Course
Radiation Protection Expert

Problems Book

dr. F. Pleiter and dr. H.F. Boersma

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CONTENTS

MEASURING RADIOACTIVITY

1. ^{14}C-dating (1996-1-2)

In the atmosphere, the radionuclide ^{14}C is continuously produced by the interaction of cosmic radiation with ^{14}N. The mass activity of ^{14}C in carbon dioxide (CO_2) in the air has remained more or less constant through the centuries and amounts to 220 Bq per kg elementary carbon (C). As long as the exchange with and uptake of CO_2 from the atmosphere occurs, this value is also valid for plants and trees. After the plant or tree dies, the amount of ^{14}C decreases due to physical decay. The carbon-dating method is based on this fact.

The activity determination occurs with the use of a proportional counter. The counter is filled with CO_2 gas that arises by the burning of the experimental sample. The counting efficiency of the used counter amounts to 0.95 counts per second (cps) per Bq ^{14}C. One can determine the background rate using coal; due to the great age of the coal layer, it no longer contains ^{14}C. After counting background for 32 hours, it follows that the background counting rate is on average 0.00300 cps.

Given:

- the atomic weight of C is 12.0 g mol^{-1}
- the volume of 1 mol of gas amounts to 22.4 l under standard conditions
- $T_{½}(^{14}C)$ = 5730 y

Table 1. One-tailed probability P(k) for a deviation kσ.

k	*0.0*	*0.1*	*0.2*	*0.3*	*0.4*	*0.5*	*0.6*	*0.7*	*0.8*	*0.9*
0	0.500	0.460	0.421	0.382	0.345	0.308	0.274	0.242	0.212	0.184
1	0.159	0.136	0.115	0.097	0.081	0.067	0.055	0.045	0.036	0.029
2	0.023	0.018	0.014	0.011	0.008	0.006	0.005	0.003	0.003	0.002

Questions:

1. Determine the mass activity of ^{14}C (in Bq per kg elementary carbon) for a piece of wood from the year zero.

2. A tree trunk found in a prehistoric grave has a mass ^{14}C-activity of 135 Bq per kg of elementary carbon. How old is this tree trunk?

3. In the counter used, 100 cm^3 of CO_2 gas is introduced, obtained by burning a sample from a wooden object. In 32 hours, 513 counts accumulate. Determine the mass activity of ^{14}C (in Bq kg^{-1} of elementary carbon).

4. Calculate the age of the object from Question 3.

5. What is the maximum age of the object from Question 3 using a 95% confidence level and taking into account the standard deviation in the mass activity?

2. Activity of strontium isotopes (1988-1-4)

Air is aspirated through a filter during the passage of the radioactive cloud from Chernobyl. After γ-spectrometry analysis of the filter, the radionuclides ^{131}I, ^{137}Cs, ^{103}Ru *etcetera* are determined. Besides these, also the strontium isotopes ^{89}Sr and ^{90}Sr are expected. The sample was taken on 02-05-86 from 09:00-11:00 hrs.

In order to quantitatively determine the amount of strontium, this must be chemically separated from the other elements on the filter. The time point at which separation occurs is on 02-09-86 at 10:00 hrs and is defined as $t = 0$. The Sr-sample is measured immediately after the separation using a proportional counter. The counting time is 1 hr and the number of counts amounts to 6450.

Exactly one month later on 02-10-86, the sample is measured again. The number of counts is then 7622 counts in 1 hour.

Given:

- the flow rate of the air pump with which the sample is taken amount to 50 $m^3\ h^{-1}$
- the capture efficiency of the filter is 100%
- the activity concentration in the air during the sampling is constant
- the background counting rate of the counter amounts to 0.02 counts per second
- the counting efficiency of the measurement setup for β-particles is 28%
- absorption of β-radiation may be neglected
- the activity during measuring may be assumed to be constant
- the simplified decay schemes from ^{89}Sr and ^{90}Sr (see Figure 1)

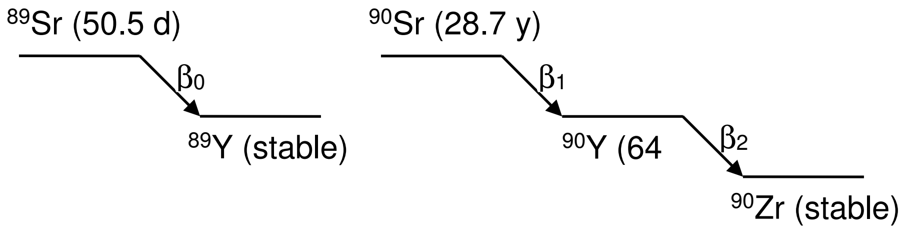


Figure 1. The simplified decay schemes of the radionuclides ^{89}Sr, ^{90}Sr and ^{90}Y.

Questions:

1. Calculate the activity of ^{89}Sr and ^{90}Sr on the filter at the time of sampling, starting from the results of the two measurements.

2. Calculate the activity concentration (in Bq m^{-3}) of both isotopes in air at the time of sampling.

3. Simultaneous measuring of α- and β-activity (1987-2-4)

For a proportional counter, the relationship between counting rate and tube voltage exhibits a plateau for both α- and β-activity. These plateaus display partial overlap, as shown in Figure 1, by which both the α- as well as the β-activity can be determined in the same sample. This is done by performing measurements at two different tube voltages, U_1 and U_2. By using the counting efficiencies for α- and β-radiation and the background counting rates at the voltages U_1 and U_2, the α- and β-activity can be separately calculated.

There are two samples taken. For the first sample at voltage U_1, 400 gross counts are measured and at voltage U_2, there are 700 counts.

The second sample contains so much α-activity that at voltage U_1 500 gross counts are measured. One wants to determine whether this sample also contains of β-activity by taking measurements at voltage U_2.

Given:

- the counting rate as a function of the tube voltage (see Figure 1)
- the calibration data of the proportional counter (see Table 1)
- all measurement results, including those from the background, are obtained in a measuring time of 40 minutes
- assume for this Problem that one particle is emitted per disintegration
- the β-activity is detectable if the increase in the counting rate at tube voltage U_2 relative to the counting rate when there is no β-activity present is twice the standard deviation of the last-named gross counting rate

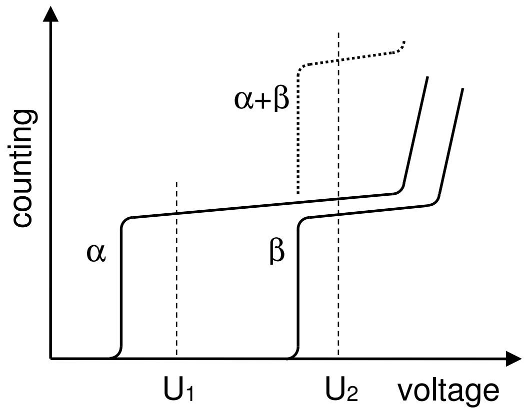


Figure 1. Counting rate as a function of the voltage across the proportional counter.

Table 1. Calibration data for the proportional counter.

voltage	*background (cpm)*	*counting efficiency (cps Bq⁻¹)* α	β
U_1	0.2	0.25	0
U_2	1.0	0.30	0.40

Questions:

1. Calculate the α- and β-activity (in Bq) with corresponding standard deviations for the first sample.

2. What is the minimally detectable β-activity (in Bq) for the second sample at voltage U_2 for a counting time of 40 min?

4. Surface contamination with ^{45}Ca and ^{46}Sc (1995-2-3)

In a radionuclide laboratory, the radionuclides ^{45}Ca and ^{46}Sc are used. One day, a contamination is discovered on the floor. A wipe test is done on the contaminated portion of the floor and is measured in two different apparatuses: a β-counter and a γ-spectrometer. Using the β-teller, 50 000 counts per minute (cpm) are obtained. Using the γ-spectrometer, 1000 cpm are measured in a small channel around the photopeak at 1.12 MeV.

Given:
- the wiped area of the floor is 100 cm^2
- in this question, the wipe efficiency is set at 50%
- the dead time of the β-counter amounts to 200 μs
- the counting efficiency of the β-counter is 40% for values of $E_{\beta,max}$ between 200 and 400 keV
- the counting efficiency of the γ-spectrometer for the photopeak at 1.12 MeV is 8%
- the background counting rate of both counters may be neglected
- the decay scheme of ^{45}Ca (see Appendix, Figure 7)
- the decay scheme of ^{46}Sc (see Appendix, Figure 8)
- for the calculation, one does not need to take radioactive decay into account

Questions:

1. Calculate the β-counting rate of the wipe test sample, correcting for the dead time.

2. Calculate the total β-activity of the wipe test sample (in Bq).

3. Calculate the ^{46}Sc-activity (in Bq).

4. How large were the surface contaminations (in Bq cm^{-2}) of ^{45}Ca and ^{46}Sc separately?

5. Was the contamination permissible according to the (now outdated) Directive on Radionuclide Laboratories?

5. Measuring ^{13}N with a gamma camera (1981-1-3)

To study the workings of the liver, a test subject receives a one-time injection into the blood stream of an amino acid that has been labeled with the radionuclide ^{13}N. The distribution of the activity to the different organs achieves equilibrium within 5 minutes. At that point, a picture of the liver is taken using the gamma camera, which is set to the annihilation-radiation photopeak at 0.511 MeV.

Given:

- 10% of the activity is taken up by the liver from the bloodstream
- assume for the calculation that the activity is concentrated in one point at a distance of 20 cm from the camera
- the average path length of the annihilation radiation through body tissue amounts to 8 cm
- the thickness of the NaI-crystal in the gamma camera amounts to 10 mm
- 30% of the interactions in NaI occur via the photo-electric effect
- the mass attenuation coefficients for a γ-energy of 0.511 MeV are μ/ρ(tissue) = 0.095 $cm^2\ g^{-1}$ and μ/ρ(NaI) = 0.093 $cm^2\ g^{-1}$
- the densities are ρ(tissue) = 1.00 g cm^{-3} and ρ(NaI) = 3.67 g cm^{-3}
- to make a usable photo, the fluence rate at the camera must be at least 1000 photons per cm^2 and per second
- radiation that reaches the camera from portions of the body other than the liver is disregarded for this Problem
- the contributions of scattered photons in this Problem are also disregarded.
- the decay scheme of ^{13}N (see Figure 1)

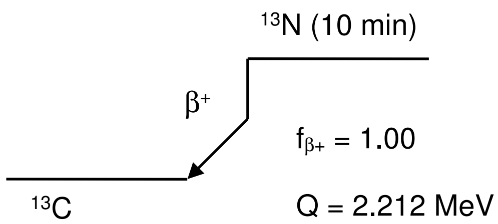


Figure 1. The decay scheme of radionuclide ^{13}N.

Questions:

1. Determine the photopeak efficiency of the NaI crystal for a γ-energy of 0.511 MeV.

2. How much ^{13}N-activity should be administered to obtain a usable photo?

6. Detection of a laboratory contamination (1981-2-2)

In a radiochemical laboratory, the radionuclides ^{22}Na, ^{55}Fe, ^{81}Kr and ^{125}I are used. A contamination monitor is available, with two cylindrically-shaped measuring heads A and B. Both heads contain a NaI(Tl)-scintillation detector, but their sensitivity as a function of the photon energy is different.

During a routine check with this monitor, a contamination on the table surface is found. Both heads measure a counting rate. The rates, corrected for background, amount to 10 862 counts per minute (cpm) for head A and 5440 cpm for head B.

Table 1. Decay data for the radionuclides ^{22}Na, ^{55}Fe, ^{81}Kr and ^{125}I. Energies are in keV.

nuclide	^{22}Na		^{55}Fe	^{81}Kr	^{125}I	
$T_{½}$	2.602 y		2.7 y	2.3×10^5 y	59.39 d	
decay	β^+		EC	EC	EC	
radiation	γ	$\gamma_\pm$	X_K	X_K	X_K	γ
energy	1275	511	6	12	27	35
$f_{emission}$	1.00	1.81	0.28	0.53	1.39	0.07

Given:

- decay data for the radionuclides ^{22}Na, ^{55}Fe, ^{81}Kr and ^{125}I (see Table 1)
- detector efficiency of the heads A and B as a function of the photon energy (see Figure 1)
- the effective surface area of the heads A and B amounts to 4.5 cm² and 3.1 cm², respectively.
- the distance between the detector and the table surface during the measurement amounts to 30 mm.
- the geometry factor for a point source and a cylindrically-shaped detector is:

$$f_{geo} = 0{,}5 \times [1 - \cos(\alpha)]$$

$$\cos(\alpha) = \frac{h}{\sqrt{h^2 + r^2}}$$

h = distance from the source to the front surface of the detector
r = radius of the circle-shaped front surface

Questions:

1. Determine the nuclide in the contamination using the data in Table 1 and Figure 1, assuming that the contamination consists of only one of the four nuclides listed in the Table. Explain your answer.

2. Calculate the activity of the contamination from one of the measurements. Consider the contamination to be a point source. One does not need to take into account attenuation in air.

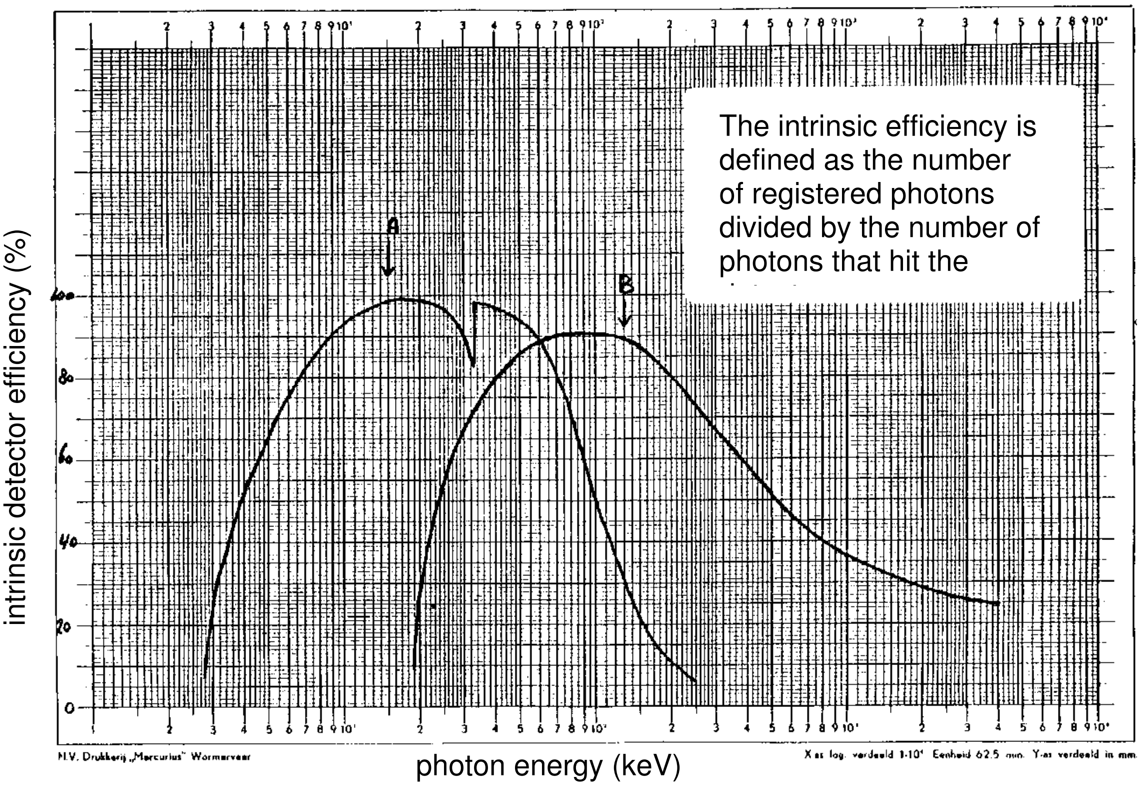


Figure 1. Detector efficiency of the heads A and B as a function of the photon energy.

