

# **HEALTH PHYSICS PROBLEMS**

**for radiation protection officers**

**dispersible radioactive materials  
- level C**

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**edition 2025**

This collection of problems is designed to support the syllabus 'HEALTH PHYSICS for radiation protection officers - dispersible radioactive materials - level C' by Frits Pleiter and Hielke Freerk Boersma (GARP, Groningen, 2025).

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# **MEASURING RADIOACTIVITY**



## 1 Measurement and statistics

To measure a small amount of activity, a measuring setup with a very low background is used. Two measurements are performed with this setup. First, a measurement is taken with a flat counting tray containing a quantity of evaporated liquid placed just below the detector. This detects 85 particles in 1000 seconds (measurement A). The measurement is then repeated with a clean counting tray, measuring 45 particles in 1000 seconds (measurement B).

### Question 1

Calculate the gross counting rate and its standard deviation. Express both quantities in counting pulses per second (cps) and give the result in the form  $R_{\text{gross}} \pm \sigma_{\text{gross}}$ .

### Question 2

Calculate the background effect and its standard deviation. Express both quantities in counting pulses per second (cps) and give the result in the form  $R_{\text{background}} \pm \sigma_{\text{background}}$ .

### Question 3

Calculate the net counting rate and its standard deviation. Express both quantities in counting pulses per second (cps) and give the result in the form  $R_{\text{net}} \pm \sigma_{\text{net}}$ .

### Question 4a

Calculate the relative error in the net counting rate.

### Question 4b

How long must one count, at a least, to obtain a relative error of 10% with a confidence level of 95%? The counting times for measurement A and measurement B remain the same.

**Rating**      **1: 3**      **2: 1**      **3: 5**      **4a: 1**      **4b: 6**

## 2 Minimum detectable activity

The radiation protection officer has a GM counter tube with a circular end window with a diameter of 10 mm. The zero effect of this tube is 24 counting pulses per minute. A point-shaped radioactive source is located on the axis of the tube, at a distance of 10 cm from the window.

### Data

- The radioactive source emits only  $\beta$  particles.
- Self-absorption in the source and absorption in the window of the counting tube may be neglected.
- The geometric efficiency ( $f_{\text{geometry}}$ ) is defined as the number of  $\beta$  particles reaching the detector window divided by the number of  $\beta$  particles emitted by the source in the same time.
- The intrinsic detector efficiency ( $f_{\text{detector}}$ ) is defined as the net number of counting pulses divided by the number of  $\beta$  particles reaching the counting gas in the same time. The intrinsic detector efficiency of this GM counter tube for the emitted  $\beta$  particles is 100%.
- The detection efficiency ( $\epsilon$ ) is defined as the net number of counting pulses per second (cps) divided by the activity of the source (expressed in Bq).
- The minimum detectable activity is defined as the activity that leads to a significant increase in the count rate. For this question, that increase is equated to a doubling of the background: the gross count rate then becomes twice the background.

### Question 1

Calculate the geometric efficiency  $f_{\text{geometry}}$  of the measuring setup.

### Question 2

Calculate the detection efficiency  $\epsilon$  of the measuring setup.

### Question 3

Calculate the minimal detectable activity.

The GM counter tube is then moved to a position close to the point-shaped radioactive source.

### Question 4

Calculate the minimum detectable activity once again.

**Rating**      **1: 4**      **2: 4**      **3: 4**      **4: 4**

### 3 Liquid scintillation counter

A radionuclide laboratory only works with the radionuclides  $^3\text{H}$ ,  $^{14}\text{C}$  en  $^{32}\text{P}$ . These nuclides emit only  $\beta$  particles with a maximum energy of 19 keV, 156 keV en 1710 keV, respectively. A liquid scintillation counter with a fixed setting is used to perform control measurements.

#### Data

- The detection efficiency for  $^3\text{H}$ ,  $^{14}\text{C}$  en  $^{32}\text{P}$  in the different channels (see Table 1).
- The background in counting pulses per minute (cpm) in the different channels, measured during 1000 minutes (see Table 1).
- The minimum detectable activity is defined as the activity that leads to a significant increase in count rate. Here, the criterion is that the net count rate is equal to twice the standard deviation of the background.

<i>nuclide</i>	<i><math>^3\text{H}</math> channel</i>	<i><math>^{14}\text{C}</math> channel</i>	<i><math>^{32}\text{P}</math> channel</i>
	<i>counting efficiency (cps per Bq)</i>		
$^3\text{H}$	0.20	0.00	0.00
$^{14}\text{C}$	0.12	0.54	0.00
$^{32}\text{P}$	0.015	0.11	0.80
	<i>background (cpm)</i>		
	13.5	9.7	18.9

Table 1. Specifications of the liquid scintillation counter.

#### Question 1

For the  $^{32}\text{P}$  channel, determine the background in the form  $R \pm \sigma$ . Express both quantities in counting pulses per second (cps).

#### Question 2

Calculate the minimum detectable  $^{32}\text{P}$  activity for each of the three channels at a measuring time of 10 minutes.

#### Question 3

For the  $^{32}\text{P}$  channel, calculate the counting time that is minimally required to just detect 0.1 Bq of  $^{32}\text{P}$ . The criterion here is again that the net counting rate is equal to twice the standard deviation of the background.

**Rating**      **1: 5**      **2: 6**      **3: 5**

## 4 Determining counting efficiency

A quantity of 100 mg of indium metal is dissolved in diluted acid, transferred to a vial, which is then filled with scintillation liquid.

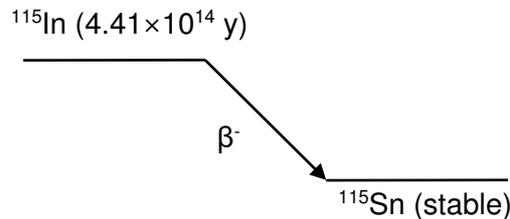


Figure 1. Decay scheme of the radionuclide  $^{115}\text{In}$ .

### Data

- The decay scheme of the radionuclide  $^{115}\text{In}$  (see Figure 1).
- The mass number of indium is 114.8 g/mol.
- Natural indium consists of 95.7 atomic % of the radioactive nuclide  $^{115}\text{In}$ .
- Avogadro's number is  $N_{\text{Avo}} = 6.022 \times 10^{23}$  atoms per mol.

### Question 1

Calculate the number of  $^{115}\text{In}$  atoms in 100 mg indium.

### Question 2

Calculate the activity of 100 mg indium.

The vial is then placed in the liquid scintillation counter. Over a measuring period of 8 hours, 2116 counting pulses are registered. The background is 1440 counting pulses, also measured over 8 hours.

### Question 3

Calculate the net count rate ( $R_{\text{net}}$ ) and the standard deviation of the net count rate ( $\sigma_{\text{net}}$ ), both expressed in counting pulses per second (cps).

### Question 4

Calculate the counting efficiency ( $\epsilon$ ) and the standard deviation of the counting efficiency ( $\sigma_{\epsilon}$ ), both expressed in cps/Bq.

Rating      1: 4      2: 4      3: 4      4: 4



## 6 Mother-daughter equilibrium

(1987-2-4)

The filter through which air was sucked during the passage of the activity cloud as a result of the Chernobyl incident is expected to contain the isotopes  $^{89}\text{Sr}$  and  $^{90}\text{Sr}$ , among others. The sampling took place on 02-05-86 from 9:00 a.m. to 11:00 a.m. In order to be able to quantitatively demonstrate the strontium, it is chemically separated from the other elements on the filter. The time of separation is 02-09-86 at 10:00 a.m. The Sr sample is measured immediately after separation using a proportional counter (measurement I). The net count rate is 1.77 counting pulses per second (cps). Exactly one month later, on 02-10-86, the sample is measured again (measurement II). The net count rate is then 2.10 cps.

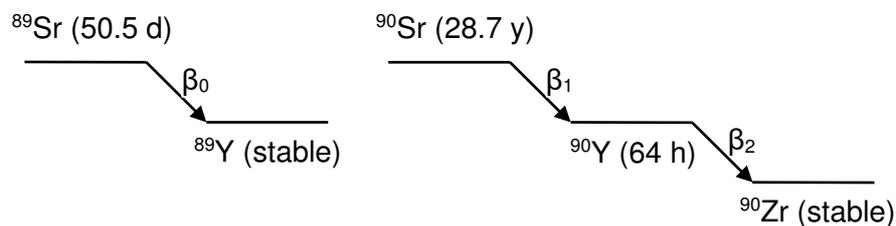


Figure 1. Simplified decay schemes of the radionuclides  $^{89}\text{Sr}$ ,  $^{90}\text{Sr}$  and  $^{90}\text{Y}$ .

### Data

- The simplified decay schemes of  $^{89}\text{Sr}$ ,  $^{90}\text{Sr}$  and  $^{90}\text{Y}$  (see Figure 1).
- The counting efficiency of the measuring setup for  $\beta$  particles is 28%.
- Absorption of  $\beta$ -radiation may be neglected.

### Question 1

Calculate the total activity of  $^{89}\text{Sr}$ ,  $^{90}\text{Sr}$  and  $^{90}\text{Y}$  on the filter during measurement I.

### Question 2

Calculate the total activity of  $^{89}\text{Sr}$ ,  $^{90}\text{Sr}$  and  $^{90}\text{Y}$  on the filter during measurement II.

### Question 3a

Argue that during measurement I, the activity of  $^{90}\text{Y}$  is negligible.

### Question 3b

Argue that during measurement II the activities of  $^{90}\text{Y}$  and  $^{90}\text{Sr}$  are (almost) equal.

### Question 3c

Calculate the decay correction for  $^{89}\text{Sr}$  and  $^{90}\text{Sr}$  for the time between measurements I and II.

### Question 4

Calculate the activity of  $^{89}\text{Sr}$  and the activity of  $^{90}\text{Sr}$  during the sampling.

Rating

1: 4

2: 1

3a: 2

3b: 2

3c: 2

4: 5

## 7 Activity of a $^{22}\text{Na}$ -source

A point source containing  $^{22}\text{Na}$  is surrounded on all sides by plastic that is so thick that all  $\beta^+$  particles are stopped in the enclosure. The  $^{22}\text{Na}$  source is placed in the source holder of a NaI scintillation detector. In the photopeak, 130 980  $\gamma$ -photons are detected in 5 minutes.

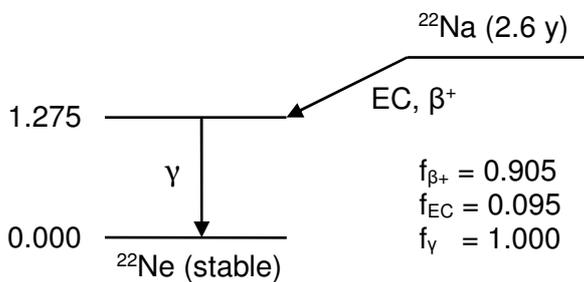


Figure 1. Decay scheme of the radionuclide  $^{22}\text{Na}$ . Energies are given in MeV.

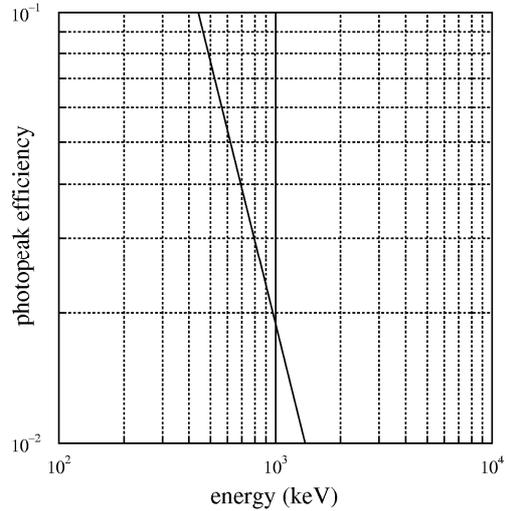


Figure 2. Absolute photopeak efficiency of the NaI-detector as a function of the  $\gamma$ -energy.

### Data

- The decay scheme of  $^{22}\text{Na}$  (see Figure 1).
- The absolute photopeak efficiency for the used measuring geometrie, i.e. the probability that a  $\gamma$ -photon emitted by the source will cause a counting pulse in the photopeak (see figure 2).

### Question 1

Determine the photopeak efficiency for  $\gamma$ -photons in the decay of  $^{22}\text{Na}$ .

### Question 2

Calculate the activity of the source.

### Question 3

Sketch the  $\gamma$ -ray spectrum as measured with a NaI scintillation detector.

### Question 4

Does the radioactive radiation from  $^{22}\text{Na}$  cause multiple photo peaks? If so, give the  $\gamma$ -energy and the count rate (in counting pulses per minute) for each photo peak. If necessary, correct the  $\gamma$ -ray spectrum sketched in Question 3.

**Rating**      **1: 2**      **2: 5**      **3: 3**      **4: 6**

## 8 Attenuation of $\gamma$ -radiation by iron

A source of  $^{60}\text{Co}$  is placed 20 cm away from a cylindrical GM tube, on the axis of the tube. Absorption measurements are performed in a wide-beam geometry, with iron plates placed between the source and the counter tube, perpendicular to the aforementioned axis. The series of measurements is repeated in a narrow-beam geometry, with the  $\gamma$  beam collimated by a thick lead plate with a cylindrical hole positioned such that the entire detector can "see" the source.

thickness (cm)	broad beam (cpm)	narrow beam (cpm)
0	9990	10 003
2	7343	4274
4	4506	1826
6	2605	780
8	1450	333
10	777	142

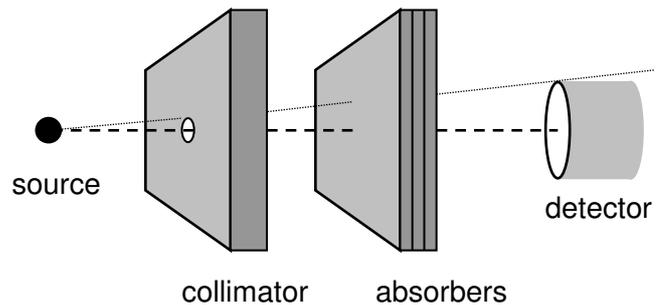


Figure 1. Diagram of the measuring setup.

Table 1 Net number of counting pulses per minute (cpm) as a function of the thickness of the absorber (in cm).

### Data

- Diagram of the measuring setup (see Figure 1).
- Measured net count rate (in cpm) for broad-beam and narrow-beam geometries (see Table 1).
- The density of iron is  $\rho = 7.8 \text{ g/cm}^3$ .

### Question 1

Plot the measured values against the absorber thickness in a graph. Choose graph paper and units that best present the measured values.

### Question 2a

Using the graph for the narrow-beam geometry, determine the transmission of 7 cm of iron.

### Question 2b

Using the graph for the broad-beam geometry, determine the transmission of 7 cm of iron.

### Question 2c

Calculate the buildup factor for a thickness of 7 cm iron.

### Question 3

Calculate the mass attenuation coefficient  $\mu/\rho$  of iron for  $\gamma$ -radiation of  $^{60}\text{Co}$ .

**Rating**      **1: 4**      **2a: 2**      **2b: 2**      **2c: 3**      **3: 5**

## 9 Measurement on a $^{131}\text{I}$ -solution

A fixed measuring setup with a NaI scintillation detector (detector I) is calibrated using  $^{241}\text{Am}$ ,  $^{113}\text{Sn}$ ,  $^{137}\text{Cs}$ , and  $^{60}\text{Co}$ . All calibration sources have an activity of 370 kBq. A test tube containing 5.0 ml of aqueous solution containing the radionuclide  $^{131}\text{I}$  is then placed in the same position as the calibration sources were previously.

nuclide	$E_\gamma$ (keV)	$f_\gamma$	$N_\gamma$ (cpm)
$^{241}\text{Am}$	60	0.36	75 300
$^{113}\text{Sn}$	255	0.02	2790
	392	0.64	52 700
$^{137}\text{Cs}$	662	0.85	36 800
$^{60}\text{Co}$	1170	1.00	17 300
	1330	1.00	13 300
$^{131}\text{I}$	365	0.81	1072

Table 1. Radioactive decay data of the used radionuclides and net number of counting pulses (in cpm) measured with detector I.

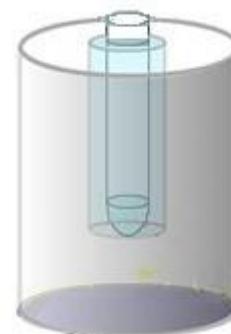


Figure 1. NaI well crystal (detector II)

### Data

- Radioactive decay data for the radionuclides used (see Table 1).
- Net number of counting pulses per minute (cpm) measured with detector I in the photopeak (see Table 1).
- The counting efficiency ( $\epsilon$ ) is defined as the net number of counting pulses divided by the number of  $\gamma$ -photons emitted by the source in the same time.

### Question 1

Calculate the counting efficiency of detector I as a function of the  $\gamma$ -energy. Plot the results on double-logarithmic graph paper.

### Question 2

Calculate the activity concentration (in Bq/ml) of the  $^{131}\text{I}$ -solution.

Finally, the test tube containing the  $^{131}\text{I}$  solution is placed in the cavity of a NaI well crystal (detector II; see Figure 1). The net count rate, measured at the photo peak, is 65 800 cpm.

### Question 3

Calculate the counting efficiency  $\epsilon$  of the NaI well crystal for  $^{131}\text{I}$ .

**Rating**      **1: 6**      **2: 5**      **3: 5**

## 10 Air contamination monitor

(1991-1-1)

A monitor for measuring radioactivity in the open air consists of a Ge detector, a filter tape, and a pump. Every two hours, the filter tape moves forward so that a clean spot on the filter appears in front of the inlet of the pump. While the air is being sucked in, the radioactivity deposited on the filter is simultaneously recorded using the Ge detector.

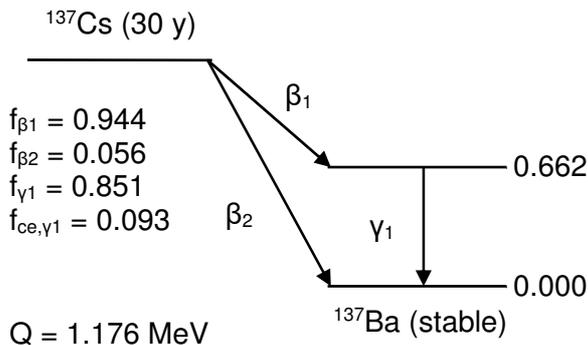


Figure 1. Decay scheme of the radionuclide  $^{137}\text{Cs}$ . Energies are given in MeV.

