EMBARGO May 10th 2021

ANSWERS

Exam
Radiation protection expert on the level of coordinating expert

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Exam date: May 10th 2021

- The solutions below 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. Internal contamination with ^{131}I

Question 1.1 [4 points]

Calculate the committed effective dose for the employee, if the I_2-vapor contamination would have taken place on the Friday morning of the previous week – at the start of the working day.

Net count rate: 89 cps
Detection efficiency thyroid count: 9.5 cps/kBq ^{131}I
Activity = R/ε = 89 [cps]/9.5 [cps/kBq] = 9.4 kBq = $9.4 \cdot 10^3$ Bq in the thyroid [1 point]

Handboek Radionucliden: $A_{thyroid}$ after 3 days following inhalation I_2: $2.0 \cdot 10^{-1}$ Bq per Bq intake:
$A_{intake} = 9.4 \cdot 10^3$ [Bq] / $2.0 \cdot 10^{-1}$ [Bq per Bq intake] = $4.7 \cdot 10^4$ Bq [2 points]

$E_{50} = 4.7 \cdot 10^4$ [Bq] × $2.0 \cdot 10^{-8}$ [Sv/Bq] = $9.4 \cdot 10^{-4}$ Sv (= 0.94 mSv) [1 point]

Question 1.2a [2 points]

Use a calculation to estimate the absorbed dose in the thyroid, assuming the situation in question 1.1 and the tissue weighting factors from ICRP-60.

$D_{R,T} = E/(W_R \times W_T)$
$W_R = 1$ [0,5 point]
$W_T = 0.05$ [0,5 point]
$D_{thyroid} = 9.4 \cdot 10^{-4}$ [Sv] / (1×0.05) = 0.0188 Gy = 0.02 Gy [1 point]

Question 2b [2 points]

Argue whether the absorbed dose from question 1.2a can lead to harmful tissue reactions.

It is not possible for tissue reactions to occur in the thyroid at an absorbed dose of 0.02 Gy, and in other tissue the absorbed dose is much lower.

Question 1.3 [4 points]

Calculate as accurately as possible the committed effective dose for the worker.

30% of the ingested activity accumulates in the thyroid [1 point]

The effective half-life is 7.35 days:

$$\frac{1}{T_{1/2,eff.}} = \frac{1}{T_{1/2,bio.}} + \frac{1}{T_{1/2,phys.}} \rightarrow T_{1/2,eff.} = \frac{1}{\left(\frac{1}{90}+\frac{1}{8}\right)} = 7.35\ dags$$ [1 point]

This can be used to calculate the activity in the thyroid:

$$A_{T(thyroid)}(t) = 0.30 \times A_{in} \times \left(1/2\right)^{t/T_{1/2,\mathrm{eff}}}$$

$$\mathrm{A_{in}} = \frac{\mathrm{A_T(t)}}{0.30 \times \left(1/2\right)^{t/T_{1/2,\mathrm{eff}}}} = \frac{9.4 \cdot 10^3\ [Bq]}{0.30 \times 0.059} = 5.31 \cdot 10^5\ \mathrm{Bq}$$ [1 point]

The committed effective dose is then:

$E_{50} = 5.31 \cdot 10^5$ [Bq] × $2.0 \cdot 10^{-8}$ [Sv/Bq] = $10.6 \cdot 10^{-3}$ Sv (= 10.6 mSv) [1 point]

Alternative solution:

The *Handboek Radionucliden* does not contain any thyroid count data 30 days after intake. The biological half-life of the thyroid is given, which is effectively equal to 90 days.

To be able to calculate the value for 30 days after intake, we can assume the value for 3 days after intake: $2.0 \cdot 10^{-1}$ Bq per Bq intake

A_{intake} = $9.4 \cdot 10^3$ [Bq] / $2.0 \cdot 10^{-1}$ [Bq per Bq intake] = $4.7 \cdot 10^4$ Bq [1 point]

For a duration of 30 days, another 30-3=27 days remain.