7. Measuring foil thicknesses using a β-source (2000-1-1)

In a plastics factory, one wants to measure the foil thickness during production using the transmission of β-radiation.

Before proceeding to purchase a strong source, first a less active test source from $^{90}Sr/^{90}Y$ is used to measure thicknesses up to 400 mg cm^{-2}. According to the certificate which is provided with the source, the ^{90}Sr activity on 01-01-1995 is 185 kBq. Without foil, 4899 counts (net) were registered from this source in 10 s on May 1, 2000. When measuring a foil on the same day, the detector registered 1952 counts (net) in 10 s.

Given:

- the decay scheme of ^{90}Sr (see Appendix, Figure 16)
- the decay scheme of ^{90}Y (see Appendix, Figure 17)
- the transmission of β^--particles of $^{90}Sr/^{90}Y$ through plastics (see Figure 1)
- the absorbed dose rate in air for a point-shaped β^--source (see Figure 2)

Questions:

1. Determine the total efficiency of the used measuring setup without foil.

2. Calculate the thickness (in mg cm^{-2}) of the measured foil.

3. What is the minimum counting time for a foil thickness of 200 mg cm^{-2} such that the relative standard deviation of the end result is equal to 2.5% ?

In the industrial setup to be used, a much stronger $^{90}Sr/^{90}Y$-source will be used, namely 185 MBq ^{90}Sr in equilibrium with the daughter ^{90}Y.

4. Calculate the absorbed dose rate in air at 1 m distance from the unshielded source in the final setup.

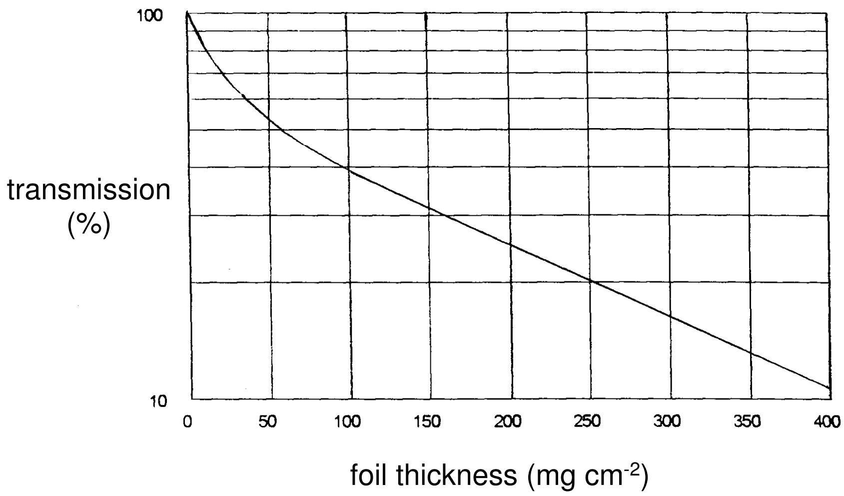


Figure 1. Transmission of β-particles of $^{90}Sr/^{90}Y$ through plastic.

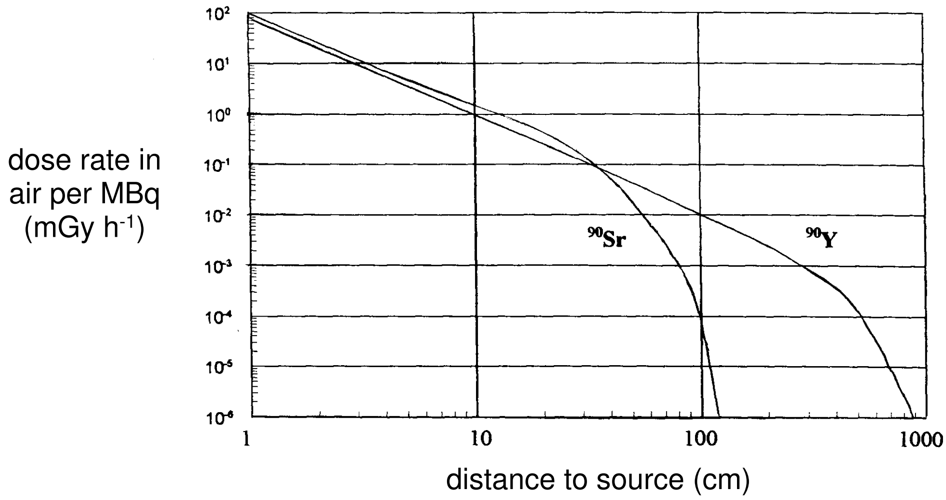


Figure 2. The absorbed dose rate in air for a point-shaped β-source.

8. Detection limit (1998-1-4)

The discharge of the radionuclide ^{210}Po via a ventilation shaft is regularly checked with an air-sampling device. For each sample, a volume of 20 m^3 of air is streamed through the apparatus.

To obtain a first indication of the activity, a sample is measured after 30 d in a suitable measuring setup with a counting efficiency of 20% for α-radiation. In 30 min, 240 counts are accumulated. The background causes 3361 counts in 8 h in this setup.

In the current license, the maximal activity concentration is set to 50 mBq m^{-3} for α-emitters.

Given:

- $T_{½}(^{210}Po)$ = 138 d
- the emission efficiency is $f_{\alpha} = 1$
- the contribution of γ-radiation to the counting rate may be neglected
- the minimally detectable activity A_{min} can be calculated using the formula

$$A_{min} = \frac{k}{\varepsilon}\sqrt{T_{zero}\left[\frac{1}{t_{gross}} + \frac{1}{t_{zero}}\right]}$$

k = desired confidence interval (= number of standard deviations)
ε = counting efficiency
T_{zero} = counting rate as a result of background radiation
T_{gross} = sample measuring time
T_{zero} = background radiation measuring time

Questions:

1. Calculate the activity at the time of sampling.

2. Calculate the standard deviation of this activity.

3. Calculate the minimally detectable activity A_{min} at the time of sampling. Assume a confidence interval of 95% (twice the standard deviation, thus k = 2).

4. Is the minimally-detectable activity in Question 3 low enough to determine whether the concentration limit stated in the license is exceeded?

9. Fill-height measuring (2000-2-3)

A beer brewery needs to determine whether cans of beer on a conveyer belt are sufficiently filled. This can occur using a radioactive ^{85}Kr-source that emits γ-radiation. The source strength amounts to 10 GBq. Radiation is detected using a NaI(Tl)-crystal which converts γ-radiation into electrical pulses.

Given:
- the decay scheme of ^{85}Kr (see Appendix, Figure 13)
- a sketch of the measuring setup (see Figure 1)
- the beer can has a diameter of 48 mm
- the influence of the can on the transmission may de neglected
- the background radiation may also be neglected
- the photon beam is strongly collimated
- the total detection efficiency (including geometry factor) for the photons of ^{85}Kr is 1.6×10^{-4}
- the mass attenuation coefficient of beer for photons with an energy of 514 keV amounts to 0.0097 $m^2\ kg^{-1}$
- beer has a density of 1008 kg m^{-3}
- the one-tailed probability P(k) for a deviation kσ (see Table 1)

Questions:

1. Calculate the counting rate registered by the detector in case of an empty can.

2. Calculate the counting rate registered by the detector in case of a full can in-between source and detector.

3. The integration time of the detector is set at 20 ms (that means the counting rate is averaged over a period of 20 ms). How large is the standard deviation in the counting rate with a full can of beer?

4. The selection threshold for discriminating between full and empty cans is set at precisely the average of the counting rates for a full and an empty can. Calculate the probability that a full can will be read as empty (= false empty) as a result of statistical fluctuations in the counting rate for a full can.

5. The management of the brewery thinks that the number of false empty cans, as calculated in Question 4, is too large. Give at least two ways to reduce this number; give for each way one disadvantage.

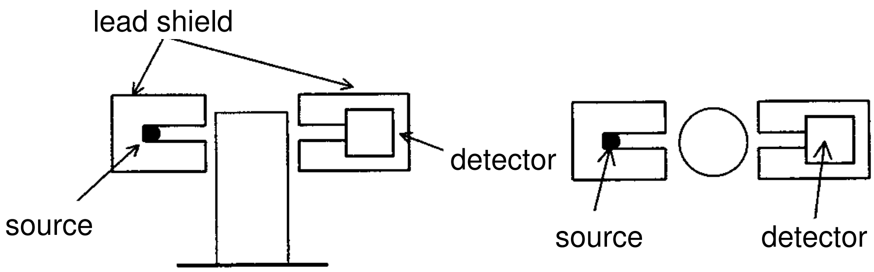


Figure 1. Side-view (left) and top-view (right) of the setup.

Table 1. One-tailed probability P(k) for a deviation kσ.

k	*0.0*	*0.1*	*0.2*	*0.3*	*0.4*	*0.5*	*0.6*	*0.7*	*0.8*	*0.9*
0	0.500	0.460	0.421	0.382	0.345	0.308	0.274	0.242	0.212	0.184
1	0.159	0.136	0.115	0.097	0.081	0.067	0.055	0.045	0.036	0.029
2	0.023	0.018	0.014	0.011	0.008	0.006	0.005	0.003	0.003	0.002

10. Waste monitor (1994-1-1)

A hospital is considering purchasing a waste monitor to sort radioactive waste. The device must be able to measure ^{131}I in waste bags to well below the legal exemption value, which is 100 Bq g^{-1}.

A manufacturer offers an instrument for sale in which bags of waste up to 20 kg may be placed in a chest. The side walls of the chest are equipped with scintillation detectors with a large surface area. To reduce the background counting rate, the entire chest is surrounded by 2.5 cm-thick lead. On the front side of the chest is a door that also contains a detector. The bottom of the chest contains a weigh scale which registers the mass of the waste bag.

Between measurements, the background counting rate is measured while the door is closed and no waste bag is present. The measuring time is always 10 minutes. Under normal circumstances, the background counting rate amounts to 1398 counts per second (cps).

After a waste bag is placed in the chest, a measurement of 10 seconds begins the moment that the door is closed. Via the computer, the measured counting rate and mass are converted into mass activity and the result is shown subsequently on the screen.

Given:
- the decay scheme of ^{131}I (see Appendix, Figure 20)
- the efficiency of the monitor (see Figure 1)
- the contribution of β-radiation to the counting rate is negligible
- the minimum detectable activity for this Problem is defined as the activity that corresponds to three standard deviations of the background

Questions:

1. Calculate the calibration factor (in cps per Bq) for the nuclide ^{131}I.

2. Calculate the gross counting rate (in cps) for a waste bag of 20 kg with an average activity concentration of 1 Bq g^{-1}.

3. How large is the number of registered counts in the measuring time of 10 seconds for a bag of 20 kg that does not contain any activity?

4. How large is the standard deviation of this number?

5. Determine the minimal detectable ^{131}I-activity (in Bq).

6. Finally, determine the minimal detectable mass ^{131}I-activity (in Bq g^{-1}) for a waste bag of 20 kg. Does the instrument fulfill the stated purpose?

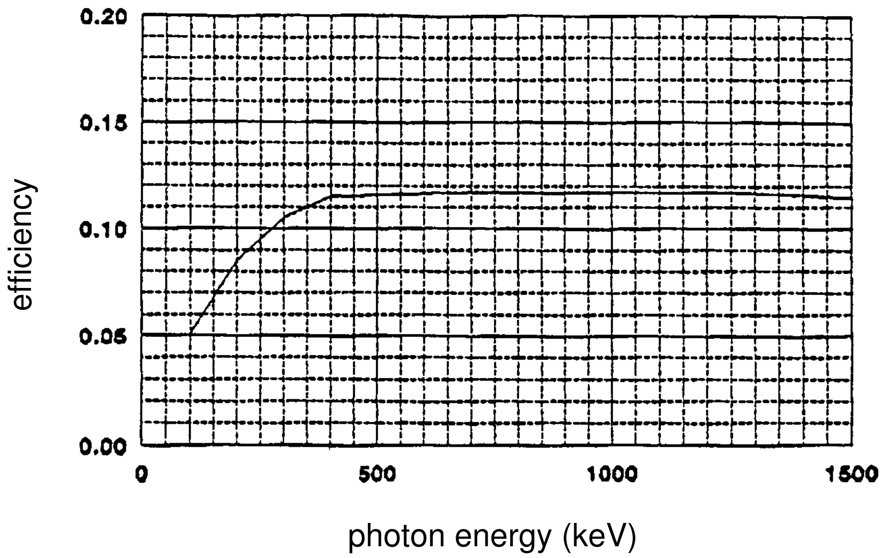


Figure 1. Total counting efficiency of the waste monitor as a function ofthe photon energy.

11. Activated instruments (1994-2-2)

During proceedings in a nuclear power plant, a tool becomes radioactive by activation. The tool has a mass of 510 gram and is exposed to thermal neutrons for 0.1 hour. As a first rough analysis, one wants to determine the half-life of the most prominent radionuclide in the tool. Therefore, 2 hours after the end of the activation, a series of measurements is begun using a scintillation counter, with the following results:

time	*counting rate (cps)*
12:00	7.09×10^5
12:15	3.20×10^5
12:30	1.71×10^5
13:00	8.77×10^4
15:00	4.45×10^4
17:00	2.60×10^4
20:00	1.16×10^4

Further investigation shows that the nuclides ^{56}Mn and ^{60m}Co have been formed due to activation of ^{55}Mn and ^{59}Co, respectively. The radionuclide ^{60m}Co has the shortest half-life.

Given:
- the background counting rate amounts to 162 cps
- the tool contains 1.1 mg manganese and 210 mg cobalt
- the atomic weight of manganese and cobalt are 54.9 g mol^{-1} and 58.9 g mol^{-1}, respectively.
- the natural abundances of ^{55}Mn and ^{59}Co are 100%
- Avogadro's number is 6.02×10^{23} mol^{-1}
- the fluence rate of the thermal neutrons is 1×10^{16} m^{-2} s^{-1}
- the cross sections for the capture of thermal neutrons are $\sigma_{th}(^{55}Mn) = 13.3 \times 10^{-28}$ m^2 and $\sigma_{th}(^{59}Co) = 20 \times 10^{-28}$ m^2, respectively.
- the activity A after irradiation of N atoms is given by:

  $$A = N\sigma_{th}\phi\left(1 - e^{-\lambda t}\right)$$

  σ_{th} = cross section per atom for the capture reaction
  φ = fluence rate of the thermal neutrons
  λ = decay constant of the activation product
  t = irradiation time

- The number of radioactive nuclei N^* that are formed by neutron irradiation is given by the formula:

  $$N^* = N\sigma\phi t$$

Questions:

1. Plot the net counting rates on single logarithmic paper. Determine from the graphs the half-lives of both dominant nuclides present.