### Data

- The decay scheme of  $^{137}\text{Cs}$  (see Figure 1).
- Diagram of the measuring setup (see Figure 2).
- The pump has a constant air flow rate of  $9.5 \text{ m}^3/\text{hour}$ .
- The filter tape has a capture efficiency of 100%.
- The absolute photopeak efficiency of the Ge detector in this geometry (see Figure 3).

### Question 1

Calculate the  $^{137}\text{Cs}$  activity on the filter at the end of the sampling and measurement period, if there is a constant  $^{137}\text{Cs}$  concentration of  $10 \text{ Bq}/\text{m}^3$  in the open air.

### Question 2

Calculate the net number of pulses recorded in the  $^{137}\text{Cs}$  photopeak after the sampling and measurement period at this activity concentration. Use the average activity on the filter, which is the activity collected halfway through the sampling and measurement period.

The minimum detectable  $^{137}\text{Cs}$  activity is defined as the activity that leads to a significant increase in the count rate. In this question, the criterion is that the net content of the  $^{137}\text{Cs}$  photopeak must contain at least 30 counting pulses.

### Question 3

Calculate the minimum  $^{137}\text{Cs}$  concentration in the open air that can just be detected with this measuring setup.

Rating      1: 6    2: 6    3: 4

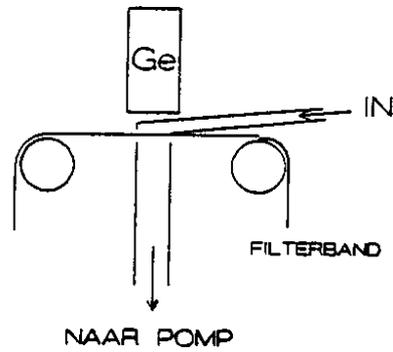


Figure 2. Diagram of the measuring setup consisting of pump, filter tape and Ge-detector.

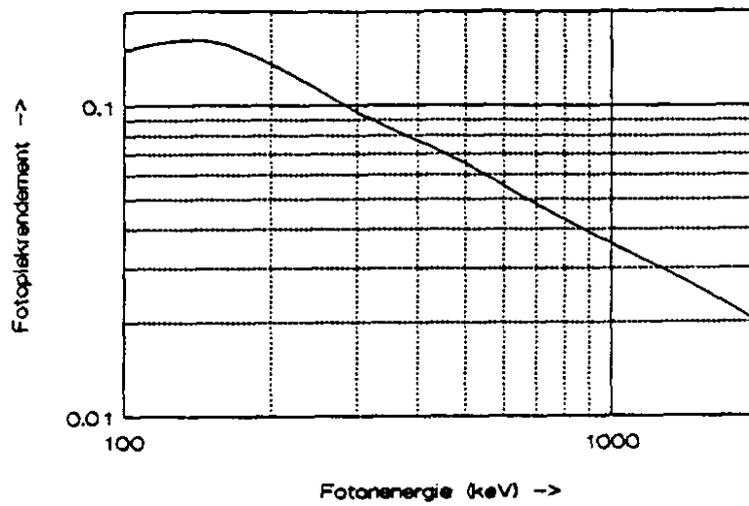


Figure 3. Absolute photopeak efficiency of the Ge-detector.

## Solutions

### Question 1

- $R_{\text{gross}} \pm \sigma_{\text{gross}} = (N_{\text{gross}} \pm \sqrt{N_{\text{gross}}}) / t = (85 \pm \sqrt{85}) / 1000 \text{ s} = 0.085 \pm 0.009 \text{ cps}$
- $R_{\text{background}} \pm \sigma_{\text{background}} = (N_{\text{background}} \pm \sqrt{N_{\text{background}}}) / t = (45 \pm \sqrt{45}) / 1000 \text{ s} = 0.045 \pm 0.007 \text{ cps}$
- $R_{\text{net}} = R_{\text{gross}} - R_{\text{background}} = 0.085 \text{ cps} - 0.045 \text{ cps} = 0.040 \text{ cps}$   
 $\sigma_{\text{net}} = \sqrt{(\sigma_{\text{gross}}^2 + \sigma_{\text{background}}^2)}$   
 $= \sqrt{(N_{\text{gross}} + N_{\text{background}})} / t = \sqrt{(85 + 45)} / 1000 \text{ s} = \sqrt{130} / 1000 \text{ s} = 0.011 \text{ cps}$
- a  $\sigma_{\text{net}} / R_{\text{net}} = 0.011 \text{ cps} / 0.040 \text{ cps} = 0.28 = 28\%$  for a counting time of 1000 s
- a 95% confidence level corresponds to  $2\sigma$   
thus  $2 \times 28\% = 56\%$  for a counting time of 1000 s  
this should be 10%  $\rightarrow$  counting time must be  $1000 \text{ s} \times (56\% / 10\%)^2 = 31\,360 \text{ s} = 8.7 \text{ h}$

### Question 2

- $f_{\text{geometry}} = (\text{area detector window}) / (\text{area sphere with radius of } 10 \text{ cm})$   
 $= [\pi \times (0.5 \text{ cm})^2] / [4\pi \times (10 \text{ cm})^2] = 6.25 \times 10^{-4}$
- $\epsilon = f_{\text{emission}} \times f_{\text{geometry}} \times f_{\text{absorption}} \times f_{\text{detector}} = 1 \times 6.25 \times 10^{-4} \times 1 \times 1 = 6.25 \times 10^{-4} \text{ cps/Bq}$
- $\epsilon \times A_{\text{min}} = R_{\text{background}}$   
 $A_{\text{min}} = R_{\text{background}} / \epsilon = (24 \text{ cpm} / 60 \text{ s/min}) / 6.25 \times 10^{-4} \text{ cps/Bq} = 640 \text{ Bq}$
- $f_{\text{geometry}} = 0.5$  (2 $\pi$ -geometry)  
 $\epsilon = 1 \times 0.5 \times 1 \times 1 = 0.5 \text{ cps/Bq}$   
 $A_{\text{min}} = R_{\text{background}} / \epsilon = (24 \text{ cpm} / 60 \text{ s/min}) / 0.5 \text{ cps/Bq} = 0.8 \text{ Bq}$

### Question 3

- $N = R \times t$       $\sigma_N = \sqrt{N}$       $R = N / t$       $\sigma_T = \sigma_N / t$   
 $^{32}\text{P}$ -kanaal      $N = 18.9 \text{ cpm} \times 1000 \text{ min} = 18\,900$       $\sigma_N = \sqrt{18\,900} = 137$   
                          $t = 1000 \text{ min} \times 60 \text{ s/min} = 60\,000 \text{ s}$   
                          $R = 18\,900 / 60\,000 \text{ s} = 0.315 \text{ cps}$       $\sigma_T = 137 / 60\,000 \text{ s} = 0.0023 \text{ cps}$
- $2\sigma = 2\sqrt{(18.9 \text{ cpm} \times 10 \text{ min})} = 27.5$   
 $= A_{\text{min}} \times f_{\text{emission}} \times f_{\text{geometry}} \times f_{\text{detector}} \times t$   
 $= A_{\text{min}} \times 1 \times 1 \times f_{\text{detector}} \times (10 \text{ min} \times 60 \text{ s/min}) = 600 \text{ s} \times f_{\text{detector}} \times A_{\text{min}}$   
 $A_{\text{min}} = 2\sigma / (600 \text{ s} \times f_{\text{detector}}) = 27.5 / (600 \text{ s} \times f_{\text{detector}}) = 0.046 \text{ s}^{-1} / f_{\text{detector}}$   
 $^{3}\text{H}$       $A_{\text{min}} = 0.046 \text{ s}^{-1} / 0.015 = 3.1 \text{ Bq}$   
 $^{14}\text{C}$       $A_{\text{min}} = 0.046 \text{ s}^{-1} / 0.11 = 0.42 \text{ Bq}$   
 $^{32}\text{P}$       $A_{\text{min}} = 0.046 \text{ s}^{-1} / 0.80 = 0.058 \text{ Bq}$
- $^{32}\text{P}$ -kanaal      $(0.058 \text{ Bq} / 0.1 \text{ Bq})^2 \times 10 \text{ min} = 3.36 \text{ min} = 202 \text{ s}$

### Question 4

- $N_{\text{indium}} = (\text{mass} / \text{mass number}) \times N_{\text{Avo}}$   
 $= (100.0 \times 10^{-3} \text{ g} / 114.8 \text{ g/mol}) \times 6.022 \times 10^{23} \text{ atoms/mol}$   
 $= 5.25 \times 10^{20} \text{ In atoms}$   
 $N_{^{115}\text{In}} = 95.7 \times 10^{-2} \times N_{\text{indium}} = 0.957 \times 5.25 \times 10^{20} = 5.02 \times 10^{20} \text{ }^{115}\text{In atoms}$
- $A = \lambda N$   
 $\lambda = 0.693 / (4.41 \times 10^{14} \text{ y} \times 365 \text{ d/y} \times 24 \text{ uur/d} \times 3600 \text{ s/h}) = 4.98 \times 10^{-23} \text{ s}^{-1}$   
 $A = 4.98 \times 10^{-23} \text{ s}^{-1} \times 5.02 \times 10^{20} = 0.0250 \text{ Bq}$
- $R_{\text{gross}} \pm \sigma_{\text{gross}} = (2116 \pm \sqrt{2116}) / (8 \text{ h} \times 3600 \text{ s/h}) = 0.0735 \pm 0.0016 \text{ cps}$   
 $R_{\text{background}} \pm \sigma_{\text{background}} = (1440 \pm \sqrt{1440}) / (8 \text{ h} \times 3600 \text{ s/h}) = 0.0500 \pm 0.0013 \text{ cps}$   
 $R_{\text{net}} = R_{\text{gross}} - R_{\text{background}} = 0.0735 \text{ cps} - 0.0500 \text{ cps} = 0.0235 \text{ cps}$   
 $\sigma_{\text{net}} = \sqrt{(\sigma_{\text{gross}}^2 + \sigma_{\text{background}}^2)} = \sqrt{(0.000\,0026 + 0.000\,0017)} = \sqrt{0.000\,0043} = 0.0021 \text{ cps}$
- $\epsilon A = R_{\text{net}}$   
 $\epsilon \pm \sigma_{\epsilon} = (R_{\text{net}} \pm \sigma_{\text{net}}) / A = (0.0235 \text{ cps} \pm 0.0021 \text{ cps}) / 0.0250 \text{ Bq} = 0.94 \pm 0.08 \text{ cps/Bq}$

Question 5

- 1  $N_{\beta} = A \times (f_{\beta 1} + f_{\beta 2}) \times f_{\text{geometry}} \times f_{\text{detector}} \times t = A \times 1.0 \times 0.5 \times 1 \times 1 \text{ s} = 0.5 \text{ s} \times A$   
 $= N_{\text{gross}} - N_{\text{background}} = 170 - 10 = 160 \text{ counting pulses}$   
 $A = 160 / 0.5 \text{ s} = 320 \text{ Bq}$   
 sampled area = area of contamination monitor = 200 cm<sup>2</sup>  
 total activity = 320 Bq  $\times (10 \text{ m}^2 \times 10^4 \text{ cm}^2/\text{m}^2 / 200 \text{ cm}^2)$   
 $= 1.6 \times 10^5 \text{ Bq} = 160 \text{ kBq}$
- 2  $N_{\beta} = A \times f_{\gamma} \times (f_{\text{geometry}} \times f_{\text{detector}}) \times t = A \times 0.85 \times 0.15 \times 1 \text{ min} \times 60 \text{ s/min} = 7.7 \text{ s} \times A$   
 $= N_{\text{gross}} - N_{\text{background}} = 546 - 87 = 459 \text{ counting pulses}$   
 $A = 459 / 7.7 \text{ s} = 60 \text{ Bq}$   
 sampled area = area cut-out piece of filter = 25 cm<sup>2</sup>  
 total activity = 60 Bq  $\times (10 \text{ m}^2 \times 10^4 \text{ cm}^2/\text{m}^2 / 25 \text{ cm}^2) = 2.4 \times 10^5 \text{ Bq} = 240 \text{ kBq}$
- 3 transmission = (result measurement I) / (result measurement II) = 160 kBq / 240 kBq = 2/3  
 absorption = 1 - transmission = 1 - 2/3 = 1/3 = 33%

Question 6

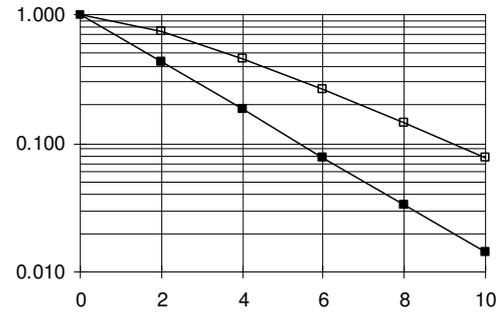
- 1  $N_I = A \times f_{\beta} \times (f_{\text{geometry}} \times f_{\text{detector}}) \times t = A \times 1 \times 0.28 \times 1 \text{ s} = 0.28 \text{ s} \times A$   
 $= 1.77 \text{ counting pulses}$   
 $A_I = N_I / 0.28 \text{ s} = 1.77 / 0.28 \text{ s} = 6.32 \text{ Bq}$
- 2  $A_{II} = N_{II} / 0.28 \text{ s} = 2.10 / 0.28 \text{ s} = 7.50 \text{ Bq}$
- 3a daughter <sup>90</sup>Y grows with a half-life of 64 h  
 immediately after the separation, hardly any <sup>90</sup>Y has been formed  
 $\rightarrow A_I = A_{89\text{Sr},I} + A_{90\text{Sr},I} + A_{90\text{Y},I} = A_{89\text{Sr},II} + A_{90\text{Sr},I}$
- 3b measurement II took place a month after the separation  
 meanwhile, 30 d  $\times 24 \text{ h/d} / 64 \text{ h} = 11$  half-lives have elapsed  
 mother and daughter are in equilibrium, so that  $A_{90\text{Y},II} = A_{90\text{Sr},II}$   
 $\rightarrow A_{II} = A_{89\text{Sr},II} + A_{90\text{Sr},II} + A_{90\text{Y},II} = A_{89\text{Sr},II} + 2 A_{90\text{Sr},II}$
- 3c between measurement I and m measurement II, <sup>89</sup>Sr partly decayed, whilst the decay of <sup>90</sup>Sr is negligible  
 $\rightarrow A_{II} = e^{-0.693 \times 30 / 50.5} A_{89\text{Sr},I} + 2 A_{90\text{Sr},I} = 0.66 A_{89\text{Sr},I} + 2 A_{90\text{Sr},I}$
- 4 we have 2 equations with 2 unknowns  
 Question 3a  $A_I = A_{89\text{Sr},I} + A_{90\text{Sr},I} = 6.32 \text{ Bq} \quad | +2 |$   
 Question 3c  $A_{II} = 0.66 A_{89\text{Sr},I} + 2 A_{90\text{Sr},I} = 7.50 \text{ Bq} \quad | -1 |$   
 $1.34 A_{89\text{Sr},I} = 2 \times 6.32 \text{ Bq} - 7.50 \text{ Bq} = 5.14 \text{ Bq}$   
 $A_{89\text{Sr},I} = 5.14 \text{ Bq} / 1.34 = 3.84 \text{ Bq}$   
 $A_{90\text{Sr},I} = 6.32 \text{ Bq} - A_{90\text{Sr},I} = 6.32 \text{ Bq} - 3.84 \text{ Bq} = 2.48 \text{ Bq}$

Question 7

- 1 reading from Figuur 1 at 1275 keV  $\rightarrow \epsilon_{1275} = 0.012$
- 2  $N_{1275} = A \times f_{1275} \times \epsilon_{1275} \times t = A \times 1.0 \times 0.012 \times 5 \text{ min} \times 60 \text{ s/min} = 3.6 \text{ s} \times A$   
 $= 130 \text{ 980}$   
 $A = 130 \text{ 980} / 3.6 \text{ s} = 3.6 \times 10^4 \text{ Bq} = 36 \text{ kBq}$
- 3 in addition to  $\gamma$ -photons with an energy of 1275 keV, annihilation photons with an energy of  $E_{\pm} = 511 \text{ keV}$  are also emitted; the energy spectrum therefore consists of two photon peaks, each with a corresponding Compton edge
- 4 reading from Figuur 1 at 511 keV  $\epsilon_{511} = 0.07$   
 furthermore,  $f_{511} = 2 f_{\beta+} = 2 \times 0.905 = 1.81$   
 $t = 5 \text{ min} \times 60 \text{ s/min} = 300 \text{ s}$   
 $R_{511} = N_{511} / t = A \times f_{511} \times \epsilon_{511} = 3.6 \times 10^4 \text{ Bq} \times (2 \times 0.905) \times 0.07 = 4.6 \times 10^3 \text{ cps}$   
 $R_{1275} = N_{1275} / t = 130 \text{ 980} / 300 \text{ s} = 437 \text{ cps} = 0.44 \times 10^3 \text{ cps}$

### Question 8

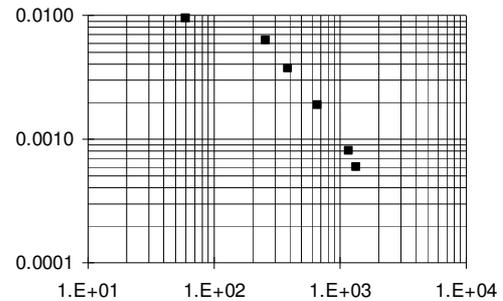
- 1 use single-logarithmic graph paper
- 2a reading graph at 7 cm  
→  $T_{\text{broad beam}} = 0.20$
- 2b reading graph at 7 cm  
→  $T_{\text{narrow beam}} = 0.050$
- 2c  $B = T_{\text{broad beam}} / T_{\text{narrow beam}}$   
 $= 0.20 / 0.050 = 4.0$
- 3 reading graph bij 10 cm  
→  $T_{\text{narrow beam}} = 0.015$   
 $T(10 \text{ cm}) = e^{-(\mu/\rho)(d\rho)} = e^{-(10 \times 7.87)(\mu/\rho)} = e^{-78.6(\mu/\rho)}$   
 $\mu/\rho = \ln(0.015) / (-78.7 \text{ g/cm}^2) = 0.053 \text{ cm}^2/\text{g}$



