EMBARGO **December 13th 2021**

ANSWERS

Exam
Radiation protection expert on the level of coordinating expert

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Nuclear Research and consultancy Group	NRG
Delft University of Technology	TUD
University of Groningen	RUG
Radboudumc	RUMC

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exam date: December 13th 2021

- These solutions are meant as a guideline for correctors. The corrector can deviate from these with proper argumentation per sub question. The examination candidate cannot derive any rights from the proposed point distribution.

Question 1: Risk inventory and evaluation (RI&E) veterinary clinic [19 points]

Question 1.1 [5 points]

Calculate the dose area product per image [in Gy·cm^2].

Read from caption attachment 1 yields: 6.1 $mGy \cdot m^2 \cdot mA^{-1} \cdot min^{-1}$ [1 point]

$$6.1\ [mGy \cdot m^2 \cdot mA^{-1} \cdot min^{-1}] \times \frac{1^2\ [m^2]}{1.1^2\ [m^2]} \times 8.0\ [mA \cdot s] \times \frac{1}{60} [min \cdot s^{-1}] \times 10^{-3} \left[\frac{Gy}{mGy}\right] \times 600\ [cm^2] = 0.4\ Gy \cdot cm^2$$

Other operations; 1 point per processing step [3 points]
Calculation (incl. converting units) [1 point]

Question 1.2a [2 points]

Argue why, for increasing lead thickness, all curves approach a value which is significantly lower than 100%.

The protection efficiency indicates the effect of the lead apron on the effective dose. Because various parts of the body (amongst which the thyroid, salivary glands, part of the skin and the brain) are not protected, even an apron that completely stops all radiation from passing through would not protect for 100%.

Question 1.2b [4 points]

Calculate the yearly effective dose for the vet.

Read protection efficiency just below the 70 kV line: range 80-83% is considered correct. [1 point]

$$0.4\ [Gy \cdot cm^2 \cdot image] \times 1000 [images \cdot year^{-1}] \times 16.0\ [\mu Gy \cdot (Gy \cdot cm^2)^{-1}] \times 0.8 [Sv \cdot Gy^{-1}] \times (1 - 0.83) = 8.7 \cdot 10^2 \mu Sv = 0.9\ mSv$$

Correction protection efficiency dose reduction: (1 – 0.83) [1 point]
Other operations; 1 point per processing step. [2 points]

Question 1.3 [4 points]

Calculate the equivalent skin dose of the hand, averaged over any cm² irradiated skin surface, caused by the described unintentional event.

Read attachment 1.1 for 0.5 mm lead: 4·10⁻² $[mGy \cdot m^2 \cdot mA^{-1} \cdot min^{-1}]$ [1 point]
All values between 2.5·10⁻² and 5·10⁻² are considered correct.

$$0.4\ [Gy \cdot cm^2] \times 1.25 \times \frac{4 \cdot 10^{-2}\ [mGy \cdot m^2 \cdot mA^{-1} \cdot min^{-1}]}{6.1\ [mGy \cdot m^2 \cdot mA^{-1} \cdot min^{-1}]} \times \frac{1}{600[cm^2]} \times 1.0[Sv \cdot Gy^{-1}]$$
$$= 5.5 \cdot 10^{-6}[Sv] = 5.5\ \mu Sv$$

Normalization (divide by 6.1 $[mGy \cdot m^2 \cdot mA^{-1} \cdot min^{-1}]$) [1 point]
Other operations: 1 point per processing step. [2 points]

Alternatively (following the calculation method of question 1.1)

$$4 \cdot 10^{-2}\ [mGy \cdot m^2 \cdot mA^{-1} \cdot min^{-1}] \times \frac{1^2\ [m^2]}{1.1^2\ [m^2]} \times 8.0[mA \cdot s] \times \frac{1}{60}[min \cdot s^{-1}]$$
$$\times 1.25 \times 1 \left[\frac{Sv}{Gy}\right] \times 1 \cdot 10^3 \left[\frac{\mu Sv}{mSv}\right] = 5.5\ \mu Sv$$

Question 1.4 [4 points]

Conclude based on previous calculations, available data, and relevant dose criteria in which exposure category the vet needs to be classified.