2. Calculate the activity of ^{56}Mn and ^{60m}Co immediately after the irradiation.

3. The nuclide ^{60}Co ($T_{½}$ = 5.27 y) is formed in the decay of ^{60m}Co. Calculate the ^{60}Co-activity 24 hours after irradiation.

4. ^{60}Co can arise both by decay of ^{60m}Co as well as by neutron capture by ^{59}Co. The cross section for this reaction is 18×10^{-28} m^2 and, therefore, the total cross section is not 20×10^{-28} m^2, but is rather 38×10^{-28} m^2. Calculate the ^{60}Co-activity 24 hours after the irradiation, using this data.

5. If the contribution of other long-lived activation products is negligible, then ^{60}Co determines the mass activity in the end. After how much time is the mass activity of the tool smaller than the legal exemption value of 10 Bq g^{-1}?

12. Detection of ^{55}Fe (1993-1-1)

One of the most important activation products formed by neutron irradiation of iron and steel is ^{55}Fe. Only low-energy characteristic X-radiation has to be taken into account for this problem.

To be able to measure the degree of activation of iron and steel surfaces, one must use a special detector that is capable of detecting such low-energy photons. The following detector is available: a very thin NaI(Tl)-crystal with a thickness of 0.1 mm, a surface area of 20 cm^2 and an entrance film of beryllium with a thickness of 0.1 mm.

Given:

- the decay scheme of ^{55}Fe (see Appendix, Figure 10)
- the densities of beryllium and sodium iodide amount to 1.85 g cm^{-3} and 3.67 g cm^{-3}, respectively.
- the mass attenuation coefficients for a photon energy of 6.4 keV are μ/ρ(Be) = 2.07 cm^2 g^{-1} and μ/ρ(NaI) = 450 cm^2 g^{-1}, respectively.
- for this problem, the following information is given: the distance between the detector and the surface to be monitored may be neglected; half the X-radiation is emitted into the direction of the detector; and each interaction in the detector leads to a count.

Questions:

1. Calculate the transmission of the beryllium foil.

2. Indicate what fraction of the number of photons that reach the crystal do not interact with the crystal.

3. Calculate the calibration factor for measuring ^{55}Fe-containing surfaces with this monitor in counts per second (cps) per Bq cm^{-2}.

4. To determine the response of the detector, a calibrated and sufficiently-large flat-shaped source is used with a ^{55}Fe-activity of 2000 Bq cm^{-2}. Assume that the ^{55}Fe is located in a very thin layer on the surface of the plate. If one holds the detector against this plate, the counting rate amounts 5000 cps. Calculate the calibration factor from this data (in cps per Bq cm^{-2}).

13. Determination of the mass attenuation coefficient (1992-1-1)

In Figure 1 (left), the γ-spectrum of ^{137}Cs is given which has been determined using a Ge-detector. The source has an activity of 412 kBq and was placed at a distance of 5 cm from the detector. The measuring time amounted to 1 min.

In Figure 1 (right), the same spectrum is shown, but this time determined using a plate of lead with a thickness of 5.0 mm between source and detector.

Given:
- the decay scheme of ^{137}Cs (see Appendix, Figure 21)
- the density of lead is ρ = 11 340 kg m^{-3}
- the measured net number of counts in the photopeak is given in Figure 1 as CNTS

Questions:

1. Calculate the photopeak efficiency for the detection of γ-radiation with an energy of 662 keV in the given geometry, without lead.

2. Calculate the attenuation coefficient μ/ρ of lead for 662 keV γ-radiation. Why does one not have to take into account the build-up factor?

3. Give an explanation for the appearance of the two photopeaks at 75 keV and 85 keV.

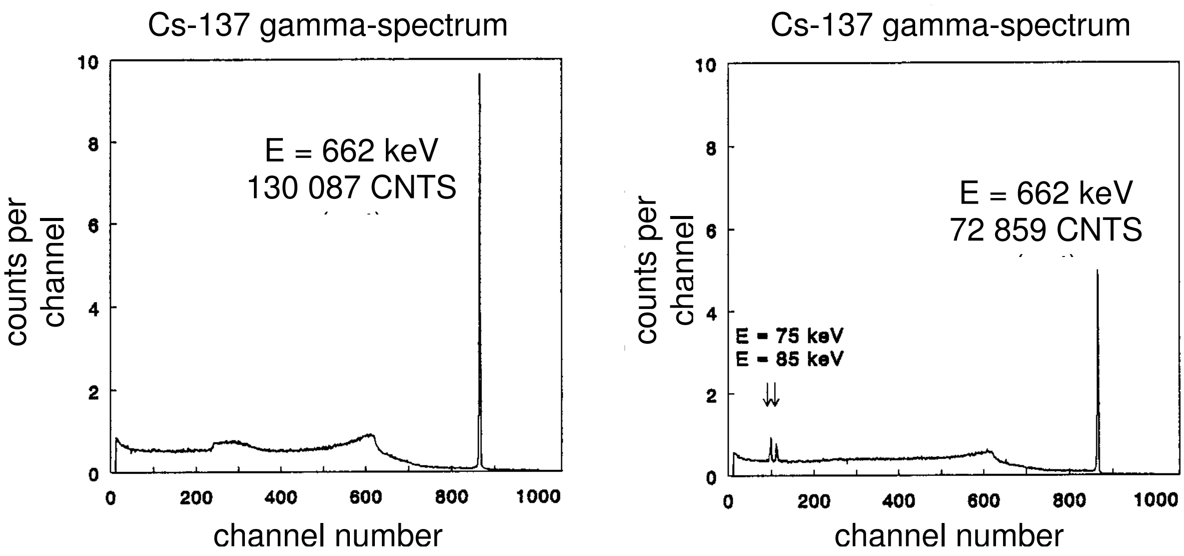


Figure 1. The γ-spectrum of ^{137}Cs, measured without an absorber (left) and with an absorber of 5 mm lead (right).

14. Measuring ^{125}I (1999-1-4)

One wants to measure a quantity of ^{125}I in a liquid scintillation counter. A sample of 100 μl is pipetted into a plastic counting vial. After adding 3 ml of scintillation fluid, the contents of the vial are homogenized. The net counting rate is 100 counts per minute.

Electrons are formed from the interaction of the X-radiation and γ-radiation emitted by the ^{125}I and the wall of the counting vial. These electrons cause scintillation light to be produced in the fluid in the same manner as the conversion and Auger electrons emitted from ^{125}I do. The scintillation light is subsequently detected by the photomultiplier tube. The liquid scintillation counter is set up such that electrons with an energy level between 10 keV and 100 keV are measured with a counting efficiency of 80%. Scintillations that arise from electrons with an energy level smaller than 10 keV are not registered.

Table 1. Energy E and emission probability $f_{emission}$ of photons and electrons.

type of emission	*E (keV)*	$f_{emission}$
γ-photons	35.5	0.067
X-ray photons	3.8-4.1	0.120
	31.0	0.255
	27.3	1.140
conversion electrons	3.7	0.803
	30-35	0.130
Auger electrons	3.1-4.4	1.600
	22-30	0.192

Given:

- the decay scheme of ^{125}I (see Appendix, Figure 19)
- energy and emission probability of photons and electrons (see Table 1)
- the mass attenuation coefficient of the counting fluid/vial combination for photons with an energy level of 30 keV amounts to 3 cm^2 g^{-1}
- the density of the counting fluid/vial combination is 1 g cm^{-3}

Questions:

1. Calculate the detection efficiency for photons with an energy of 30 keV. The average path length of the photons inside the counting vial amounts to 3 mm.

2. Calculate the contribution of the conversion electrons and Auger electrons to the counting rate for an activity of 1 Bq.

3. Calculate the contribution of the X-ray photons and γ-photons to the counting rate for an activity of 1 Bq. Assume that the photons with an energy between 20 keV and 40 keV all have an effective energy of 30 keV.

4. Calculate the ^{125}I-activity in the sample.

15. Liquid waste (1990-2-3)

In a laboratory, the radionuclides ^{3}H, ^{14}C and ^{32}P are used. The radiation protection expert uses a liquid scintillation counter with three channels (A, B and C) to measure the liquid waste. On February 1, 1990, a liquid-waste container is turned in with the marking **P-32**. The expert collects 2 ml from the vat and processes it as sample #1. From the measurement results, he calculates the date on which the contents of the container may be disposed of to the public sewer.

On the calculated date, he takes three additional samples (#2, #3, and #4) from the container. Because he detects more activity than expected, it appears that there is also ^{3}H and/or ^{14}C in the liquid. To determine the activity, he adds a very small volume containing 160 Bq ^{3}H to sample #3 to create sample #5. In the same way, he adds a very small volume containing 300 Bq ^{14}C to sample #4 to create sample #6. Samples #5 and #6 are then counted.

Given:
- the decay properties of the used radionuclides (see Table 1)
- the exemption value for ^{32}P was 0.25 Bq ml^{-1} in 1990 (!)
- counting efficiency for ^{32}P in channels A, B and C are 5%, 26% and 65%, respectively
- the measuring results corrected for background in counts per minute (see Table 2)

Questions:

1. What is the correct date to discharge this waste, as calculated by the expert?

2. Calculate the counting efficiency for ^{14}C in channels A and B.

3. Calculate the counting efficiency for ^{3}H in channels A and B.

4. Calculate the concentration of ^{14}C and/or ^{3}H in the waste liquid (in Bq ml^{-1}).

5. Could the concentration of ^{3}H and/or ^{14}C calculated in Question 4 already have been determined on February 1, 1990? Explain your answer.

Table 1. Decay properties of the used radionuclides.

nuclide	*$T_{½}$*	*$E_{β,max}$ (keV)*
^{3}H	12.35 y	18.6
^{14}C	5730 y	156
^{32}P	14.29 d	1710

Table 2. Measuring time (in minutes) and net measuring results (in counts per minute).

sample	*measuring time (min)*	*A: 0-20 keV (cpm)*	*B: 20-160 keV (cpm)*	*C: 160-1750 keV (cpm)*
#1	1	5.8×10^{5}	3.0×10^{6}	7.8×10^{6}
#2	10	1026	1405	19
#3	10	1002	1423	21
#4	10	1040	1413	20
#5	10	4187	1417	19
#6	10	7498	10 265	21

16. Leaking ^{131}I-source (1991-2-1)

In an area with a volume of 50 m^3, an installation is leaking a variable amount of ^{131}I. A repair must be done in this area. The ventilation system of the area under normal usage has a ventilation rate of ten times per hour. To make the repair, the ventilation must be turned off. In the past, it was measured that the activity concentration of ^{131}I can increase to a maximum of 250 mBq m^{-3} with a working ventilation system.

The repair takes 5 hours in total, and the technician must be present in the area during the first and the last hour.

Given:

- $T_{½}(^{131}\mathrm{I})$ = 8.02 d
- the technician is a normal nose-breather with a breathing rate of 1.2 m^3 h^{-1}

Questions:

1. Calculate the activity that maximally leaks out of the installation (in Bq h^{-1}). Assume for the calculation that the leak is constant.

2. Give a formula that describes the average activity concentration in the area as a function of the time from the moment that the ventilation system in turned off. Assume that the leak is maximal (see Question 1) and that the average concentration at the beginning of the work amounts to 20 mBq m^{-3}.

3. Make an estimate of the maximal activity that the technician has inhaled. Assume that the activity concentration locally can amount to ten-times the average activity concentration as calculated with the formula obtained in Question 2.

17. Mercury in a coal power plant (2000-1-2)

To study the behavior of mercury contamination in a coal power plant, one can use a mercury tracer. This is activated mercury that is added to the incoming coal stream. Subsequently, the concentration of the radioactive mercury is measured in the various waste streams of the plant.

About 25% of the mercury appears as mercury vapor in the exhaust air stream, 1% appears as mercury oxide in the bottom ash (slag) and 40% appears as mercury oxide in the fly ash. The rest is caught by the desulphurization installation and is not considered further here.

The experiment is conducted using 300 MBq ^{203}Hq. This activated mercury is obtained via the reaction ^{202}Hg(n,γ)^{203}Hg by irradiating pure mercury in a nuclear reactor. The neutron fluence rate at the irradiation facility is 1×10^{18} m^{-2} s^{-1} and the cross section for the given capture reaction is 5×10^{-28} m^{2}. To allow the simultaneously-formed, short-lived mercury isotopes to decay, a waiting time of 30 d is taken into account.

In the license issued for this experiment, a limit of 1 Re$_{inh}$ per experiment is set for discharge in air and a limit of 100 Bq g^{-1} for solid waste materials.

Table 1. The production rate of the waste materials.

waste stream	*production rate*
air	2.0×10^{6} m^{3} h^{-1}
bottom ash	3.3×10^{3} kg h^{-1}
fly ash	24.2×10^{3} g h^{-1}

Given:

- the production rate of the waste materials (see Table 1)
- the atomic weight of mercury is 200.59 g mol^{-1}
- the natural abundance of ^{202}Hg is 29.86%
- Avogadro's number is 6.02×10^{23} mol^{-1}
- a number of radiation protection details for ^{203}Hg (see Appendix, Figure 23)
- the production rate of ^{203}Hg is determined by the number of atoms of ^{202}Hg, the neutron fluence rate and the cross section
- assume that the activity appears in the ash within one hour

Questions:

1. Calculate the ^{203}Hg-activity that must be produced such that one has 300 MBq available at the moment of injection in the plant.

2. Calculate the number of atoms of ^{202}Hg in 1 gram of mercury.

3. Calculate the number of atoms of ^{203}Hg that are formed per second in 1 g of mercury.

4. Calculate the ^{203}Hg-activity that is produced per second in 1 gram of mercury.

5. How long should 1 gram of mercury be irradiated to produce 300 MBq?

6. Calculate the discharge to air. Does this conform to the license requirements?

7. Calculate the mass activity in bottom and fly ash. Does this conform to the license requirements?

8. During the injection into the power plant feed, an area surrounding the injection point is marked off such that outside of this area $H^* < 1$ μSv h^{-1}. Calculate the distance to the ^{203}Hg-source that this demarcation minimally must have.

18. Air contamination monitors (1991-1-1)

To detect γ-emitting radioactive aerosols in the outside air, band-filter aerosol monitors are used. This device is equipped with a filter band such that every two hours a clean piece of filter material is moved in front of the suction nozzle of the pump. While the air outside is being aspirated in, the radioactive aerosols are deposited on the filter and are recorded with the aid of a germanium detector.

Given:
- a sketch of the setup (see Figure 1)
- the decay scheme of ^{137}Cs (see Appendix, Figure 21)
- the pump ensures a constant air flow of 9.5 m^3 h^{-1}
- the filter has a capture efficiency of 100%
- the photopeak efficiency of the Ge-detector in the used geometry (see Figure 2)
- to determine the minimally-detectable ^{137}Cs-activity, it is assumed in this Problem that a photopeak is only recognized if it has a net content of 30 counts

Questions:

1. Calculate the ^{137}Cs-activity on the filter after the sampling and measuring period of 2 hours, if a constant activity concentration of 10 Bq m^{-3} ^{137}Cs is present in the outside air during this period.

2. Calculate the net number of registered counts in the photopeak of ^{137}Cs after the sampling and measuring period at the given activity concentration.

3. Calculate the activity concentration of ^{137}Cs in air that can just be detected with this setup.

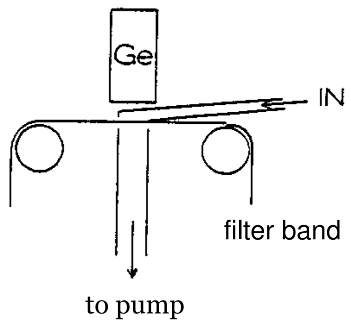


Figure 1. Measuring setup with a Ge-detector.