### Question 9

- 1  $N_Y = A \times f_Y \times \varepsilon \times t = 370 \times 10^3 \text{ Bq} \times f_Y \times \varepsilon \times 60 \text{ s}$   
 $= 2.22 \times 10^7 f_Y \times \varepsilon$   
 $\varepsilon = N_Y / (2.22 \times 10^7 f_Y)$

nuclide	$E_Y$ (keV)	$f_Y$ (%)	$N_Y$	$\varepsilon$
$^{241}\text{Am}$	60	36	75 300	$9.4 \times 10^{-3}$
$^{113}\text{Sn}$	255	2	2790	$6.3 \times 10^{-3}$
	392	64	52 700	$3.7 \times 10^{-3}$
$^{137}\text{Cs}$	662	85	36 800	$1.9 \times 10^{-3}$
$^{60}\text{Co}$	1170	100	17 300	$0.8 \times 10^{-3}$
	1330	100	13 300	$0.6 \times 10^{-3}$



- 2 reading of graph at  $E_Y = 365 \text{ keV} \rightarrow \varepsilon_{365} = 0.004$   
 $N_{365} = A \times f_{365} \times \varepsilon_{365} \times t = A \times 0.81 \times 0.004 \times 60 \text{ s} = 0.19 \text{ s} \times A$   
 $= 1072 \text{ counting pulses}$   
 $A_{365} = 1072 / 0.19 \text{ s} = 5.6 \times 10^3 \text{ Bq} = 5.6 \text{ kBq}$   
volume = 5 ml  
activity concentration is  $5.6 \text{ kBq} / 5 \text{ ml} = 1.1 \text{ kBq/ml}$
- 3  $N_{365} = A \times f_{365} \times \varepsilon_{365} \times t = 5.6 \times 10^3 \text{ Bq} \times 0.81 \times \varepsilon_{365} \times 60 \text{ s} = 2.7 \times 10^5 \varepsilon_{365}$   
 $= 65 800 \text{ counting pulses}$   
 $\varepsilon_{365} = 65 800 / 2.7 \times 10^5 = 0.24$

### Question 10

- 1 due to the long half-life of  $^{137}\text{Cs}$ , radioactive decay does not play a role  
 $A = \text{activity concentration} \times \text{flow rate} \times \text{capture efficiency} \times \text{time}$   
 $= 10 \text{ Bq/m}^3 \times 9.5 \text{ m}^3/\text{h} \times 1 \times 2 \text{ h} = 190 \text{ Bq}$
- 2 the activity builds up linearly during sampling (and therefore during measurement)  
activity halfway through sampling  $\langle A \rangle = 190 \text{ Bq} / 2 = 95 \text{ Bq}$   
reading of Figuur 1  $f_Y = 0.851$   
reading of Figuur 3 at 662 keV  $\varepsilon_Y = 0.05$   
 $N = \langle A \rangle \times f_Y \times \varepsilon_Y \times t = 95 \text{ Bq} \times 0.851 \times 0.05 \times 2 \text{ h} \times 3600 \text{ s/h} = 2.9 \times 10^4 \text{ counting pulses}$
- 3  $10 \text{ Bq/m}^3$  gives  $2.9 \times 10^4$  counting pulses  
 $30 \text{ counting pulses correspond to } 10 \text{ Bq/m}^3 \times (30 / 2.9 \times 10^4) = 0.010 \text{ Bq/m}^3$

# **SOURCES, SHIELDING AND TRANSPORT**



### 11 Leakage test on a <sup>60</sup>Co-source

The license for a <sup>60</sup>Co source requires, among other things, that the source be subjected to an annual leak test under the responsibility of a registered radiation protection expert (RPE). The test can be carried out, for example, by means of a wipe test, in which the source is wiped with a piece of filter paper. A NaI detector and a liquid scintillation counter are available for this purpose.

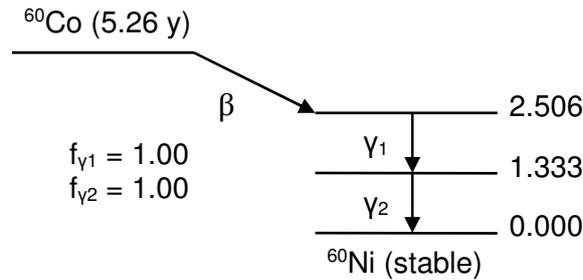


Figure 1. Decay scheme of the radionuclide <sup>60</sup>Co. Energies are given in MeV.

**Data**

- The decay scheme of the radionuclide <sup>60</sup>Co (see Figure 1).
- The counting efficiency is defined as the measured number of counting pulses divided by the number of  $\gamma$ -photons that hit the detector in the same time. The counting efficiency of the NaI detector for  $\gamma$ -photons from <sup>60</sup>Co is 12%.
- The NaI detector is insensitive to the  $\beta$ -particles of <sup>60</sup>Co
- The liquid scintillation counter is insensitive to the  $\gamma$ -photons of <sup>60</sup>Co.
- According to the ANVS Ordonance on Basic Safety Standards Radiation Protection, the source must be considered to leak if the wiped activity exceeds 185 Bq. If the holder is wiped instead of the source itself, the criterion is 18.5 Bq.

The RPE wipes the source and first places the piece of paper on the NaI detector. The result of the measurement is 917 counts per minute (cpm) with a background of 485 cpm.

**Question 1**

Calculate the wiped-off activity from the measurement with the NaI detector.

**Question 2**

Should the source in question be classified as leaking? Justify your conclusion.

The paper is then placed in a counting vial containing scintillation liquid and counted in the liquid scintillation counter. The result is 1645 cpm with a background of 25 cpm.

**Question 3**

Calculate the counting efficiency  $\epsilon$  of the liquid scintillation counter for <sup>60</sup>Co.

**Rating**            1: 7            2: 2            3: 7

## 12 Loss of a $^{133}\text{Ba}$ -source

(2001-2-3)

A missing  $^{133}\text{Ba}$  calibration source with an activity of 0.40 MBq is to be detected using a NaI monitor. The efficiency of the NaI monitor is first calibrated using a  $^{137}\text{Cs}$  calibration source of 4.0 MBq held at a distance of 50 cm in front of the monitor. The counting rate is 285 counts per second (cps), with a background of 10 cps.

### Data

- The relative detection efficiency of the monitor (see Figure 1).
- Energy  $E_\gamma$  and emission efficiency  $f_\gamma$  of the  $\gamma$ -photons emitted during the radioactive decay of  $^{133}\text{Ba}$  and  $^{137}\text{Cs}$  (see Table 1).
- According to the Regulation on Basic Safety Standards Radiation Protection, the exemption limits for  $^{133}\text{Ba}$  in moderate quantities ( $< 1000$  kg) are:
  1. exemption limit for activity is  $A_v = 1 \times 10^6$  Bq
  2. exemption limit for activity concentration is  $C_v = 1 \times 10^2$  Bq/g

nuclide	$E_\gamma$ (keV)	$f_\gamma$	nuclide	$E_\gamma$ (keV)	$f_\gamma$
$^{133}\text{Ba}$	81	0.338	$^{137}\text{Cs}$	662	0.85
	276	0.071			
	303	0.184			
	356	0.621			
	384	0.089			

Table 1. Data on the radioactive decay of the radionuclides  $^{133}\text{Ba}$  and  $^{137}\text{Cs}$ .

### Question 1

Determine the weighted relative detection efficiency  $\sum (f_\gamma \times f_{\text{detector}}^{\text{rel}})$  for the  $\gamma$  radiation of the radionuclides  $^{133}\text{Ba}$  and  $^{137}\text{Cs}$ .

### Question 2

Calculate the expected count rate if a  $^{133}\text{Ba}$  source of 4.0 MBq is located 50 cm from the monitor.

### Question 3

Calculate the minimum distance at which the missing calibration source can still be detected by the monitor in a significant manner. In this context, significant means that the indication of the monitor is at least twice the background.

Once the calibration source has been found, the intention is to transfer it to a partner company.

### Question 4

Indicate whether a nuclear energy act license is required for the possession of this calibration source. Justify your answer.

**Rating**      **1: 5**      **2: 4**      **3: 5**      **4: 2**

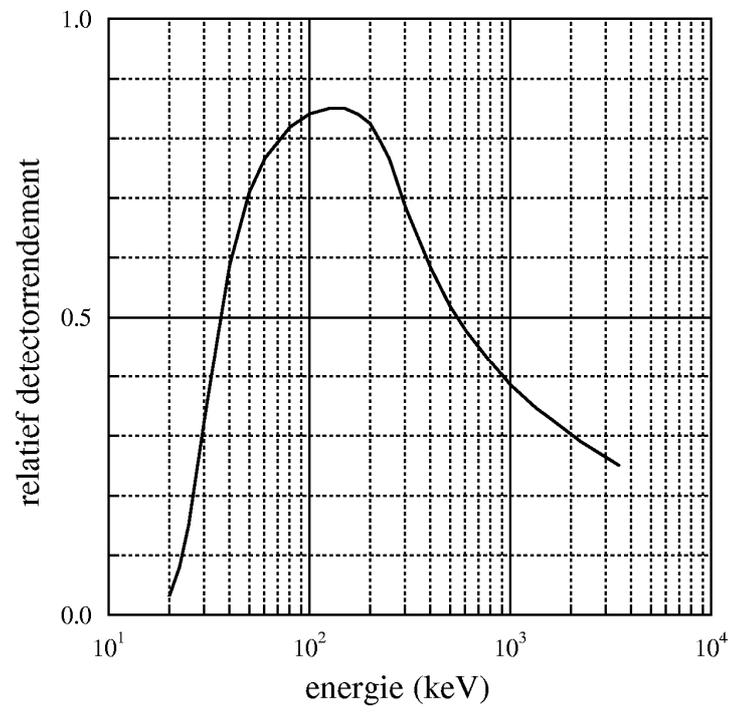


Figure 1. Relative detection efficiency  $f_{detector}^{rel}$ .

### 13 Contaminated $^{51}\text{CrCl}_3$

(1987-1-2)

For labeling experiments, a jar containing 100 grams of chromium chloride has been ordered, which is labeled with an exempt amount of  $^{51}\text{Cr}$  activity. After a preparation has been made with this in the C laboratory, it appears to be contaminated with  $^{42}\text{K}$  and to emit  $\beta$  radiation. The radiation protection expert has a GM counter with an end window. He places this GM counter 10 cm from the sample and measures a net count rate of  $3.5 \times 10^3$  counts per minute (cpm).

#### Data

- Radiation protection data for the radionuclide  $^{42}\text{K}$  (see Appendix, Figure 4).
- Radiation protection data for the radionuclide  $^{51}\text{Cr}$  (see Appendix, Figure 5).
- The maximum mass range of  $\beta$ -particles (see Appendix, Figure 10).
- The effective surface area of the GM counter window is  $1 \text{ cm}^2$ .
- The detector efficiency of the GM counter is zero for  $\gamma$ -photons and 100% for  $\beta$  particles.
- The sample may be considered a point source.
- Self-absorption and absorption in air may be neglected.
- The density of perspex is  $\rho = 1.19 \text{ g/cm}^3$ .
- According to the Decree on Basic Safety Standards Radiation Protection, the exemption limits for  $^{51}\text{Cr}$  in moderate quantities ( $< 1000 \text{ kg}$ ) are:
  1. exemption limit for activity is  $A_v = 1 \times 10^6 \text{ Bq}$
  2. exemption limit for activity concentration is  $C_v = 1 \times 10^2 \text{ Bq/g}$

#### Question 1

Calculate the geometry factor of this measuring setup.

#### Question 2

Calculate the  $^{42}\text{K}$  activity. If you fail to answer this question, assume 100 kBq when answering the next question.

#### Question 3

Check whether this activity is exempt. Justify your answer.

#### Question 4

Calculate the minimum thickness of a perspex screen that can stop all  $\beta$  radiation.

Rating            1: 4            2: 5            3: 2            4: 5

## 14 Lead container

In the center of a cylindrical lead container there is a cylindrical cavity with a diameter of 4 cm. In the center of this cavity there is a  $^{60}\text{Co}$  calibration source with an activity of 20 MBq. At a distance of 50 cm from the source, the ambient equivalent dose rate is  $10\ \mu\text{Sv/h}$ .

### Data

- The source constant of  $^{60}\text{Co}$  is  $h = 0.36\ \mu\text{Sv/h}$  per MBq/m<sup>2</sup>.
- The source constant of  $^{137}\text{Cs}$  is  $h = 0.093\ \mu\text{Sv/h}$  per MBq/m<sup>2</sup>.
- Transmission of broad-beam  $\gamma$ -radiation through lead (see Appendix, Figure 11).

### Question 1

Calculate the thickness of the lead-container wall. Round the result up to whole centimeters.

A  $^{137}\text{Cs}$  calibration source will be added. Both sources are located in the center of the lead container. For the next questions, assume the wall thickness calculated in Question 1.

### Question 2

Calculate the maximum activity of the  $^{137}\text{Cs}$  source, if it is required that the ambient equivalent dose rate resulting from both sources together is not more than  $10\ \mu\text{Sv/h}$  at a distance of 1 meter from the surface of the lead container.

### Question 3

In that case, calculate the ambient equivalent rate on the surface of the lead container.

### Question 4

Can this lead container be transported as a Type A package without further action?

**Rating**      **1: 4**      **2: 5**      **3: 3**      **4: 4**

## 15 Choice of a transport container

An ampoule containing 37 GBq of  $^{60}\text{Co}$  must be shipped from a radionuclide laboratory. Various cylindrical lead containers are available for this purpose, as specified in the information below.

### Data

- All lead containers have the same external diameter of 40 cm.
- All lead containers have a cylindrical cavity in the center with a diameter of 2 cm; the radioactive source is located in the middle of this cavity.
- The lead containers differ from each other in the amount of lead in the wall: the smallest thickness is 3 cm of lead and the subsequent thicknesses are each 1 cm greater; the shielding effect of the other material in the wall may be neglected.
- The source constant of  $^{60}\text{Co}$  is  $h = 3,6 \times 10^{-13}$  Sv/h per Bq/m<sup>2</sup>.
- Transmission of broad-beam  $\gamma$ -radiation through lead (see Appendix, Figure 11).
- The requirements for the ambient equivalent dose rate during transport are:
  1. less than 2 mSv/h on the surface of the container;
  2. less than 0.1 mSv/h at 1 meter from the surface of the container.

### Question 1

Calculate the minimum lead thickness required to meet transport requirement 1. Round the result to whole centimeters.

### Question 2

Calculate the minimum lead thickness required to meet transport requirement 2. Round the result to whole centimeters.

The radiation protection officer responsible for arranging the shipment chooses the lightest container that meets both transport requirements.

### Additional data

- Transporting the container takes 4 hours.
- The distance between the driver and the surface of the container is 2 meters.
- There is no further shielding between the driver and the container.
- The ambient equivalent dose  $H^*$  is a good estimate of the effective dose  $E$ .
- The driver is not classified as an exposed worker.

### Question 3

Calculate the effective dose that the driver will be exposed to during the drive.

### Question 4

How many such drives is the driver allowed to make per year?

**Rating**      **1: 4**      **2: 4**      **3: 6**      **4: 2**

## Solutions

### Question 11

- $$N_V = A \times (f_{V1} + f_{V2}) \times (f_{\text{geometrie}} \times f_{\text{detector}}) \times t = A \times (1.0 + 1.0) \times 12 \times 10^{-2} \times 60 \text{ s} = A \times 14.4 \text{ s}$$

$$= 917 - 485 = 432 \text{ counting pulses}$$

$$A = 432 / 14.4 \text{ (s)} = 30 \text{ Bq}$$
- the criterion is 185 Bq since the source itself is wiped  
the source doesn't have to be classified as leaking
- $$N_\beta = \varepsilon A t = \varepsilon \times 30 \text{ Bq} \times 60 \text{ s} = 1800 \times \varepsilon$$

$$= 1645 - 25 = 1620 \text{ counting pulses}$$

$$\varepsilon = 1620 / 1800 = 0.90$$

### Question 12

1	radionuclide	$E_\gamma$ (keV)	$f_\gamma$	$f_{\text{detector}}^{\text{rel}}$ (see Figure 1)	$f_\gamma \times f_{\text{detector}}^{\text{rel}}$	$\Sigma (f_\gamma \times f_{\text{detector}}^{\text{rel}})$
	$^{137}\text{Cs}$	662	0.85	0.46	0.39	0.39
	$^{133}\text{Ba}$	81	0.338	0.82	0.28	0.90
		276	0.071	0.73	0.05	
		303	0.184	0.68	0.13	
		356	0.621	0.63	0.39	
		384	0.089	0.60	0.05	

- $$R = A \times \Sigma (f_\gamma \times f_{\text{detector}})$$

herein,  $f_\gamma \times f_{\text{detector}}$  depends on the radionuclide  
the count rate R is therefore proportional to  $\Sigma (f_\gamma \times f_{\text{detector}})$   

$$R_{\text{net}}(4.0 \text{ MBq } ^{133}\text{Ba}) = (0.90 / 0.39) \times R_{\text{net}}(4.0 \text{ MBq } ^{137}\text{Cs})$$

$$= (0.90 / 0.39) \times (285 \text{ cps} - 10 \text{ tps}) = 635 \text{ cps}$$
- $$R_{\text{net}}(0.4 \text{ MBq } ^{133}\text{Ba}) = (0.4 \text{ MBq} / 4 \text{ MBq}) \times 635 \text{ cps} = 64 \text{ cps}$$

at a distance of 50 cm  
the criterion is  $R_{\text{net}}(r) = R_{\text{background}} = 10 \text{ cps}$   

$$= (r / 50 \text{ cm})^2 \times 64 \text{ cps}$$

$$r = 50 \text{ cm} \times \sqrt{(64 \text{ cps} / 10 \text{ cps})} = 50 \text{ cm} \times \sqrt{6.4} = 126 \text{ cm}$$
- $$0.4 \text{ MBq} = 4 \times 10^5 \text{ Bq} < 1 \times 10^6 \text{ Bq} = A_v$$

→ below the exemption limit  
→ no license required if this is the only activity

### Question 13

- $$f_{\text{geometry}} = (\text{area detector window}) / (\text{area sphere with radius of 10 cm})$$

$$= 1 \text{ cm}^2 / [4\pi \times (10 \text{ cm})^2] = 8.0 \times 10^{-4}$$
- $$\dot{N} = A \times f_{\text{geometry}} \times f_{\text{absorption}} \times f_{\text{detector}} = A \times 8.0 \times 10^{-4} \times 1 \times 1 = 8.0 \times 10^{-4} \times A$$

$$= 3.5 \times 10^3 \text{ cpm} = 58 \text{ cps}$$

$$A = 58 \text{ cps} / 8.0 \times 10^{-4} = 7.3 \times 10^4 \text{ Bq}$$
- $$A = 7.3 \times 10^4 \text{ Bq} < 1 \times 10^6 \text{ Bq} = A_v$$

$$C = 7.3 \times 10^4 \text{ Bq} / 100 \text{ g} = 7.3 \times 10^2 \text{ Bq/g} > 1 \times 10^2 \text{ Bq/g} = C_v$$