The effective dose following regular exposure equals: $\frac{0.9\ [mSv]}{(1-0.83)} = 5.3\ mSv$ [1 point]

Argument or calculation: the influence of the anticipated unintended event on the effective dose is irrelevant. [0.5 point]

> Argument: the potential exposure of the anticipated unintended event results in such a small increase in the effective dose that it is considered irrelevant.
>
> Calculation: the anticipated unintended event occurs 1000/50 = 20 times a year so:
>
> $$\frac{20\ [aue's]}{1000\ [images]} \times 0.25[additional\ irradiation\ time] \times 5.3\ [mSv] + 5.3\ [mSv] = 5.3\ mSv$$

The equivalent skin dose per aue: 0.7 mSv; this occurs 20 times a year.
H_{skin} = 20 × 0.7 = 14 mSv. [1 point]

Conclusions:
Based on unshielded effective dose (5.3 mSv < 6 mSv) and the unshielded equivalent skin dose (14 mSv << 150 mSv) the vet should be classified as a category B worker. [1.5 points]
0.5 point per dose criterium and 0.5 point for the conclusion.

NB When argued that there are many uncertainties in the calculation (such as the distance) which can cause the calculated yearly exposure to be larger than 6 mSv, thus resulting in a category A classification, this will be considered correct.

Point rating:

Question 1	
Question	**Point**
1.1	5
1.2a	2
1.2b	4
1.3	4
1.4	4
Total	***19***

Question 2: Activation of fixation masks in proton therapy [15 points]

Question 2.1 [2 points]

Give a possible nuclear reaction which occurs when ^{11}C is produced during proton irradiation of the mask.

The requested reaction (shortened notation) is: $^{12}C(p,pn)^{11}C$ [2 points]
In the long notation: $^{1}_{1}H + ^{12}_{6}C \rightarrow ^{11}_{6}C + ^{1}_{1}H + ^{1}_{0}n$

Also correct: $^{12}C(p,d)^{11}C$ or $^{1}_{1}H + ^{12}_{6}C \rightarrow ^{11}_{6}C + ^{2}_{1}H$

Question 2.2 [4 points]

Using a calculation, show that the chance of interaction of a proton with the fixation mask (and where a ^{11}C nucleus is produced) equals $2.3 \cdot 10^{-4}$.

The cross section for this reaction with 150 MeV protons can be determined from table 1: 46 mbarn (through linear interpolation, where the answer 46.4 mbarn is also correct, but when is argued that linear interpolation is not required because the tabulated value is close to 150 MeV is also correct). [1 point]

The chance of interaction is: $1 - e^{-\sigma n d}$, with σ the cross section, n the number of atomic nuclei per unit volume and d the thickness of material to be passed through.

$\sigma = 46$ mbarn $= 46 \cdot 10^{-27}$ cm^2

$$n = \frac{\rho \cdot N_A}{M} = \frac{1.0\ [g \cdot cm^{-3}] \times 6.022 \cdot 10^{23}\ [atoms \cdot mol^{-1}]}{12\ [g \cdot mol^{-1}]} = 5.02 \cdot 10^{22}\ atoms \cdot cm^{-3}$$

[1 point]

d = 1.0 mm = 0.10 cm

Yielding an interaction chance equal to:
$46 \cdot 10^{-27} [cm^2] \times 5.02 \cdot 10^{22} [atoms \cdot cm^{-3}] \times 0.1\ [cm] = 2.3 \cdot 10^{-4}$ [2 points]

N.B. The approximation *σnd*, which applies to small chance values, is also correct of course – the mask should never have a large influence on the dose (distribution) in the patient.

Question 2.3 [3 points]
Calculate the radiation-induced ^{11}C activity in the mask.

Only 0.5% of the produced protons is incident on the mask, equal to $5 \cdot 10^{-3} \times 1.8 \cdot 10^{13} = 9.0 \cdot 10^{10}$ protons.

