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 14th 2020
exam duration: 13.30 - 16.30 hours

Instructions:

- **This exam contains 10 numbered pages and a separate attachment containing 12 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 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.
- 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: 15 points
  Question 2: 16 points
  Question 3: 14 points
  Question 4: 20 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: Level measurement [15 points]

High activity sources are used for level measurements in storage tanks in industry. A source is located on one side of the tank and a detector is on the other side directly opposite the source. The emitted gamma rays are registered by the detector. The detector will measure more or fewer pulses depending on the height of the stock in the tank.

The radioactive source is located in a source holder and can be closed with a shutter. The source holder is attached to the outside of the tank and contains a ^{60}Co source with an initial activity of 4 GBq. This source has been purchased six years ago, and has been in the source holder attached to the same tank ever since.

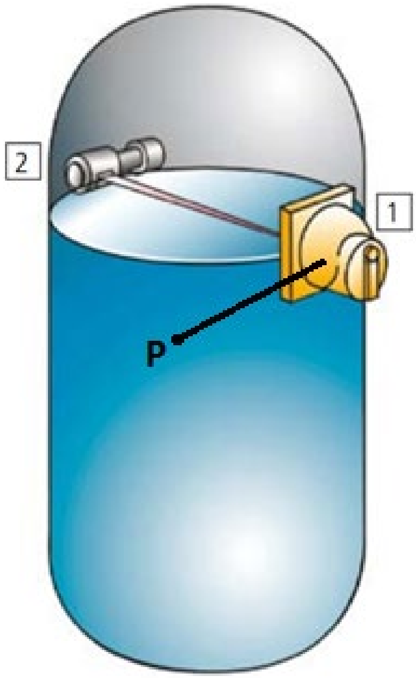

Figure 1. Filled tank with a high activity source attached. The radioactive source is located at 1, and the detector on the opposite side at 2.

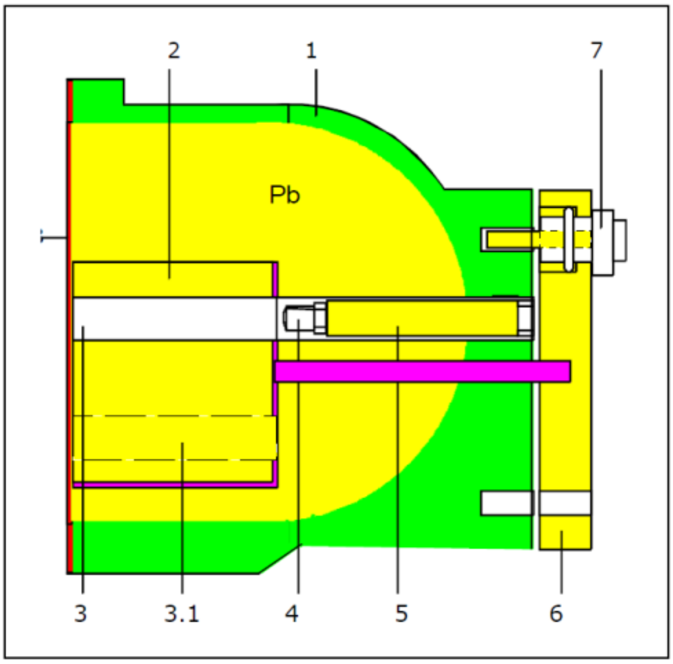

Figure 2. Sketch of the source holder containing the radioactive source. In this figure, the source is located at 4. The shutter that can be rotated in front of the source opening is shown at 3.1.

Given:

- **Attachment, pg. 3**: Handboek Radionucliden, A.S. Keverling Buisman (3rd edition 2015) pg. 74, ^{60}Co data.
- **Attachment pg. 4**: Radiological Health Handbook pg. 148, transmission data of several gamma sources through lead.
- The source holder may be regarded as a sphere with a 22 cm diameter.
- The high activity source is located in the center of the source holder, enclosed by 97 mm thick lead.
- The outside of the source holder is composed of steel, the shielding effect of which may be ignored.
- Total transmission of ^{60}Co through both walls of the tank is 0.71.
- The detector is located at a distance of 210 cm from the source.
- The detector surface is 40 cm^2.
- The detector efficiency for photons emitted by ^{60}Co is 0.01 counts/photon.

Question 1.1 [4 points]

Calculate the current ambient dose equivalent rate at one meter distance (in point P, figure 1) from the surface of the source holder containing the ^{60}Co source. The shutter is closed.

When the shutter is opened, a beam emerges from the opening which is wide enough to irradiate exactly the entire detector surface (on the opposite side of the tank).

