10^9\ [Bq] + 100 \times 1.50 \cdot 10^8\ [Bq]) \cdot year^{-1} \times 40\ years = 6.60 \cdot 10^{12}\ Bq$

Radiochemically, ^{99m}Tc and ^{99}Tc are mother-daughter nuclides, but there is no equilibrium. All ^{99m}Tc cores became ^{99}Tc cores in a relatively short time. ^{99}Tc has a very long half-life; the decrease in the ^{99}Tc activity in those 40 years does not need to be taken into account.
The connecting link is the number of cores (N).

General: $A = \lambda \times N$

$A_{Tc\text{-}99m} = \lambda_{Tc\text{-}99m} \times N$ and also $A_{Tc\text{-}99} = \lambda_{Tc\text{-}99} \times N$

$$N = \frac{A_{Tc\text{-}99m}}{\lambda_{Tc\text{-}99m}} = \frac{A_{Tc\text{-}99}}{\lambda_{Tc\text{-}99}}$$

$$A_{Tc\text{-}99} = A_{Tc\text{-}99m} \times \frac{\lambda_{Tc\text{-}99}}{\lambda_{Tc\text{-}99m}} = 6{,}66 \cdot 10^{12}\ [\text{Bq}] \times \frac{1{,}03 \cdot 10^{-13}\ [\text{s}^{-1}]}{3{,}21 \cdot 10^{-5}\ [\text{s}^{-1}]} = 21{,}4 \cdot 10^{3}\ \text{Bq}$$

Alternative: This activity of the daughter ^{99}Tc can also be calculated with a formula such as 1.15 from *Inleiding tot de Stralingshygiëne* [Introduction to Radiation Protection], A.J.J. Bos et al, 2nd edition, 2007. This alternative takes more time.

^{99}Mo decays with a yield of 0.876 to ^{99m}Tc. And also with a yield of 0.124 directly to ^{99}Tc. This ^{99}Tc also ends up in the eluate, and has also been injected into animals and has entered the ground.
The maximum ^{99}Tc activity that entered the ground at the animal enclosures in 40 years =

$$A_{Tc\text{-}99} = 21{,}4 \cdot 10^{3}\ [\text{Bq}] \times \frac{1}{0{,}876} = 24{,}2 \cdot 10^{3}\ \text{Bq}$$

Scoring:

Problem		
Question	**Points**	**Assessment agreements**
1a	3	
1b	3	For the greatest accuracy, TI = 1.3 must be used, otherwise -1 pt
2	3	
3	3	
4	5	Forgotten x40 years: -1 pt Omitted 1/0.876: -0 pt
Total	***17***	

Problem 2. Contamination during ^{131}I therapy

Question 2.1

Explain why continuously emptying the bladder can lead to a significant dose reduction for the patient. Use the absorption progression and decay diagram for this purpose.

Three possible explanations:

1. According to the Figure “Progression of ^{131}I absorption including decay in two organs...” the largest part of the administered activity is absorbed by the bladder.
2. In particular, the beta radiation will cause a high absorbed dose in the bladder.
3. Since the bladder is a radiation-sensitive organ, the quick discharge of the activity from the bladder leads to a significant dose reduction for the patient.

Question 2.2

Using the ambient dose equivalent rate, demonstrate that the activity of the remaining urine in the collection container is around 3 GBq. You can assume a point source geometry for the calculation.

$\dot{H}*(10)$ = h(10) × A / r^2, therefore: A = $\dot{H}*(10)$ × r^2 / h(10) =

= 22 [µSv/h] × 3.0^2 [m^2] / 0.066 [µSv·m²·MBq^{-1}·h^{-1}] = $3.0 \cdot 10^3$ MBq = 3.0 GBq

Question 2.3

Estimate the activity of the ^{131}I in the thyroid of the contaminated employee at the time of the measurement.

A (Bq) = R_n (counts·s^{-1}) / (y (photon·disintegration^{-1}) × ε (counts·photon^{-1})) = ((567 / 60) – (80 / 60)) / (0.812 × $1.0 \cdot 10^{-3}$) = 10 kBq

Question 2.4

Estimate the committed effective dose for the contaminated employee. Assume internal contamination resulting from the inhalation of sodium iodide and use Appendix 2.

The intake is estimated on the basis of the measured thyroid absorption and the absorption fraction in the thyroid 24 hours after the intake based on the table for thyroid counts from the information in the Radionuclide Handbook in the appendix.

Absorption fraction = $1.2 \cdot 10^{-1}$ (category F)

Intake is $10 / 1.2 \cdot 10^{-1} = 83.3$ kBq

The committed effective dose $E_{50} = A \times e_{50,\,inh} = 83.3 \cdot 10^{3}$ [Bq] $\times\ 1.1 \cdot 10^{-8}$ [Sv/Bq] = 0.92 mSv.

