Under embargo until 11 May 2015

Coordinated examination in radiation protection
Expertise Level 3

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Delft University of Technology	TUD
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Examination date: 11 May 2015
Duration of examination: 13.30-16.30

Instructions:

- **This examination comprises 11 numbered pages and a separate 14-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 question and the answer is needed to solve the rest of the question, 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 67 points for solving the problems correctly. The points are distributed across the problems as follows:

  Problem 1: 18 points
  Problem 2: 17 points
  Problem 3: 16 points
  Problem 4: 16 points

Problem 1 Internal contamination control

A new supervising radiation expert has been appointed at a radionuclide laboratory (level C). This expert wants to reassess all protocols, risks and control measurements. The laboratory personnel work with DNA, which is labelled with ^{32}P. This labelling is performed with a non-volatile nuclide. 1 MBq of ^{32}P is used for each labelling.

The radiation expert first wonders if this labelling should be performed on a table in the laboratory, as has been standard practice up to this point. He uses the calculation from the 'Appendix Radionuclide Laboratory' permit appendix to make this determination.

Supporting data:

- **Appendix, pp. 3-4**: Handboek Radionucliden, [Radionuclide Manual], A.S. Keverling Buisman (2nd edition 2007), pp. 32-33, data for ^{32}P.
- **Appendix, pp. 5-7**: 'Appendix Radionuclide Laboratory' permit appendix, pp. 10, 11 and 12.
- Assume a class F compound.

Question 1.1
Demonstrate that it is permissible to perform the labelling outside of the fume hood.

The internal regulations stipulate that NDRIS[1] must be notified of a committed effective dose of 10 µSv or more resulting from internal contamination. The new radiation expert wonders if the periodic examination of the laboratory employees' urine is adequate for detecting this committed effective dose.
In order to ensure that the examination is not too taxing, the option of examining the laboratory employees' urine every Monday morning is considered. A sample of 2.5 mL is taken, which is then measured in a liquid scintillation counter.

[1] NDRIS = **National Dose Registration and Information System**

Supporting data:

- Assume in all calculations that a single contamination has occurred 7 days before the examination.
- The daily urine production is 1400 mL.
- The detection efficiency of the liquid scintillation counter for urine samples with ^{32}P is: $\varepsilon = 0.80$ cpm/dpm.
- The data from the Radionuclides Handbook may be used for these urine samples.

Question 1.2a
Calculate the activity of the ^{32}P nuclide that an employee must inhale in order to receive a committed effective dose of 10 μSv.

Question 1.2b
Calculate which activity (as calculated in 1.2a) would end up in the urine sample.

The sample is measured for 10 minutes. During an extremely long measuring period, it was determined that the background count rate was 10.0 cpm.

Question 1.3
Would it be possible to measure the activity calculated above in this urine sample? The following is considered significant: a confidence interval of 3σ above the background count rate.

Because the radiation expert suspect that the background count rate fluctuates, the background is measured for a short period after each measurement of the urine sample.
The following measurements are performed on a certain Monday morning:
- A urine sample is measured for 10 minutes and the result is: 13.1 cpm.
- The background count rate is measured immediately afterwards for 10 minutes, yielding the following result: 9.3 cpm.

Question 1.4
Calculate the activity in the urine sample and the spread in this answer. Does the calculation of the committed effective dose from this activity yield a value that must be reported to the NDRIS?

Problem 2 Mobile accelerator for IORT

Intra-operative radiotherapy (IORT) is a treatment in which a local therapeutic dose of electron radiation (hereinafter referred to simply as the therapeutic dose) is administered after the removal of a tumour – before the surgical wound is even closed. This ensures that the skin and other tissue do not need to receive a dose of radiation.
The option of purchasing a mobile electron accelerator for the purpose of performing intra-operative radiotherapy is considered. This accelerator can produce an electron beam with a maximum electron energy value of 10 MeV. Before proceeding with the purchase, the shielding measures required to comply with the legal limits must first be identified. The required therapeutic dose is 20 Gy (absorbed dose).

Supporting data:

- For this problem, assume that the irradiation direction is perpendicularly down.
- When a beam of electron radiation is used, photons are created in the patient.
- **Appendix, page 8, Table 1:** Ambient dose equivalent (μSv) at various distances and positions around the patient for a therapeutic dose of electron radiation of 10 Gy.
- **Appendix, page 8, Table 2:** Measured half-value and tenth-value layers (respectively *HVL* and *TVL*) for broad photon radiation beams for lead, concrete and iron as a function of the applied electron acceleration voltage during IORT. From: Introduction to Health Physics, Herman Cember, third edition.
- An effective dose constraint of 1 mSv/year for persons present in all adjacent and underlying areas is applicable.
- The floor is composed of 30 cm of concrete.
- The distance between the part of the patient that will be irradiated and the head height of the people in the underlying area is at least 3.5 metres.

Question 2.1

Explain how a therapeutic dose of 20 Gy, originating from a 10-MeV electron beam, can result in a significant ambient dose equivalent ($H^*(10)$) for people other than the patient.