Question 1.2 [5 points]

How many cps will the detector display when the storage tank is empty?

The company decides to replace the old source. The ^{60}Co source supplier offers to provide another source which fits in the same source holder. This is an 8 GBq ^{137}Cs source.

Additional given:

- **Attachment pg. 5**: Handboek Radionucliden, A.S. Keverling Buisman (3rd edition 2015) pg. 172, ^{137}Cs data.
- The detector efficiency for photons emitted by ^{137}Cs is 0.03 counts/photon.
- Total transmission of ^{137}Cs through both walls of the tank is 0.63.

Question 1.3 [6 points]

There are advantages and disadvantages associated with replacing the ^{60}Co source with a ^{137}Cs source. Name four advantages and/or disadvantages and give an argument for each (dis)advantage. You score 1.5 point per correct combination of (dis)advantage and the argument. More than four correct answers do not yield additional points, incorrect answers result in points deducted.

Question 2: Internal contamination [16 points]

In a laboratory where people regularly work with titrated water, the activity concentration of tritium in the air is routinely determined using liquid scintillation counting (LSC). Water vapor (from the air in the lab) is condensed on a cold surface. A scintillation vial is filled with 1.0 mL of the condensed water and scintillation cocktail is added, to a total volume of 10 mL.
On a Monday evening, this sample yielded an average count rate of 7355 counts per minute (cpm) after 10 minutes of counting in a liquid scintillation counter. This is well above the average background of 25 cpm. The measurement was not anomalous the previous Friday. It is therefore concluded that an amount of tritium has leaked in the meantime. It turns out that a vial containing tritiated water has been standing there uncapped. The radiation protection expert calculates the possible radiation exposure of an employee who has worked in this lab for 8 hours. This involves looking at the amount of inhaled contaminated air.

Given:

- **Attachment pg. 6-7:** Handboek Radionucliden, A. Keverling Buisman (3rd edition 2015), pg. 18-19, ^{3}H data.
- The laboratory area has a constant humidity of 15 gram water per m^3 air.
- ρ_{water}=1 g/cm^3.
- Assume a breathing volume rate 1.2 m^3/h.
- The counting efficiency of the used liquid scintillation counter is 0.31 cpm/dpm for tritium containing samples.
- A one-hour background measurement resulted in a background of 25 cpm in the tritium channel of the liquid scintillation counter.

Question 2.1 [3 points]

Calculate the tritium activity concentration (in Bq/mL) of the condensed water using the liquid scintillation counts.

Question 2.2 [4 points]

Calculate the maximum activity concentration (in Bq/mL), assuming a statistical uncertainty of 3 sigma in the calculated activity.

Question 2.3a [2 points]
As radiation protection expert calculating the exposure of the employee, would you assume the activity concentration to be at equilibrium? Substantiate your answer.

Question 2.3b [3 points]
What is the maximum activity concentration **in the air** (in Bq/m^3) of the contaminated laboratory?

Question 2.4 [4 points]
Calculate the effective dose received by the employee through inhalation, using the activity concentration in the air calculated in question 2.3b.

Question 3: Needle accident [14 points]

For brain research on laboratory animals a number of rats is injected with 50 MBq ^{123}I-IBZM (iodobenzamide) per animal. A small amount of radioactive material remains in the syringe after injection. The laboratory technician pricks her finger with the needle, despite several safety regulations. A small amount of radioactive liquid ends up in the tip of the finger. After consulting with a nuclear radiologist it is decided to perform a thyroid count. A gross count rate of 95 cpm is measured approximately one hour after the incident. The background count rate at this setup is 45 cpm. The used detector has been shielded in such a way that it detects mainly radiation originating from the thyroid. For this reason, the contribution of the radioactive iodine in the rest of the body may be ignored for this measurement.

Figure 1. Thyroid counting.

Given:

- Detection efficiency of the used measurement set-up: 60 cpm/kBq.
- ^{123}I half-life: 13.22 hours.
- **Attachment pg. 8:** Percentage radioactivity distribution over the organs after ^{123}I-IBZM administration, Nicolaas P.L.G. Verhoeff e.a., European Journal of Nuclear Medicine, September 1993.
- Committed effective dose coefficient ^{123}I-IBZM: 0.034 mSv/MBq.

Question 3.1 [2 points]

Calculate the activity in the thyroid at the time of measurement.

There is no data available for prick incidents with ^{123}I. This is why you can use the table "Percentage radioactivity distribution over the organs after ^{123}I-IBZM administration" which contains the ^{123}I distribution data upon intravenous injection for six healthy volunteers. For this question, the averages as given in the table can be used without the standard deviation.