This needs to be calculated using the effective half-life, which equals:

$$\frac{1}{T_{1/2,eff.}} = \frac{1}{T_{1/2,bio.}} + \frac{1}{T_{1/2,phys.}} \rightarrow T_{1/2,eff.} = \frac{1}{\left(\frac{1}{90}+\frac{1}{8}\right)} = 7.35\ days$$ [1 point]

Decayed fraction in this period is $½^{t/T½}$ = $½^{27/7,35}$ = 0.0784

Correction for this fraction: $4.7 \cdot 10^4$ [Bq]/ 0.0784 = $6.0 \cdot 10^5$ Bq [1 point]

E_{50} = $6.0 \cdot 10^5$ [Bq]× $2.0 \cdot 10^{-8}$ [Sv/Bq] = $12 \cdot 10^{-3}$ Sv (= 12 mSv) [1 point]

You can also use the data for other days, such as day 7, for this calculation. However, the distribution of the activity over the different tissues is only complete after 1 days. Because of this, 1 point needs to be deducted for a calculation from 0.25 days.

Question 1.4 [2 points]

Calculate what the value of the committed effective dose coefficient would be for the inhalation of I_2-vapor, based on the tissue weighing factors from ICRP-103.

Handboek Radionucliden: e(50)(w) for inhalation of I_2= $2.0 \cdot 10^{-8}$ Sv/Bq.
The effective dose is mainly caused by the absorbed dose in the thyroid. $E = D_{R,T} \times W_R \times H_T$ where $D_{R,T}$ and W_R have not changed. The tissue weighing factor for the thyroid has decreased from 0.05 to 0.04.

The effective dose coefficient based on ICRP-103 is therefore:
$0.04/0.05 \times 2.0 \cdot 10^{-8}$ [Sv/Bq] = $1.6 \cdot 10^{-8}$ Sv/Bq

Additional note: ICRP-137 states that the value is $1.7 \cdot 10^{-8}$ Sv/Bq. The calculated value matches well.

Point rating

Question 1	**Points**
1.1	4
1.2a	2
1.2b	2
1.3	4
1.4	2
Total	**14**

Question 2: Risk analysis nuclear physics experiment

Question 2.1 [2 points]

Calculate the effective dose the experimenter is exposed to each time while aligning the proton beam.

t_1 = 30 min = 0.5 h

$E_1 \approx H_1^*(10) = 0.1\,[\mu Sv/h] \times 0.5\,[h] \times \frac{15^2\,[m]}{0.5^2\,[m]} = 45\,\mu Sv$ [2 points]

Question 2.2a [6 points]

Calculate the number of neutrons produced in the target slide while the experimenter watches through the viewing window.

$N_n = N_p \cdot N_{Se} \cdot \sigma \cdot yield$

The number of protons incident on the target slide: [2 points]

$$N_p = \frac{I}{e} \cdot t = \frac{50 \cdot 10^{-9}\,[C \cdot s^{-1}]}{1.6 \cdot 10^{-19} [C \cdot proton^{-1}]} [s^{-1}] \times 10[min] \times 60[s \cdot min^{-1}]$$

$= 1.9 \cdot 10^{14}\, protonen$

The number of selenium atoms per cm² in the target slide: [2 points]

$$N_{Se} = \frac{1.2 \cdot 10^{-3} [g \cdot cm^{-2}] \times 6.0 \cdot 10^{23} [mol^{-1}]}{284\,[g \cdot mol^{-1}]} = 2.5 \cdot 10^{18}\, selenium\ atoms \cdot cm^{-2}$$

The cross section of the nuclear reaction in cm², from attachment: [1 point]
100 mbarn = $0.1 \cdot 10^{-24}$ cm²
(values between 75 – 100 mbarn are considered correct)

$yield$ = 1 neutron per nuclear reaction, to be deduced from the given nuclear reaction.

Enter and calculate: [1 point]

$1.9 \cdot 10^{14} \times 2.5 \cdot 10^{18} \times 0.1 \cdot 10^{-24} \times 1 = 4.8 \cdot 10^{7}\, neutrons$

Question 2.2b [3 points]

Show through calculations that the equivalent eye lens dose the experimenter incurs during beam alignment is approximately 80 µSv each time.

The fluence of the isotropically emitted neutrons: [2 points]

$$\Phi_n = \frac{4.8 \cdot 10^7}{4\pi 5^2 [cm^2]} = 1.5 \cdot 10^5 \; cm^{-2}$$

Calculation of $H_{eye\ lens}$: [1 point]

$$H_{eye\ lens} \approx \; H_1^*(10)^1 = 500 \cdot 10^{-12} \; [Sv \cdot cm^2] \times 1.5 \cdot 10^5 \; [cm^2] = 7.5 \cdot 10^{-5} \; Sv = 75 \; \mu Sv$$

Question 2.3 [2 points]

Calculate the effective dose the experimenter incurs each time during replacement of the nitrogen tank.

t_2 = 2 × 15 (s) + 2 × 60 (s) = 150 s = 0.042 h [1 point]
$E_2 \approx H^*_2(10)$ = 110 (µSv/h) × 0.042 (h) = 4.6 µSv [1 point]

Question 2.4 [5 points]

Conclude based on a calculation of the yearly effective dose and equivalent eye lens dose whether the experimenter should be classified as exposed worker, and if so, in which category.