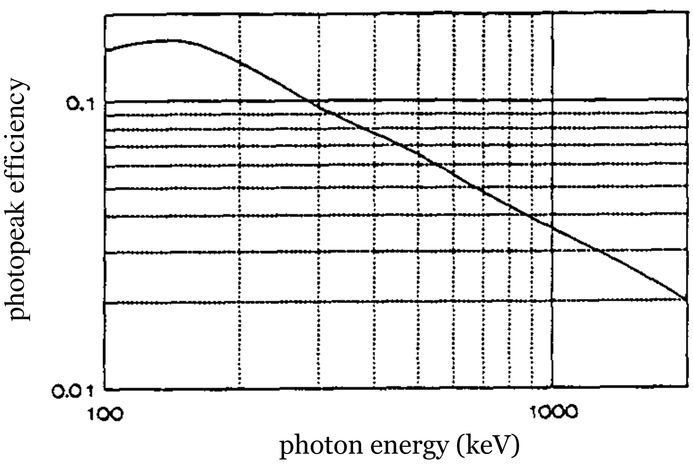


Figure 2. Photopeak efficiency of band filter and Ge-detector.

19. ^{88}Kr-activity in aerosols (1996-1-4)

In a closed, unventilated area with a volume of 1000 m^3 at a nuclear power plant, the radioactive noble gas ^{88}Kr escapes from a leaking ventilation duct. One wants to determine the activity concentration of the ^{88}Kr in the area by measuring the activity concentration of ^{88}Rb, which is a decay product of ^{88}Kr.

Air is sucked from the specific room for 30 minutes through a filter, and the β^--activity on the filter is then determined. The measurement begins 10 minutes after the end of the sampling period and lasts 30 minutes. At the beginning of the sampling period, no activity is present on the filter. After correction for background, the number of measured counts in 30 minutes is 150 000.

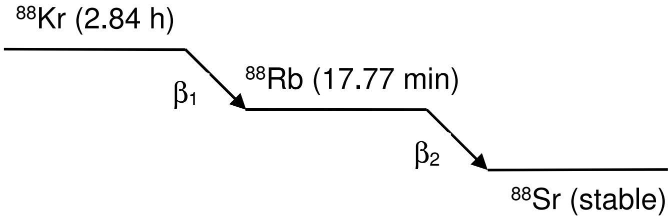


Figure 1. The simplified decay scheme of the radionuclides ^{88}Kr and ^{88}Rb.

Given:
- assume that the leakage rate of ^{88}Kr during the week previous to the measurement was constant
- the air flow of the sampling setup amounts to 30 l min^{-1}
- the capture efficiency of the filter for ^{88}Rb is 100%
- the capture efficiency of the filter for ^{88}Kr is zero
- the counting efficiency of the counting setup for β-particles of ^{88}Rb amounts to 10%
- the simplified decay schemes of ^{88}K and ^{88}Rb (see Figure 1)
- assume in the calculation that for ^{88}Kr and ^{88}Rb no other removal mechanisms exist exept removal by radioactive decay
- use the formula below if necessary:

$$\int_0^T e^{-\lambda t}\, dt = \frac{1}{\lambda}(1 - e^{-\lambda T})$$

Questions:

1. Calculate the ^{88}Rb-activity on the filter at the start of the measurement.

2. Calculate the ^{88}Rb-activity on the filter at the end of the sampling period.

3. Calculate the ^{88}Rb-concentration in the sampled air.

4. Make an estimate of the ^{88}Kr-concentration in the area.

20. Grinding wheels of naturally-radioactive materials (1995-2-4)

A grinding wheel which is used to cut metal pipes is composed of a material containing a fairly large amount of natural radioactivity. The nuclides detected belong to the ^{238}U-series (Table 1 shows the ^{226}Ra-subseries) and the ^{232}Th-series. Using a γ-spectrometer, an analysis of this material is performed, but not all the nuclides from these series can be detected in this way. However, the activity of a few key nuclides can be demonstrated (see Table 1).

Given:
- decay ^{226}Ra: ^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po, ^{210}Pb, ^{210}Bi, ^{210}Po, ^{206}Pb (stable)
- decay ^{232}Th: ^{228}Ra, ^{228}Ac, ^{228}Th, ^{224}Ra, ^{220}Rn, ^{216}Po, ^{212}Pb, ^{212}Bi, ^{208}Tl, ^{208}Pb (stable)
- all beforementioned daughters of ^{226}Ra ($T_{½}$ = 1600 y) and ^{232}Th ($T_{½}$ = 1.405×10^{10} y) have a much shorter half-life than their respective mothers
- for this problem, the activity of ^{238}U and its daughters up to ^{226}Ra are negligible relative to that of the ^{226}Ra-subseries
- a grinding wheel consists of 390 g grinding material
- the exemption values according to the Decree on Basic Safety Standards Radiation Protection (see Table 2)

Table 1. Measured mass activity (in Bq kg^{-1}) of a few radionuclides from the ^{226}Ra- and ^{232}Th-series. All γ-energies are given in keV.

^{238}U-series nuclide	E_γ	mass activity	*^{232}Th-serires* nuclide	E_γ	mass activity
^{226}Ra	186	127	^{228}Ac	911	153
^{214}Bi	1120	120	^{212}Pb	239	164
^{214}Bi	1764	130	^{212}Pb	300	139
			^{208}Tl	583	133
			^{208}Tl	2614	181

Table 2. Exemption values for activity concentration (in Bq g^{-1}) and activity (in Bq).

radionuclide	*activity concentration*	*activity*	
Ra-226 +	1	1×10^4	+, sec
Th-232 sec	1	1×10^3	in equilibrium with daughter nuclide only the mother nuclide value is tested

Questions:

1. What conclusions can be drawn with regards to the radiological equilibrium between the measured radionuclides from the two individual series? Note that in both series a nuclide from the gaseous element radon occurs.

2. Make an estimate of the total mass activity per (sub)series (in Bq kg^{-1}). This is the activity of all radionuclides from the (sub)series combined.

3. Does a supply of 100 grinding wheels require a license?

Solutions

<u>Problem 1</u>

1. $220\ \mathrm{Bq\ kg^{-1}} \times e^{-0.693\times 2013/5730} = 220\ \mathrm{Bq\ kg^{-1}} \times 0.784 = 172\ \mathrm{Bq\ kg^{-1}}$
2. $220\ \mathrm{Bq\ kg^{-1}} \times e^{-0.693\, t/5730} = 135\ \mathrm{Bq\ kg^{-1}}$
   $t = (5730\ \mathrm{y} / 0.693) \times \ln(220\ \mathrm{Bq\ kg^{-1}} / 135\ \mathrm{Bq\ kg^{-1}}) = (5730\ \mathrm{y} / 0.693) \times 0.488 = 4035\ \mathrm{y}$
3. $T_{\mathrm{net}} = T_{\mathrm{gross}} - T_{\mathrm{zero}}$
   $= 513 / (32\ \mathrm{h} \times 3600\ \mathrm{s\ h^{-1}}) - 0.003\ 00\ \mathrm{cps}$
   $= 0.004\ 45\ \mathrm{cps} - 0.003\ 00\ \mathrm{cps} = 0.001\ 45\ \mathrm{cps}$
   $\sigma_{\mathrm{Tnet}} = \sqrt{(T_{\mathrm{gross}}/t_{\mathrm{gross}} + T_{\mathrm{zero}}/t_{\mathrm{zero}})}$
   $t_{\mathrm{gross}} = t_{\mathrm{zero}} = 32\ \mathrm{h} \times 3600\ \mathrm{s\ h^{-1}} = 115\ 200\ \mathrm{s}$
   $\sigma_{\mathrm{Tnet}} = \sqrt{[(0.004\ 45\ \mathrm{cps} + 0.003\ 00\ \mathrm{cps}) / 115\ 200\ \mathrm{s}]} = 0.000\ 25\ \mathrm{cps}$
   activity $A = (0.001\ 45 \pm 0.000\ 25)\ \mathrm{cps} / 0.95 = (1.53 \pm 0.26)\times 10^{-3}\ \mathrm{Bq}$
   volume CO_2-gas $100\ \mathrm{cm^3} \times 10^{-3}\ \mathrm{l\ cm^{-3}} = 0{,}10\ \mathrm{l}$
   this corresponds to $0.10\ \mathrm{l} / 22.4\ \mathrm{l\ mol^{-1}} = 4.46\times 10^{-3}\ \mathrm{mol}$
   mass of carbon $M = 4.46\times 10^{-3}\ \mathrm{mol} \times 12.0\ \mathrm{g\ mol^{-1}} \times 10^{-3}\ \mathrm{kg\ g^{-1}} = 5.35\times 10^{-5}\ \mathrm{kg}$
   mass activity $A / M = (1.53 \pm 0.26)\times 10^{-3}\ \mathrm{Bq} / 5.35\times 10^{-5}\ \mathrm{kg} = 28.6 \pm 4.9\ \mathrm{Bq\ kg^{-1}}$
4. $220\ \mathrm{Bq\ kg^{-1}} \times e^{-0.693\, t/5730} = 28.6\ \mathrm{Bq\ kg^{-1}}$
   $t = (5730\ \mathrm{y} / 0.693) \times \ln(220\ \mathrm{Bq\ kg^{-1}} / 28.6\ \mathrm{Bq\ kg^{-1}}) = (5730\ \mathrm{y} / 0.693) \times 2.04 = 16\ 870\ \mathrm{y}$
5. 95% corresponds to a one-tailed probability $P(k) = 0.05$
   according to Table 1, $k = 1.65$
   $A > 28.6\ \mathrm{Bq\ kg^{-1}} - 1.65 \times 4.9\ \mathrm{Bq\ kg^{-1}} = 20.5\ \mathrm{Bq\ kg^{-1}}$
   $t < (5730\ \mathrm{y} / 0.693) \times \ln(220\ \mathrm{Bq\ kg^{-1}} / 20.5\ \mathrm{Bq\ kg^{-1}}) = (5730\ \mathrm{y} / 0.693) \times 2.37 = 19\ 596\ \mathrm{y}$

<u>Problem 2</u>

1. measurement 1 at $t = 0$:
   according to the data, there is only ^{89}Sr and ^{90}Sr
   $T_{\mathrm{gross}} = 6450 / (1\ \mathrm{h} \times 3600\ \mathrm{s\ h^{-1}}) = 1.79\ \mathrm{cps}$
   $T_{\mathrm{net}} = T_{\mathrm{gross}} - T_{\mathrm{zero}} = 1.79\ \mathrm{cps} - 0.02\ \mathrm{cps} = 1.77\ \mathrm{cps}$
   $A(^{89}\mathrm{Sr}, 0) + A(^{90}\mathrm{Sr}, 0) = T_{\mathrm{net}} / 28\times 10^{-2} = 1.77\ \mathrm{cps} / 0.28 = 6.32\ \mathrm{Bq}$ (a)
   measurement 2 at $t = 30$ d:
   ^{89}Sr partially decayed $A(^{89}\mathrm{Sr}, 30\ \mathrm{d}) = A(^{89}\mathrm{Sr}, 0) \times e^{-0.693\times 30/50.5} = 0.66\, A(^{89}\mathrm{Sr}, 0)$
   ^{90}Sr hardly decayed $A(^{90}\mathrm{Sr}, 30\ \mathrm{d}) = A(^{90}\mathrm{Sr}, 0)$
   ^{90}Y in equilibrium with ^{90}Sr $A(^{90}\mathrm{Y}, 30\ \mathrm{d}) = A(^{90}\mathrm{Sr}, 30\ \mathrm{d}) = A(^{90}\mathrm{Sr}, 0)$
   $T_{\mathrm{gross}} = 7622 / (1\ \mathrm{h} \times 3600\ \mathrm{s\ h^{-1}}) = 2.12\ \mathrm{cps}$
   $T_{\mathrm{net}} = T_{\mathrm{gross}} - T_{\mathrm{zero}} = 2.12\ \mathrm{cps} - 0.02\ \mathrm{cps} = 2.10\ \mathrm{cps}$
   $0.66\, A(^{89}\mathrm{Sr}, 0) + A(^{90}\mathrm{Sr}, 0) + A(^{90}\mathrm{Sr}, 0) = 2.10\ \mathrm{cps} / 0.28 = 7.50\ \mathrm{Bq}$ (b)
   from (a) and (b) follow the next two equations:
   $2\, A(^{89}\mathrm{Sr}, 0) + 2\, A(^{90}\mathrm{Sr}, 0) = 12.64\ \mathrm{Bq}$
   $\underline{0.66\, A(^{89}\mathrm{Sr}, 0) + 2\, A(^{90}\mathrm{Sr}, 0) = 7.50\ \mathrm{Bq}}$ -
   $1.34\, A(^{89}\mathrm{Sr}, 0) = 5.14\ \mathrm{Bq}$ $A(^{89}\mathrm{Sr}, 0) = 5.14\ \mathrm{Bq} / 1.34 = 3.84\ \mathrm{Bq}$
   $2A(^{90}\mathrm{Sr}, 0) = 12.64\ \mathrm{Bq} - (2 \times 3.84\ \mathrm{Bq})$
   $A(^{90}\mathrm{Sr}, 0) = 6.32\ \mathrm{Bq} - 3.84\ \mathrm{Bq} = 2.48\ \mathrm{Bq}$
   since 02-05-86, 123 days have elapsed:
   $A(^{89}\mathrm{Sr}) = A(^{89}\mathrm{Sr}, 0)\, e^{0.693\times 123/50.5} = 3.84\ \mathrm{Bq} \times 5.41 = 20.8\ \mathrm{Bq}$
   $A(^{90}\mathrm{Sr}) = A(^{90}\mathrm{Sr}, 0) = 2.48\ \mathrm{Bq}$

2. pump time $t = 2$ h
   pump flow $D = 50\ m^3\ h^{-1}$
   volume of sampled air $V = D \times t = 50\ m^3\ h^{-1} \times 2\ h = 100\ m^3$
   capture percentage is 100%, thus the activity concentrations are:
   $c(^{89}Sr) = 20.8\ Bq / 100\ m^3 = 0.21\ Bq\ m^{-3}$
   $c(^{90}Sr) = 2.48\ Bq / 100\ m^3 = 0.025\ Bq\ m^{-3}$

Problem 3

1. α-channel:
   measuring time = 40 min × 60 s min^{-1} = 2400 s
   $T_\alpha(U_1) = T_{gross}(U_1) - T_{zero}(U_1)$
   $= (400 / 40\ min) - 0.2\ cpm = 10.0\ cpm - 0.2\ cpm = 9.8\ cpm = 0.163\ cps$
   $\sigma_\alpha = \sqrt{[T_{gross}(U_1) / t_{gross}(U_1) + T_{zero}(U_1) / t_{zero}(U_1)]}$
   $= \sqrt{[(10.0\ cpm / 40\ min) + (0.2\ cpm / 40\ min)]} = 0.505\ cpm = 0.008\ cps$
   counting efficiency $\varepsilon_\alpha(U_1) = 0.25\ cps\ Bq^{-1}$
   α-activity $A_\alpha = T_\alpha(U_1) / \varepsilon_\alpha(U_1) = (0.163 \pm 0.008)\ cps / 0.25\ cps\ Bq^{-1}$
   $= 0.65 \pm 0.03\ Bq$