Question 3.2 [4 points]
Calculate the amount of activity which has ended up in the body of the technician during this incident.

Question 3.3 [2 points]
Calculate the committed effective dose for the technician due to this incident.

All urine excreted by the technician (300 mL) is collected three hours after the incident. 10 mL of the urine is mixed with scintillation cocktail and measured for 1 minute in the liquid scintillation counter.

Additional given
- **Attachment pg. 9:** Handboek Radionucliden, A. Keverling Buisman (3rd edition 2015), pg. 156, ^{123}I data.
- Because of the emitted electrons, ^{123}I can be detected quite well in a liquid scintillation counter. The electrons of ^{123}I are detected with a detection efficiency of 0.6 counts per emitted electron. The contribution of the photons to the count rate may be ignored.

Question 3.4 [6 points]
Calculate the count rate in cpm per injected kBq of this urine sample.

Question 4: Lutetium-177 [20 points]

Recent years have seen a strong increase in the use of lutetium for cancer treatment. The lutetium is produced in a nuclear reactor according to the following reaction:

$^{176}Lu(n,\gamma)^{177}Lu$

A customer asks for a shipment of 500 GBq ^{177}Lu. For this irradiation, the customer supplies 2 mg lutetium nitrate ($Lu(NO_3)_3$) in which ^{176}Lu is enriched to 85% (the natural abundance of ^{176}Lu is 2.59%). The time between production and delivery amounts to 5 hours.

Given:

- **Attachment, pg. 10-11:** Handboek Radionucliden, A.S. Keverling Buisman (3rd edition 2015), pg. 204-205, ^{177}Lu data.
- The molar mass of the enriched lutetium is 175.85 $g \cdot mol^{-1}$.
- The molar mass of NO_3^{2-} is 62.03 $g \cdot mol^{-1}$.
- Avogadro's constant equals $6.022 \cdot 10^{23}$ mol^{-1}.
- The cross section for thermal neutrons for the reaction $^{176}Lu(n,\gamma)^{177}Lu$ is $\sigma = 2.1 \cdot 10^{-3}$ barn (Should be $2.1 \cdot 10^{3}$ barn, typo in original exam).
- The neutron flux in the reactor is $5 \cdot 10^{19}$ neutrons$\cdot m^{-2} \cdot s^{-1}$.
- Activation can be calculated using the following equation:
  $A_t = N \varphi \sigma (1-e^{-\lambda t})$, in which:

A_t	=	activity ^{177}Lu after irradiation time t (in Bq)
N	=	number of irradiated atoms
Φ	=	flux ($m^{-2} s^{-1}$)
σ	=	cross section (m^2)
λ	=	decay constant ^{177}Lu
t	=	Irradiation time (s)

Question 4.1 [3 points]
Calculate the number of ^{176}Lu atoms in the supplied 2 mg lutetium nitrate.

Question 4.2 [5 points]
Calculate what the irradiation time (in hours) should be to meet the customer's request.

The transport takes place in a Type-A collo. This collo consists of a container with 7 mm lead shielding packed in a cardboard box of 42 x 42 x 42 cm. The box has been filled with Styrofoam in such a way that the activity is located exactly in the center of the collo.

Additional given:

- You only have to take the lead shielding into account for the transmission calculations.
- The density of lead: $\rho_{lead} = 11.34\ g \cdot cm^{-3}$.
- The build-up of the photons of ^{177}Lu through 7 mm lead may be equated to 1.0.
- **Attachment, pg. 12:** Mass attenuation coefficient of lead.
- **Attachment, pg. 13:** Conversion coefficients of air kerma to ambient dose equivalent as function of the photon energy.

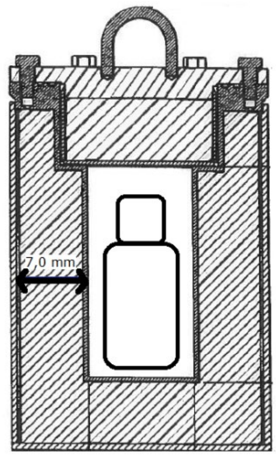

Figure 4.1: lead container

Question 4.3a [6 points]

Calculate the maximum air kerma rate ($\dot{K}$) on the surface of the collo. Assume all the β-radiation is absorbed by the lead, and that only a negligible amount of bremsstrahlung is formed.

Question 4.3b [4 points]

Calculate the transport index of this collo.

Question 4.4 [2 points]

Which label should be attached to the collo? Give all the data which should be written on the label.