→ one of the two values is below the exemption limit  
→ no license required if this is the only activity
- reading of Appendix, Figure 4  
→  $E_{\beta, \text{max}} = 3521 \text{ keV} = 3.5 \text{ MeV}$   
reading of Appendix, Figure 10 at 3.5 MeV  
→  $R_{\beta, \text{max}} \times \rho = 1.7 \times 10^3 \text{ mg/cm}^2 = 1.7 \text{ g/cm}^2$   
minimum thickness is  $1.7 \text{ g/cm}^2 / \rho = 1.7 \text{ g/cm}^2 / 1.19 \text{ g/cm}^3 = 1.4 \text{ cm}$  of perspex

### Question 14

- 1 without shielding at 50 cm  $\dot{H}^*_{50\text{cm}} = h A / r^2$   
 $= 0.36 \mu\text{Sv/h per MBq/m}^2 \times 20 \text{ MBq} / (0.50 \text{ m})^2$   
 $= 29 \mu\text{Sv/h}$   
transmission =  $T = 10 \mu\text{Sv/h} / 29 \mu\text{Sv/h} = 0.34$   
reading of Appendix, Figure 11 for  $^{60}\text{Co}$   
→ 2.5 cm lead rounded up 3 cm
2. distance to source  $r = 100 \text{ cm} + 3 \text{ cm} + 4 \text{ cm} / 2 = 105 \text{ cm}$   
reading of Appendix, Figure 11 for  $^{60}\text{Co}$  and 3 cm  
→ transmission =  $T(^{60}\text{Co}) = 2.3 \times 10^{-1}$   
contribution from  $^{60}\text{Co}$   $\dot{H}^*(^{60}\text{Co})_{105\text{cm}} = h A T / r^2$   
 $= 0.36 \mu\text{Sv/h per MBq/m}^2 \times 20 \text{ MBq} \times 2.3 \times 10^{-1} / (1.05 \text{ m})^2$   
 $= 1.5 \times 10^{-3} \mu\text{Sv/h}$   
contribution of  $^{137}\text{Cs}$  should be  $10 \mu\text{Sv/h} - 1.5 \mu\text{Sv/h} = 8.5 \mu\text{Sv/h}$  at most  
reading of Appendix, Figure 11 for  $^{137}\text{Cs}$  and 3 cm  
→ transmission =  $T = 4 \times 10^{-2}$   
contribution from  $^{137}\text{Cs}$   $\dot{H}^*(^{137}\text{Cs})_{105\text{cm}} = h A T / r^2$   
 $= 0.093 \mu\text{Sv/h per MBq/m}^2 \times A \times 4 \times 10^{-2} / (1.05 \text{ m})^2$   
 $= 4.1 \times 10^{-3} \mu\text{Sv/h} \times A$   
 $= 8.5 \mu\text{Sv/h}$   
maximum  $^{137}\text{Cs}$  activity  $A = 8.5 \mu\text{Sv/h} / 4.1 \times 10^{-3} \mu\text{Sv/h}$   
 $= 2.1 \times 10^3 \text{ MBq} = 2.1 \text{ GBq}$
- 3 distance to source  $r = 3 \text{ cm} + 4 \text{ cm} / 2 = 5 \text{ cm}$   
equivalent dose rate  $\dot{H}^*_{5\text{cm}} = \dot{H}^*_{105\text{cm}} \times (105 \text{ cm} / 5 \text{ cm})^2$   
 $= 10 \mu\text{Sv/h} \times 441 = 4.4 \times 10^3 \mu\text{Sv/h} = 4.4 \text{ mSv/h}$
- 4 reading of Appendix, Figure 12  
→  $\dot{H}^* < 2000 \mu\text{Sv/h} = 2.0 \text{ mSv/h}$  on surface (label III-YELLOW)  
→  $\dot{H}^*_{5\text{cm}} = 4.4 \text{ mSv/h}$  is too much  
→ transport lead container in larger package

### Question 15

- 1  $\dot{H}^* = h A / r^2$   
distance to source  $r_1 = 40 \text{ cm} / 2 = 20 \text{ cm} = 0.2 \text{ m}$   
without shielding  $\dot{H}^* = 3.6 \times 10^{-13} \text{ Sv/h per Bq/m}^2 \times 37 \times 10^9 \text{ Bq} / (0.2 \text{ m})^2$   
 $= 0.33 \text{ Sv/h} = 330 \text{ mSv/h}$   
required transmission  $T_1 = 2 \text{ mSv/h} / 330 \text{ mSv/h} = 6 \times 10^{-3}$   
reading of Appendix, Figure 11 for  $^{60}\text{Co}$  and  $6 \times 10^{-3}$   
→ 9.5 cm of lead rounded up 10 cm
- 2 on surface  $r_2 = r_1 + 1 \text{ m} = 0.2 \text{ m} + 1 \text{ m} = 1.2 \text{ m}$   
without shielding  $\dot{H}^* = 3.6 \times 10^{-13} \text{ Sv/h per Bq/m}^2 \times 37 \times 10^9 \text{ Bq} / (1.2 \text{ m})^2$   
 $= 9.3 \times 10^{-3} \text{ Sv/h} = 9.3 \text{ mSv/h}$   
required transmission  $T_2 = 0.1 \text{ mSv/h} / 9.3 \text{ mSv/h} = 1.1 \times 10^{-2}$   
reading of Appendix, Figure 11 for  $^{60}\text{Co}$  and  $1.1 \times 10^{-2}$   
→ 8.3 cm of lead rounded up 9 cm

- 3 transport requirement 1 is decisive → 10 cm of lead in container wall  
distance between driver and source

$$r_3 = r_1 + 2 \text{ m} = 0.2 \text{ m} + 2 \text{ m} = 2.2 \text{ m}$$

without shielding  $\dot{H}^* = 3.6 \times 10^{-13} \text{ Sv/h per Bq/m}^2 \times 37 \times 10^9 \text{ Bq} / (2.2 \text{ m})^2$   
 $= 2.8 \times 10^{-3} \text{ Sv/h}$

reading of Appendix, Figure 11 for  $^{60}\text{Co}$  and 10 cm

→ transmissione =  $T_3 = 4.5 \times 10^{-3}$

driving time  $t_3 = 4 \text{ h}$

effective dose per drive  $E \approx \dot{H}^* T_3 t_3$   
 $= 2.8 \times 10^{-3} \text{ Sv/h} \times 4.5 \times 10^{-3} \times 4 \text{ h}$   
 $= 5.0 \times 10^{-5} \text{ Sv} = 0.05 \text{ mSv}$

- 4 annual limit non-exposed worker 1 mSv/y  
maximum number of drives  $1 \text{ mSv/y} / 0.05 \text{ mSv} = 20 \text{ per year}$



# **RADIONUCLIDE LABORATORY**



## 16 Radioimmunoassay (RIA)

A radioimmunoassay (RIA) using the radionuclide  $^{125}\text{I}$  is performed in the fume hood of the C laboratory for 4 hours per week.

### Data

- Radiation protection data for the radionuclide  $^{125}\text{I}$  (see Appendix, Figure 8).
- The p, q en r parameters according to the former Directive on Radionuclide Laboratories (see Appendix, Figure 13).
- The fume hood complies with the NEN-EN 14175 standard.
- Activity per practice is 100 kBq.

### Question 1

Calculate the maximum activity that may be used per practice.

### Question 2

Calculate the contribution of these practices to the load factor B of the radionuclide laboratory.

### Question 3

Under which two conditions may someone with a VRS-C diploma supervise this practice?

During the periodic contamination survey, the radiation protection officer wipes a spot on the surface at 10 locations with a tissue, after which the activities of the tissues are measured.

### Additional data

- The wiped surface area is  $10\text{ cm} \times 10\text{ cm}$  each time.
- On three occasions an activity of 0.4 kBq is measured.
- On seven occasions an activity of 1.2 kBq is measured.

### Question 4a

Calculate the surface contamination (in  $\text{Bq}/\text{cm}^2$ ) for the highest measured activity.

### Question 4b

Is this surface contamination more or less than the maximum permissible value? Justify your answer.

### Question 4c

Which of the 10 measured contamination values should be included in the nuclear energy act file?

**Rating**      **1: 5**      **2: 3**      **3: 2**      **4a: 2**      **4b: 2**      **4c: 2**

## 17 Labeling with $^{35}\text{S}$

On a bench in the C laboratory, a nonvolatile liquid is labeled with the radionuclide  $^{35}\text{S}$  for 4 hours per week

### Data

- Radiation protection data for the radionuclide  $^{35}\text{S}$  (see Appendix, Figure 3).
- The p, q en r parameters according to the former Directive on Radionuclide Laboratories (see Appendix, Figure 13).
- The compound in question belongs to inhalation class F.
- Activity per practice is 1 MBq.

### Question 1

Calculate the maximum activity that may be used per practice.

### Question 2

Calculate the contribution of these practices to the load factor B of the radionuclide laboratory.

Because the liquid splashes up during the work, part of the laboratory technician's face becomes contaminated. The radiation protection officer quickly grabs a NaI detector in order to check whether there is actually any contamination.

Unfortunately,  $10\text{ cm}^2$  of the facial skin turns out to be contaminated with  $5\text{ kBq }^{35}\text{S}$ . He instructs the laboratory technician to wash his face, after which 20% of the original contamination is still present on the skin.

### Additional data

- Assume that the remaining contamination will remain on the face for two weeks.
- The laboratory technician is classified as an exposed B worker.
- According to the rule of thumb for  $\beta$  emitters, a skin contamination of  $1\text{ kBq/cm}^2$  results in an equivalent skin dose rate of  $2\text{ mSv/h}$ .

### Question 3a

Calculate the surface contamination (in  $\text{Bq/cm}^2$ ) of the skin.

### Question 3b

Calculate the equivalent skin dose resulting from this surface contamination.

### Question 3b

Check whether this is more or less than the legal annual limit for the skin. Justify your answer.

**Rating**      **1: 5**      **2: 3**      **3a: 3**      **3b: 2**      **3c: 3**

## 18 Labeling of phosphate with $^{32}\text{P}$

On a bench in the C laboratory, a nonvolatile phosphate solution is labeled with the radionuclide  $^{32}\text{P}$  for 8 hours per week.

### Data

- Radiation protection data for the radionuclide  $^{32}\text{P}$  (see Appendix, Figure 2).
- The p, q en r parameters according to the former Directive on Radionuclide Laboratories (see Appendix, Figure 13).
- The compound in question belongs to inhalation class F.
- Activity per practice is 6 MBq.

### Question 1

Calculate the maximum activity that may be used per practice.

### Question 2

Calculate the contribution of these practices to the load factor B of the radionuclide laboratory.

During the periodic contamination survey, a  $^{32}\text{P}$  contamination is detected. The net count rate of the contamination monitor is 30 counting pulses per second (cps).

### Additional data

- Calibration of the LB 122A contamination monitor according to the manufacturer (see Table 1)
- Surface area of the LB 122A contamination monitor is 218 cm<sup>2</sup>.
- Surface area of the contamination is 3 cm × 3 cm.

<i>nuclide</i>	<i>calibration constant (Bq/cm<sup>2</sup> per cps)</i>
<sup>14</sup> C	0.04
<sup>32</sup> P	0.015
<sup>99m</sup> Tc	0.15
<sup>125</sup> I	0.27
<sup>131</sup> I	0.02
<sup>137</sup> Cs	0.02

Table 1. Calibration constant in the case of a homogeneously contaminated surface.

### Question 3

Calculate the surface contamination (in Bq/cm<sup>2</sup>).

### Question 4

Check whether this is more or less than the maximum permissible value. Justify your answer.

**Rating**      **1: 5**      **2: 3**      **3: 5**      **4: 3**

## 19 Incident with $^{131}\text{I}$

In the fume hood of the C laboratory, a volatile iodine compound is labeled with the radionuclide  $^{131}\text{I}$  five days a week. The next day, the laboratory technician tells the radiation protection officer that she may have inhaled some  $^{131}\text{I}$  activity. The radiation protection officer immediately decides to measure the activity in the thyroid gland using a NaI detector.

### Data

- Radiation protection data for the radionuclide  $^{131}\text{I}$  (see Appendix, Figure 9).
- The p, q en r parameters according to the former Directive on Radionuclide Laboratories (see Appendix, Figure 13).
- Deposition data according to the lung model of ICRP-66 (see Appendix, Figure 14).
- The fume hood complies with the NEN-EN 14175 standard.
- Activity per practice is 15 MBq.
- Measured activity in the thyroid gland is 4.2 kBq.
- The laboratory technician is classified as an exposed A worker.

### Question 1

Calculate the maximum activity that may be used per practice.

### Question 2

Calculate the contribution of these practices to the exposure factor B of the radionuclide laboratory.

### Question 3

Calculate the activity inhaled by the laboratory technician.

### Question 4a

Calculate the committed effective dose resulting from this incident.

### Question 4b

Check whether the annual limit for the laboratory technician has been exceeded. Justify your answer.

**Rating**      **1: 5**      **2: 3**      **3: 4**      **4a: 2**      **4b: 2**

## 20 Molybdenum cow

On a bench in the D laboratory of the Nuclear Medicine Department stands a molybdenum cow. Five days a week, the radionuclide  $^{99m}\text{Tc}$  is eluted from it. This practice takes 1 hour.

### Data

- Radiation protection data for the radionuclide  $^{99m}\text{Tc}$  (see Appendix, Figure 7).
- The p, q en r parameters according to the former Directive on Radionuclide Laboratories (see Appendix, Figure 13).
- Each time, 600 MBq of  $^{99m}\text{Tc}$  chloride is eluted.

### Question 1

Calculate the maximum activity that may be used per practice.

### Question 2

Calculate the contribution of these practices to the exposure factor B of the radionuclide laboratory.

During the periodic contamination survey, the radiation protection officer wipes a spot on the surface at 10 locations with a tissue, after which the activities of the tissues are measured.

### Additional data

- The wiped surface area is 10 cm × 10 cm each time.
- On five occasions an activity of 0.1 kBq is measured.
- On five occasions an activity of 10 kBq is measured.

### Question 3a

Calculate the surface contamination (in Bq/cm<sup>2</sup>) for the lowest measured activity.

### Question 3b

Is this surface contamination more or less than the maximum permissible value? Justify your answer.

### Question 3c

Which of the 10 measured contamination values should be included in the nuclear energy act file?

### Question 4

May this contamination survey be carried out under the responsibility of a radiation protection officer with a VRS-C diploma?

**Rating**      **1: 5**      **2: 3**      **3a: 2**      **3b: 2**      **3c: 2**      **4: 2**



## Solutions

### Question 16

- 1 RIA with iodine  $\rightarrow p = -3$   
 C laboratorium  $\rightarrow q = 2$   
 fume hood complying with NEN standard  $\rightarrow r = 2$   
 inhalation class F  $\rightarrow e(50)_{\text{inhalation}} = 7.3 \times 10^{-9} \text{ Sv/Bq}$   
 $A_{\text{max}} = 0.02 \times 10^{p+q+r} / e(50)_{\text{inhalation}} = 0.02 \times 10^{-3+2+2} / 7.3 \times 10^{-9} \text{ Sv/Bq} = 2.7 \times 10^5 \text{ Bq}$
- 2  $B = (4 \text{ h} / 40 \text{ h}) \times (1 \times 10^5 \text{ Bq} / 2.7 \times 10^5 \text{ Bq}) = 0.04$
- 3 the two conditions are:
  - a radiation protection expert at the level of coordinating expert or higher is present in the organization.
  - the practice must (be allowed to) take place in a C laboratory
- 4a surface contamination =  $1.2 \times 10^3 \text{ Bq} / (10 \text{ cm} \times 10 \text{ cm}) = 12 \text{ Bq/cm}^2$
- 4b maximum permissible value for  $\beta$ - and  $\gamma$ -emitters is  $4 \text{ Bq/cm}^2$   
 $\rightarrow$  contamination is above the maximum permissible level
- 4c all results must be included in the nuclear energy act file

### Question 17

- 1 labeling with nonvolatile liquid  $\rightarrow p = -2$   
 C laboratory  $\rightarrow q = 2$   
 bench  $\rightarrow r = 0$   
 inhalation class F  $\rightarrow e(50)_{\text{inhalation}} = 8.0 \times 10^{-11} \text{ Sv/Bq}$   
 $A_{\text{max}} = 0.02 \times 10^{p+q+r} / e(50)_{\text{inhalation}} = 0.02 \times 10^{-2+2+0} / 8.0 \times 10^{-11} \text{ Sv/Bq} = 2.5 \times 10^8 \text{ Bq}$
- 2  $B = (4 \text{ h} / 40 \text{ h}) \times (1 \times 10^6 \text{ Bq} / 2.5 \times 10^8 \text{ Bq}) = 4 \times 10^{-4}$
- 3a surface contamination =  $5 \text{ kBq} / 10 \text{ cm}^2 = 0.5 \text{ kBq/cm}^2$
- 3b after washing, contamination is  $0.20 \times 0.5 \text{ kBq/cm}^2 = 0.1 \text{ kBq/cm}^2$   
 exposure time =  $2 \text{ wk} \times 7 \text{ d/wk} \times 24 \text{ h/d} = 336 \text{ h}$   
 $H_{\text{skin}} = 0.1 \text{ kBq/cm}^2 \times 2 \text{ mSv/uur} \times 336 \text{ h} = 67 \text{ mSv}$
- 3c annual limit for equivalent skin dose of exposed B worker  
 $0.3 \times 500 \text{ mSv} = 150 \text{ mSv} \rightarrow$  skin dose is less than annual limit

### Question 18

- 1 labeling with nonvolatile material  $\rightarrow p = -2$   
 C laboratory  $\rightarrow q = 2$   
 bench  $\rightarrow r = 0$   
 inhalation class F  $\rightarrow e(50)_{\text{inhalation}} = 1.4 \times 10^{-10} \text{ Sv/Bq}$   
 $A_{\text{max}} = 0.02 \times 10^{p+q+r} / e(50)_{\text{inhalation}} = 0.02 \times 10^{-2+2+0} / 1.4 \times 10^{-10} \text{ Sv/Bq} = 1.4 \times 10^8 \text{ Bq}$
- 2  $B = (8 \text{ h} / 40 \text{ h}) \times (6 \times 10^6 \text{ Bq} / 1.4 \times 10^8 \text{ Bq}) = 9 \times 10^{-3}$
- 3 calibration constant =  $0.015 \text{ Bq/cm}^2$  per cps in case of homogeneously contaminated area  
 net count rate = 30 cps  
 surface area of contamination monitor =  $218 \text{ cm}^2$   
 activity =  $0.015 \text{ (Bq/cm}^2 \text{ per cps)} \times 30 \text{ cps} \times 218 \text{ cm}^2 = 98 \text{ Bq}$   
 surface area of contamination =  $3 \text{ cm} \times 3 \text{ cm} = 9 \text{ cm}^2$   
 surface contamination =  $98 \text{ Bq} \times 9 \text{ cm}^2 = 11 \text{ Bq/cm}^2$
- 4 maximum permissible value for  $\beta$ - and  $\gamma$ -emitters is  $4 \text{ Bq/cm}^2$   
 $\rightarrow$  contamination is above the maximum permissible level