The number of produced ^{11}C nuclei equals:
$N = 9.0 \cdot 10^{10} \times 2.31 \cdot 10^{-4} = 2.1 \cdot 10^{7}$ [1 point]

$$\lambda = \frac{\ln(2)}{20.39\ [min] \times 60[s \cdot min^{-1}]} = 5.67 \cdot 10^{-4}\ s^{-1}$$

The activity = A = λ·N, so:
$5.67 \cdot 10^{-4}[s^{-1}] \times 2.1 \cdot 10^{7} = 11.8 \cdot 10^{3}\ Bq = 12\ kBq$ [2 points]

N.B. In practice, you would also need to calculate the total number of produced protons based on the 'total charge' per irradiation. In this question a proton beam is produced with a total charge of 0.8 nAh (= 0.8 (nC/s)h). The elementary charge is $1.6 \cdot 10^{-19}$ C, so the total number of produced protons equals:
0.8 (nC/s)h x 3600 (s/h) / $1.6 \cdot 10^{-19}$ (C per proton) = $1.8 \cdot 10^{13}$ protons.

Question 2.4 [3 points]
Calculate the number of hours required to allow release of the mask.

The activity concentration immediately after irradiation equals:
$C(0) = A(0)/40 = 11.8 \cdot 10^{3}\ [Bq]/\ 40\ [g] = 294\ Bq/g = 2.9 \cdot 10^{2}\ Bq/g$ [1 point]

To be allowed to release the mask the activity concentration has to be lower than 1 Bq/g.

The required time can be calculated using: $C(t) = C(0) \cdot e^{-\lambda \cdot t}$
With $\lambda = ln2\ /\ T_{1/2}$ and $T_{1/2} = 0.034\ min^{-1}$, we find:
$t = ln(C(0)\ /\ C(t))\ /\ \lambda = ln(294[Bq/g]/1[Bq/g])\ /\ 0.034\ [min^{-1})] = 167\ min$
$t = 167\ [min]\ /\ 60\ [min/h] = 2.8\ h.$ [2 points]

Assuming 10 kBq: $C(0) = 10 \cdot 10^{3}\ /\ 40 = 250\ Bq/g$
$t = ln(250[Bq/g]/1[Bq/g])/0.034\ [min^{-1}] = 162\ min = 2.7\ h$

Question 2.5 [3 points]
Verify that the operational criterion used by the therapy center meets the legal release limit.

For operational release the gross count rate equals twice the background count rate, or 20 cps.
The net count rate then equals $20 - 10 = 10\, cps$. [1 point]

The measuring instrument has a total detection efficiency of 0.3 counts per ^{11}C disintegration. The activity at release is
$10\ (cps)\ /\ 0.30\ (pulses/disintegration) = 33\ Bq$ [1 point]

The activity concentration in the mask then equals $33/40 = 0.83\, Bq/g$.
The criterion therefore meets the legal release limit. [1 point]

Point rating:

Question 2	
Question	**points**
2.1	2
2.2	4
2.3	3
2.4	3
2.5	3
Total	***15***

Question 3. Internal contamination with I-125 [18 points]

Question 3.1 [4 points]

Calculate the activity of the iodine absorbed on the filter at the moment the filter is replaced.

6 half-lives have passed after 1 year, so you can assume equilibrium has been reached (or: $A_{equilibrium} = \frac{\dot{P}}{\lambda}$). [1 point]

1 year equals 52 weeks

$$A_{equilibrium} = \frac{\dot{P}}{\lambda} = \frac{0.01[1\,\%] \times 50[MBq \cdot week^{-1}]}{1.35 \cdot 10^{-7}\,[s^{-1}] \times 3600[s \cdot h^{-1}] \times 24[h \cdot d^{-1}] \times 7[d \cdot week^{-1}]}$$

$= 6.1\,MBq$

Production rate [1 point]
Decay constant [1 point]
Calculation [1 point]

Calculating the activity using the general formula $A(t) = \frac{\dot{P}}{\lambda}\left(1 - e^{-\lambda \cdot t}\right)$ is also correct of course.

Partial credit can be obtained for a substantiated estimation of the equilibrium activity without calculation.

Question 3.2a [3 points]

Calculate the committed effective dose caused by this internal contamination.