   β-channel:
   contribution of A_α is proportional to the counting efficiency
   $T_\alpha(U_2) = 9.8\ cpm \times (0.30 / 0.25) = 11.8\ cpm$
   $T_\beta(U_2) = T_{gross}(U_2) - T_{zero}(U_2) - T_\alpha(U_2)$
   $= (700 / 40\ min) - 1.0\ cpm - 11.8\ cpm$
   $= 17.5\ cpm - 1.0\ cpm - 11.8\ cpm = 4.7\ cpm = 0.078\ cps$
   $\sigma_\beta = \sqrt{[(17.5\ cpm / 40\ min) + (1.0\ cpm / 40\ min) + (11.8\ cpm / 40\ min)]}$
   $= 0.87\ cpm = 0.015\ cps$
   counting efficiency $\varepsilon_\beta(U_2) = 0.40\ cps\ Bq^{-1}$
   β-activity $A_\beta = T_\beta(U_2) / \varepsilon_\beta(U_2) = (0.078 \pm 0.015)\ cps / 0.40\ cps\ Bq^{-1}$
   $= 0.20 \pm 0.04\ Bq$
2. net-counting rate in α-channel:
   $T_\alpha(U_1) = (500 / 40\ min) - 0.2\ cpm = 12.5\ cpm - 0.2\ cpm = 12.3\ cpm$
   contribution of α-activity to β-channel:
   $T_\alpha(U_2) = 12.3\ cpm \times (0.30 / 0.25) = 14.8\ cpm$
   counting rate for U_2 without β-activity:
   $T_{gross,\ \beta=0}(U_2) = T_\alpha(U_2) + T_{zero}(U_2) = 14.8\ cpm + 1.0\ cpm = 15.8\ cpm$
   $\sigma_{gross,\ \beta=0}(U_2) = \sqrt{[(14.8\ cpm / 40\ min) + (1.0\ cpm / 40\ min)]}$
   $= 0.63\ cpm = 0.011\ cps$
   minimally-detectable increase in the counting rate for U_2 as a result of β-radiation:
   $T_{min,\beta} = 2\sigma_{gross,\ \beta=0}(U_2) = 2 \times 0.011\ cps = 0.022\ cps$
   minimally-detectable β-activity:
   counting efficiency $\varepsilon_\beta(U_2) = 0.40\ cps\ Bq^{-1}$
   minimal activity $A_{min,\beta} = T_{min,\beta} / \varepsilon_\beta(U_2) = 0.022\ cps / 0.40\ cps\ Bq^{-1} = 0.055\ Bq$

Problem 4

1. the formula is $T_{actual} = T_{measured} / (1 - \lambda \times T_{measured})$
   $T_{measured} = 50\ 000\ cpm = 833\ cps$
   dead time $\tau = 200\ \mu s = 200\times10^{-6}\ s$
   thus $T_{actual} = 50\ 000\ cpm / (1 - 200\times10^{-6}\ s \times 833\ cps)$
   $= 50\ 000\ cpm / (1 - 0.17) = 60\ 000\ cpm$
2. $E_{\beta,max}(^{45}Ca) = 256$ keV $f_\beta = 1.0$
   $E_{\beta,max}(^{46}Sc) = 357$ keV $f_\beta = 1.0$
   because both nuclides emit β-radiation between 200 and 400 keV, $f_{det} = 40\%$
   $A(^{45}Ca) + A(^{46}Sc) = T_{actual} / (f_\beta \times f_{det}) = 1.0\times10^3\ cps / (1.0 \times 40\times10^{-2}) = 2.5\times10^3\ Bq$

3. ^{46}Sc emits γ-radiation with $E_\gamma = 1.121$ MeV and emission efficiency $f_\gamma = 1.0$
   efficiency γ-spectrometer $f_{det} = 8\%$
   counting rate is 1000 cpm = 16.7 cps
   $A(^{46}Sc) = T / (f_\gamma \times f_{det}) = 16.7 \text{ cps} / (1.0 \times 8\times10^{-2}) = 2.1\times10^2$ Bq on 100 cm²
4. $A(^{45}Ca) = 2.5\times10^3 \text{ Bq} - 2.1\times10^2 \text{ Bq} = 2.3\times10^3$ Bq on 100 cm²
   taking into account a wipe efficiency of 50%, the surface contaminations are:
   - ^{45}Ca $2 \times 2.3\times10^3 \text{ Bq} / 100 \text{ cm}^2 = 46 \text{ Bq cm}^{-2}$
   - ^{46}Sc $2 \times 2.1\times10^2 \text{ Bq} / 100 \text{ cm}^2 = 4.2 \text{ Bq cm}^{-2}$
5. according to the (now former) directive on radionuclide laboratories, the maximum permissible non-fixed β- and γ-activity is 4 Bq cm^{-2}
   in total, the amount of non-fixed activity is 2.5×10^3 Bq per 100 cm² = 25 Bq cm^{-2}
   the contamination is not permissible

<u>Problem 5</u>

1. mass thickness of NaI-crystal $d \times \rho = 10 \text{ mm} \times 10^{-1} \text{ cm mm}^{-1} \times 3.67 \text{ g cm}^{-3} = 3.67 \text{ g cm}^{-2}$
   transmission $e^{-(\mu/\rho)(d\times\rho)} = e^{-0.093\times3.67} = 0.71$
   total efficiency = 1 - transmission = 1 - 0.71 = 0.29
   photo peak efficiency = 0.30 × (total efficiency) = 0.30 × 0.29 = 0.087
2. number of photons per cm² and per second $\varphi = A \times f_{liver} \times f_{decay} \times f_{em} \times f_{geom} \times f_{abs}$
   10% goes to the liver $f_{liver} = 0.1$
   decay in 5 min $f_{decay} = e^{-0.693\times5/10} = 0.707$
   2 annihilation photons per β^+-particle $f_{em} = 2 \times 1.0 = 2.0$
   geometry factor for 1 cm² and 20 cm distance $f_{geom} = 1 \text{ cm}^2 / [4\pi \times (20 \text{ cm})^2] = 1.99\times10^{-4}$
   transmission through 8 cm tissue $f_{abs} = e^{-0.095\times(8\times1.00)} = 0.47$
   $\varphi = A \times 0.1 \times 0.707 \times 2.0 \times 1.99\times10^{-4} \times 0.47 = 1.32\times10^{-5} A > 1000 \text{ cm}^{-2} \text{ s}^{-1}$
   $A > 1000 \text{ cm}^{-2} \text{ s}^{-1} / 1.32\times10^{-5} = 76\times10^6 \text{ Bq} = 76 \text{ MBq}$

<u>Problem 6</u>

1. it is not ^{22}Na, because measuring head A can not detect 511 keV and 1275 keV photons
   it is not ^{55}Fe, because measuring head B can not detect of 6 keV photons
   it is not ^{81}Kr, because it is gaseous and measuring head B can not detect 12 keV photons
   $N_A / N_B = 10\,862 \text{ cpm} / 5440 \text{ cpm} = 2{,}0$
   surface area$_A$ / surface area$_B$ = 4.5 cm² / 3.1 cm² = 1.45
   → efficiency$_A$ / efficiency$_B$ = 2.0 / 1.45 = 1.4
   according to the efficiency curve $E_\gamma \approx 25$ keV, thus it must be ^{125}I; check:
   $f_{geom} = 0.5 \times (1 - \cos\alpha)$
   distance source-detector is 30 mm = 3.0 cm
   measuring head A $r = \sqrt{4.5 \text{ cm}^2 / \pi} = 1.2$ cm
   $\tan(\alpha) = 1.2 \text{ cm} / 3.0 \text{ cm} = 0.40$
   $\alpha = 22°$
   $f_{geom}^A = 0.036$
   measuring head B $r = \sqrt{3.1 \text{ cm}^2 / \pi} = 1.0$ cm
   $\tan(\alpha) = 1.0 \text{ cm} / 3.0 \text{ cm} = 0.33$
   $\alpha = 18°$
   $f_{geom}^B = 0.024$
   $\sum (f_\gamma \times f_{det}^A) = (1.39 \times 0.95) + (0.07 \times 0.98) = 1.39$
   $\sum (f_\gamma \times f_{det}^B) = (1.39 \times 0.65) + (0.07 \times 0.73) = 0.95$
   $N_A / N_B = [f_{geom}^A \times \sum (f_\gamma \times f_{det}^A)] / [f_{geom}^B \times \sum (f_\gamma \times f_{det}^B)]$
   $= (0.036 \times 1.39) / (0.024 \times 0.95) = 2{,}2$ → thus it's true

2. $N = A \times f_{geom} \times \sum (f_\gamma \times f_{det}) \times t$
   measuring head A $A \times 0.036 \times 1.39 \times 60$ s = 3.0 A = 10 862 cpm
   A = 10 862 cpm / 3.0 = 3.6×10^3 Bq
   measuring head B $A \times 0.024 \times 0.95 \times 60$ s = 1.4 A = 5440 cpm
   A = 5440 cpm / 1.4 = 3.9×10^3 Bq

Problem 7

1. $N = A \times f_\beta \times (f_{geom} \times f_{det}) \times f_{abs} \times t$
   since the time of purchase, 5.33 y have elapsed and there is meanwhile an equilibrium between mother and daughter
   $A(^{90}Sr) = A(^{90}Y) = 185\times10^3 \times e^{-0.693\times5.33/28.7} = 185\times10^3 \times 0.879 = 1.63\times10^5$ Bq
   both ^{90}Sr and ^{90}Y emit a β-particle, thus $f_\beta(^{90}Sr) = f_\beta(^{90}Y) = 1$
   there is no foil, thus no absorption, thus $f_{abs} = 1$
   there are N = 4899 counts measured in a measurement time t = 10 s
   dus $(f_{geom} \times f_{det}) = N / [\{A(^{90}Sr) \times f_\beta(^{90}Sr) + A(^{90}Y) \times f_\beta(^{90}Y)\} \times f_{abs} \times t]$
   $= 4899 / [\{1.63\times10^5 \text{ Bq} \times 1 + 1.63\times10^5 \text{ Bq} \times 1\} \times 1 \times 10 \text{ s}]$
   $= 4899 / (1.63\times10^5 \text{ Bq} \times 2 \times 1 \times 10 \text{ s}) = 1.5\times10^{-3}$
2. measured transmission 1952 counts / 4899 counts = 0.40
   from Figure 1 95 mg cm^{-2}
3. transmission at 200 mg cm^{-2} 0.25
   counting rate 0.25 × 4899 counts / 10 s = 122 cps
   required for σ_{rel} = 2.5% $1 / (2.5\times10^{-2})^2$ = 1600 counts
   counting time 1600 counts / 122 cps = 13.1 s
4. $A(^{90}Sr) = A(^{90}Y)$ = 185 MBq
   according to Figure 2 $D(^{90}Sr)$ = 185 MBq × 1.0×10^{-4} mGy h^{-1} per MBq = 0.02 mGy h^{-1}
   $D(^{90}Y)$ = 185 MBq × 1.0×10^{-2} mGy h^{-1} per MBq = 1.85 mGy h^{-1}
   total $D(^{90}Sr) + D(^{90}Y)$ = 1.87 mGy h^{-1}

Problem 8

1. t_{gross} = 30 min × 60 s min^{-1} = 1800 s
   t_{zero} = 8 h × 3600 s h^{-1} = 28 800 s
   $T_{net} = T_{gross} - T_{zero} = N_{gross} / t_{gross} - N_{zero} / t_{zero}$
   = (240 / 1800 s) - (3361 / 28 800 s) = 0.133 cps - 0.117 cps = 0.016 cps
   $T_{net} = A \times f_\alpha \times (f_{geom} \times f_{det} \times f_{abs})$
   $= A \times 1 \times 20\times10^{-2} = 0.20\,A$
   A = 0.016 cps / 0.20 = 0.080 Bq at the day of measurement, this is 30 d after sampling
   $A(0) = 0.080 \text{ (Bq)} \times e^{0.693\times30/138} = 0.080 \text{ (Bq)} \times 1.16 = 0.093$ Bq
2. $\sigma_{Tnet} = \surd(T_{gross} / t_{gross} + T_{zero} / t_{zero})$
   $= \surd[(0.133 \text{ cps} / 1800 \text{ s}) + (0.117 \text{ cps} / 28\,800 \text{ s})] = 0.0088$ cps
   $\sigma_A = \sigma_{Tnet} / 0.20 = 0.0088 \text{ cps} / 0.20 = 0.044$ Bq
   $\sigma_{A(0)} = 0.044 \text{ Bq} \times 1.16 = 0.051$ Bq
3. substitute in formula:
   $A_{min} = (2 / 20\times10^{-2}) \times \surd[0.117 \text{ cps} \times (1 / 1800 \text{ s} + 1 / 28\,800 \text{ s})] = 0.083$ Bq
   $A_{min}(0) = 0.083 \text{ Bq} \times 1.16 = 0.096$ Bq
4. per sampling, 20 m^3 of air is sample
   minimum air activity is thus:
   0.096 Bq / 20 m^3 = 0.0048 Bq m^{-3} = 4.8 mBq m^{-3} << 50 mBq m^{-3}
   (well) within the scope of the license

Problem 9

1. according to Appendix, Figure 13 is E_γ = 514 keV and f_γ = 0.0043
   $T_0 = A \times f_\gamma \times (f_{geom} \times f_{det}) \times f_{abs}$
   $= 10\times10^9$ Bq × 0.0043 × 1.6×10^{-4} × 1 = 6.9×10^3 cps
2. $f_{abs} = e^{-(\mu/\rho)(d\times\rho)} = e^{-0.0097\times(0.048\times1008)} = 0.625$
   $T_1 = T_0 \times f_{abs} = 6.9\times10^3$ cps × 0.625 = 4.3×10^3 cps
3. in t = 20 ms, $N = 20\times10^{-3}$ s × 4.3×10^3 cps = 86 counts recorded
   with standard deviation $\sigma_N = \lambda N = \lambda 86$ = 9.3 counts
   $\sigma_{T_1} = \sigma_N / t = 9.3 / 20\times10^{-3}$ s = 465 cps
4. threshold lies at $(T_0 + T_1) / 2 = (6.9\times10^3 \text{ cps} + 4.3\times10^3 \text{ cps}) / 2 = 5.6\times10^3$ cps
   difference with counting speed for a full can is 5.6×10^3 cps - 4.3×10^3 cps = 1.3×10^3 cps
   this corresponds to $k = 1.3\times10^3$ cps / 465 cps = 2.8 standard deviations
   Table 1 gives a one-tailed probability $P(2.8)$ = 0.003
5. - increase source strength → radiation protection disadvantages
   - set threshold higher → more false full cans
   - increase counting efficiency → (possibly) costs more money
   - increase integration time → production rate decreases

Problem 10

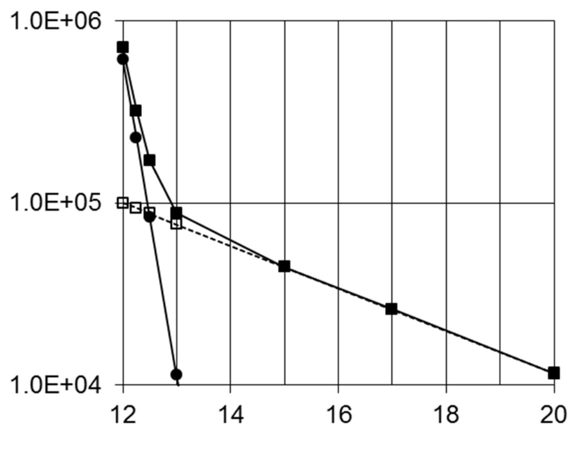
1. reading Figure 1 and Appendix, Figure 20