### Question 19

- 1 labeling with volatile iodine  $\rightarrow p = -3$   
C laboratory  $\rightarrow q = 2$   
fume hood complying with NEN standard  $\rightarrow r = 2$   
inhalation class F  $\rightarrow e(50)_{\text{inhalation}} = 1.1 \times 10^{-8} \text{ Sv/Bq}$   
 $A_{\text{max}} = 0.02 \times 10^{p+q+r} / e(50)_{\text{inhalation}} = 0.02 \times 10^{-3+2+2} / 1.1 \times 10^{-8} \text{ Sv/Bq} = 1.8 \times 10^7 \text{ Bq} = 18 \text{ MBq}$
- 2  $B = (5 \text{ d} / 5 \text{ d}) \times (15 \text{ MBq} / 18 \text{ MBq}) = 0.8$
- 3 reading of Appendix, Figure 14 for AMAD = 5  $\mu\text{m}$   
 $\rightarrow$  deposition is total -  $ET_1 = 0.82 - 0.34 = 0.48$   
reading of Appendix, Figure 9  
 $\rightarrow$  inhalation class F and  $f_i = 1 \rightarrow f_{\text{TC}} = 1$  (100% of deposition to TC)  
 $\rightarrow f_{\text{thyroid gland}} = 0.3$  (30% from TC to thyroid gland)  
 $A_{\text{thyroid gland}} = A_{\text{inhalation}} \times \text{deposition} \times f_{\text{TC}} \times f_{\text{thyroid gland}}$   
 $= A_{\text{inhalation}} \times 0.48 \times 1 \times 0.3 = 0.144 A_{\text{inhalation}}$   
 $= 4.2 \text{ kBq}$   
 $A_{\text{inhalation}} = A_{\text{thyroid gland}} / 0.144 = 4.2 \text{ kBq} / 0.144 = 29 \text{ kBq} = 2.9 \times 10^4 \text{ Bq}$
- 4a  $E(50) = A_{\text{inhalation}} \times e(50)_{\text{inhalation}} = 2.9 \times 10^4 \text{ Bq} \times 1.1 \times 10^{-8} \text{ Sv/Bq} = 3.2 \times 10^{-4} \text{ Sv} = 0.3 \text{ mSv}$
- 4b annual limit for effective dose of A worker is 20 mSv  
 $\rightarrow$  annual limit not exceeded

### Question 20

- 1 elution of Tc generator  $\rightarrow p = -1$   
D laboratory  $\rightarrow q = 1$   
bench  $\rightarrow r = 0$   
chloride belongs to inhalation class M  $\rightarrow e(50)_{\text{inhalation}} = 2.8 \times 10^{-11} \text{ Sv/Bq}$   
 $A_{\text{max}} = 0.02 \times 10^{p+q+r} / e(50)_{\text{inhalation}} = 0.02 \times 10^{-1+1+0} / 2.8 \times 10^{-11} \text{ Sv/Bq} = 7.1 \times 10^8 \text{ Bq} = 710 \text{ MBq}$
- 2  $B = (5 \times 1 \text{ h} / 40 \text{ h}) \times (600 \text{ MBq} / 710 \text{ MBq}) = 0.1$
- 3a surface contamination =  $0.1 \times 10^3 \text{ Bq} / (10 \text{ cm} \times 10 \text{ cm}) = 1 \text{ Bq/cm}^2$
- 3b maximum permissible value for  $\beta$ - and  $\gamma$ -emitters is 4 Bq/cm<sup>2</sup>  
 $\rightarrow$  contamination is below the maximum permissible level
- 3c all results must be included in the nuclear energy act file
- 4 yes

# **INTERNAL CONTAMINATION**



**21 Internal contamination with  $^3\text{H}$** 

(1987-2-2)

Urine analysis reveals elevated tritium concentrations in an exposed worker. Further investigation reveals that he wears a watch with a tritium-based luminous dial. The watch is then removed (time  $t = 0$ ) and urine measurements are continued for another 63 days.

<i>time</i> (d)	<i>concentration</i> (Bq/ml)
0	0.067
7	0.044
14	0.029
21	0.020
28	0.011
63	0.001

*Table 1. Measured tritium concentration (in Bq/ml).  
After the first measurement, the watch was removed.*

**Data**

- $T_{1/2}(^3\text{H}) = 12.35 \text{ y}$ .
- Measured tritium concentration (see Table 1).
- Reference man consists of 42 l of water.
- The water balance of reference man:
  - 1.4 l/d urine
  - 0.65 l/d sweat
  - 0.95 l/d other fluids.
- The dose conversion coefficient of tritiated water is  $e(50) = 1.8 \times 10^{-11} \text{ Sv/Bq}$ .

**Question 1**

Plot the tritium concentration against time on single-logarithmic graph paper and determine the effective half-life.

**Question 2**

Calculate the  $^3\text{H}$  activity absorbed by the body per year during the time the watch was worn.

**Question 3**

Calculate the effective annual dose before removal of the watch.

**Question 4**

Calculate the committed effective dose in the event that this measurement was carried out after a single intake just before the production of the first urine sample. Assume that tritium distributes instantaneously and homogeneously throughout all body fluids.

**Rating**      **1: 4**      **2: 5**      **3: 2**      **4: 5**

## 22 Urine testing after a contamination with $\text{H}^{36}\text{Cl}$

Following an incident involving the inhalation of  $\text{H}^{36}\text{Cl}$ , the radiation protection officer, in consultation with the radiation protection expert, decides to perform a urine analysis on the worker concerned. He asks the worker to collect his urine for 24 hours and then takes a sample. This procedure is repeated on day 14 after the incident. Each sample contains 8 ml of urine and the activity in it is determined using a liquid scintillation counter. The measured net count rate is 11 520 counting pulses per minute (cpm) and 5130 cpm, respectively.

### Data

- $T_{1/2}({}^{36}\text{Cl}) = 3.0 \times 10^5 \text{ y}$ .
- In this question it is assumed that 48% of the inhaled activity remains in the lungs.
- Chlorine is absorbed into the blood within a few hours.
- The retention formula describes the excretion of a (radioactive) substance from the body. In the case of chlorine, this function can be written as:  
$$R(t) = e^{-0.693 \times t / T_{1/2}}$$
- HCl belongs to solubility type F with  $f_1 = 1$ .
- The dose conversion coefficient for inhalation of  ${}^{36}\text{Cl}$  is  $e(50)_{\text{inhalation}} = 4.9 \times 10^{-10} \text{ Sv/Bq}$ .
- The urine production of reference man is 1400 ml per day.
- The counting efficiency of the liquid scintillation counter is 0.80 counting pulses per second per Bq (cps per Bq).

### Question 1

Calculate the effective half-life based on the two measurement results.

### Question 2a

Using the measured tritium concentration in the urine, calculate the amount of  ${}^{36}\text{Cl}$  activity excreted on the first day.

### Question 2b

Using the retention function  $R(t)$ , calculate the fraction of the activity absorbed by the body that is excreted on the first day.

### Question 2c

Calculate the amount of activity that has been inhaled.

### Question 3

Calculate the committed effective dose.

**Rating**            **1: 3**        **2a: 4**        **2b: 3**        **2c: 4**        **3: 2**

**23 Injection with  $^{67}\text{Ga}$ -citrate**

(1997-1-2)

In the Nuclear Medicine Department, patients are injected with  $^{67}\text{Ga}$  citrate to detect tumors. The activity, which is injected into the bloodstream during a normal examination, is 200 MBq. After a few days, the gallium is sufficiently absorbed into the tumor to enable imaging using a  $\gamma$  camera. The measurement with the  $\gamma$  camera takes place 72 hours after administration.

**Data**

- Radiation protection data for the radionuclide  $^{67}\text{Ga}$  (see Appendix, Figure 6).
- Deposition data according to the lung model of ICRP-66 (see Appendix, Figure 14).

**Question 1**

Calculate the committed effective dose that a patient receives during a gallium scan.

**Question 2**

Why may total-body scan data for inhalation class F be used after injection?

**Question 3a**

Determine the fraction of the injected activity that is present in the body 72 hours after injection.

**Question 3b**

Calculate the activity still present in the patient at the time of the  $\gamma$ -scan.

One day, the nurse drops the syringe, causing it to land on the plunger and releasing some of the radioactive contents in the form of aerosols into the workspace. The nurse is measured in a whole-body counter 24 hours after this incident. It turns out that at the time of measurement, 8.5 kBq of  $^{67}\text{Ga}$  is still present in the body.

**Question 4a**

Determine the fraction of the inhaled activity that is still present in the body after 24 hours.

**Question 4b**

Calculate the committed effective dose for the nurse.

**Rating**      **1: 3**      **2: 2**      **3a: 2**      **3b: 2**      **4a: 2**      **4b: 3**

## 24 Discharge of $^{41}\text{Ar}$ by a nuclear power plant

(1995-2-1)

The ventilation shaft of a nuclear reactor contains a noble gas monitor that continuously measures the activity concentration of the radioactive noble gas  $^{41}\text{Ar}$  in the discharged air. This radionuclide is produced by neutron activation of air, which contains approximately 1% argon. The reactor's license conditions stipulate a maximum permitted discharge of 17 TBq  $^{41}\text{Ar}$  per each quarter.

### Data

- 1500 m<sup>3</sup> of air is discharged per hour.
- The calibration factor of the monitor is 1 counting pulse per second (cps) at a  $^{41}\text{Ar}$  concentration of 4.2 kBq/m<sup>3</sup> in the discharged air.
- The background of the monitor is 5 cps.
- Radioactive decay can be neglected for the calculations over the period considered.

### Question 1

In a given quarter,  $8.4 \times 10^8$  counting pulses were recorded. Calculate the average activity concentration in the air.

### Question 2

Calculate the  $^{41}\text{Ar}$  discharge in that quarter. Is the discharge in accordance with the license?

There is a house located 1 km away from the reactor. If the wind is blowing in the direction of this house, the residents will receive an effective dose as a result of exposure to the released argon.

### Additional data

- The  $^{41}\text{Ar}$  concentration at the house is a factor of  $10^6$  smaller than in the ventilation shaft.
- After spending 1 hour in air with a  $^{41}\text{Ar}$  contamination of 1 Bq/m<sup>3</sup>, an effective dose of  $2.2 \times 10^{-10}$  Sv is received.
- The ambient equivalent dose  $H^*$  is a good estimate of the effective dose  $E$ .
- Any shielding effect of the house can be neglected.

### Question 3

Calculate the ambient equivalent dose rate to which residents are exposed when the wind blows in their direction.

### Question 4

Calculate the maximum annual effective dose that residents may receive as a result of the  $^{41}\text{Ar}$  discharge. Assume that the discharge is equal to the limit set in the license and that the wind blows in the direction of the house throughout the year.

**Rating**      **1: 5**      **2: 3**      **3: 3**      **4: 5**

## 25 Grinding wheels of naturally-radioactive materials (1995-2-4)

A grinding wheel used for cutting metal pipes appears to contain a fairly high concentration of natural radioactivity. The radionuclides found are  $^{226}\text{Ra}$  + daughters and  $^{232}\text{Th}$  + daughters. All radionuclides within the same series are in equilibrium with each other.

### Data

- Measured activity concentrations as far as detectable (see Table 1).
- The mass of a wheel is 390 g.
- Volgens het Besluit Basisveiligheidsnormen Stralingsbescherming zijn de vrijstellingsgrenzen voor  $^{226}\text{Ra}$  + dochters in matige hoeveelheden (1000 kg):
  1. vrijstellingsgrens voor activiteit is  $A_v = 1 \times 10^4$  Bq
  2. vrijstellingsgrens voor activiteitsconcentratie is  $C_v = 1 \times 10^1$  Bq/g.
- According to the Decree on Basic Safety Standards Radiation Protection, the exemption limits for  $^{226}\text{Ra}$  + daughters in moderate quantities (1000 kg) are:
  1. exemption limit for activity is  $A_v = 1 \times 10^3$  Bq
  2. exemption limit for activity concentration is  $C_v = 1$  Bq/g.

<i>radionuclide</i>	<i>activity concentration</i>	<i>radionuclide</i>	<i>activity concentration</i>
$^{226}\text{Ra}$ -series	(Bq/kg)	$^{232}\text{Th}$ -series	(Bq/kg)
$^{226}\text{Ra}$	127	$^{232}\text{Th}$	--
$^{222}\text{Rn}$	--	$^{228}\text{Rn}$	--
$^{218}\text{Po}$	--	$^{228}\text{Ac}$	153
$^{214}\text{Pb}$	--	$^{228}\text{Th}$	--
$^{214}\text{Bi}$	125	$^{224}\text{Ra}$	--
$^{214}\text{Po}$	--	$^{220}\text{Rn}$	--
$^{210}\text{Pb}$	--	$^{216}\text{Po}$	--
$^{210}\text{Bi}$	--	$^{212}\text{Pb}$	151
$^{210}\text{Po}$	--	$^{212}\text{Bi}$	--
$^{206}\text{Pb}$	stabiel	$^{208}\text{Tl} + ^{212}\text{Po}$	157
		$^{208}\text{Pb}$	stabiel

Table 1 Measured activity concentrations of the various radionuclides, as far as detectable.

### Question 1

In both series, the gaseous element radon occurs as a daughter product. What conclusion can be drawn regarding the escape of this gas from the material? Justify your answer.

### Question 2

Calculate the total activity and activity concentration of a grinding wheel.

### Question 3

Indicate whether maintaining a working stock of 10 grinding wheels is exempt from registration or licensing. Justify your answer.

Grinding generates very fine dust. Assume that a fraction of  $10^{-6}$  of the ground material is inhaled.

**Additional data**

- The wheel is replaced when 90% of the material is worn away.
- The dose conversion factors for inhalation are:
  1.  $e(50)_{inh} = 1.6 \times 10^{-5} \text{ Sv/Bq}$  for  $^{226}\text{Ra}$  + daughters
  2.  $e(50)_{inh} = 6.2 \times 10^{-5} \text{ Sv/Bq}$  for  $^{232}\text{Th}$  + daughters.

**Question 4**

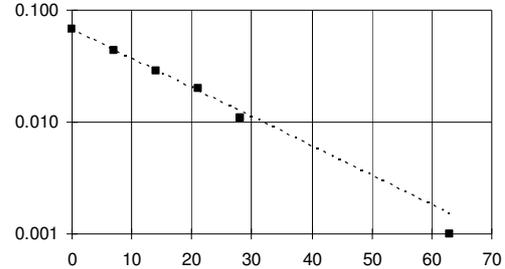
Calculate the committed effective dose for an employee who has worn out a grinding wheel.

**Rating**      **1: 3**      **2: 5**      **3: 5**      **4: 3**

## Solutions

### Question 21

- entering data into a spreadsheet  
+ linear regression yields  $T_{1/2}^{\text{eff}} = 11.5 \pm 0.2 \text{ d}$
- activity concentration before removal  
 $a = 0.067 \text{ Bq/ml}$   
total water exchange per year  
 $V = (1.4 \text{ l/d} + 0.65 \text{ l/d} + 0.95 \text{ l/d}) \times 365 \text{ d/y}$   
 $= 1.1 \times 10^3 \text{ l/j} = 1.1 \times 10^6 \text{ ml/d}$   
activity excretion = intake  
 $A = a \times V$   
 $= 0.067 \text{ Bq/ml} \times 1.1 \times 10^6 \text{ ml/d}$   
 $= 7.4 \times 10^4 \text{ Bq/y}$
- annual committed effective dose  $E(50) = A \times e(50)$   
 $= 7.4 \times 10^4 \text{ Bq/y} \times 1.8 \times 10^{-11} \text{ Sv/Bq}$   
 $= 1.3 \times 10^{-6} \text{ Sv/y} = 1.3 \mu\text{Sv/}$
- after single intake, the body contains 42 liters of water with an activity concentration of 0.067 Bq/ml  
body activity = intake  $A = 42 \text{ l} \times 10^3 \text{ ml/l} \times 0.067 \text{ Bq/ml} = 2.8 \times 10^3 \text{ Bq}$   
committed effective dose  $E(50) = A \times e(50)$   
 $= 2.8 \times 10^3 \text{ Bq} \times 1.8 \times 10^{-11} \text{ Sv/Bq}$   
 $= 5.0 \times 10^{-8} \text{ Sv} = 0.05 \mu\text{Sv}$



### Question 22

- excretion is proportional to measured net count rate  
count rate ratio  $T(14) / T(0) = e^{-0.693 \times 14 / T_{1/2}}$   
 $= 11\,520 \text{ cpm} / 5130 \text{ cpm} = 2.25$   
effective half-life  $T_{1/2, \text{eff}} = 0.693 \times 14 \text{ d} / \ln(2.25) = 0.693 \times 14 \text{ d} / 0.81 = 12 \text{ d}$
- $N_{\text{net}} = \text{activity} \times \text{counting efficiency} \times \text{counting time}$   
 $= A(t) \times 0.80 \text{ cps/Bq} \times 60 \text{ s} = 48 \text{ per Bq} \times A(t)$   
activity in 8 ml urine  $N_{\text{net}} / 48 \text{ per Bq} = 11\,520 / 48 \text{ per Bq} = 240 \text{ Bq}$   
activity in 1.4 l urine  $240 \text{ Bq} \times (1400 \text{ ml} / 8 \text{ ml}) = 240 \text{ Bq} \times 175 = 4.2 \times 10^4 \text{ Bq}$
- insert in retention function  $R(0) = 1, R(1) = e^{-0.693 \times 1/12} = 0.944$   
fraction in urine  $R(0) - R(1) = 1 - 0.944 = 0.056$
- activity in body  
urine activity / urine fraction  
 $= 4.2 \times 10^4 \text{ Bq} / 0.056 = 7.5 \times 10^5 \text{ Bq}$   
lung depositie  $48\% = 0.48$   
solubility stype F and  $f_1 = 1 \rightarrow 100\%$  of deposited activity to TC  
activity in body =  $A_{\text{inhalation}} \times \text{lung deposition}$   
 $A_{\text{inhalation}} = \text{body activity} / \text{lung deposition} = 7.5 \times 10^5 \text{ Bq} / 0.48 = 1.6 \times 10^6 \text{ Bq}$
- comitted effective dose  $E(50) = A_{\text{inhalation}} \times e(50)_{\text{inhalation}} = 1.6 \times 10^6 \text{ Bq} \times 4.9 \times 10^{-10} \text{ Sv/Bq}$   
 $= 7.8 \times 10^{-4} \text{ Sv} = 0.8 \text{ mSv}$