$A_{thyroid}$ = 5.7 kBq
A_{intake} = 5.7 [kBq] / $2.6 \cdot 10^{-1}$[Bq/Bq_{intake}] = 22 kBq [1 point]

$$E_{50} = A_{intake} \times e(50)_{inh} = 22\,[kBq] \times 1.4 \cdot 10^{-8} \left[\frac{Sv}{Bq}\right] = 3.07 \cdot 10^{-4} Sv = 0.31\,mSv$$

[2 points]

Assuming 30% uptake in the thyroid is also considered correct:
A_{intake} = 5.7 [kBq] / $3.0 \cdot 10^{-1}$ = 19 kBq [1 point]

$$E_{50} = A_{intake} \times e(50)_{inh} = 19\,[kBq] \times 1.4 \cdot 10^{-8} \left[\frac{Sv}{Bq}\right] = 2.66 \cdot 10^{-4} Sv = 0.27\,mSv$$

[2 points]

Question 3.2b [2 points]

Argue based on the data from the "Handboek Radionucliden" that in this specific case the chemical form in which the contamination occurred hardly matters for the committed effective dose.

Inhalation of SR-1 (I_2 vapor) has a 2x higher e_{50} compared to class F (other molecular forms or compounds). According to the thyroid count data, an intake of 1 Bq I_2 vapor leads to an approximately 2x higher accumulation in the thyroid after 3 days compared to inhalation of class F. From this follows that *for a 1 Bq measurement in the thyroid* as a result of I_2 vapor, the inhaled activity will be approximately half that of a class F molecular form. Both will therefore result in approximately the same committed effective dose.

It is always advised to do a *worst case* calculation in case of accidents, which is why usually the most conservative $e_{inh/ing}(50)$ is assumed – this reasoning is NOT sufficient to answer this question (1 point deducted).

N.B. In case of internal contamination in a radionuclide laboratory, by default inhalation is assumed, as ingestion should not be possible when the standard safety requirements are upheld. Ingestion would actually result in approximately the same committed effective dose.

Question 3.3a [4 points]

Calculate the number of disintegrations in the thyroid ($U_{thyroid}$) during the 50 years following the occurrence of the internal contamination.

The activity of the thyroid is 5.7 kBq.

The biological half-life is 90 days, the physical half-life is 60 days. $T_{½\ eff}$ = 1/(1/90 + 1/60) = 36 days [2 points]

$$U_s = {}^{A}\!/_{\lambda_{eff}} = \frac{5.7[kBq]}{\left[{}^{\ln(2)}\!/_{(36\cdot 24\cdot 60\cdot 60)}\right]} = 5.7\cdot 10^3/2.56\cdot 10^{-7} = 26\cdot 10^9 disintegrations$$

[2 points]

Question 3.3b [5 points]
Calculate which percentage of the in question 3.2a calculated committed effective dose is caused by the uptake of ^{125}I in the thyroid.

$$H_{thyroid} = 1.6 \cdot 10^{-19}[J/eV] \times \sum_i U_{thyroid} \cdot w_{R,i} \cdot y_i \cdot E_i \cdot AF_i(thyroid \leftarrow thyroid)/m_{thyroid}$$

[1 point]

$$= 1.6 \cdot 10^{-19}[J/eV] \times 26 \cdot 10^9 \times$$
$$(1 \times 41 \cdot 10^3[eV] \times 0.18 + 1 \times 16.5 \cdot 10^3[eV] \times 1)/0.020[kg] = 4.9 \cdot 10^{-3}\left(\frac{J}{kg}\right) = 4.9\, mGy$$

[2 points]

every 'missed' or incorrectly entered factor results in a 0.5 point deduction.

Contribution to E_{50} = $4.9 \cdot 10^{-3}$ [Gy] × 1 [Sv/Gy]× 0.05 = 0.24 mSv. [1 point]

The percentage is then 0.24 [mSv] / 0.31 [mSv] = 0.79 = 79%
or 0.24 [mSv] / 0.266 [mSv] = 0.92 = 92% [1 point]

N.B.1 In this question, a tissue weighing factor of 0.05 has been chosen to match the data from the *Handboek Radionucliden,* which is also based on this tissue weighing factor.
N.B.2 The true value is very close to 100%. Using the modeled thyroid uptake of 30% is in close agreement with this value.
N.B.3 Calculations using the fictitious value yields numbers which are about 25% lower than calculated here.