E_γ (keV)	f_γ (Bq s)$^{-1}$	$f_{geom} \times f_{det} \times f_{abs}$
365	0.812	0,11
284	0,061	0,10
80	0,026	0,05

   calibration factor = $\sum (f_\gamma \times f_{geom} \times f_{det} \times f_{abs})$
   = 1 × (0,812 × 0,11 + 0,061×0,10 + 0,026×0.05) = 0,096 tps per Bq
2. A = 20 kg × 1 Bq g^{-1} × 10^3 g kg^{-1} = 2.0×10^4 Bq
   $T_{net} = 2.0\times10^4$ Bq × 0.089 cps per Bq = 1.78×10^3 cps
   $T_{gross} = T_{net} + T_{zero}$ = $1{,}78\times10^3$ cps + 1398 cps = 3.18×10^3 cps
3. only zero effect in t = 10 s, there are 10 s × 1398 cps = 1.40×10^4 counts registered
4. standard deviation $\sigma_{zero} = \surd 1.40\times10^4$ = 118 counts
5. minimally-detectable activity corresponds to $3\sigma_{zero}$
   A_{min} × calibration factor = $3\sigma_{zero} / t$ = 3 × 118 / 10 s = 35 cps
   A_{min} = 35 cps / calibration factor = 35 cps / 0,096 tps per Bq = 365 Bq
6. minimum mass activity 365 Bq / 20 kg = 18 Bq kg^{-1} = 0,018 Bq g^{-1}
   (well) under the exemption value of 100 Bq g^{-1}

Problem 11

1. the graph consists of two almost straight parts
   draw a straight line through the last three points; this gives:
   $\lambda(^{54}Mn)$ = 0.27 h^{-1}
   $T_{½}(^{54}Mn)$ = 0.693 / 0.27 h^{-1} = 2.6 h
   extrapolate the line to t = 0
   deduct this contribution from the experimental value and draw a straight line through the corrected values; this yields:
   $\lambda(^{60m}Co)$ = 3.9 h^{-1}
   $T_{½}(^{60m}Co)$ = 0.693 / 3.9 h^{-1} = 0.18 h



2. activity in $t = 0.1$ h (because λ in h^{-1})
   $A = N \times \sigma \times \varphi \times (1 - e^{-\lambda \times 0.1})$
   $N(^{55}Mn) = (m_{Mn} / M_{Mn}) \times N_A$
   $= (1.1\times10^{-3}\ g / 54.9\ g\ mol^{-1}) \times 6.02\times10^{23}\ mol^{-1} = 1.21\times10^{19}$
   $A(^{56}Mn) = 1.21\times10^{19} \times 13.3\times10^{-28}\ m^2 \times 1\times10^{16}\ m^{-2}\ s^{-1} \times (1 - e^{-0.27\times0.1})$
   $= 4.28\times10^{6}$ Bq = 4.28 MBq
   $N(^{59}Co) = (m_{Co} / M_{Co}) \times N_A$
   $= (210\times10^{-3}\ g / 58.9\ g\ mol^{-1}) \times 6.02\times10^{23}\ mol^{-1} = 2.15\times10^{21}$
   $A(^{60m}Co) = 2.15\times10^{21} \times 20\times10^{-28}\ m^2 \times 1\times10^{16}\ m^{-2}\ s^{-1} \times (1 - e^{-3.9\times0{,}1})$
   $= 1.39\times10^{10}$ Bq = 13.9 GBq
3. number of ^{60m}Co-nuclei formed in $t = 0.1$ h = 360 s (in seconds, because φ in s^{-1}):
   $N(^{60m}Co) = N(^{59}Co) \times \sigma \times \varphi \times t$
   $= 2.15\times10^{21} \times 20\times10^{-28}\ m^2 \times 1\times10^{16}\ m^{-2}\ s^{-1} \times 360\ s = 1.55\times10^{13}$
   these all decay to ^{60}Co:
   $N(^{60}Co) = N(^{60m}Co) = 1.55\times10^{13}$
   $\lambda(^{60}Co) = 0.693 / (5.27\ y \times 365\ d\ y^{-1} \times 24\ h\ d^{-1} \times 3600\ s\ h^{-1}) = 4.17\times10^{-9}\ s^{-1}$
   $A(^{60}Co) = \lambda(^{60}Co) \times N(^{60}Co)$
   $= 4.17\times10^{-9}\ (s^{-1}) \times 1.55\times10^{13} = 6.46\times10^{4}$ Bq
4. total cross section for the reaction $^{59}Co \rightarrow {}^{60}Co$ is:
   $\sigma_{tot} = 20\times10^{-28}\ m^2 + 18\times10^{-28}\ m^2 = 38\times10^{-28}\ m^2$
   $A(^{60}Co)_{total} = (38\times10^{-28}\ m^2 / 20\times10^{-28}\ m^2) \times 6.46\times10^{4}\ Bq = 1.23\times10^{5}$ Bq
5. mass activity = 1.23×10^{5} Bq / 510 g = 241 Bq g^{-1}
   exemption value is 10 Bq g^{-1}, thus:
   $241\ Bq\ g^{-1} \times e^{-0.696\,t/5.272} = 10\ Bq\ g^{-1}$
   $t = (5.272\ y / 0.693) \times \ln(241\ Bq\ g^{-1} / 10\ Bq\ g^{-1}) = (5.272\ y / 0.693) \times 3.18 = 24\ y$

<u>Problem 12</u>

1. Be-foil $\mu \times d = (\mu/\rho) \times (d \times \rho)$
   $= 2.07\ cm^2\ g^{-1} \times (0.10\times10^{-1}\ cm \times 1.85\ g\ cm^{-3}) = 0.038$
   transmission Be $e^{-\mu d} = e^{-0.038} = 0.96$
2. NaI-crystal $\mu \times d = (\mu/\rho) \times (d \times \rho)$
   $= 450\ cm^2\ g^{-1} \times (0.10\times10^{-1}\ cm \times 3.67\ g\ cm^{-3}) = 16.5$
   transmission NaI $e^{-\mu d} = e^{-16.5} = 7\times10^{-8}$
   detector efficiency $f_{det} = 1 - \text{transmission} = 1 - 7\times10^{-8} \approx 1$
3. calibration factor is per Bq cm^{-2}, surface area of detector is 20 cm^2
   thus $A = (1\ Bq\ cm^{-2} \times 20\ cm^2)$ per Bq cm^{-2} = (20 Bq) per Bq cm^{-2}
   2π-geometry, thus $f_{geom} = 0.5$
   $T_{net} = A \times f_{x\text{-}ray} \times f_{geom} \times f_{abs} \times f_{det}$
   = 20 Bq per Bq cm^{-2} × 0.25 × 0.50 × 0.96 × 1 = 2.4 cps per Bq cm^{-2}
4. measured counting rate N = 5000 cps
   activity A = 2000 Bq cm^{-2}
   experimental calibration factor N / A = 5000 cps / 2000 Bq cm^{-2} = 2.5 cps per Bq cm^{-2}

<u>Problem 13</u>

1. $N = A \times f_\gamma \times (f_{geom} \times f_{det}) \times f_{abs}$
   $= 412\times10^{3}\ Bq \times (0.946 \times 0.898) \times (f_{geom} \times f_{det}) \times 1 = 3.5\times10^{5} \times (f_{geom} \times f_{det})$ cps
   $f_{geom} \times f_{det} = N$ (in cps) / 3.5×10^{5}
   measured for 0 cm of lead CNTS(0) = 130 089 cpm = 2.17×10^{3} cps
   $\varepsilon = f_{geom} \times f_{det} = 2.17\times10^{3}\ cps / 3.5\times10^{5}\ cps = 6.2\times10^{-3}$

2. measured for 5 mm = 0.5 cm lead CNTS(0.5) = 72 859 cpm
   transmission = CNTS(0.5) / CNTS(0) = 72 859 cpm / 130 089 cpm = 0.560
   $= e^{-\mu d}$
   $\mu \times d = -\ln(0.560) = 0.58$ $\mu = 0.58 / d = 0.58 / 0.5\ (\text{cm}) = 1.16\ \text{cm}^{-1}$
   $\rho = 11\,340\ \text{kg m}^{-3} = 11.34\ \text{g cm}^{-3}$
   $\mu/\rho = 1.16\ \text{cm}^{-1} / 11.34\ \text{g cm}^{-3} = 0.102\ \text{cm}^2\ \text{g}^{-1}$
   build-up does not play any role because scattered photons do not contribute to the photopeak
3. γ-radiation leads to photo-electric effect and Compton effect in lead, and thus to ionizations
   β-radiation gives rise likewise to ionizations in lead
   characteristic K-X-radiation of lead follows as a secondary radiation

Problem 14

1. for the combination counting liquid/counting vials
   $\mu \times d = (\mu/\rho) \times (d \times \rho) = 3\ \text{cm}^2\ \text{g}^{-1} \times (3\times10^{-1}\ \text{cm} \times 1\ \text{g cm}^{-3}) = 0.9$
   transmission of photons with an energy level of 30 keV is thus $e^{-\mu d} = e^{-0.9} = 0.41$
   interaction probability = 1 - transmission = 1 - 0.41 = 0.59
   there is an 80% chance that the interaction will be detected by the photomultiplier tube
   $f_{\text{det, photons}} = 0.59 \times 80\times10^{-2} = 0.47$
2. for electrons there is a 100% interaction chance
   $f_{\text{det, electrons}} = 1 \times 80\times10^{-2} = 0.80$
   $f_{\text{electrons} > 10\ \text{keV}} = 0.130 + 0.192 = 0.322$
   $\varepsilon_{\text{electrons}} = f_{\text{electrons} > 10\ \text{keV}} \times f_{\text{det, electrons}} = 0.322 \times 0.80 = 0.26\ \text{cps Bq}^{-1}$
3. $f_{\text{photons} > 10\ \text{keV}} = 0.067 + 0.255 + 1.140 = 1.462$
   $\gamma_{\text{photons}} = f_{\text{photons} > 10\ \text{keV}} \times f_{\text{det, photons}} = 1.462 \times 0.47 = 0.69\ \text{cps Bq}^{-1}$
4. detection efficiency $\varepsilon = \varepsilon_{\text{electrons}} + \varepsilon_{\text{photons}}$
   $= 0.26\ \text{cps Bq}^{-1} + 0.69\ \text{cps Bq}^{-1} = 0.95\ \text{cps Bq}^{-1}$
   measured $N = 100\ \text{cpm} = 1.67\ \text{cps}$
   activity $A = N / \varepsilon = 1.67\ \text{cps} / 0.95\ \text{cps Bq}^{-1} = 1.76\ \text{Bq}$

Problem 15

1. activity of ^{32}P measured in three channels:
   $T_A / (\varepsilon_A \times \text{time} \times \text{volume}) = 5.8\times10^5\ \text{cpm} / (0.05 \times 60\ \text{s min}^{-1} \times 2\ \text{ml}) = 97\times10^3\ \text{Bq ml}^{-1}$
   $T_B / (\varepsilon_B \times \text{time} \times \text{volume}) = 3.0\times10^6\ \text{cpm} / (0.26 \times 60\ \text{s min}^{-1} \times 2\ \text{ml}) = 96\times10^3\ \text{Bq ml}^{-1}$
   $T_C / (\varepsilon_C \times \text{time} \times \text{volume}) = 7.8\times10^6\ \text{cpm} / (0.65 \times 60\ \text{s min}^{-1} \times 2\ \text{ml}) = 100\times10^3\ \text{Bq ml}^{-1}$
   Average value $\langle T \rangle = (97 + 96 + 100)\times10^3\ \text{Bq ml}^{-1} / 3 = 98\times10^3\ \text{Bq ml}^{-1}$
   required reduction factor = norm / $\langle T \rangle = 0.25\ \text{Bq ml}^{-1} / 98\times10^3\ \text{Bq ml}^{-1} = 2.55\times10^{-6}$
   $= e^{-0.693\times t/14.29}$
   $t = -(14.29\ \text{d} / 0.693) \times \ln(2.55\times10^{-6}) = (14.29\ \text{d} / 0.693) \times 12.88 = 266\ \text{d}$
   release date: 25 October 1990

   Note: exemption value for ^{32}P in solid substances, according to the current Decree on Basic Safety Standards Radiation Protection is 1000 Bq ml^{-1}; in addition, an exemption value of 1000 Re_{ing} applies provided it is allowed to drain it to the sewer

2. efficiency determination with 300 Bq ^{14}C in sample #4; this becomes sample #6
   $\delta T_A = 7498\ \text{cpm} - 1040\ \text{cpm} = 6458\ \text{cpm}$
   $\varepsilon_{A,14C} = 6458\ \text{cpm} / (300\ \text{Bq} \times 60\ \text{s min}^{-1}) = 0.36$
   $\delta T_B = 10\,265\ \text{cpm} - 1413\ \text{cpm} = 8852\ \text{cpm}$
   $\varepsilon_{B,14C} = 8852\ \text{cpm} / (300\ \text{Bq} \times 60\ \text{s min}^{-1}) = 0.49$

3. efficiency determination with 160 Bq ^3H in sample #3; this becomes sample #5
   δT_A = 4187 cpm - 1002 cpm = 3185 cpm
   $\varepsilon_{A,3H}$ = 3185 cpm / (160 Bq × 60 s min^{-1}) = 0.33
   δT_B = 1417 cpm - 1423 cpm ≈ 0
   $\varepsilon_{B,3H}$ = 0 / (160 Bq × 60 s min^{-1}) ≈ 0
   more precisely: $\delta T_B < \sigma_{\delta TB} = \lambda(T_B / t_B)$
   = λ[(1417 cpm / 10 min) + (1423 cpm / 10 cpm)] = 17 cpm
   $\varepsilon_{B,3H}$ < 17 cpm / (160 Bq × 60 s min^{-1}) = 0.002
4. average of samples #2, #3 and #4 are T_A = 1023 cpm and T_B = 1414 cpm, respectively
   channel B only contains a contribution from ^{14}C
   channel A (possibly) contains contributions from ^3H en ^{14}C
   remaining activity ^{32}P on October 25, 1990 is 0.25 Bq ml^{-1} × 2 ml = 0.5 Bq, thus:
   contribution to channel A activity × $\varepsilon_{A,32P}$ × time = 0.5 Bq × 0.05 × 60 s min^{-1} = 1.5 cpm
   contribution to channel B activity × $\varepsilon_{B,32P}$ × time = 0.5 Bq × 0.26 × 60 s min^{-1} = 7.8 cpm
   contaminating ^{14}C:
   contribution ^{14}C to channel B T_{net} / ($\varepsilon_{B,14C}$ × time) =
   (1414 cpm - 7.8 cpm) / (0.49 × 60 s min^{-1}) = 48 Bq
   concentration of ^{14}C 48 Bq / 2 ml = 24 Bq ml^{-1}

