Examination
Co-ordinating Radiation Protection Expert

Nuclear Research and consultancy Group	NRG
Delft University of Technology	TU Delft
Boerhaave CME/LUMC	BN/LUMC
University of Groningen	RUG
Radboudumc	RUMC
Eindhoven University of Technology	TU/e

examination date: 11 December 2017
duration of examination: 13:30 - 16:30

Instructions:

- **This examination comprises 13 numbered pages and a separate 16-page appendix containing data. Please check whether it is complete!**
- Write your solutions and answers on the worksheets provided. You must return all worksheets, including any unused ones.
- Write **only your examination number** on the worksheets (not your name and address).
- You are permitted to consult books, personal notes and other relevant documentation when answering the questions.
- *You are explicitly reminded that you must also indicate the* ***calculation method*** *and/or* ***reasoning*** *that you used in order to arrive at the solution*.
- If you are unable to calculate part of a problem and the answer is needed to solve the rest of the problem, you may assume a fictitious answer.
- Some problems may not require you to use all of the data provided.
- You can earn a total of 63 points for solving the problems correctly. The points are distributed across the problems as follows:
  - Problem 1: 15 points
  - Problem 2: 14 points
  - Problem 3: 17 points
  - Problem 4: 17 points
- You will pass this examination if you obtain at least 55% of the total number of points. This corresponds to a score of at least 34.65 points.

Problem 1. Radium Girls

Applications of radioactivity started to be developed soon after it was discovered by Henri Becquerel in 1896. However, the dangers also slowly started to become apparent. A well-known example is watch dials, that were made luminous with a paint that consisted of zinc sulphide mixed with a radium salt.

An old Westclox alarm clock with luminous hand tips is set up as a demonstration model in a laboratory. To find out how much radioactivity the hands still emit, the hand tips are gathered together and measured with a dose rate meter (this measures only photons). At approximately 5 cm distance from the tips, the ambient dose equivalent rate is 0.4 $\mu Sv \cdot h^{-1}$.

Supporting data:

- **Appendix, pp. 3-4**: *Handboek Radionucliden*, [Radionuclides Handbook], A.S. Keverling Buisman (2nd edition 2007), pp. 230-231, ^{226}Ra data
- The geometry of the measurement is such that the point source approach may be applied.

Question 1.1

Estimate the ^{226}Ra activity still present on the hands of this alarm clock. You can assume that the dose rate is solely caused by ^{226}Ra (including its daughters).

Watch dial painters were prohibited from using their mouths to make sharp points on their brushes in 1925, and severe bone sarcoma has only been identified in people who were employed in the business before that year. The mouth is therefore seen to be the main route of contamination among these dial painters. In September 1994, R.E. Rowland of the Argonne National Laboratory in Illinois published a major review of ‘Radium in Humans’.

In this question we will use 'Case 00-003' from Rowland's article as an example. This concerns a woman who was born in 1894 and died in 1927, the cause of death being malignant bone tumours in her upper body. We will call her 'Casie'. Casie started work as a dial painter in 1917. She worked for 104 weeks and in that time ingested a dose of 603.7 µCi of ^{226}Ra. The article describes a corresponding dose of 3404 cGy.

Question 1.2

Assume that Casie received 1/104th part of the total activity each week. Calculate the committed effective dose ingested by Casie during one working week. Assume a single intake for that week.

A radiation expert makes a number of assumptions to be able to make a rough estimate of the energy transfer of 603.7 µCi of ^{226}Ra.

Supporting data and assumptions:

- Assume that the ^{226}Ra was in equilibrium with all its daughters at the moment of intake.
- You can also assume that the alpha yield of the ^{226}Ra and each of its daughters is 100%.

Question 1.3

Suppose that 603.7 µCi of ^{226}Ra is in equilibrium with all its daughters and dissolved in a tightly-sealed container holding 70 litres of water. Calculate the absorbed dose (in Gy) in this container for one year. Only the energy of the alpha radiation is required for this calculation.