During one week of experiments the experimenter accumulates the following effective dose:

$$E_{Operation\ 1} = 45 \; [\mu Sv \cdot alignment^{-1}] \times \frac{24 \; [h \cdot d^{-1}]}{8 [h]} [alignment \cdot d^{-1}] \times 7 \; [d]$$

$$= 0.9 \cdot 10^3 \mu Sv = 0.9 \; mSv$$ [1 point]

$$E_{Operation\ 2} = 4{,}6 \; [\mu Sv \cdot tank\ replacement^{-1}] \times 2 \; [replacements\ per\ day] \times 7 \; [d]$$

$$= 64.4 \; \mu Sv = 0.06 \; mSv$$ [1 point]

$$E_{tot} = 6 [year^{-1}] \times (0.945 \; [mSv] + 0.064 \; [mSv]) = 6.1 \; mSv$$ [1 point]

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[1] This article from Manger et al. (https://academic.oup.com/rpd/article/148/4/507/1609361) indicates that the conversion factor for the eye lens dose in AP geometry is in the order of 60 pGy cm^2 for 10 – 20 MeV neutrons. With a w_R for neutrons of approximately 8, $H_{eye\ lens}/\ \Phi_n$ should be in the order of 500 pSv cm^2.

The experimentor incurs the following equivalent eye lens dose per year:
$H_{eye\ lens}$ = 21 (times alignment) × 6 (per year) × 0.075 (mSv)
= 9.5 mSv [1 point]

Based on the effective yearly dose the experimenter should be classified as exposed worker (effective dose > 1 mSv). As the dose can exceed 30% of the dose limit (6 mSv) he/she should be classified as exposed worker category-A. The eye lens dose is NO reason for classification as exposed worker (< 15 mSv).
[1 point]

Point rating:

Question 2	**Points**
2.1	2
2.2a	6
2.2b	3
2.3	2
2.4	5
Total	***18***

Question 3: Shielding at an MRI-accelerator

Question 3.1 [5 points]

Calculate the yearly ambient dose equivalent in point P1.

Workload: 8 [pt/day] x 20 [Gy/pt] x 250 [days] = 40,000 Gy [1 point]
Transmission 140 cm concrete at 6 MV = $6.0 \cdot 10^{-5}$ (attachment 1) [1 point]
Any T between $6 \cdot 10^{-5}$ and $7 \cdot 10^{-5}$ is considered correct; values outside of these bounds are incorrect.
Fraction absorbed dose = 0.1% = 0.001

H*(10) = $40 \cdot 10^{3}$ [Gy/y] x 0.001 x $(1[m]/5[m])^2$ x 1 [occupation] x $6.0 \cdot 10^{-5}$ x 1.0 [Sv/Gy] = $9.6 \cdot 10^{-5}$ Sv/year = 96 μSv/year

Square law [1 point]
E/K [1 point]
Calculation H*(10) [1 point]

Question 3.2 [6 points]

Calculate the yearly ambient dose equivalent in point P2 via route A.

H*(10) = $40 \cdot 10^{3}$ [Gy/y] x 0.001 x $(1[m]/6.5[m])^2$ x $0.0042 \cdot 10^{-2}$ x ($10 \cdot 10^{4}$ [cm^2]/100 [cm^2]) x $(1[m]/8[m])^2$ x 0.5 [transmission lead]
x 1 [Sv/Gy] = $3.1 \cdot 10^{-4}$ Sv/year = 0.31 mSv/year

$40 \cdot 10^{3}$ [Gy/y] x 0,001 [1 point]
Square law (2x) [2 points]
Determined from attachment 2 (0.0042% op 1 meter per 100 cm^2 irradiated surface) [1 point]
Correct application fraction and surface [1 point]
T_{steel} [1 point]
deduction E/K = 0.5 pt.

Question 3.3a [2 points]

Argue whether you would consider the exposure of the evaluated event a radiation incident as described in attachment 1 of the Bbs.

