Exam
Radiation protection expert on the level of coordinating expert

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

exam date: December 13th 2021
exam duration: 13.30 - 16.30 hours

Instructions:

- **This exam contains 11 numbered pages and a separate attachment containing 8 pages of data. Please check!**
- Write your solutions and answers on the worksheets provided. You will also need to hand in any unused worksheets at the end of the exam.
- State **only your exam number** on the worksheets (so not your name and address).
- It is allowed to consult books, personal notes, and other documentation materials to answer the questions.
- When answering the questions, make sure you state which **calculation** and/or which **reasoning** helped you reach the solution.
- If you are unable to calculate part of a question and you need that answer to be able to solve the other parts, you are allowed to assume a fictional answer.
- For some of the questions you might not necessarily need to use all of the supplied data.
- Pay attention to the use of the correct quantities and units.
- You can acquire a total of 65 points if you correctly answer all of the questions. The points are distributed between the questions as follows:

  Question 1: 19 points
  Question 2: 15 points
  Question 3: 18 points
  Question 4: 13 points
- You will have passed this exam if you have obtained at least 55% of the total amount of points. This corresponds to a score of at least 35.75 points.

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

X-rays of pets are taken in a veterinary clinic. You will make a risk inventory and evaluation (RI&E) for the vet.

Figure 1.1: The vet holds the pet while taking an X-ray image.

The vet always wears a lead apron and holds the pet with lead gloves, see figure 1.1. The lead gloves are meant to protect the hands of the vet against scatter radiation, and have a negligible effect on the effective dose. The lead gloves are not intended to enter the primary beam.

Given:

- Maximum set tube voltage according to protocol: 75 kV
- Average tube charge (mAs-value) per image: 8.0 m·As
- A maximum of 1000 X-ray images are taken each year
- The average irradiated surface when taking an image at a distance of 1.1 meters from the focal point is 600 m^2
- The average distance from the vet to the animal is 0.5 m
- The air kerma free-in-air (K_a) caused by scatter radiation equals 16.0 μGy/(Gy·cm^2) at a distance of 0.5 meters from the scattering object.
- Conversion factor for the primary beam: H_{skin}/K_a = 1.0 Sv/Gy
- Conversion factor for the scatter radiation: E/K_a = 0.8 Sv/Gy
- The thickness of the lead apron is 0.25 mm lead equivalent
- The thickness of the lead gloves is 0.5 mm lead equivalent
- **Attachment pg. 3:** Output of an X-ray tube and transmission of a wide X-ray beam through lead
- **Attachment pg. 4:** The protection efficiency of lead aprons

It is common to use the dose area product (the DAP value) for radiological applications. The DAP value is the dose of the primary beam multiplied with the surface of the X-ray beam.

Question 1.1 [5 points]

Calculate the dose area product per image [in $Gy \cdot cm^2$].

Carefully study **Attachment pg. 4**.

Question 1.2a [2 points]

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

If you did not find an answer to question 1.1, you can use 0.4 $Gy \cdot cm^2$ per image for subsequent calculations.

Question 1.2b [4 points]

Calculate the yearly effective dose for the vet.

The vet indicates that he sometimes enters the primary beam with his hands (in lead gloves). He estimates that this occurs in 1 out of every 50 images he takes.

The images are taken with an automatic exposure control (AEC). When the lead glove attenuates the primary beam before it reaches the detector, the AEC will increase the exposure time for the same tube current. Assume that the exposure time is increased by a factor of 1.25.

Question 1.3 [4 points]

Calculate the equivalent skin dose of the hand, averaged over any cm^2 irradiated skin surface, caused by the described unintentional event.

The classification of workers in an exposure category must always be done based on a calculation of the sum of the regular and potential dose, without applying any shielding effect of personal protective equipment.

Additional given

- An unshielded equivalent skin dose of 0.7 mSv may be assumed for the described anticipated unintended event.
- There is no need to consider the equivalent eye lens dose for the remainder of this question.