   Note: the exemption value for ^{14}C in <u>solid</u> substances, according to the Decree on Basic Safety Standards Radiation Protection is 1 Bq ml^{-1}

   contaminating ^3H:
   contribution ^{14}C to channel A
   activity × $\varepsilon_{A,14C}$ × time = 48 Bq × 0.36 × 60 s min^{-1} = 1037 cpm
   contribution ^3H to channel A
   T_{net} / ($\varepsilon_{A,3H}$ × time) = (1023 cpm - 1,5 cpm - 1037 cpm) / (0.33 × 60 s min^{-1}) ≈ 0
   more precisely:
   σ_{Tnet} = √[(1023 cpm / 10 min) +(1,5 cpm / 10 min) + (1037 cpm / 10 min)] = 14 cpm
   $T_{net} < \sigma_{Tnet}$ / ($\varepsilon_{A,3H}$ × time) = 14 cpm / (0.33 × 60 s min^{-1}) = 0.7 Bq
   concentration of ^3H < 0.7 Bq / 2 ml = 0.35 Bq ml^{-1}

   Note: the exemption value for ^3H in <u>solid</u> substances, according to the Decree on Basic Safety Standards Radiation Protection is 100 Bq ml^{-1}

5. the standard deviation of the counting rate in channel B on February 1, 1990 is:
   σ = √(T / t) = √(3.0×10^6 cpm / 1 min) = 1732 cpm
   contribution from ^{14}C to the counting rate in channel B is:
   1414 cpm - 7.8 cpm = 1406 cpm < σ (see Question 4)
   it was thus impossible to determine the presence of ^{14}C in the liquid waste

<u>Problem 16</u>

1. flow D = 10 h^{-1} × V_{lab}
   = 10 h^{-1} × 50 m^3 = 500 m^3 h^{-1}
   maximum activity concentration a_{max} = 250 mBq m^{-3} = 0.25 Bq m^{-3}
   maximum removed activity dA/dt = a_{max} × D
   = 0.25 Bq m^{-3} × 500 m^3 h^{-1} = 125 Bq h^{-1}
   the maximal leakage is thus 125 Bq h^{-1}

2. start concentration $20 \text{ mBq m}^{-3} = 0.02 \text{ Bq m}^{-3} \text{ h}^{-1}$
   for maximal leakage, the additional leakage per hour is:
   $125 \text{ Bq h}^{-1} / 50 \text{ m}^3 = 2.5 \text{ Bq m}^{-3}$
   the required formula $a(t) = 0.02 + (2.5 \times t)$
   with $a(t)$ in Bq m^{-3} and t in h
3. average concentration during the first hour $a(0.5) = 0.02 + (2.5 \times 0.5) = 1.27 \text{ Bq m}^{-3}$
   average concentration during the fifth hour $a(4.5) = 0.02 + (2.5 \times 4.5) = 11.27 \text{ Bq m}^{-3}$
   average concentration $a_{\text{average}} = (1.27 + 11.27) \text{ Bq m}^{-3} / 2$
   $= 6.27 \text{ Bq m}^{-3}$
   maximum concentration is 10 times larger $a_{\max} = 10 \times a_{\text{average}}$
   $= 10 \times 6.27 \text{ Bq m}^{-3} = 62.7 \text{ Bq m}^{-3}$
   maximal inhaled activity $A_{\max} = 2 \text{ h} \times 1.2 \text{ m}^3 \text{ h}^{-1} \times 62.7 \text{ Bq m}^{-3}$
   $= 150 \text{ Bq}$

<u>Problem 17</u>

1. decay correction $e^{-0.693 \times 30/46.61} = 0.64$
   required production $300 \text{ MBq} / 0.64 = 469 \text{ MBq}$
2. $N(^{202}\text{Hg})$ = (mass / atomic weight) × abundance(^{202}Hg) × Avogadro's number
   $= (1 \text{ g} / 200.59 \text{ g mol}^{-1}) \times 29.86\times10^{-2} \times 6.02\times10^{23} \text{ mol}^{-1} = 9.0\times10^{20}$ per gram
3. $dN(^{203}\text{Hg})/dt = N(^{202}\text{Hg}) \times \varphi_{th} \times \sigma_{th}$
   production rate $dN(^{203}\text{Hg})/dt = 9.0\times10^{20}$ per gram $\times 1\times10^{18} \text{ m}^{-2} \text{ s}^{-1} \times 5\times10^{-28} \text{ m}^2$
   $= 4.5\times10^{11} \text{ s}^{-1}$ per gram
4. $\lambda(^{203}\text{Hg}) = 0.693 / (46.61 \text{ d} \times 24 \text{ h d}^{-1} \times 3600 \text{ s h}^{-1}) = 1.72\times10^{-7} \text{ s}^{-1}$
   activity = $\lambda(^{203}\text{Hg}) \times N(^{203}\text{Hg})$
   $= 1.72\times10^{-7} \text{ s}^{-1} \times 4.5\times10^{11}$ per gram $= 7.74\times10^4 \text{ Bq s}^{-1}$ per gram
5. irradiation time follows from: $7.74\times10^4 \text{ Bq s}^{-1}$ per gram $\times t = 300\times10^6$ Bq per gram
   $t = 300\times10^6$ Bq per gram / $7.74\times10^4 \text{ Bq s}^{-1}$ per gram
   $= 3876 \text{ s} = 1.08 \text{ h}$
6. 25% is removed from the air, thus $25\times10^{-2} \times 300\times10^6 \text{ Bq} = 7.5\times10^7 \text{ Bq}$
   mercury vapor belongs to class SR-1 with a $Re_{inh}(^{203}\text{Hg}) = 1.4\times10^8 \text{ Bq}$
   thus discharge amounts to $7.5\times10^7 \text{ Bq} / 1.4\times10^8 \text{ Bq} = 0.54 \ Re_{inh}$
   this is within the license limits
7. 1% appears in the bottom ash, thus $1\times10^{-2} \times 300\times10^6 \text{ Bq} = 3.0\times10^6 \text{ Bq}$
   activity appears within one hour in the ash
   production bottom ash is $3.3\times10^3 \text{ kg h}^{-1} \times 1 \text{ h} = 3.3\times10^3 \text{ kg}$
   maximal activity concentration = $3.0\times10^6 \text{ Bq} / 3.3\times10^3 \text{ kg} = 0.9\times10^3 \text{ Bq kg}^{-1} = 0.9 \text{ Bq g}^{-1}$
   this is well within the license limits
   40% appears in the fly ash, thus $40\times10^{-2} \times 300\times10^6 \text{ Bq} = 1.2\times10^8 \text{ Bq}$
   production bottom ash is $24.2\times10^3 \text{ kg h}^{-1} \times 1 \text{ h} = 2.42\times10^4 \text{ kg}$
   maximal activity concentration = $1.2\times10^8 \text{ Bq} / 2.42\times10^4 \text{ kg} = 5.0\times10^3 \text{ Bq kg}^{-1} = 5.0 \text{ Bq g}^{-1}$
   both concentrations are well within the license limits
8. $H^*(10) = h\,A / r^2 = 0.040\ \mu\text{Sv m}^2 \text{ MBq}^{-1} \text{ h}^{-1} \times 300 \text{ MBq} / r^2 = 12\ \mu\text{Sv m}^2 \text{ h}^{-1} / r^2 < 1\ \mu\text{Sv h}^{-1}$
   thus $r > \lambda 12 = 3.5$ m

<u>Problem 18</u>

1. due to the long half-live of ^{137}Cs, radioactive decay does not play a role
   activity A = concentration × flow × capture efficiency × time
   $= 10 \text{ Bq m}^{-3} \times 9.5 \text{ m}^3 \text{ h}^{-1} \times 1 \times 2 \text{ h} = 190 \text{ Bq}$

2. the activity linearly increases during sampling (and thus during the measurement)
   we may thus use the average activity $\langle A \rangle = (0 + 190)$ Bq / 2 = 95 Bq
   according to the data, the emission efficiency is $f_\gamma = 0.947 \times 0.898 = 0.85$
   reading the photopeak efficiency from Figure 2 $\varepsilon = 0.05$
   $N = \langle A \rangle \times f_\gamma \times \varepsilon \times t = 95$ Bq × 0.85 × 0.05 × (2 h × 3600 s h^{-1}) = 2.9×10^4 counts
3. 10 Bq m^{-3} gives 2.9×10^4 counts
   30 counts correspond to (30 / 2.9×10^4) × 10 Bq m^{-3} = 0.010 Bq m^{-3} = 10 mBq m^{-3}

Problem 19

1. $T_{½}(^{88}Rb) = 17.77$ min
   $\lambda = 0.693 / T_{½}(^{88}Rb) = 0.693 / 17.77$ min = 0.0390 min^{-1} = 6.50×10^{-4} s^{-1}
   $N = f_\beta \times f_{det} \times {}_0\int^{30} A(0)\, e^{-\lambda t}\, dt$
   $= 1 \times 10\times10^{-2} \times A(0) \times (1 - e^{-0.0390\times30}) / 6.50\times10^{-4}$ s^{-1}
   $= 1 \times 10\times10^{-2} \times A(0) \times 0{,}69 / 6.50\times10^{-4}$ s^{-1} $= 106\, A(0)$
   = 150 000

   Note: in the exponent, λ is expressed in min^{-1} because the measurement time is given in minutes; in the denominator λ is expressed in s^{-1} because the activity is in Bq

   activity at the start of the measurement $A(0) = 150\,000 / 106 = 1.4\times10^3$ Bq
2. decay correction $e^{0.0390\times10} = 1.48$
   activity at the end of sampling $A(-10) = 1.48 \times 1.4\times10^3$ Bq = 2.1×10^3 Bq
3. set ^{88}Rb concentration a_{Rb} Bq m^{-3}
   flow $D = 30$ l min^{-1} × 10^{-3} m^3 l^{-1} = 3.0×10^{-2} m^3 min^{-1}
   during sampling, the activity decays
   $A(-10) = D \times {}_0\int^{30} a_{Rb}\, e^{-\lambda t}\, dt = 3.0\times10^{-2}$ m^3 min^{-1} × $a_{Rb} \times (1 - e^{-0.0390\times30}) / 0.0390$ min^{-1}
   = 3.0×10^{-2} m^3 min^{-1} × a_{Rb} Bq m^{-3} × 0.69 / 0.0390 min^{-1} = 0.53 m^3 × a_{Rb}
   thus ^{88}Rb concentration is $a_{Rb} = A(-10) / 0.53$ m^3 = 2.1×10^3 Bq / 0.53 m^3 = 4.0×10^3 Bq m^{-3}
4. because $T_{½}(^{88}Rb) \ll T_{½}(^{88}Kr) \ll$ 1 week, there is equilibrium between mother and daughter
   thus $a_{Kr} = a_{Rb} = 4.0\times10^3$ Bq m^{-3}

Problem 20

1. because the mass activities of ^{226}Ra and ^{214}Bi are almost equal according to the measurement, it follows that no ^{222}Rn has escaped from the material
   the same is true for the activities of ^{228}Ac and ^{212}Pb, showing that no significant amount of ^{220}Rn has escaped from the material
   thus both series are in equilibrium and within a (sub)series, all activities are equal
2. ^{226}Ra-subseries:
   contains nine radioactive radionuclides which are all in equilibrium
   the total mass activity is therefore 9 times the average reading
   (127 + 120 + 130) Bq kg^{-1} × (9 / 3) = 1.13×10^3 Bq kg^{-1} = 1.13 Bq g^{-1}
   ^{232}Th-series:
   contains ten radioactive radionuclides which are all in equilibrium
   the total mass activity is therefore ten times the average reading
   (153 + 164 + 139 + 133 + 181) Bq kg^{-1} × (10 / 5) = 1.54×10^3 Bq kg^{-1} = 1.54 Bq g^{-1}

3. mass activity ^{226}Ra $1.13\ Bq\ g^{-1} / 9 = 0.13\ Bq\ g^{-1}$
   mass activity ^{232}Th $1.54\ Bq\ g^{-1} / 10 = 0.15\ Bq\ g^{-1}$
   weighted sum of both values:
   $(0.13\ Bq\ g^{-1} / 1\ Bq\ g^{-1}) + (0.15\ Bq\ g^{-1} / 1\ Bq\ g^{-1}) = 0.13 + 0.15 = 0.28$
   this is well under the exemption value, and thus does not require a license
   total activity ^{226}Ra $100 \times 390\ g \times 0.13\ Bq\ g^{-1} = 5.1\times10^{3}\ Bq$
   total activity ^{232}Th $100 \times 390\ g \times 0.15\ Bq\ g^{-1} = 5.9\times10^{3}\ Bq$
   weighted sum of both values:
   $(5.1\times10^{3}\ Bq / 1\times10^{4}\ Bq) + (5.9\times10^{3}\ Bq / 1\times10^{3}\ Bq) = 0.51 + 5.9 = 6.4$
   this is definitely above the exemption value, but that is not relevant in this case

EXTERNAL DOSIMETRY AND SHIELDING

21. Fluence rate and photon counting (1984-1-4)

One wants to determine the ambient dose equivalent in air of a mixed radiation field of photons with energies of 511 keV and 60 keV. The flux densities of both types of photons are equal. One has a NaI(Tl)-detector with a surface detection area of 10 cm^2 and a thickness of 1 mm.

Given:
- appendix, Figures 27 and 28
- flux density = fluence rate = number photons per cm^2 per second
- the density of NaI is 3.67 g cm^{-3}
- the mass attenuation coefficients of NaI are μ/ρ = 6.62 cm^2 g^{-1} for 60 keV and μ/ρ = 0.0941 cm^2 g^{-1} for 511 keV.
- absorption in the casing of the NaI(Tl)-crystal may be neglected
- assume that each γ-photon that interacts with NaI causes an electrical signal and is registered

Questions:

1. Determine the kerma rate in air as a result of 1 photon per cm^2 per second for each of the given energies.

2. Calculate the number of counts per second if the kerma rate in air is 10 μGy h^{-1}.

3. Calculate the ambient dose equivalent $H^*(10)$ per unit time in this radiation field (in μSv h^{-1}).

22. Contaminated $^{51}CrCl_3$ (1987-1-2)

For a labeling experiment, one has ordered a batch of ^{51}Cr-labeled chromium chloride. After delivery to the C-laboratory, it appears that the batch also emits β-radiation. It is found that the batch is contaminated with potassium chloride which has been labeled with ^{42}K. The radiation expert has two detectors at his/her disposal: an ionization chamber filled with atmospheric air, and an end-window GM-counter.

The expert first places the ionization chamber at 50 cm distance from the batch. During a time period of 6 minutes, an electrical charge of 94.6 pC has accumulated. The expert subsequently places the end-window GM-counter at 50 cm distance from the batch and, after correction for dead time and background, measures 3.53×10^6 counts per minute.