Scoring:

Problem 2		
Question	**Points**	
2.1	4	
2.2	4	
2.3	4	
2.4	4	
Total	***16***	

Problem 3. Release of absolute filters

Question 3.1

Demonstrate that the efficiency of the set-up for ^{57}Co energy of 136 keV is equal to $4.5 \cdot 10^{-4}$ counts per photon.

t= 1/12/2016 – 1/4/2015 = 610 d (2016 is a leap year)

$$A(t) = A(0) \times \left(\frac{1}{2}\right)^{\frac{t}{T_{1/2}}} = 469\,[kBq] \times \left(\frac{1}{2}\right)^{\frac{610}{271,84}} = 99\ kBq$$

$N_n = N_g - N_b = 50.2 \cdot 10^3 - 41.7 \cdot 10^3 = 8.5 \cdot 10^3$ counts
$R_n = N_n / t_n = 8.5 \cdot 10^3$ [counts] / 1800 [s] $= 4.72\ s^{-1}$

$$\varepsilon = \frac{R_n}{A \times y_{136}} = \frac{4,72\,[s^{-1}]}{99 \cdot 10^3\,[Bq] \times 0,106\,[(Bq \cdot s)^{-1}]} = 4,5 \cdot 10^{-4} \text{ counts per foton}$$

Question 3.2

Verify that the yield of 141-keV photons of ^{99}Mo in equilibrium with ^{99m}Tc is equal to 0.828 $(Bq \cdot s)^{-1}$.

via the decay of ^{99}Mo:		0.049 $(Bq \cdot s)^{-1}$
via the decay of ^{99m}Tc:	0.876 × 0.889 =	0.779 $(Bq \cdot s)^{-1}$

The total is therefore y_{141} = 0.049 $(Bq \cdot s)^{-1}$ + 0.779 $(Bq \cdot s)^{-1}$ = 0.828 $(Bq \cdot s)^{-1}$

Question 3.3

Demonstrate that both the MDA for the total activity (^{99}Mo and ^{99m}Tc) and the MDC for the activity concentration are smaller than the release limits for ^{99}Mo.

$R_{min} = 3 \times \sqrt{(50.9 \cdot 10^3)}$ / 1800 [s] $= 0.38\ s^{-1}$

$$A_{\min} = \frac{R_{\min}}{\varepsilon \times y_{141}} = \frac{0,38\,[s^{-1}]}{4,5 \cdot 10^{-4} \times 0,828\,[(Bq \cdot s)^{-1}]} = 1,02\ kBq$$

MDA = 1 kBq
A_v = 1 MBq
MDC = 1 kBq / 3200 g = 0.3 $Bq \cdot g^{-1}$
C_v = 100 $Bq \cdot g^{-1}$
Both the MDA and the MDC are under the release limits.

Question 3.4a

Using the measurement of the absolute filter, determine the maximum amount of activity
(^{99}Mo and ^{99m}Tc) *present in the absolute filter, including the 95% confidence interval (2σ) of that activity.*

$N_n = N_g - N_b = 331.3 \cdot 10^3 - 50.9 \cdot 10^3 = 280.4 \cdot 10^3$
$R_n = 280.4 \cdot 10^3$ / 1800 [s] = 156 s^{-1}

$$A_{\min} = \frac{R_{\min}}{\varepsilon \times y_{141}} = \frac{156\,[s^{-1}]}{4{,}5 \cdot 10^{-4} \times 0{,}828\,[(Bq \cdot s)^{-1}]} = 419\ kBq$$

$\sigma_g = \sqrt{(331.3 \cdot 10^3)}$ / 1800 [s] = 0.320 s^{-1}

$\sigma_b = \sqrt{(50.9 \cdot 10^3)}$ / 1800 [s] = 0.125 s^{-1}

$\sigma_R = \sqrt{(\sigma_g^2+\sigma_b^2)} = \sqrt{(0.102+0.0157)} = 0.343\ s^{-1}$

$$\sigma_A = \frac{\sigma_R}{\varepsilon \times y_{141}} = \frac{0{,}343\,[s^{-1}]}{4{,}5 \cdot 10^{-4} \times 0{,}828\,[(Bq \cdot s)^{-1}]} = 0{,}92\ kBq$$

A + 2σ = 419 [kBq] + 2 × 0.92 [kBq] = 421 kBq

Question 3.4b

Determine whether this absolute filter can be released, assuming that no other radionuclides have been found besides ^{99}Mo/^{99m}Tc.

The release limit for the activity is A_v = 1 MBq. The total activity in the filter is 421 kBq. This is under the release limit.
The release limit for the activity concentration is C_v = 100 Bq·g^{-1}. The activity concentration in the filter is 421 [kBq] / 3200 [g] = 132 Bq·g^{-1}. This exceeds the release limit.
The absolute filter can be released, because only one of the two limits was exceeded.

Scoring:

Problem 3	
Question	**Points**
3.1	4
3.2	3
3.3	4
3.4a	4
3.4b	2

Total	***17***

Problem 4. Lecture bottle

Question 4.1

Demonstrate that all β-particles originating from the decay of ^{14}C enter the wall of the gas bottle.