Question 2.2
Use **Table 2 (Appendix, p. 8)** to demonstrate that the build-up factor in concrete – for photons created when an electron acceleration voltage of 10 MV is used – is 1 for thicknesses up to and including the tenth-value layer. Do this by proving that there is an exponential relationship between the transmission of the photon radiation and the thickness of the concrete in the case of the above-mentioned concrete layers.

Question 2.3
How many patients can be irradiated per year without exceeding the applicable dose constraint for people in the underlying area?

The answer to Question 2.3 reveals that the shielding effect of the concrete is insufficient when several dozens of patients are irradiated each year. The amount of lead that must be installed under the patient to comply with the applicable dose limit will therefore be determined.
If you were unable to obtain the answer to Question 2.3, assume a number of 25 patients.

Question 2.4
Calculate the extra lead thickness that is required to comply with the applicable dose constraint when 200 patients are being treated each year.

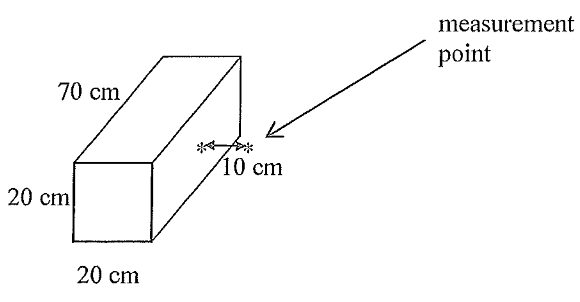
Problem 3 Wood from Latvia

An inhabitant of Diemen called the fire brigade in 2010. He had purchased firewood, but reports in the media made him worry that the firewood was contaminated with radioactive substances. The firewood originated in Latvia and was growing there at the time of the Chernobyl disaster. The inhabitant had twelve sacks of wood in the garden in 2010, each having a mass of 15 kg.
The Hazardous Substances Advisor (AGS) arrived at the location after the fire brigade had been called and measured a net maximum ambient dose equivalent rate of 0.45 μSv/h on 10 cm of the surface of a sack of wood. Because the wood with an elevated radiation level was discovered in the possession of a private individual, the Environmental Hygiene Inspectorate, as it was known then, was alerted. The Environmental Hygiene Inspectorate explained the potential risks posed by wood from a region affected by the Chernobyl disaster to the inhabitant of Diemen. The inspector forbade the use of the wood as fuel for fire. In addition, he asked the RIVM to pick up the wood and dispose of it in a responsible manner.
In this problem, you will try to determine the underlying arguments for the inspector's decision.

Supporting data:

- **Appendix, pp. 9-10:** Handboek Radionucliden, [Radionuclide Manual], A.S. Keverling Buisman (2nd edition 2007), pp. 172-173, ^{137}Cs data.
- The maximum ambient dose equivalent rate measured can be used as a good estimator for the ambient dose equivalent rate.
- ^{137}Cs is mainly found to be present in/on the wood. Other radionuclides may be ignored in this problem.
- The transmission of the photon radiation emitted by ^{137}Cs through wood is 1.
- The average background ambient dose equivalent rate in the open air in the Netherlands amounts to 70 nSv/h.

Figure 1 Sketch of a sack of wood and the measurement point.



The AGS performed measurements at a distance of 10 cm from the surface of the sack of wood (see Figure 1). Because this sack of wood is 20 cm deep, 20 cm wide and 70 cm high, the point source approximation method cannot be used. The point source method may only be used when the distance to the sack of wood is equal to or greater than 5 times the maximum dimension of the sack.
According to DOVIS-B[2], the plate source approximation method can be applied with the help of the following formula if the maximum dimension (L_{max}) of a source is smaller than 5 times the minimum dimension of that source (L_{min}).

$$\dot{H}^*(10,g) = \frac{4 \cdot A}{(L_{\min})^2} \cdot h(10) \cdot \ln\left(\frac{(L_{\min})^2}{4g^2} + 1\right) \cdot T$$

In this formula, L_{min} is the plate's minimum dimension (in metres) and g is the distance to its centre (in metres). Furthermore, A is the activity (in MBq), $\dot{H}^*(10,g)$ is the ambient dose equivalent rate (in μSv/h) at a distance of g (in m), *h(10)* is the ambient dose equivalent rate constant (in μSv/h per MBq on 1 m) and T is the transmission for photons from the plate source.
Even though the sack of wood cannot actually be considered a plate source, this method is still chosen for practical reasons. In this case, the distance g (in m) is equal to the distance from the measurement point to the centre of the sack of wood.

Question 3.1
Demonstrate that the activity of the ^{137}Cs in/on the wood is equal to 0.22 MBq. Use the plate source scenario for this question.

Question 3.2
Demonstrate that the AGS would not have been able to perform a measurement in accordance with the point source method model. Assume that a measurement is only significantly different from the background when the background ambient dose equivalent rate has been increased at least once.