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.

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

Patients with head and neck tumors are irradiated with protons in a proton therapy center. In this question, these protons are assumed to have an energy of 150 MeV.

Patients are fixated with a face mask during irradiation. This fixation mask becomes slightly radioactive due to the proton radiation. The mask is therefore only allowed to leave the treatment room after a specified time. You are asked to calculate this 'cooling time'.

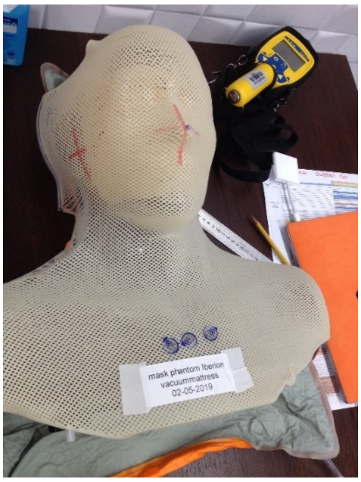

Figure 2.1: fixation mask (face mask)

Given:

- The relevant isotope in the fixation mask material is ^{12}C, the relevant produced radioisotope is ^{11}C.
- The mass concentration of ^{12}C in the material equals 1.0 g per cm^3
- The thickness of the mask equals 1.0 mm
- The half life of ^{11}C is 20.39 min
- Avogadro's constant is $N_{Avogadro} = 6.022 \cdot 10^{23}$ per mol
- The chance of interaction between a proton and the fixation mask is $1 - e^{-\sigma n d}$, with σ the cross section, n the number of atomic nuclei per irradiated unit volume and d the thickness of the material to be passed through
- The total number of protons produced during an irradiation equals $1.8 \cdot 10^{13}$
- 0.5% of these produced protons reaches the fixation mask
- In this question, you may assume that all protons are incident perpendicular to the fixation mask

- Table 2.1: cross sections for the production of ^{11}C for several energies (from F. Horst et al, Phys. Med. Biol. 64 (2019) 205012)

Proton energy (MeV)	**σ (mbarn)**
122	50
153	46
184	42

Table 2.1: Cross sections for the production of ^{11}C

Question 2.1 [2 points]
Give a possible nuclear reaction which occurs when ^{11}C is produced during proton irradiation of the mask.

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 decay of ^{11}C during irradiation may be neglected for the next question.

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

Additional given:

- The relevant release limit of ^{11}C in solid material equals 1 Bq/g (Regeling basisveiligheidsnormen stralingsbescherming, Rbs)
- The weight of the face mask equals 40 g
- If you did not find an answer for question 2.3, you may assume 10 kBq for question 2.4

Question 2.4 [3 points]

Calculate the number of hours required to allow release of the mask.

A measurement taken after irradiation is used to determine if the mask can be released. As operational criterion for the release of the mask, the therapy center uses a gross count rate which should not exceed twice the background count rate.

Additional given:

- The background count rate of the measuring instrument equals 10 counts per second (cps)
- The total detection efficiency of the used measuring instrument equals 0.3 counts per ^{11}C desintegration

Question 2.5 [3 points]

Verify that the operational criterion used by the therapy center meets the legal release limit.

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

In a radionuclide laboratory, 50 MBq ^{125}I is used to label proteins on a weekly basis. The iodine is volatile during one phase of the experiment. About 1% of the used iodine is released in this phase in the form of I_2

The labeling is performed in a fume hood with active carbon filter, which absorbs practically all the released iodine. This filter is replaced each year by instructed personnel.