The maximum energy of β-particles originating from the decay of ^{14}C amounts to $E_{\beta,max}$ = 156 keV = 0.156 MeV. The reduced electron range is greatly overestimated for this energy due to the standard approach

$$R_{\beta,max} \text{ (in cm)} \times \rho \text{ (in g}\cdot\text{cm}^{-3}) = 0.5\, E_{\beta,max} \text{ (in MeV)}$$

whereby ρ is the density of iron. Entering the given values in this formula results in $R_{\beta,max}$ = (0.5 x 0.156) / 7.9 = 0.010 cm = 0.1 mm.
This value is much smaller than the wall thickness of the gas bottle (3 mm). All β-particles will therefore enter the wall.
Although unnecessary, a better approach may be used, of course. To give an indication: the formula of Flammersfeld yields the answer 0.034 mm.

Question 4.2

Calculate the 'effective' value of μ/ρ of iron for the bremsstrahlung of ^{14}C, based on the transmission of iron. Using this value, determine the 'effective' photon energy E_{photon} (in other words, the energy corresponding to the calculated value of μ/ρ) of the bremsstrahlung.

Reading Figure 3 with d = 3.0 mm = 0.30 cm results in T = 0.02; given: B = 1
$T = B\, e^{-\mu d} = e^{-\mu d} = 0.02$

$\rightarrow$ $\mu d = -\ln(0.02) = 3.91$

$\mu/\rho = 3.91 / (0.30\ [\text{cm}] \times 7.9\ [\text{g}\cdot\text{cm}^{-3}]) = 1.65\ \text{cm}^2\ \text{g}^{-1}$

Linear interpolation of Appendix 2 yields E_{photon} = 0.054 MeV; a rough estimate between 0.05 and 0.06 MeV is also considered satisfactory.
(this is nearly equal to the average β-energy $\langle E_\beta \rangle$ = 49 keV = 0.049 MeV)

Question 4.3a

Calculate the total bremsstrahlung energy per unit of time (in MeV s^{-1}). For this calculation, use the fraction g of the β-energy emitted per unit of time.

The fraction converted into bremsstrahlung is

$$g = 2\cdot10^{-4} \times 26 \times 0.156\ [\text{MeV}] = 8.1\cdot10^{-4}$$

The total activity is A = 480 MBq and the average β-energy is 49 keV = 0.049 MeV. The total emitted β-energy per unit of time is therefore

$$E_\beta = A \times \langle E_\beta \rangle = 480\ [\text{MBq}] \times 0.049\ [\text{MeV}] = 23.5\cdot10^6\ \text{MeV s}^{-1}$$

The total bremsstrahlung energy produced per unit of time is

$$E_{brem} = g \times E_\beta = 8.1\cdot10^{-4} \times 23.5\cdot10^6\ [\text{MeV}\cdot\text{s}^{-1}] = 1.90\cdot10^4\ \text{MeV s}^{-1}$$

Question 4.3b

Calculate the average flux density or fluence rate φ (in photons·cm^{-2} s^{-1}) that produces the imaginary linear photon source on the exterior of the gas bottle (see Figure 3). You do not need to take the ends of the gas bottle into account; you can assume that the photons exclusively come into contact with the inside of the side wall.

The transmission of the cylinder wall for bremsstrahlung is T = 0.02 (see Figure 3).
The distance between the central line and the exterior of the cylinder is

$$r = 0.5 \times 3.2\ [\mathrm{cm}] = 1.6\ \mathrm{cm}$$

Length of the cylinder is l = 18 cm
The surface area of the cylinder is

$$S = 2\pi \times r \times l = 2\pi \times 1.6\ [\mathrm{cm}] \times 18\ [\mathrm{cm}] = 181\ \mathrm{cm}^2$$

The flux density is

$$\varphi = T \times (E_{brem} / E_{photon}) / S$$
$$= 0.02 \times (1.90 \cdot 10^4\ [\mathrm{MeV \cdot s^{-1}}] / 0.054\ [\mathrm{MeV}]) / 181\ \mathrm{cm}^2$$
$$= 39\ \mathrm{photons \cdot cm^{-2}\ s^{-1}}$$

Question 4.4

Based on the answer to Question 3b,calculate the ambient dose equivalent rate $\dot{H}^*(10)$ (in *µSv·h^{-1}*)*on the exterior of the gas bottle. If you were unable to obtain the answer to Question 3b, use* $^{40\ photons\cdot}$*cm^{-2}·s^{-1}.*

Linear interpolation of Appendix 3 results in H*(10)/Φ = 0.53 pSv·cm^2

$$\rightarrow \quad \dot{H}^*(10) = 0.53\ \mathrm{pSv \cdot cm^2} \times 39\ \mathrm{cm^{-2} \cdot s^{-1}} \times 3600\ \mathrm{s \cdot h^{-1}}$$
$$= 74 \cdot 10^3\ \mathrm{pSv \cdot h^{-1}} = 0.074\ \mu\mathrm{Sv\ h^{-1}}$$

Working with 40 photons·cm^{-2}·s^{-1} yields the final answer $\dot{H}^*(10)$ = 0.076 µSv·h^{-1}

Scoring:

Problem 4		
Question	**Points**	**Assessment agreements**
4.1	3	
4.2	4	Reading with a thickness other than 3 mm: -1 pt
4.3a	3	
4.3b	3	
4.4	4	
Total	***17***	