### Question 23

- reading opf Appendix, Figure 6 at 'Diversen'  $\rightarrow e(50)_{\text{injection}} = 8.4 \times 10^{-11} \text{ Sv/Bq}$   
injected activity  $A(0) = 200 \text{ MBq} = 2.0 \times 10^8 \text{ Bq}$   
committed effective dose  $E(50) = A(0) \times e(50)_{\text{injection}}$   
 $= 2.0 \times 10^8 \text{ Bq} \times 8.4 \times 10^{-11} \text{ Sv/Bq}$   
 $= 1.7 \times 10^{-2} \text{ Sv} = 17 \text{ mSv}$

- 2 with inhalation class F, 100% of inhalation goes to TC  
with injection, 100% goes to TC  
→ injection corresponds to inhalation class F
- 3a reading of Appendix, Figure 6 at 'Data for whole body counting' and inhalation class F  
after 72 uur = 3 d  $1.4 \times 10^{-1}$  Bq per Bq intake
- 3b activity after 72 h  $A(72) = A(0) \times 1.4 \times 10^{-1}$  Bq per Bq inname  
 $= 200 \text{ MBq} \times 0.14 = 28 \text{ MBq}$
- 4a reading of Appendix, Figure 6  
citrate belongs to other compounds → inhalation class F  
reading of Appendix, Figure 6 at 'Data for whole body counting' and inhalation class F  
after 24 h = 1 d  $4.3 \times 10^{-1}$  Bq per Bq intake
- 4b activity na 24 h  $A(24) = A_{\text{inhalation}} \times 4.3 \times 10^{-1}$  Bq per Bq inname  
 $= 8.5 \text{ kBq}$   
inhalation  $A_{\text{inhalation}} = 8.5 \text{ (kBq)} / 0.43 = 20 \text{ kBq}$   
reading of Appendix, Figure 6 at inhalation class F  
 $e(50)_{\text{inhalation}} = 1.1 \times 10^{-10} \text{ Sv/Bq}$   
committed effective dose  $E(50) = A_{\text{inhalation}} \times e(50)_{\text{inhalation}}$   
 $= 20 \times 10^3 \text{ Bq} \times 1.1 \times 10^{-10} \text{ Sv/Bq}$   
 $= 2.2 \times 10^{-7} \text{ Sv} = 0.2 \text{ } \mu\text{Sv}$

### Question 24

- 1  $t = 1 \text{ quarter} = (365 \text{ d/y} \times 24 \text{ h/d}) / 4 = 2190 \text{ h} = 7.9 \times 10^6 \text{ s}$   
gross count rate  $R_{\text{gross}} = N_{\text{gross}} / t = 8.4 \times 10^8 / 7.9 \times 10^6 \text{ s} = 106 \text{ cps}$   
background  $R_{\text{background}} = 5 \text{ cps}$   
net count rate  $R_{\text{net}} = 106 \text{ cps} - 5 \text{ cps} = 101 \text{ cps}$   
activity concentration  $a = R_{\text{net}} \times \text{calibration factor}$   
 $= 101 \text{ cps} \times 4.2 \text{ kBq/m}^3 \text{ per cps}$   
 $= 424 \text{ kBq/m}^3 = 4.2 \times 10^5 \text{ Bq/m}^3$
- 2 volume of air discharged  $V = 2190 \text{ h} \times 1500 \text{ m}^3/\text{h} = 3.3 \times 10^6 \text{ m}^3$   
discharged activity  $A = a \times V$   
 $= 4.2 \times 10^5 \text{ Bq/m}^3 \times 3.3 \times 10^6 \text{ m}^3$   
 $= 1.4 \times 10^{12} \text{ Bq} = 1.4 \text{ TBq}$   
→ this is well within the license
- 3 activity concentration at house  $10^{-6} \times a = 10^{-6} \times 4.2 \times 10^5 \text{ Bq/m}^3 = 0.42 \text{ Bq/m}^3$   
ambient equivalent dose rate  $\dot{H}^* \approx \dot{E} = a \times e$   
 $= 0.42 \text{ Bq/m}^3 \times 2.2 \times 10^{-10} \text{ Sv/uur per Bq/m}^3$   
 $= 9.2 \times 10^{-11} \text{ Sv/h}$
- 4 actual discharge per quarter  $A = 1.4 \text{ TBq}$   
maximum discharge per quarter  $A_{\text{max}} = 17 \text{ TBq}$   
maximum ambient equivalent dose rate  $\dot{H}^*_{\text{max}} = \dot{H}^* \times (A_{\text{max}} / A)$   
 $= 9.2 \times 10^{-11} \text{ Sv/h} \times (17 \text{ TBq} / 1.4 \text{ TBq})$   
 $= 1.1 \times 10^{-9} \text{ Sv/h}$   
maximale exposure time  $t_{\text{max}} = 365 \text{ d/y} \times 24 \text{ h/d} = 8.8 \times 10^3 \text{ h}$   
maximale annual effective dose  $E_{\text{max}} \approx \dot{H}^*_{\text{max}} \times t_{\text{max}}$   
 $= 1.1 \times 10^{-9} \text{ Sv/h} \times 8.8 \times 10^3 \text{ h}$   
 $= 9.7 \times 10^{-6} \text{ Sv} = 10 \text{ } \mu\text{Sv}$

### Question 25

- 1 within a series, the measured activity concentrations of radionuclides before and after the noble gas radon are not significantly different, so it can be concluded that no gas escapes from the material

2  $^{226}\text{Ra}$  series

9 nuclides with an average activity concentration of  $126 \text{ Bq/kg} = 0.126 \text{ Bq/g}$

activity concentration  $a_{\text{Ra}^+} = 9 \times 0.126 \text{ Bq/g} = 1.13 \text{ Bq/g}$

activity per wheel  $A_{\text{Ra}^+} = a_{\text{Ra}^+} \times m_{\text{wheel}} = 1.13 \text{ Bq/g} \times 390 \text{ g}$   
 $= 440 \text{ Bq} = 0.44 \text{ kBq}$

 $^{232}\text{Th}$  series

10 nuclides with an average activity concentration of  $154 \text{ Bq/kg} = 0.154 \text{ Bq/g}$

activity concentration  $a_{\text{Th}^+} = 10 \times 0.154 \text{ Bq/g} = 1.54 \text{ Bq/g}$

activity per wheel  $A_{\text{Th}^+} = a_{\text{Th}^+} \times m_{\text{wheel}} = 1.54 \text{ Bq/g} \times 390 \text{ g}$   
 $= 600 \text{ Bq} = 0.60 \text{ kBq}$

total activity concentration  $a_{\text{Ra}^+} + a_{\text{Th}^+} = 1.13 \text{ Bq/g} + 1.54 \text{ Bq/g} = 2.67 \text{ Bq/g}$

total activity per wheel  $A_{\text{Ra}^+} + A_{\text{Th}^+} = 0.44 \text{ kBq} + 0.60 \text{ kBq} = 1.04 \text{ kBq}$

3  $^{226}\text{Ra}$  series

activity concentration =  $1.13 \text{ Bq/g}$

activity =  $10 \text{ wheels} \times 0.44 \text{ kBq per wheel} = 4.4 \text{ kBq}$

 $^{232}\text{Th}$  series

activity concentration =  $1.54 \text{ Bq/g}$

activity =  $10 \text{ wheels} \times 0.60 \text{ kBq per wheel} = 6.0 \text{ kBq}$

## weighted sum

activity concentration =

$$(1.13 \text{ Bq/g} / 10 \text{ Bq/g}) + (1.54 \text{ Bq/g} / 1 \text{ Bq/g}) = 2.67 > 1$$

activity =

$$(4.4 \text{ kBq} / 10 \text{ kBq}) + (6.0 \text{ kBq} / 1 \text{ kBq}) = 6.44 > 1$$

both limit values are exceeded

→ work inventory is not exempt from reporting/license requirements

4  $^{226}\text{Ra}$  series

inhaled activity

$$10^{-6} \times 0.90 \times A_{\text{Ra}^+} = 0.9 \times 10^{-6} \times 440 \text{ Bq} = 4.0 \times 10^{-4} \text{ Bq}$$

committed effective dose

$$E(50)_{\text{Ra}^+} = 4.0 \times 10^{-4} \text{ Bq} \times 1.6 \times 10^{-5} \text{ Sv/Bq}$$

$$= 6.4 \times 10^{-9} \text{ Sv} = 6.4 \text{ nSv}$$

 $^{232}\text{Th}$ 

inhaled activity

$$10^{-6} \times 0.90 \times A_{\text{Th}^+} = 0.9 \times 10^{-6} \times 600 \text{ Bq} = 5.4 \times 10^{-4} \text{ Bq}$$

committed effective dose

$$E(50)_{\text{Th}^+} = 5.4 \times 10^{-4} \text{ Bq} \times 6.2 \times 10^{-5} \text{ Sv/Bq}$$

$$= 33.5 \times 10^{-9} \text{ Sv} = 33.5 \text{ nSv}$$

total committed effective dose

$$E(50)_{\text{Ra}^+} + E(50)_{\text{Th}^+} = 6.4 \text{ nSv} + 33.5 \text{ nSv}$$

$$= 40 \text{ nSv}$$



# **APPENDIX**



## Units, constants and prefixes

### Basiseenheden

<i>grootheid</i>	<i>symbool</i>	<i>eenheid</i>	<i>afkorting</i>
lengte	l	meter	m
massa	m	kilogram	kg
tijd	t	seconde	s
temperatuur	T	kelvin	K
stroomsterkte	I	ampère	A
lichtsterkte	l	candela	cd
hoeveelheid stof	mol	mol	

### Afgeleide eenheden

<i>grootheid</i>	<i>symbool</i>	<i>eenheid</i>	<i>afkorting</i>	<i>dimensie</i>
kracht	F	newton	N	$\text{kg m s}^{-2}$
energie	E	joule	J	$\text{kg m}^2 \text{s}^{-2}$
vermogen	P	watt	W	$\text{J s}^{-1}$
lading	Q	coulomb	C	A s
spanning	V	volt	V	$\text{J C}^{-1}$
weerstand	R	ohm	$\Omega$	$\text{V A}^{-1}$
capaciteit	C	farad	F	$\text{C V}^{-1}$
frequentie <sup>1</sup>	f of $\nu$	hertz	Hz	$\text{s}^{-1}$
activiteit <sup>1</sup>	A	becquerel	Bq	$\text{s}^{-1}$

### Fysische constanten

lichtsnelheid	$2.9979 \times 10^8 \text{ m s}^{-1}$
constante van Planck	$6.6262 \times 10^{-34} \text{ J s}$
getal van Avogadro	$6.0220 \times 10^{26} \text{ mol}^{-1}$
elementaire lading	$1.6022 \times 10^{-19} \text{ C}$
1 joule	$6.2422 \times 10^{18} \text{ eV}$
1 ame	$931.50 \text{ MeV} = 1.6606 \times 10^{-27} \text{ kg}$

### Voorvoegsels <sup>2</sup>

<i>voorvoegsel</i>	<i>factor</i>	<i>symbool</i>	<i>voorvoegsel</i>	<i>factor</i>	<i>symbool</i>
kilo	$10^3$	k	milli	$10^{-3}$	m
mega	$10^6$	M	micro	$10^{-6}$	$\mu$
giga	$10^9$	G	nano	$10^{-9}$	n
tera	$10^{12}$	T	pico	$10^{-12}$	p
peta	$10^{15}$	P	femto	$10^{-15}$	f
exa	$10^{18}$	E	atto	$10^{-18}$	a

<sup>1</sup> Er zijn twee verschillende eenheden die beide de dimensie  $\text{s}^{-1}$  hebben: de ene is periodiek (Hz) en de andere is stochastisch en onderhevig aan statistische fluctuaties (Bq).

<sup>2</sup> Let op het gebruik van hoofdletters en kleine letters.