The daughter of ^{226}Ra, the noble gas radon-222 (^{222}Rn), has a half-life of 3.82 days. For humans, it is assumed that after ingestion of ^{226}Ra, two thirds of the radon will be expelled from the body through the lungs.

Question 1.4

Apply the calculation from Question 1.3a for a situation where the container with 70 litres of water is no longer tightly sealed and two thirds of the radon that is formed immediately escapes.

Problem 2. Production of ^{18}F

To produce ^{18}F, protons are accelerated in a cyclotron and transported by a beam guidance system to a water target enriched with stable ^{18}O ($H_2{}^{18}O$, enriched to approx. 97%).

Supporting data:

- The radioactive nuclide ^{18}F is formed by the reaction ^{18}O (p, n);
- The production rate $\dot{P}$ (s^{-1}) of ^{18}F is determined by:

  $$\dot{P} = f \cdot \frac{m \cdot N_A}{M} \cdot \sigma \cdot \varphi = 0.97 \cdot \frac{4.44 \cdot 6.022 \cdot 10^{23}}{20} = 1.30 \cdot 10^{23} \cdot \sigma \cdot \varphi,$$

  with σ being the cross-section in cm^2 and
  φ being the proton fluence rate in cm^{-2} s^{-1};
- The cross-section (σ) of the ^{18}O for the protons is $11 \cdot 10^{-3}$ barn per atom;
- 1 barn = 10^{-24} cm^2;
- $\varphi = I / (e \cdot O)$ = beam current in Ampere divided by the elementary charge in Coulomb times the surface area of the proton beam (O);
- The beam current is I = 120 μA = 120 μC/s;
- The elementary charge is $e = 1.60 \cdot 10^{-19}$ C;
- The beam surface area is O = 1.0 cm^2;
- The activity of the ^{18}F in the water target at time t is determined by a supply and removal process and is given as a function of time by: $A(t) = \dot{P} \times (1 - e^{-\lambda t})$;
- The half-life of ^{18}F is 109.7 minutes.

Question 2.1

Calculate the activity of the ^{18}F that is produced if the water target enriched with ^{18}O is irradiated for 120 minutes.

At a certain point, the decay rate of the produced radionuclide is equal to the production rate, and saturation is reached.

Question 2.2

Calculate the minimum irradiation time(in number of whole half-lives) required to reach at least 95% saturation activity (maximum activity).

After irradiation, the ^{18}F produced in the enriched water is transported as a liquid through a pipe under a concrete floor to a hot cell in the cleanroom (the ^{18}F laboratory) (Figure 1).

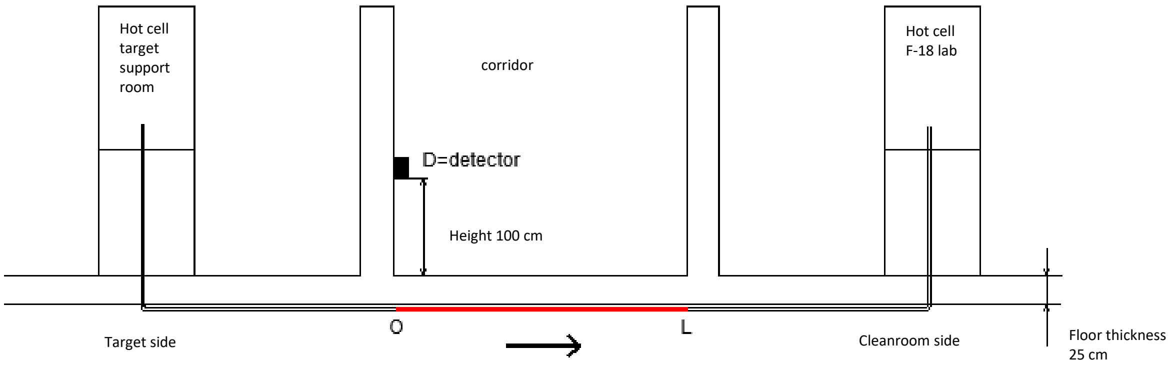

Figure 1: Side view of the pipeline (figure is not to scale).