Given

- **Attachment pg. 5-6:** Handboek Radionucliden, A.S. Keverling Buisman (3rd edition 2015), pg. 160-161, ^{125}I data
- For the Absorbed Fraction (AF) for ^{125}I photons in the thyroid – AF (Thyroid ← Thyroid) – an average value of 0.18 may be used for all photons
- Total emitted photon energy per disintegration: 41 keV
- Total emitted electron energy per disintegration: 16.5 keV
- With total emitted energy is meant: $\sum_i y_i \cdot E_i$ where y_i is the emission probability of the emitted photons and electrons respectively, and E_i the energy, summed over all photons/electrons i
- Mass of the thyroid: 20 gram
- Tissue weighing factor thyroid: 0.05 (ICRP-60)

Question 3.1 [4 points]

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

A lab technician performs the weekly labeling on Friday. On Monday morning it turns out that, due to the yearly filter replacement, the exhaust had been turned off. As this could have caused the lab technician to have an internal ^{125}I contamination, a suitable detector is used to perform a thyroid count on Monday morning, 3 days after the labeling. An activity of 5.7 kBq is measured in the thyroid. You may neglect the decay of iodine in the intervening weekend in this assignment.

Assume for question 3.2a that inhalation of iodine fumes has caused this internal contamination.

Question 3.2a [3 points]
Calculate the committed effective dose caused by this internal contamination.

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.

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.

If you did not find an answer to question 3.3a, you may assume $U_{thyroid} = 2 \cdot 10^{10}$ for the next question.

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.

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

During the production process in a factory, they want to perform out layer thickness measurements of a foil using the transmission of beta radiation, as this is best suited for the rapid process. A gaseous ^{85}Kr source with an activity of 3.7 GBq is used in the measurement setup.

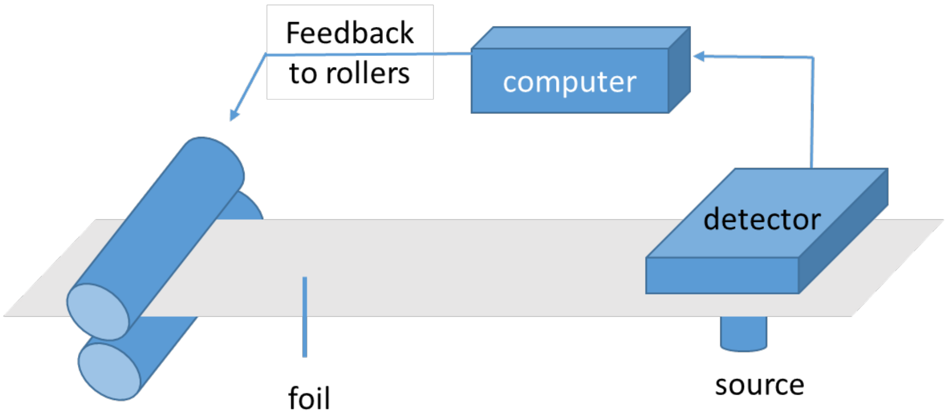

Figure 4.1: schematic thickness measurement plate material.

Given:
- The distance between the point source and the detector is 20 mm
- The windows of the source and the detector together have an area density (=mass thickness) of 10 mg/cm^2
- Each beta particle passing the window of the detector is registered
- The desired relative standard deviation in the amount of measured pulses is 0.1%
- **Attachment pg. 7:** Percentage absorption beta particles in matter
- **Attachment pg. 8:** Handboek Radionucliden, A.S. Keverling Buisman (3rd edition 2015), pg. 92, ^{85}Kr data.

Question 4.1 [5 points]
Calculate the measurement efficiency of the used measurement setup in cps/Bq when a layer thickness of 50 mg/cm^2 is measured. Indicate which assumption(s) you have made regarding the parameters influencing the efficiency.

Question 4.2 [4 points]
Calculate the minimum measurement time (in ms) required for a foil thickness measurement of 50 mg/cm^2 to meet the desired relative standard deviation.

Question 4.3 [2 points]
Argue or calculate how many years the source can be used before the measurement time is doubled.

The radiation protection expert gives a tour through the manufacturing hall for the company fire brigade.

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.