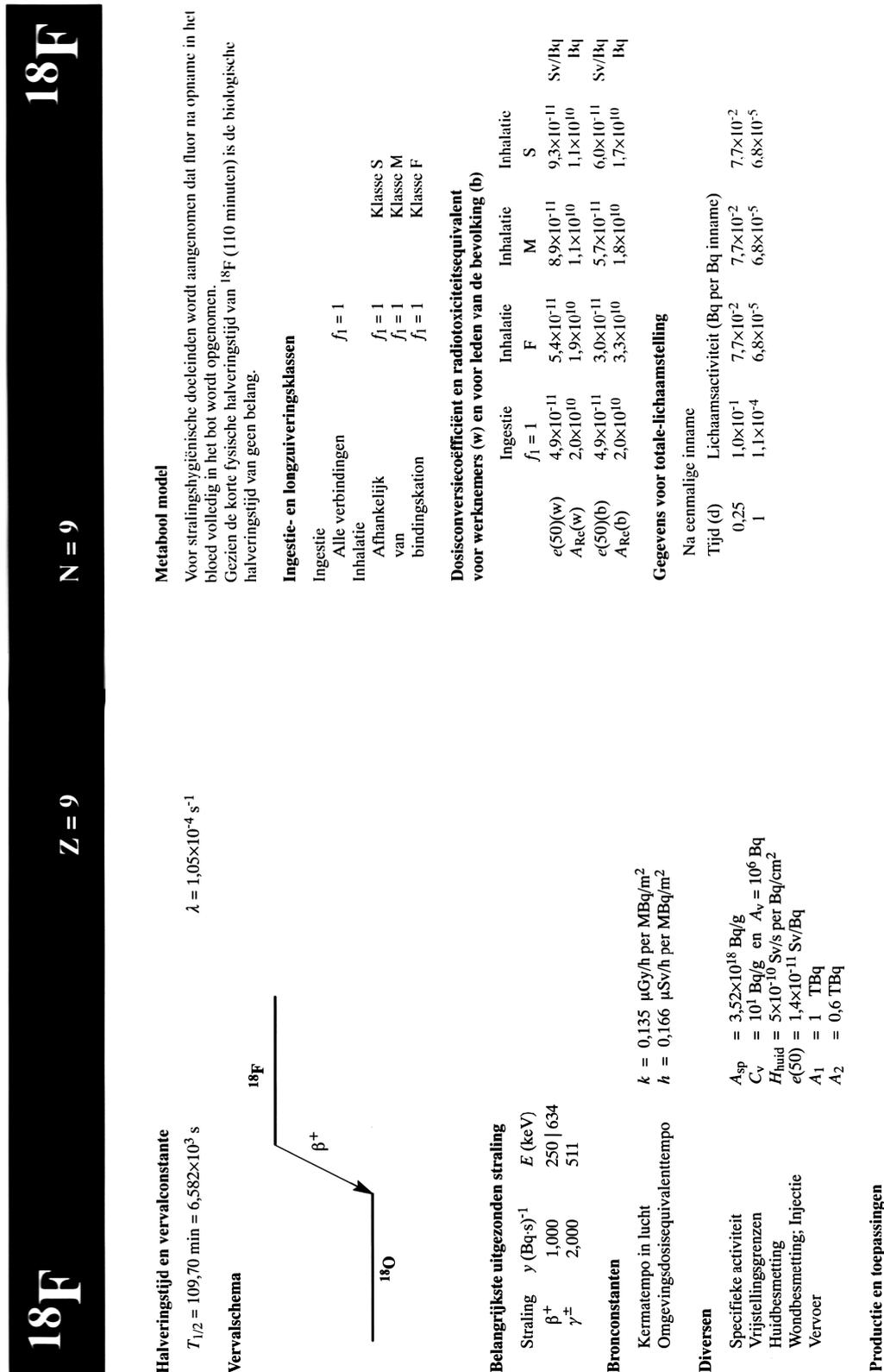


Figure 1

Radiation protection details of the radionuclide <sup>18</sup>F

# 32P

N = 17      Z = 15

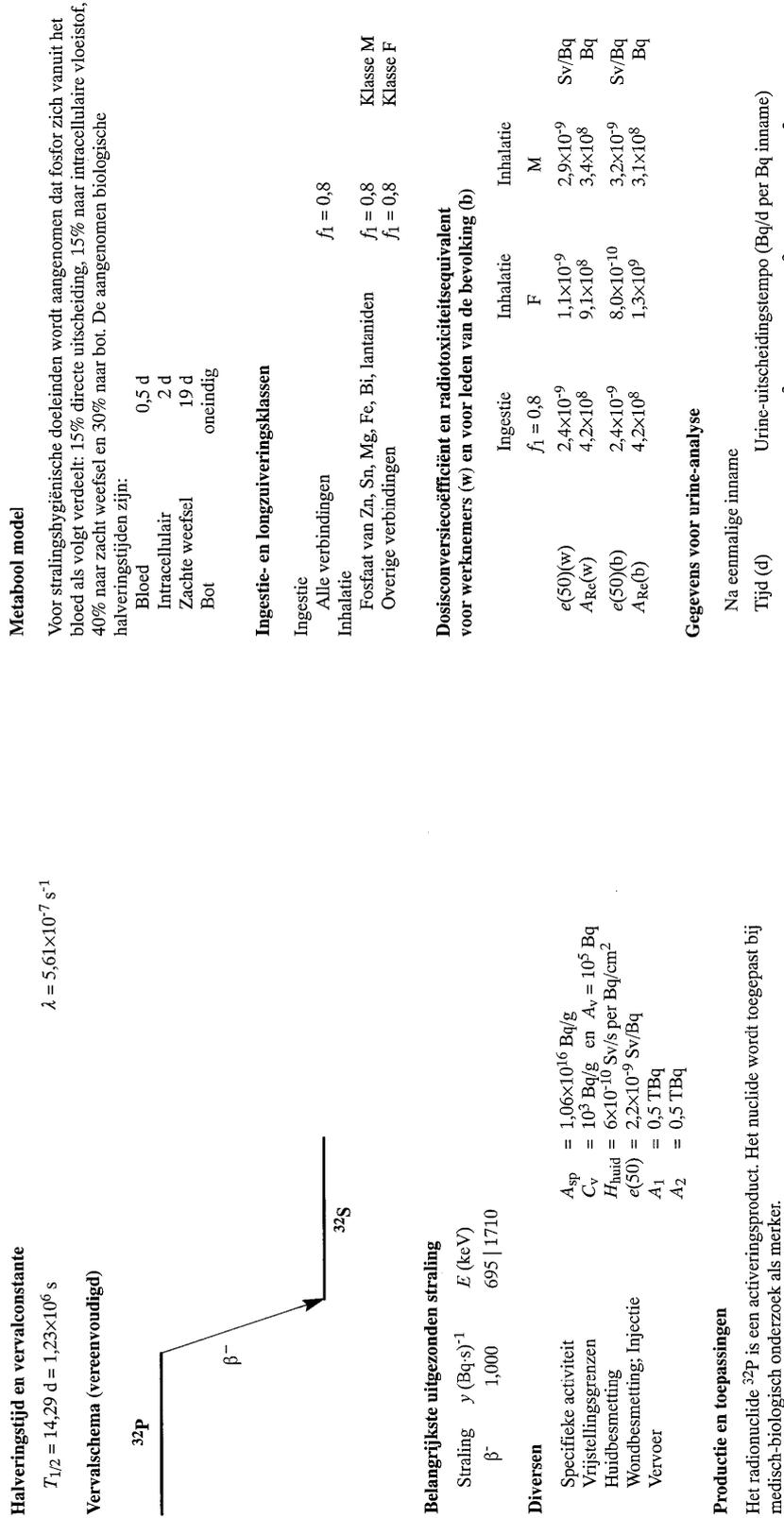


Figure 2

Radiation protection details of the radionuclide <sup>32</sup>P

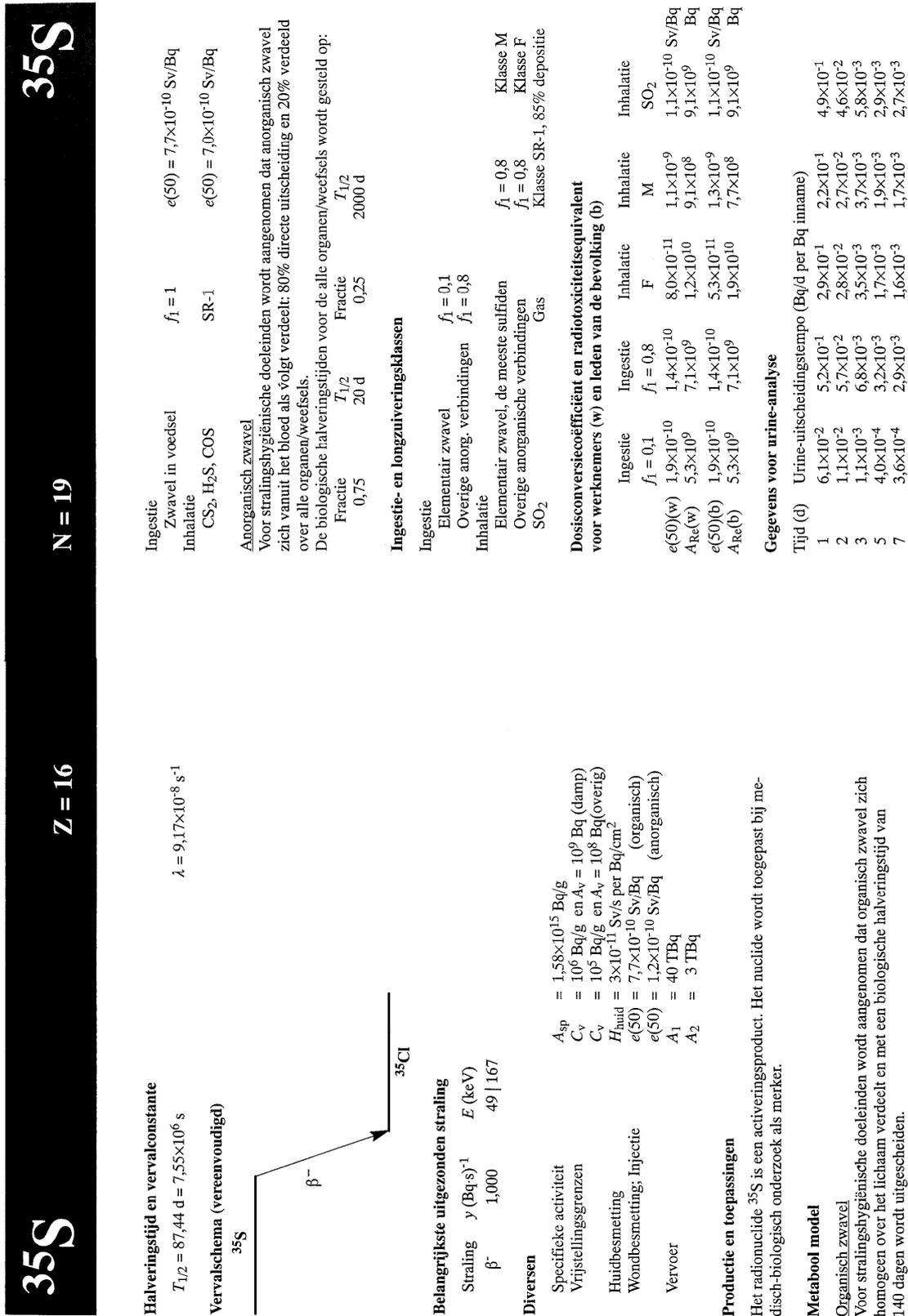


Figure 3

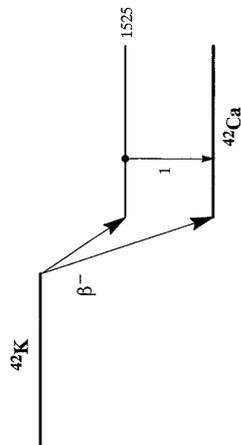
Radiation protection details of the radionuclide <sup>35</sup>S

**Halveringstijd en vervalconstante**

$T_{1/2} = 12,36 \text{ h} = 4,45 \times 10^4 \text{ s}$

$\lambda = 1,56 \times 10^{-5} \text{ s}^{-1}$

**Vervalchema (vereenvoudigd)**



**Belangrijkste uitgezonden straling**

Straling	$\gamma$ (Bq.s) <sup>-1</sup>	E (keV)
$\beta^-$	0,175	822   1996
$\beta^-$	0,821	1564   3521
$\gamma_1$	0,179	1525

**Bronconstanten**

Kermtiempo in lucht	$k = 0,032 \mu\text{Gy/h per MBq/m}^2$
Omgevingsdosis-equivalenttempo	$h = 0,037 \mu\text{Sv/h per MBq/m}^2$

**Diversen**

Specifieke activiteit	$A_{sp} = 2,24 \times 10^{17} \text{ Bq/g}$
Vrijstellingsgrenzen	$C_v = 10^2 \text{ Bq/g}$ en $A_v = 10^6 \text{ Bq}$
Huidbesmetting	$H_{\text{huid}} = 7 \times 10^{-10} \text{ Sv/s per Bq/cm}^2$
Wondbesmetting; Injectie	$e(50) = 2,3 \times 10^{-10} \text{ Sv/Bq}$
Vervoer	$A_1 = 0,2 \text{ TBq}$ $A_2 = 0,2 \text{ TBq}$

**Productie en toepassingen**

Het radionuclide  $^{42}\text{K}$  is een activeringsproduct. Het nuclide wordt onder meer gebruikt als marker bij medisch-biologisch onderzoek.

**Metabool model**

Voor stralingshygiënische doeleinden wordt aangenomen dat kalium zich vanuit het bloed homogeen over alle organen/weefsels verdeelt. De biologische halveringstijd voor deze organen/weefsels wordt gesteld op 30 dagen.

**Ingestie- en longzuiveringsklassen**

Ingestie			
Alle verbindingen	$f_1 = 1$		
Inhalatie			
Alle verbindingen	$f_1 = 1$		Klasse F

**Dosisconversiecoëfficiënt en radiotoxiceitsequivalent voor werknemers (w) en voor leden van de bevolking (b)**

	Ingestie	Inhalatie	
$e(50)(w)$	$f_1 = 1$	F	
$A_{Re}(w)$	$4,3 \times 10^{-10}$	$2,0 \times 10^{-10}$	Sv/Bq
$e(50)(b)$	$2,3 \times 10^9$	$5,0 \times 10^9$	Bq
$A_{Re}(b)$	$4,3 \times 10^{-10}$	$1,3 \times 10^{-10}$	Sv/Bq
	$2,3 \times 10^9$	$7,7 \times 10^9$	Bq

**Gegevens voor totale-lichaamstelling**

Na eenmalige inname	Lichaamsactiviteit (Bq per Bq inname)
Tijd (d)	$7,1 \times 10^{-1}$
0,25	$5,3 \times 10^{-1}$
1	$1,6 \times 10^{-1}$
2	$6,5 \times 10^{-2}$
3	$1,6 \times 10^{-2}$
5	$1,1 \times 10^{-3}$
7	$6,9 \times 10^{-5}$

Figure 4

Radiation protection details of the radionuclide  $^{42}\text{K}$

# 51Cr

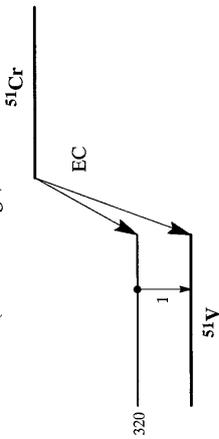
N = 27      Z = 24

**Halveringstijd en vervalconstante**

$T_{1/2} = 27,71 \text{ d} = 2,39 \times 10^6 \text{ s}$

$\lambda = 2,90 \times 10^{-7} \text{ s}^{-1}$

**Vervalchema (vereenvoudigd)**



**Belangrijkste uitgezonden straling**

Straling	$\gamma$	$\gamma$ (Bq·s) <sup>-1</sup>	E (keV)
		0,098	320
	$K_{\alpha}$	0,200	5
	KLL	0,558	4
	KLLX	0,113	5

**Bronconstanten**

Kermatempo in lucht  $k = 0,0042 \text{ } \mu\text{Cv/h per MBq/m}^2$   
 Omgevingsdosis-equivalenttempo  $h = 0,0054 \text{ } \mu\text{Sv/h per MBq/m}^2$

**Diversen**

Specifieke activiteit  $A_{sp} = 3,42 \times 10^{15} \text{ Bq/g}$   
 Vrijstellingsgrenzen  $C_v = 10^2 \text{ Bq/g}$  en  $A_v = 10^7 \text{ Bq}$   
 Huidbesmetting  $H_{\text{huid}} = 1 \times 10^{-12} \text{ Sv/s per Bq/cm}^2$   
 Wondbesmetting: Injectie  $e(50) = 5,6 \times 10^{-11} \text{ Sv/Bq}$   
 Vervoer  $A_1 = 30 \text{ TBq}$   
 $A_2 = 30 \text{ TBq}$

**Productie en toepassingen**

Het radionuclide <sup>51</sup>Cr is een bijzonder activeringsproduct: het zendt geen beta's uit en wordt zodoende niet waargenomen door de gebruikelijke besmettingsmeters. Voor de detectie van <sup>51</sup>Cr zijn daarom speciale instrumenten ontwikkeld. Het nuclide wordt gebruikt als mono-energetische gammareferentiebron.

**Metabool model**

Voor stralingshygiënische doeleinden wordt aangenomen dat chroom zich vanuit het bloed als volgt verdeelt: 30% directe uitscheiding, 5% naar bot en de rest homogeen verdeeld over de overige organen/weefsels.

De biologische halveringstijden zijn gesield op:

Bloed	0,5 d
Bot	1000 d
Rest	6 d
	0,38 80 d

**Ingestie- en longzuiveringsklassen**

Ingestie		$f_1 = 0,01$
Driewaardig chroom		$f_1 = 0,1$
Zeswaardig chroom		
Inhalatie		
Oxide, hydroxide		$f_1 = 0,1$
Halogenide, nitraat		$f_1 = 0,1$
Overige verbindingen		$f_1 = 0,1$
		Klasse S
		Klasse M
		Klasse F

**Dosisconversiecoëfficiënt en radiotoxiceitsequivalent voor werknemers (w) en voor leden van de bevolking (b)**

	Ingestie	Ingestie	Inhalatie	Inhalatie	Inhalatie
$e(50)(w)$	$f_1 = 0,01$	$f_1 = 0,1$	F	M	S
$A_{Re}(w)$	$3,7 \times 10^{-11}$	$3,8 \times 10^{-11}$	$3,0 \times 10^{-11}$	$3,4 \times 10^{-11}$	$3,6 \times 10^{-11}$
$e(50)(b)$	$2,7 \times 10^{-10}$	$2,6 \times 10^{-10}$	$3,3 \times 10^{-10}$	$2,9 \times 10^{-10}$	$2,8 \times 10^{-10}$
$A_{Re}(b)$	$3,7 \times 10^{-11}$	$3,8 \times 10^{-11}$	$2,1 \times 10^{-11}$	$3,1 \times 10^{-11}$	$3,6 \times 10^{-11}$
	$2,7 \times 10^{-10}$	$2,6 \times 10^{-10}$	$4,8 \times 10^{-10}$	$3,2 \times 10^{-10}$	$2,8 \times 10^{-10}$

**Gegevens voor totale-lichaamstelling**

Na eenmalige inname	Tijd (d)	Lichaamsactiviteit (Bq per Bq inname)
	0,25	$9,8 \times 10^{-1}$
	1	$7,0 \times 10^{-1}$
	2	$3,2 \times 10^{-1}$
	3	$1,3 \times 10^{-1}$
	5	$2,1 \times 10^{-2}$
	7	$6,4 \times 10^{-3}$
		$7,3 \times 10^{-1}$
		$4,8 \times 10^{-1}$
		$2,6 \times 10^{-1}$
		$1,5 \times 10^{-1}$
		$9,1 \times 10^{-2}$
		$7,6 \times 10^{-2}$

Figure 5

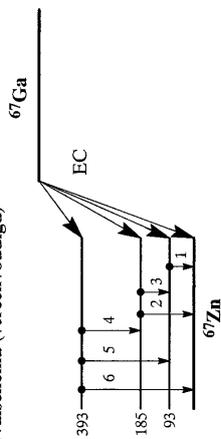
Radiation protection details of the radionuclide <sup>51</sup>Cr

**Halveringstijd en vervalconstante**

$T_{1/2} = 78,23 \text{ h} = 2,82 \times 10^5 \text{ s}$

$\lambda = 2,46 \times 10^{-6} \text{ s}^{-1}$

**Vervalchema (vereenvoudigd)**



**Belangrijkste uitgezonden straling**

Straling	$\gamma$ (Bq.s) <sup>-1</sup>	E (keV)	Straling	$\gamma$ (Bq.s) <sup>-1</sup>	E (keV)
$\gamma_1$	0,383	93	ce K $\gamma_1$	0,287	84
$\gamma_2$	0,209	185	$K_{\alpha}$	0,495	9
$\gamma_3$	0,031	91	KLL	0,467	7
$\gamma_4$	0,024	209	KLX	0,133	8
$\gamma_5$	0,168	300			
$\gamma_6$	0,047	393			

**Bronconstanten**

Kermatempo in lucht  $k = 0,018 \mu\text{Gy/h per MBq/m}^2$   
 Omgevingsdosis-equivalenttempo  $h = 0,025 \mu\text{Sv/h per MBq/m}^2$

**Diversen**

Specifieke activiteit  $A_{sp} = 2,21 \times 10^{16} \text{ Bq/g}$   
 Vrijstellingsgrenzen  $C_v = 10^2 \text{ Bq/g}$  en  $A_v = 10^6 \text{ Bq}$   
 Huidbesmetting  $H_{\text{huid}} = 9 \times 10^{-11} \text{ Sv/s per Bq/cm}^2$   
 Wondbesmetting; Injectie  $e(50) = 8,4 \times 10^{-11} \text{ Sv/Bq}$   
 Vervoer  $A_1 = 7 \text{ TBq}$   
 $A_2 = 3 \text{ TBq}$

**Productie en toepassingen**

Het radionuclide <sup>67</sup>Ga is een cyclotronproduct: protonen op zink. Het wordt toegepast in de nucleaire geneeskunde voor het lokaliseren van tumoren.

**Metabool model**

Voor stralingshygiënische doeleinden wordt aangenomen dat gallium zich vanuit het bloed als volgt verdeelt: 9% naar lever, 30% naar bot, 1% naar de milt en 60% naar de rest van het lichaam. De biologische halveringstijd voor alle organen is gesteld op:

Fractie	$T_{1/2}$	Fractie	$T_{1/2}$
0,3	1 d	0,7	50 d

N.B. Dit model geldt niet voor patiënten, zie pagina 14.

**Ingestie- en longzuiveringsklassen**

Ingestie	$f_1$	Inhalatie	$f_1$	Klasse M	Klasse F
Alle verbindingen	$f_1 = 0,001$				
Inhalatie					
Oxide, hydroxide, carbide, halogenide, nitraat	$f_1 = 0,001$				
Overige	$f_1 = 0,001$				

**Dosconversiecoëfficiënt en radiotoxiciteitsequivalent voor werknemers (w) en voor leden van de bevolking (b)**

	Ingestie	Inhalatie	Inhalatie
$e(50)(w)$	$1,9 \times 10^{-10}$	F	M
$A_{Re}(w)$	$5,3 \times 10^9$	$1,1 \times 10^{-10}$	$2,8 \times 10^{-10}$
$e(50)(b)$	$1,9 \times 10^{-10}$	$9,1 \times 10^9$	$3,6 \times 10^9$
$A_{Re}(b)$	$5,3 \times 10^9$	$6,8 \times 10^{-11}$	$2,3 \times 10^{-10}$
		$1,5 \times 10^{10}$	$4,3 \times 10^9$

**Gegevens voor totale-lichaamstelling**

Na eenmalige inname	Lichaamsactiviteit (Bq per Bq inname)
Tijd (d)	
0,25	$9,4 \times 10^{-1}$
1	$5,8 \times 10^{-1}$
2	$2,1 \times 10^{-1}$
3	$7,0 \times 10^{-2}$
5	$6,7 \times 10^{-3}$
7	$7,2 \times 10^{-4}$

Figure 6

Radiation protection details of the radionuclide <sup>67</sup>Ga

# 99mTc

N = 56

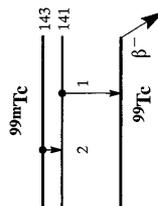
Z = 43

### Halveringstijd en vervalconstante

$$T_{1/2} = 6,006 \text{ h} = 2,17 \times 10^4 \text{ s}$$

$$\lambda = 3,21 \times 10^{-5} \text{ s}^{-1}$$

### Vervalschema (vereenvoudigd)



### Belangrijkste uitgezonden straling

Straling	$\gamma$ (Bq s) <sup>-1</sup>	E (keV)
$\gamma_1$	0,889	141
ce M $\gamma_2$	0,914	2
ce N $\gamma_2$	0,076	2
K $\alpha$	0,062	18
LMX	0,102	2

### Bronconstanten

$$k = 0,018 \text{ } \mu\text{Gy/h per MBq/m}^2$$

$$h = 0,023 \text{ } \mu\text{Sv/h per MBq/m}^2$$

### Diversen

Specifieke activiteit	$A_{sp} = 1,95 \times 10^{17} \text{ Bq/g}$
Vrijstellingsgrenzen	$C_v = 10^2 \text{ Bq/g}$ en $A_v = 10^7 \text{ Bq}$
Huidbesmetting	$H_{\text{huid}} = 5 \times 10^{-11} \text{ Sv/s per Bq/cm}^2$
Wondbesmetting: Injectie	$e(50) = 1,1 \times 10^{-11} \text{ Sv/Bq}$
Vervoer	$A_1 = 10 \text{ TBq}$ $A_2 = 4 \text{ TBq}$

### Productie en toepassingen

Het radionuclide <sup>99m</sup>Tc is de dochter van <sup>99</sup>Mo. Het wordt geproduceerd in een Mo/Tc-generator en op zeer grote schaal in de nucleaire geneeskunde gebruikt voor diagnostische doeleinden: voor afbeeldingen en functiestudies.