From the definition radiation incident:
"**unintended event** or situation of unwanted spreading **where** danger exists, or **has occurred for:**

- an exposure to ionizing radiation for workers exceeding 2 millisievert;"

In this unintended event the worker has been exposed to an effective dose of 1.5 mSv. The event was quickly discovered quickly and stopped. It is therefore also possible that the exposure would amount to more than 2 mSv. This is why it is an incident.

Points will be allocated depending on the argumentation.
Answers without argumentation will not receive any points.

Question 3.3b [4 points]

Argue whether these workers should be classified as exposed workers, and if yes, in which category.

The described event has been anticipated by the radiation protection expert, and should therefore be included in the classification of workers as potential dose (as if it would occur once a year).

The frequency of occurrence must then be calculated. All possibilities of multiple times a year, once a year, and less than once a year are considered correct. For less than once a year, it can be argued that the potential dose does not to be included for the classification.

Argumentation anticipated unintended event and frequency [2 points]
Not including the potential dose without argumentation results in the deduction of 1 point.

Classification if included as potential dose

Point 1	= 0.01 mSv/year	
Point 2	= 0.31 mSv/year	
VOG	= 1.5 mSv	
Total	= 1.8 mSv	[1 point]

→ classify as exposed worker, category B. [1 point]

Alternative classification when not including the potential dose:

Point 1	= 0.01 mSv	
Point 2	= 0.31 mSv/year	
Total	= 1.3 mSv	[1 point]

→ classify as not-exposed worker. [1 point]

Point rating

Question 3	**Points**
3.1	5
3.2	6
3.3a	2
3.3b	4
Total	**17**

Question 4: Noble gas monitor

Question 4.1 [4 points]

Prove using a calculation that the system is leaky.

The standard deviation of the measured count rate equals:

$\sigma_R = \sqrt{\frac{R}{t}} = \sqrt{\frac{532\ [cps]}{60\ [s]}} = 3.0\ cps$ [1 point]

The expected count rate based on physical decay equals:

$R(3.004) = R(0) \times \frac{1}{2}^{\frac{t}{T_{1/2}}} = 1756\ [cps] \times \frac{1}{2}^{\frac{3{,}004\ [h]}{1.83\ [h]}} = 563\ cps$ [1 point]

The difference between the calculated and measured count rate:

563 [cps] – 532 cps = 31 cps [1 point]

The deviation after 3 hours exceeds 2 σ (31 cps > 6 cps). [1 point]

Question 4.2 [3 points]

Determine using the last measurement value the effective removal constant (h^{-1}) of the measurement system.

System filled with ^{41}Ar:

$A(t) = A(0) \cdot e^{-\lambda_{eff} \cdot t}$

$83\ [cps] = 1756[cps] \cdot e^{-\lambda_{eff} \cdot 7.511[h]}$ [1 point]

$\lambda_{eff} = \frac{\ln(\frac{83}{1756})}{-7.511\ [h]} = 0.41 h^{-1}$ [1 point]

Calculation of the correct removal contribution. [1 point]

Question 4.3 [2 points]

Calculate the calibration factor (in Bq/cm^3 per cps) for the gas measurement vessel based on the measurement at t=0.

A(t) = 4.0 MBq

R_n = 1756 cps

$K = \frac{A(t)}{V \times R_n(t)} = \frac{4.0 \cdot 10^6 [Bq]}{33.3 \cdot 10^3\ [cm^3] \cdot 1756 [cps]} = 0.0684\ Bq/(cm^3 \cdot cps)$ [2 points]

Question 4.4 [3 points]

Calculate using the calibration factor of question 4.3 what the noble gas monitor indicates before and after this dilution, neglect the radioactive decay during flushing.

Prior to dilution:

$C_{before}(7.5h) = R_n(7.5h) \times K = 83\ [cps] \times 0.0684\ \left[\frac{Bq}{cm^3 \cdot cps}\right] = 5.7\ \mathrm{Bq/cm^3}$ [1 point]

Na verdunning:

$\lambda_{flush} = \frac{33.3[L \cdot min^{-1}]}{33.3[L]} = 1[min^{-1}]\ and\ t = 10\ min$ [1 point]

$C_{after} = 5.7\ \left[\frac{Bq}{cm^3}\right] \times e^{-1 \cdot 10} = 2.6 \cdot 10^{-4}\ \mathrm{Bq/cm^3}$ [1 point]

Point rating

Question 4	**Points**
4.1	4
4.2	3
4.3	2
4.4	3
Total	***12***