Point rating:

Question 3	
Question	**Points**
3.1	4
3.2a	3
3.2b	2
3.3a	4
3.3b	5
Total	***18***

Question 4: Determining layer thickness using ^{85}Kr [13 points]

Question 4.1 [5 points]

Calculate the measurement efficiency of the used measurement setup in cps/Bq when a layer thickness of 50 mg/cm² is measured. Indicate which assumption(s) you have made regarding the parameters influencing the efficiency.

The layer thickness of the foil combined with the area density of the windows of the detector and the source, equals approximately 60 mg/cm². This results in an absorption of about 85% (between 80 and 90% is considered correct) and hence a transmission of 0.15. [2 points]

Given the fact that the detector cannot measure more than 50% of the emitted radiation, the geometric efficiency cannot exceed 0.50. [1 point]

The efficiency of the measurement setup depends on the position of the detector, the aforementioned assumptions, and the transmission, which yields:

$$\varepsilon = yield \cdot \varepsilon_{geo} \cdot \varepsilon_{detector} \cdot T$$

$$\varepsilon = 0.996 \cdot 0.50 \cdot 1 \cdot 0.15 = 0.075$$ [2 points]

The yield of the beta's is 100% (or 0.996 from the *Handboek Radionucliden*), the measurement efficiency of particles passing the window is 1, and it is assumed that there are no beta's absorbed by the air in this short distance.

Question 4.2 [4 points]

Calculate the minimum measurement time (in ms) required for a foil thickness measurement of 50 mg/cm² to meet the desired relative standard deviation.

The minimum number of pulses required for a relative standard deviation of 0.1% equals:

$$\frac{\sqrt{N}}{N} = 0.1\% \rightarrow \frac{1}{\sqrt{N}} = 0.001 \rightarrow N = 1{,}000{,}000$$ [2 points]

The count rate is $R_{net} = A \cdot \varepsilon = 3.7 \cdot 10^9 \cdot 0.075 = 276{,}390{,}000\ cps$ [1 point]

The time required to measure with a relative standard deviation of 0.1% is

$$t = \frac{N}{R} = \frac{1{,}000{,}000\ [c]}{276{,}390{,}000 [cps]} = 0.0036\ s = 3.6\ ms$$ [1 point]

Question 4.3 [2 points]

Argue or calculate how many years the source can be used before the measurement time is doubled.

If you want to measure no longer than 7.2 ms, the net count rate needs to be at least

$R = \frac{N}{t} = \frac{1{,}000{,}000\ [c]}{0.0072\ [s]} = 138{,}195{,}000\ [cps]$ [1 point]

Which means the required activity is

$A = \frac{R_{net}}{\varepsilon} = \frac{138{,}195{,}000\ [cps]}{0.075} = 1.9 \cdot 10^9 Bq$ [1 point]

This is half the current activity. By that time, 1 half-life will have passed, which is 10.7 years.

N.B. Arguing from the required number of pulses is also ok. Twice longer measurement time, so half the activity for an equal number of pulses. A half-life is 10.7 years. [2 points]

Question 4.4 [2 points]

Describe which information related to the radiation safety of these types of sources is relevant for the company fire brigade during a fire. Make sure to include information concerning the external irradiation and internal contamination risks.

Internal contamination: ^{85}Kr is a gaseous nuclide, and krypton is a noble gas. If the shielding breaks there will be no, or a very low internal contamination risk. There will not be a loose source in the company. During a fire, the source has likely disappeared before the fire brigade arrives. [1 point]

External contamination: as long as the holder is intact, there is no (or very low) risk, as the thickness of the holder will exceed the range of the beta's. [1 point]

Point rating:

Question 4	
Question	**Points**
4.1	5
4.2	4
4.3	2
4.4	2
Total	***13***