The ^{18}F transport stagnates, and when the batch still has not reached the synthesis hot cell in the clean room after 10 minutes, the operator goes to investigate. He discovers that an ambient dose equivalent rate monitor is giving an alarm (position of the detector in Figure 1). He performs a number of additional tests and finds that the ^{18}F bolus (total volume of the radioactive material during transport through the pipe) has become stuck under the concrete floor between position 0 and L in Figure 1. Immediately after performing the additional tests, the operator contacts the responsible chief operator, who quickly arrives on the scene and solves the problem. The bolus continues to the synthesis hot cell in the ^{18}F laboratory without further problems.

Supporting data:

- The volume of the ^{18}F solution is 4.0 ml.
- The pipe has an inside diameter of 1.0 mm.
- The volume (V) of a tube of length L and radius r is: $V = \pi \cdot r^2 \cdot L$.
- The detector of the ambient dose equivalent rate monitor is positioned 1 m (= 100 cm) above the floor.
- The concrete floor is 25 cm thick.
- **Appendix, p. 5:** *Handboek Radionucliden*, [Radionuclides Handbook], A.S. Keverling Buisman (2nd edition 2007), p 26, ^{18}F data.
- **Appendix, p. 6:** NIST Standard Reference Database 126: Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients from 1 keV to 20 MeV for Elements Z = 1 to 92 and 48, Additional Substances of Dosimetric Interest, J. H. Hubbell and S. M. Seltzer (latest update July 2004), ordinary concrete.

- **Appendix, p. 7:** ANS-6.4.3, D.K. Trubey (September 1988), appendix II table 3, Exposure build-up factors for concrete, page 44.
- In DOVIS-B, a source may be regarded as a point source if the distance between the measuring point and the source is at least five times the largest dimension of the considered source.

Question 2.3

Calculate the length of the ^{18}F bolus and argue why the bolus in the described situation cannot be regarded a point source.

In Figure 2 below, the ^{18}F bolus is displayed as a line source with length L. In the described situation, the detector of the ambient dose equivalent rate monitor is located at position D relative to the ^{18}F bolus.

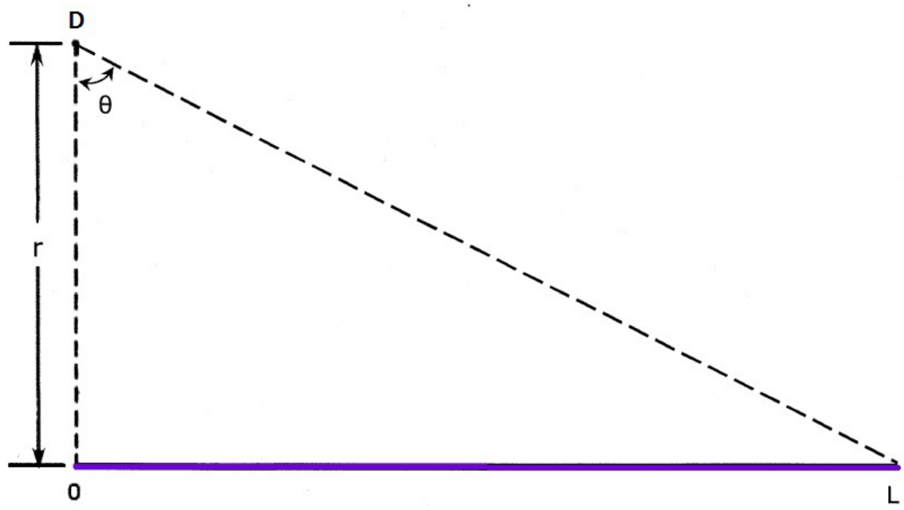

Figure 2. Line source

The ambient dose equivalent rate (including exposure build-up factor) of an isotropic straight line source in an attenuating medium (location D) can be calculated with the Sievert integral. For this specific situation, the Sievert integral for the line source between 0 and L can be approximated with:

$$\dot{H}^{*}(10) = \frac{h \cdot A \cdot \theta}{r \cdot L} \cdot \sqrt{\frac{1}{\theta \cdot \mu d}} \cdot B \cdot e^{-\mu d}$$