Question 3.3
Is the wood supply exempt in accordance with the exemption limits of the Radiation Protection Decree?

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[2] Dosisberekening voor de Omgeving bij Vergunningverlening Ioniserende Straling – DOVIS Deel B: Externe Straling [Ambient Dose Calculation for Use in Ionising Radiation Licensing – DOVIS Part B: External Radiation], J.F.A. van Hienen et al. (2002)

Suppose that the inhabitant was not aware of the contamination risk posed by the wood and had burned all of it in the fireplace. Assume that his neighbour would then have inhaled 0.1% of the stoked activity.

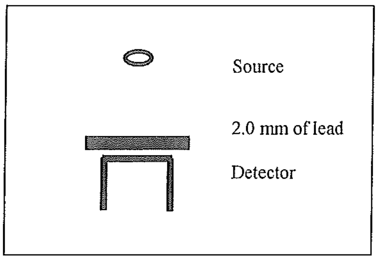
Question 3.4
Calculate the committed effective dose for the neighbour if the wood had been completely stoked.

Problem 4 Bismuth-207 calibration source

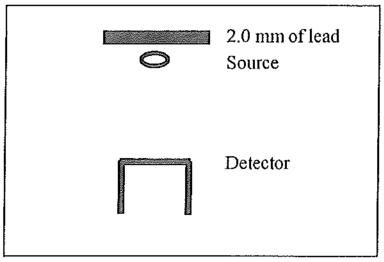
A radionuclide laboratory possesses a number of ^{207}Bi sources. These sources are used for calibrations. On 10 August 2013, measurements are performed on one of the sources. The measurements are performed with a sodium iodide (NaI) scintillation detector connected to a PC with a multichannel analyser (MCA). The screen of the MCA shows a photon spectrum ("gamma spectrum"): the channel numbers, which match the energy of the photon radiation, are shown horizontally, while the intensity is shown vertically.
Page 12 of the Appendix shows four measured photon spectra, which have each been counted 10 minutes.

- Spectrum of background radiation;
- Spectrum 1, the unshielded ^{207}Bi source;
- Spectrum 2A, the ^{207}Bi source shielded with a 2.0 mm thick lead plate between the source and the detector (see situation 2A, bottom left);
- Spectrum 2B, the unshielded ^{207}Bi source with a 2.0 mm thick lead plate on top of the source (see situation 2B, bottom right).

Situation 2A side view:



Situation 2B side view:



The distance from the source to the top of the detector is the same for spectrum 1, 2A and 2B; this distance is 10 cm in each case.
Three so-called Regions of Interest (ROI) are indicated in the spectra. The quantitative measurement data of the ROIs can be found on page 13 of the Appendix.

Supporting data:

- The source is ^{207}Bi, 10.0 kBq on 10 April 1995.
- All spectra were recorded on 10 August 2013.
- The half-life of ^{207}Bi is 31.55 years.
- **Appendix, p. 11:** Simplified decay scheme of ^{207}Bi.
- **Appendix, p. 12:** Photon spectra measured at the ^{207}Bi source.
- **Appendix, p. 13:** Table with quantitative data for the photon spectra.

- Binding energies of lead in keV:
  K shell 88.0; L_I shell 15.9; L_{II} shell 15.2; L_{III} shell 13.4 from the Handbook of Chemistry and Physics, 60th edition.
- **Appendix, p. 14:** 83-Bismuth-207 emitted radiation, http://www.orau.org library nuclide data.

Question 4.1
Calculate the total measurement efficiency of the photo peak of gamma 2 in cps/Bq for the unshielded situation (spectrum 1).

Question 4.2
Calculate the linear attenuation coefficient μ for lead in cm^{-1} for the peak in ROI II. The following applies to the build-up factor for this energy and lead thickness: B = 1.1.

A comparison between spectrum 2B and spectrum 1 reveals that spectrum 2B shows 15,976 more counts over the whole area than spectrum 1; this is a significantly higher number.
Numerically, part of this effect can be explained by an increase in ROI I; spectrum 2B has 7,317 more counts in ROI I than spectrum 1.
The other increase (calculated number = 8,659 counts) cannot be explained by a significant increase in the other ROIs, but this increase is 'spread out', as it were, over the entire spectrum 2B, especially on the lower energy side.

Question 4.3a
Explain the 'spread out' spectrum increase.

ROI I only covers a small part of the spectrum. In addition to the explanation meant in Question 4.3a, there is also another effect causing the clear ROI I increase in spectrum 2B.

Question 4.3b
Explain this ROI I increase.

Appendix 4 shows that the total combined yield of the characteristic X-radiation of ^{207}Bi is 1.08 (0.366 + 0.218 + 0.163 + 0.332 = 1.08). If the yield of the Auger electrons is added, the total yield for these follow-up processes will even be 1.65.

Question 4.4

Explain how the total yield of characteristic X-radiation and Auger electrons for ^{207}Bi can be greater than 1 on the basis of the decay data on page 14 of the Appendix.