### Metabool model

Voor stralingshygiënische doeleinden wordt aangenomen dat technetium zich vanuit het bloed als volgt over de verschillende organen en weefsels van het lichaam verdeelt: 4% naar de schildklier, 10% naar de maagwand, 3% naar de lever en de rest naar de overige organen/weefsels. De biologische halveringstijd voor verblijf in het bloed is gesteld op 0,02 dagen, terwijl voor de organen/weefsels wordt aangenomen:

Fractie	$T_{1/2}$
0,75	1,6 d
0,20	3,7 d
0,05	22 d

N.B. Dit model geldt niet voor patiënten, zie pagina 14.

### Ingestie- en longzuiveringsklassen

Ingestie	$f_1 = 0,8$	
Alle verbindingen	$f_1 = 0,8$	
Inhalatie		
Halogenide, nitraat, hydroxide, oxide	$f_1 = 0,8$	Klasse M
Overige verbindingen	$f_1 = 0,8$	Klasse F

### Dosisconversiecoëfficiënt en radiotoxiceitsequivalent voor werknemers (w) en voor leden van de bevolking (b)

	Ingestie	Inhalatie	Inhalatie
	$f_1 = 0,8$	F	M
$e(50)(w)$	$2,2 \times 10^{-11}$	$2,0 \times 10^{-11}$	$2,9 \times 10^{-11}$
$A_{re}(w)$	$4,5 \times 10^{10}$	$5,0 \times 10^{10}$	$3,4 \times 10^{10}$
$e(50)(b)$	$2,2 \times 10^{-11}$	$1,2 \times 10^{-11}$	$1,9 \times 10^{-11}$
$A_{re}(b)$	$4,5 \times 10^{10}$	$8,3 \times 10^{10}$	$5,3 \times 10^{10}$

### Gegevens voor totale-lichaamstelling

Na eenmalige inname	Lichaamsactiviteit (Bq per Bq inname)
Tijd (d)	
0,25	$4,8 \times 10^{-1}$
1	$4,4 \times 10^{-2}$
2	$1,8 \times 10^{-3}$
3	$7,9 \times 10^{-5}$
5	$1,7 \times 10^{-7}$
7	$4,1 \times 10^{-10}$

Figure 7

Radiation protection details of the radionuclide <sup>99m</sup>Tc



**<sup>131</sup>I** **N = 78**

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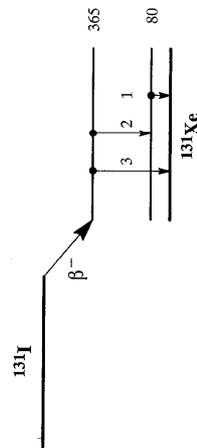
**Z = 53**

**Halveringstijd en vervalconstante**

$T_{1/2} = 8,021 \text{ d} = 6,93 \times 10^5 \text{ s}$

$\lambda = 1,00 \times 10^{-6} \text{ s}^{-1}$

**Vervalchema (vereenvoudigd)**



**Belangrijkste uitgezonden straling**

Straling	$\gamma$ (Bq.s) <sup>-1</sup>	E (keV)
$\beta^-$	0,894	192   606
$\gamma_1$	0,026	80
ce K $\gamma_1$	0,036	46
$\gamma_2$	0,061	284
$\gamma_3$	0,812	365

**Bronconstanten**

Kermtempo in lucht	$k = 0,052 \text{ } \mu\text{Gy/h per MBq/m}^2$
Omgevingsdosis-equivalenttempo	$h = 0,066 \text{ } \mu\text{Sv/h per MBq/m}^2$

**Diversen**

Specifieke activiteit	$A_{sp} = 4,60 \times 10^{15} \text{ Bq/g}$
Vrijstellingsgrenzen	$C_v = 10^2 \text{ Bq/g}$ en $A_v = 10^6 \text{ Bq}$
Huidbesmetting	$H_{\text{fluid}} = 4 \times 10^{-10} \text{ Sv/s per Bq/cm}^2$
Wondbesmetting; Injectie	$e(50) = 2,2 \times 10^{-8} \text{ Sv/Bq}$
Vervoer	$A_1 = 3 \text{ TBq}$ $A_2 = 0,7 \text{ TBq}$

**Productie en toepassingen**

Het radionuclide <sup>131</sup>I is een belangrijk spijtingsproduct. Het wordt veelvuldig toegepast in de diagnostische en therapeutische nucleaire geneeskunde.

**Metabool model**

Voor stralingshygiënische doeleinden wordt aangenomen dat jodium zich vanuit het bloed als volgt verdeelt: 70% directe uitscheiding en 30% naar de schildklier. Jodium in de schildklier verblijft aldaar met een biologische halveringstijd van 80 dagen, van waaruit het in de vorm van organisch jodium homogeen over het lichaam wordt verdeeld. Het verblijft in andere organen/weefsels dan de schildklier gescheidt met een halveringstijd van 12 dagen. Een tiende van het organisch jodium wordt onmiddellijk uitgescheiden via de faeces, terwijl de rest (90%) terugkeert in het transfercompartiment. Zodoende wordt de biologische halveringstijd in de schildklier effectief gelijk aan 90 dagen.

N.B. Dit model geldt niet voor patiënten, zie pagina 14.

**Ingestie- en longzuiveringsklassen**

Ingestie	Alle verbindingen	$f_1 = 1$	
Inhalatie			
Damp ( $I_2$ )		$f_1 = 1$	Klasse SR-1
Damp ( $\text{CH}_3\text{I}$ )		$f_1 = 1$	Klasse SR-1
Overige verbindingen		$f_1 = 1$	Klasse F

**Dosisconversiecoëfficiënt en radiotoxiciëitsequivalent voor werknemers (w) en voor leden van de bevolking (b)**

	Ingestie	Inhalatie	Inhalatie	Inhalatie
	$f_1 = 1$	F	$I_2$	$\text{CH}_3\text{I}$
$e(50)(w)$	$2,2 \times 10^{-8}$	$1,1 \times 10^{-8}$	$2,0 \times 10^{-8}$	$1,5 \times 10^{-8}$
$A_{Re}(w)$	$4,5 \times 10^7$	$9,1 \times 10^7$	$5,0 \times 10^7$	$6,7 \times 10^7$
$e(50)(b)$	$2,2 \times 10^{-8}$	$7,6 \times 10^{-9}$	$2,0 \times 10^{-8}$	$1,5 \times 10^{-8}$
$A_{Re}(b)$	$4,5 \times 10^7$	$1,3 \times 10^8$	$5,0 \times 10^7$	$6,7 \times 10^7$

**Gegevens voor schildklierretelling (na eenmalige inname)**

Tijd (d)	Activiteit in schildklier (Bq per Bq inname)	$I_2$	$\text{CH}_3\text{I}$
	$f_1 = 1$	F	$I_2$
0,25	$6,0 \times 10^{-2}$	$5,2 \times 10^{-2}$	$1,1 \times 10^{-1}$
1	$2,4 \times 10^{-1}$	$1,2 \times 10^{-1}$	$1,8 \times 10^{-1}$
2	$2,5 \times 10^{-1}$	$1,2 \times 10^{-1}$	$2,2 \times 10^{-1}$
3	$2,3 \times 10^{-1}$	$1,1 \times 10^{-1}$	$2,0 \times 10^{-1}$
5	$1,9 \times 10^{-1}$	$9,0 \times 10^{-2}$	$1,7 \times 10^{-1}$
7	$1,6 \times 10^{-1}$	$7,5 \times 10^{-2}$	$1,4 \times 10^{-1}$

Figure 9 Radiation protection details of the radionuclide <sup>131</sup>I

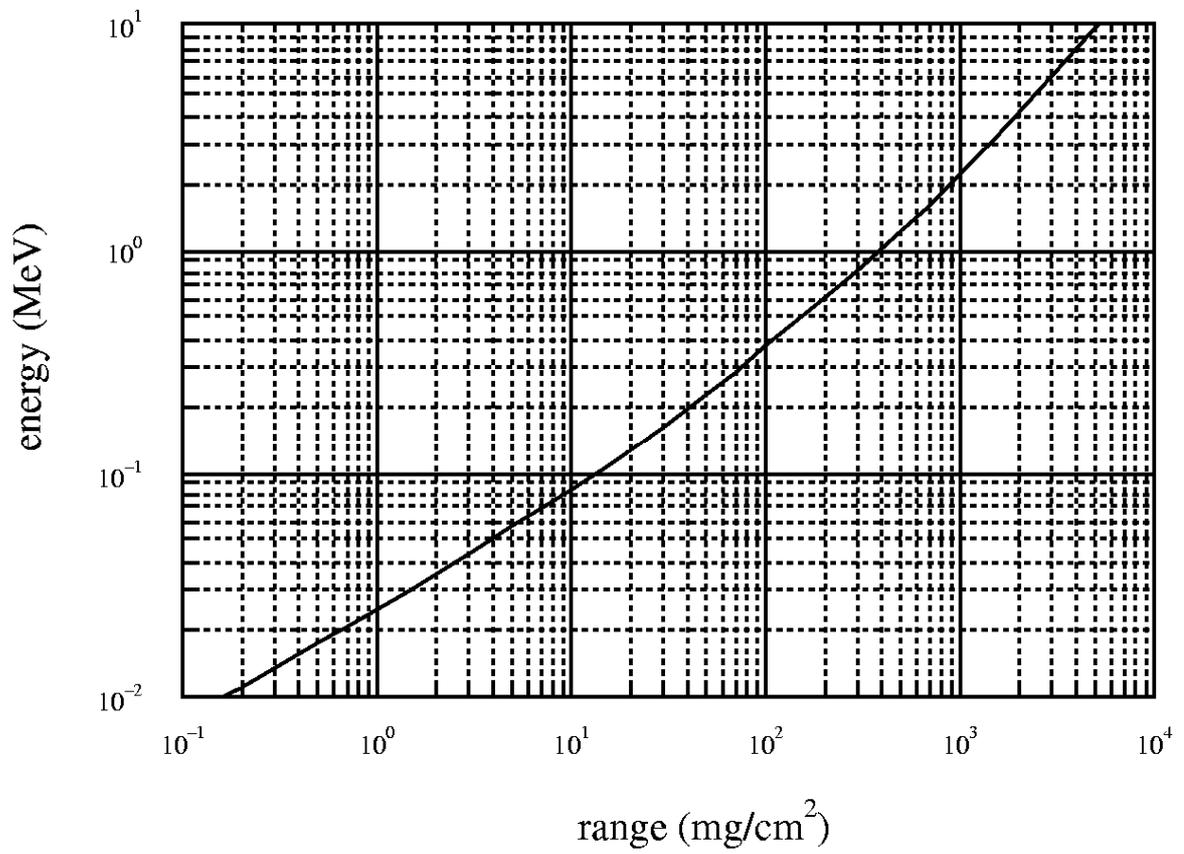


Figure 10 The maximal mass range  $\rho R_{\beta, \max}$  (in  $\text{mg}/\text{cm}^2$ ) as a function of the maximal  $\beta$ -energy  $E_{\beta, \max}$  (in MeV)

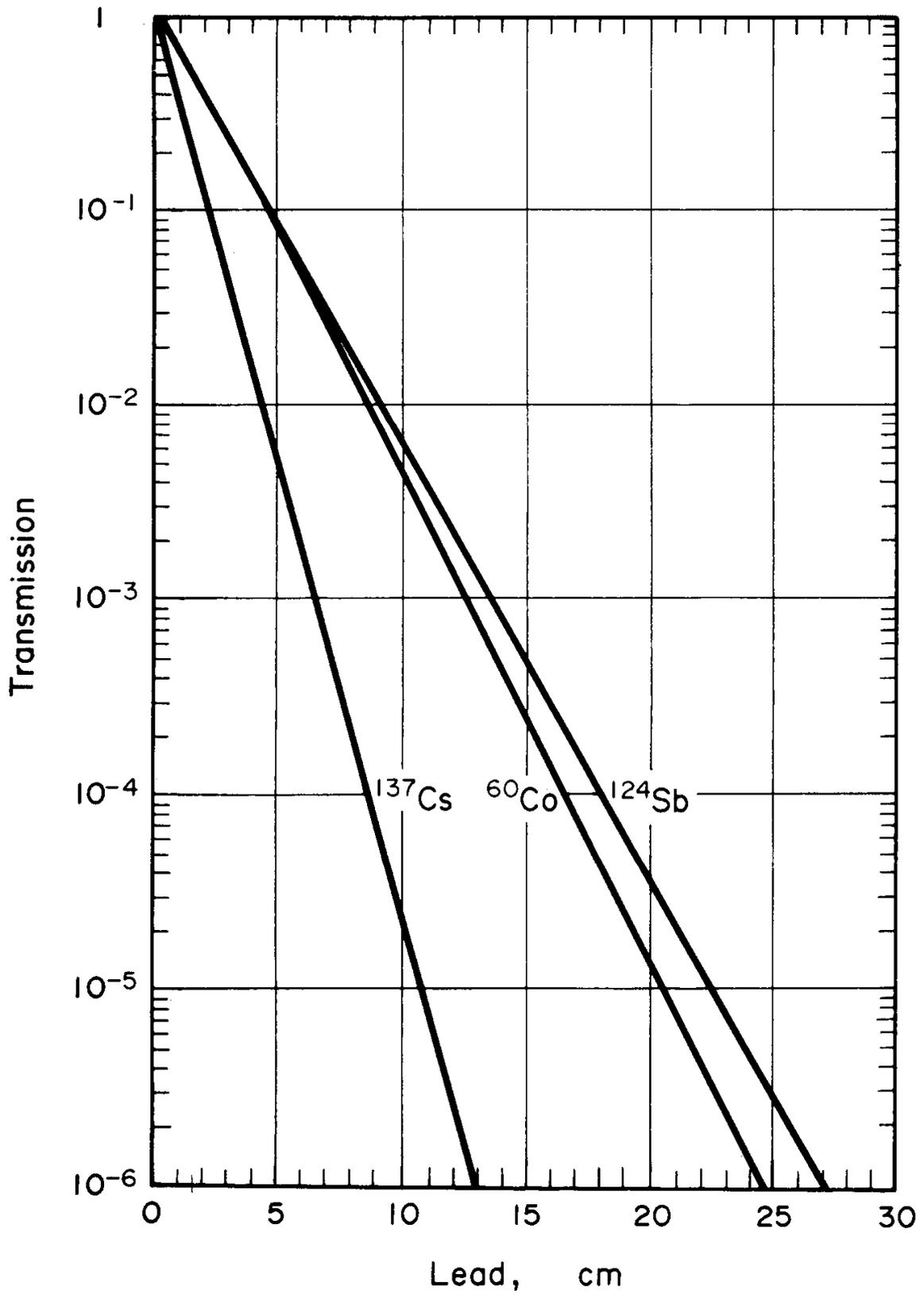


Figure 11 Transmission of broad-beam  $\gamma$ -radiation through lead (ICRP-57)

<i>categorie</i>	<i><math>\dot{H}^*</math> op het oppervlak (<math>\mu\text{Sv/uur}</math>)</i>	<i><math>\dot{H}^*</math> op 1 m van het oppervlak (<math>\mu\text{Sv/uur}</math>)</i>	<i>transportindex</i>
I-WIT	$\dot{H} < 5$		0
II-GEEL	$5 < \dot{H} < 500$	$\dot{H} < 10$	$0 < \text{TI} < 1$
III-GEEL	$500 < \dot{H} < 2000$	$10 < \dot{H} < 100$	$1 < \text{TI} < 10$

*Figure 12 Classification for transport of type A packages*

<i>p</i>	<i>practice</i>
-4	working with gases/powders in open system heating liquids to boiling strongly splashing practice
-3	working with volatile nuclides ( <sup>3</sup> H in vapor, iodine) working with powders in closed system boiling in a closed system shaking, vortexing, centrifuging storage of noble gases in closed system
-2	simple chemical practice (RIA) labeling with nonvolatile nuclide
-1	short-term very simple wet work: pipeting of nonvolatile nuclide practice in a closed system: elution technetium generator pulling up a syringe labeling in closed system measuring materials in ampules storage of radioactive waste in working area

<i>q</i>	<i>area</i>
0	area outside laboratory management
1	D laboratory ancillary space within laboratory management
2	C laboratory
3	B laboratory

<i>r</i>	<i>work space</i>
0	bench without local exhaust
1	bench with local exhaust fume hood not complying with NEN-EN 14175
2	fume hood complying with NEN-EN 14175 laminar air-flow isolator (class 2)
3	glove box closed laminar air-flow isolator (class 3)

Figure 13 Parameters according to the Directive on Radionuclide Laboratories

<i>AMAD</i> ( $\mu\text{m}$ )	<i>ET</i> <sub>1</sub>	<i>ET</i> <sub>2</sub>	<i>BB</i>	<i>bb</i>	<i>AI</i>	<i>totaal</i>
1	0.17	0.21	0.01	0.02	0.11	0.51
2	0.25	0.32	0.02	0.01	0.09	0.70
3	0.30	0.37	0.02	0.01	0.08	0.78
5	0.34	0.40	0.02	0.01	0.05	0.82
7	0.35	0.40	0.01	0.01	0.04	0.81
10	0.35	0.38	0.01	0.00	0.02	0.77

Figure 14 Lung deposition fractions nose breather (1.2 m<sup>3</sup>/hour) (ICRP-66)