In this formula, *h* = the ambient dose equivalent rate constant in μSv/h per MBq/m², A = the activity in MBq, θ = the angle in radians[1], r = the distance between the measuring point and the line source in m, L = the length of the line source in m, μ = the linear attenuation coefficient in cm^{-1}, d = the thickness of the protective layer in cm, and B = the build-up factor. Although the build-up factor depends on the source geometry, in this case you can assume that the build-up factor of an *isotropic line source* is the same as that of an *isotropic point source*.

If you did not find an answer to Question 1 you can use 0.5 TBq.

Question 2.4

Calculate the ambient dose equivalent rate that the operator reads on the monitor (assume the amount of ^{18}F activity calculated in Question 1). You can assume a photon energy of 0.5 MeV when using the tables in the appendices on pages 6 and 7.

[1] Note: check if your calculator is set to degrees or radians (1 radian = 180 / π degrees and 1 degree = π /180 radians)

Problem 3. Abou's travels

On 9 May 2015, the following item was broadcast on the Dutch news.

A woman [...] who was behaving strangely drew the attention of Spanish customs officials. She was trying to carry a suitcase across the border between Morocco and the Spanish enclave of Ceuta. When the suitcase was scanned it immediately became clear why the woman was so nervous; the suitcase contained an eight-year-old boy. When the suitcase was zipped open, the boy casually greeted the surprised customs officials in French with the words: 'Hi, my name is Abou.'

The X-ray device that is used to scan the suitcases is situated under the conveyor belt. The X-ray beam is pointed vertically upward. The customs official is exposed to scattered radiation that passes through the opening of the luggage scanner.

Figure 1: *Diagram of the luggage scanner with relevant distances*

Supporting data:

- The DC voltage of the tube is V = 150 kV.
- The average anode current is I = 0.2 mA.
- The average exposure time is 20 ms per scan.
- The distance between the focus (F, Figure 1) and the surface of the conveyor belt (C, Figure 1) is 63.5 cm.
- The distance between the surface of the conveyor belt and the top of the luggage scanner (B, Figure 1) is 47 cm.
- **Appendix, p. 8:** Broad beam transmission of X-radiation through lead according to ICRP Publication 33, p. 38, fig. 7.
- **Appendix, p. 9:** Conversion coefficients of Air Kerma to ambient dose equivalent and to effective dose (based on ICRP Publication 74).
- **Appendix, p. 10:** Scattering coefficients of X-radiation (based on ICRP Publication 33).
- **Appendix, p. 11:** Decree Radiation Protection EZ, Article 4.10 paragraph 1.
- The dimensions of the suitcase are 55 × 35 cm (these are the maximum permitted dimensions of hand luggage).
- The distance between the irradiated part of the conveyor belt and the custom official's position is 1.5 m.
- The scanner makes an average of 10 scans per minute.
- To calculate the radiation protection units, assume an effective X-ray energy of 100 keV. This applies to both the primary and secondary (i.e. scattered) radiation.

Question 3.1

Use a calculation to demonstrate that the effective dose received by Abou from a single scan in the luggage scanner is a few μSv. You may disregard the shielding provided by the conveyor belt and the suitcase for this question. Use the exposure at the level of the conveyor belt to calculate the effective dose.

Question 3.2

Calculate the average ambient dose equivalent rate (in μSv/h) at 10 cm from the top of the luggage scanner (A, Figure 1). You may disregard the shielding provided by the conveyor belt, luggage and the wall of the scanner for this question.

Question 3.3

Lead shielding is placed on the top of the scanner (B, Figure 1). Calculate the minimum required lead thickness to meet the legal requirement for radiation leakage for inherently safe devices. Round the result off to 0.5 mm.

Question 3.4 a

Calculate the maximum possible effective annual dose of the customs official caused by scattered radiation. You can assume that the area of the scattering surface is the same as the surface area of a suitcase with the maximum allowable dimensions, measured at height C (Figure 1) and with a scattering angle of 90°.

Question 3.4b

Name at least one practically feasible measure that could reduce the radiation exposure of customs officials.

Problem 4. Liquid waste analysis

An isotope laboratory uses ^{35}S and ^{32}P. The non-chemical radioactive liquid waste is collected in one 10-litre barrel. The barrel is disposed of when it is filled to 90%, but first the radioactivity of the contents has to be determined. To this end, a sample of 10 ml is collected, mixed with a liquid scintillator and measured in a liquid scintillation counter (LSC). For the sake of simplicity, you can assume that no quenching substances are present in the waste sample. The test results and the spectrum are printed on a paper slip as illustrated in Figure 1 op page 12 of the appendix. To determine how the various radionuclides are displayed in the spectrum on the print, two vials of radiochemically pure radioisotopes namely ^{35}S and ^{32}P are also measured in the same manner. Both radionuclides are pure β emitters.

Explanation of the test results:

The test results are divided into three overlapping regions: A, B and C. The boundaries of these regions are indicated with a lower level (LL) and an upper level (UL), whereby the lower level is always 0 keV. The upper level is equal to the maximum energy of three commonly used beta emitters: ^{3}H (region A, $E_{\beta,max}$ = 18.6 keV), ^{35}S (region B, $E_{\beta,max}$ = 167 keV) and ^{32}P (region C, $E_{\beta,max}$ = 1711 keV). Region C therefore also includes the contributions of region B and region A! The measurement time is always 30 seconds.

Supporting data:

- **Appendix, p. 12,** Figure 1: Test results and spectrum of the liquid waste sample.
- **Appendix, p. 13,** Figure 2: Test results and spectrum of a pure ^{32}P sample
- **Appendix, p. 14,** Figure 3: Test results and spectrum of a pure ^{35}S sample
- Assume negligible quenching for all measurements
- The contribution of background radiation to the count rate can be disregarded for all measurements
- The total efficiency in region C is 0.90 cpm/dpm for ^{35}S and 0.95 cpm/dpm for ^{32}P
- **Appendix, p. 15,** Physical half-life ($T_{½}$), radiotoxicity equivalent for ingestion (Re_{ing}) and maximum beta energy
- **Appendix, p. 16,** MR Implementation Radiation Protection EZ, Appendix 1.5, Calculations AGIS paragraaf 4.4, Discharges to water

Question 4.1 a

Why does only ^{32}P contribute in region C-B (the energy region between 167 and 2000 keV)?

Question 4.1b
Calculate the efficiency (cpm/dpm) of ^{32}P in region C-B.

Question 4.2
Calculate the relative statistical inaccuracy in the calculation of the activity of ^{32}P based on 1 sigma.

Question 4.3
Calculate the activity of ^{32}P in the 10-litre barrel.

Question 4.4
Calculate the activity of ^{35}S in the 10-litre barrel.

The laboratory produces ten barrels of waste per year (all filled to 90%) and wants to discharge these contents. To this end, they need to know how far this waste falls below the secondary level for discharges to water (W_{SN} the decision threshold). To determine the maximum yearly discharge in water, expressed in Re (W_{max}) it is important to know how much activity may be discharged per radionuclide ($A_{w,i}$). In the MR Implementation Radiation Protection EZ the calculation rules for the analysis consequences ionising radiation (AGIS) for discharges to water are described.

The activity of the maximum permissible discharge to water of radionuclide i ($A_{w,i}$) per year can be calculated using:

$$A_{W,i} = A_{\text{liquid waste},i} \times CR_{w,i}$$

$CR_{w,i}$ is the correction factor for the radioactive decay and accumulation in the environment of radionuclide i.

Assume that the activity in every barrel is equal to the activities determined in question 4.3 and 4.4.

Question 4.5
Calculate the fraction of the secondary dose level for discharges to water caused by the annual discharge of the contents of the ten 10-litre barrels.