Given:

- a number of radiation protection details of ^{42}K (see Appendix, Figure 6)
- a number of radiation protection details of ^{51}Cr (see Appendix, Figure 9)
- the reduced range of β-particles (see Appendix, Figure 25)
- the volume of the ionization chamber is 100 cm^3
- the mass thickness of the ionization-chamber wall is 2.5 g cm^{-2}
- attenuation of the photons in the wall of the ionization chamber may be neglected
- the effective detection area of the GM-counter is 1 cm^2
- the detector efficiency of the GM-counter is zero for γ-photons and 100% for β-particles
- the batch may be regarded as a point source
- any self absorption may be neglected
- the density of air is 1.205×10^{-3} g cm^{-3}
- a charge density of 1 C kg^{-1} in air corresponds to a kerma of 33.7 Gy in air

Questions:

1. Show that the β-particles can not reach the air in the ionization chamber.

2. Calculate the dose rate in air as a result of the γ-radiation at 50 cm distance from the batch.

3. Calculate the ^{42}K-activity at the time of the measurements.

4. Calculate the ^{51}Cr-activity at the time of the measurements.

5. Roughly calculate the dose rate in tissue as a result of the β-radiation at a distance of 50 cm from the batch.

6. Which measure should be taken to protect against the β-radiation?

23. Reefer Rio (1988-2-4)

A refrigerator ship contains meat that is slightly contaminated with ^{137}Cs. The meat is packed in cube-shaped boxes with a side-length of 30 cm and each box contains 27 kg meat. A mass activity of 150 Bq kg^{-1} is assumed. You are asked as an expert to answer a few questions.

Given:
- a situation sketch (see in Figure 1)
- a number of radiation protections details of ^{137}Cs (s Appendix, Figure 21)
- the mass attenuation coefficient of meat for a photon energy of 662 keV is μ/ρ = 0,085 cm^2 g^{-1}
- for this question, the build-up factor can be written as $B = 1 + 0.2\ d$ where the thickness d is expressed in cm
- the bremsstrahlung production in meat and the attenuation in air may be neglected

Questions:

1. Make an estimate of the kerma rate in air as a result of the photons at 15 cm distance from a box (point P in Figure 1). Assume for this estimate that all activity is located in the center Q of the box.

2. Calculate the contribution to the kerma rate in air at point P, caused by the neighboring box which is placed directly behind the first box. Assume for this estimate that all activity is located in the center Q' of the second box.

3. Make an estimate of the kerma rate in tissue as a result of the photons in the direct vicinity of the surface of several thousand stacked boxes, assuming that the activity is homogeneous distributed over the meat.

Hint: Consider that in such a stack, the absorbed and emitted photon energies are approximately equal, and that the kerma rate near the surface is approximately half that of the kerma rate in the center of the stack (submersion model).

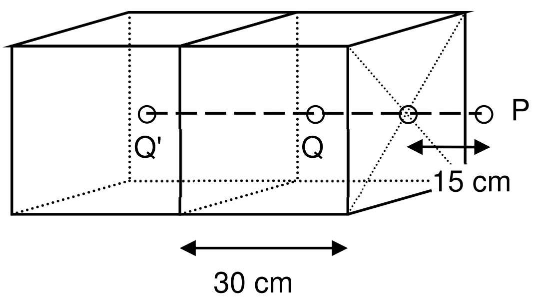


Figure 1. Situation sketch of the cube-shaped boxes.

24. TLD-personal dose monitors (1988-1-1)

A certain personal dose monitor is composed of two different thermoluminescence detectors (TLDs), specifically lithium borate ($Li_2B_4O_7$) and calcium sulphate ($CaSO_4$). These thermoluminescence detectors are calibrated at many photon energies between 10 keV and 2 MeV, using an ionization chamber. Persons P and Q both wear such a personal dose monitor. One day, the following result is registered in scale units (su):

person	$Li_2B_4O_7$	$CaSO_4$
P	85	85
Q	35	315

Given:
- the results of the lithium borate and calcium sulphate, expressed in scale units per unit of exposure (su R^{-1}) (see Figure 1)
- the conversion factor of kerma free in air K_a to personal dose equivalent $H_{p,slab}(10)$ in an ICRU-slab (see Appendix, Figure 28)
- the personal dose equivalent $H_p(10)$ is defined as the dose equivalent at 10 mm depth in the human body.
- in this Problem, assume that an exposure of 1 R corresponds to a kerma in air of 10 mGy.

Questions:

1. How large is the TLD signal, expressed in scale units, of each TLD for a kerma in air of 1 mGy, as a result of photons with an energy of 60 keV?

2. How large is the personal dose equivalent $H_p(10)$ for an exposure to a kerma in air of 1 mGy, as a result of photons with an energy of 60 keV?

3. Which personal dose equivalent do person P and Q accumulate? Assume that each person is exposed to mono-energetic photons.

   Hint: Determine the photon energy from the ratio of the two TLD signals.

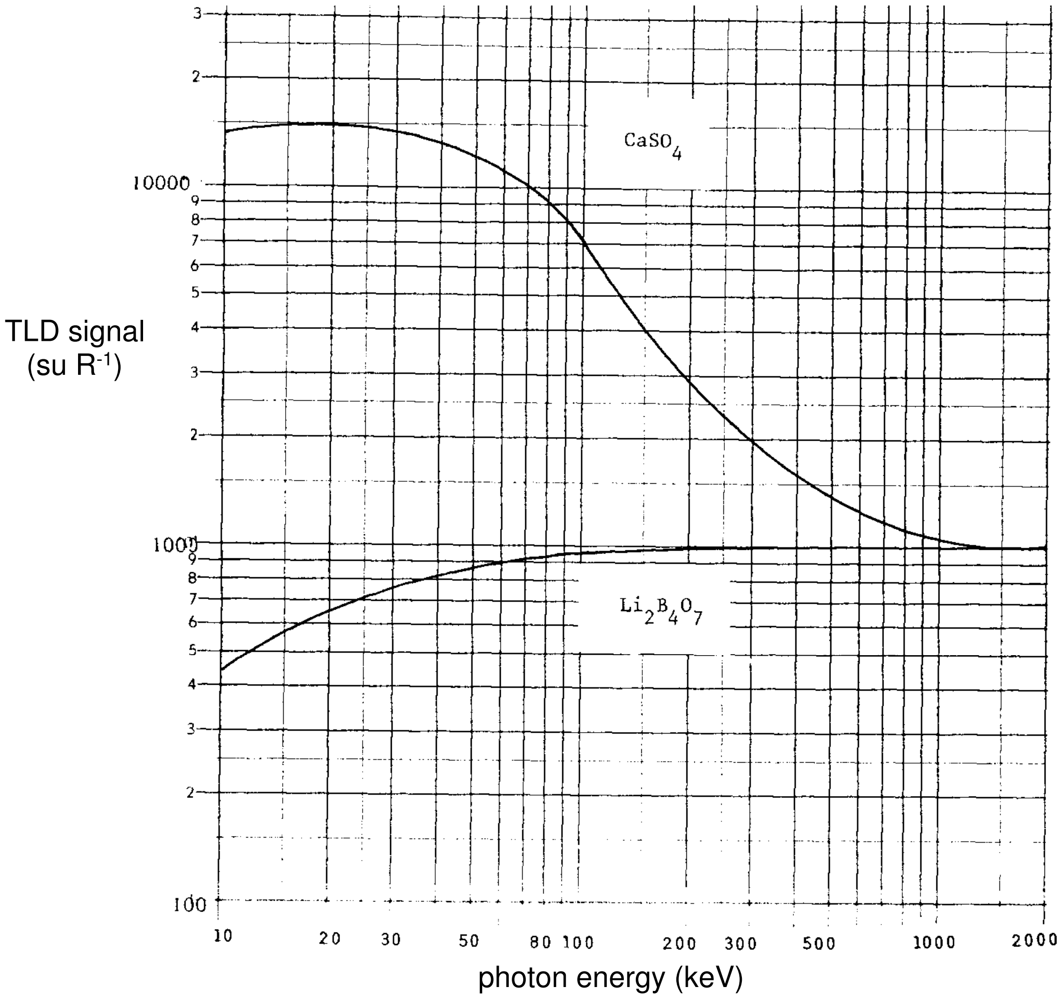


Figure 1. Relative TLD signal, normalized to 1000 su R^{-1} at 1500 keV, as a function of the photon energy, for the TLD materials $Li_2B_4O_7$ and $CaSO_4$.

25. ^{32}P-dosimetry (1998-2-2)

The radionuclide ^{32}P is often used in molecular biology research. This radionuclide is incorporated into DNA (in vitro labeling reactions). Such ^{32}P-containing liquids are often handeled in Eppendorf tubes, which have a point-shape on the bottom part of the tube. A small volume of the solution in such an Eppendorf tube may be viewed as a point source. Measurements of β^-- and bremsstrahlung dose rates at various distances *x* from a solution of 1.0 MBq ^{32}P in 0.1 ml liquid in an Eppendorf tube are reproduced below:

x (cm)	*measured dose rate and value according to inverse square law (in µGy min^{-1})*	
0,29 *	1 444	
10	4.67	4.67
20	1.25	---
30	0.58	---
40	0.25	---
50	0.17	---
60	0.13	---

* measured at the surface at the tip of the tube

Given:

- the decay scheme of ^{32}P (see Appendix, Figure 3)
- the reduced range of β-particles (see Appendix, Figure 25)
- the density of air is 1.205×10^{-3} g cm^{-3}
- the skin dose as a result of skin contamination:

$$D_{skin} = 1.602 \times 10^{-10}\ \Phi\ (S_{col}/\rho)$$

D_{skin} = skin dose (in Gy)
Φ = fluence of the β-particles (in cm^{-2})
S_{col}/ρ = mass energy loss cross section for collisions (in MeV per g cm^{-2})

- S_{col}/ρ = 2 MeV per g cm^{-2} for electrons in tissue and the energy range of the β-particles emitted by ^{32}P

Questions:

1. Determine the range in air and in water of the ^{32}P-emitted β-particles (in cm).

2. Calculate the missing numbers in the third column of the Table above. What can you conclude about the attenuation in air of the β-radiation emitted by ^{32}P within the usual source-working distance of 10 to 60 cm?

3. Calculate the equivalent dose rate in skin (in mSv h^{-1}) due to ^{32}P for a homogeneous skin contamination of 1 MBq cm^{-2}, on the basis of the above formula for D_{skin}. Repeat the calculation with the data in Figure 3 in the Appendix.

4. Calculate how long it takes in the above situation before the deterministic annual limit for equivalent skin dose for professional exposure is received.

26. Incident with a gammagraphy source (2000-2-2)

During major maintenance on a steam generator in a large hall, a source with an activity of 20 GBq ^{170}Tm is used to inspect the welds of the pipes. To perform the task as fast as possible, teams work in shifts of 8 hours. At the end of the shift work, the source is left behind in one of the pipes while the radiographs are developed.

During evaluation of the radiographs by the radiograph technician for the new shift, it appears that the weld is unsound and two workers were given the assignment to cut the weld out. The new radiography technician had not verified whether or not the source was returned to its container. Therefore, neither the two maintenance workers knew that the source still lay at the location of the weld.

Only after the weld was removed did the radiograph technician realize that the source was still in the pipe. It appeared that the source was so damaged by the repair work that a large portion of the radioactive contents was dispersed in the area. Measurements showed that there were countless hot spots in the area of the steam generator. It was decided that the area would be cleaned with an industrial vacuum cleaner, but because this was not fitted with an absolute filter, the activity was only further dispersed. In the meantime, work in the hall continued.

Only at the end of the shift was the incident reported to the responsible radiation expert of the radiography company, who subsequently immediately stopped all work. In the meantime, about 70 maintenance workers were working in the hall for shorter or longer periods and the majority of them were externally contaminated on their skin and clothes. The largest measured value amounted to 26 kBq cm^{-2}.

Given:
- a number of radiation protection details for ^{170}Tm (see Appendix, Figure 22)
- the ratio effective dose / ambient dose equivalent (see Appendix, Figure 29)
- the transmission of the γ-radiation through the pipe amounts to $5{\times}10^{-2}$

Questions:

1. Calculate the ambient dose equivalent that the maintenance worker has accumulated during the removal of the weld, as a result of external radiation. Assume that the distance from the worker to the source amounted to 0.5 m and that the task took 45 minutes to complete.

2. Make an estimate of the effective dose that the maintenance worker has accumulated, as a result of the external radiation.

3. What was the highest equivalent skin dose, assuming that the activity was present on the skin for 8 hours?

4. Name at least two radiation protection shortcomings of the procedure that was followed during this incident.

27. Shielding of a ^{24}Na-source (1991-2-2)

An activity of 37 GBq ^{24}Na is needed for an experiment. One proposes to obtain this activity by activating a suitable sodium compound in a nuclear reactor. In connection with the necessary safety, some calculations must be made. Before the activation, the sodium compound is put in an aluminum capsule to stop the β-radiation. After the activation, the capsule is placed under water.

Given:

- a number of radiation protection details of ^{24}Na (see Appendix, Figure 2)
- the reduced range of β-particles (see Appendix, Figure 25)
- the density of air is 1.205 kg m^{-3}
- the density of aluminum is 2.7×10^3 kg m^{-3}
- the linear energy transfer coefficients of air are $\mu_{tr} = 3.16\times10^{-3}$ m^{-1} for 1.37 MeV and $\mu_{tr} = 2.57\times10^{-3}$ m^{-1} for 2.75 MeV
- the linear attenuation coefficients of water are $\mu = 6.1$ m^{-1} for 1.37 MeV and $\mu = 4.3$ m^{-1} for 2.75 MeV
- build-up factors (see Appendix, Figure 30)

Questions:

1. Calculate the minimal thickness of the aluminum capsule that will shield all the β-particles emitted by ^{24}Na in the irradiated sample.

2. Calculate the expected kerma rate in air as a result of the 1.37 MeV γ-photons at a distance of 1 meter from an unshielded source of 37 GBq ^{24}Na.

3. Calculate the expected kerma rate in air as a result of the 2.75 MeV γ-photons at a distance of 1 meter from an unshielded source of 37 GBq ^{24}Na.

4. Calculate the kerma rate in air at 1 meter above the water surface if a point-shaped ^{24}Na-bron of 37 GBq is located at a depth of 2 meter under the water surface.

28. Shielding of activated material (1993-2-3)

To examine a piece of radioactive material from a nuclear reactor, it needs to be transported. The piece, hereafter called source, can be considered a point source of negligible dimensions. The self-absorption of the source may also be neglected. The measurement is taken using a monitor that is only sensitive to γ-radiation.

The first measurement of the unshielded source indicated that the kerma rate in air at a distance of 1 meter from the source amounts to 50 mGy h^{-1}. Measurements of comparable material have shown that the material mostly consists of the nuclides ^{51}Cr and ^{60}Co, which contribute about 40% and 60% of the activity, respectively.

The transport will occur two weeks after the measurement and it will be transported in a cube-shaped box with a side length of 50 cm, inside of which is a ball-shaped lead shield in the center of the box. The source is placed in the center of the ball.

The unshielded source is kept underwater at a depth of 160 cm while waiting for transport.

Given:
- a number of radiation protection details for ^{51}Cr (see Appendix, Figure 9)
- a number of radiation protection details for ^{60}Co (see Appendix, Figure 11)
- the density of lead is 11.35 g cm^{-3}
- the mass attenuation coefficients of water are μ/ρ = 0.0620 cm^2 g^{-1} for 1.33 MeV and μ/ρ = 0.1164 cm^2 g^{-1} for 0.32 MeV
- build-up factors (see Appendix, Figure 30)
- the transmission of broad-beam γ-radiation by lead (see Appendix, Figure 31)
- the required conditions for the kerma rate during transport are:
  1. less than 2 mGy h^{-1} at the surface of the packaging
  2. less than 0.1 mGy h^{-1} at 1 meter distance from the surface of the packaging

Questions:

1. Calculate the activity of the source at the time of the measurement.

2. The kerma rate in air at the water surface should remain under 25 μGy h^{-1}. Determine if this requirement is met. Assume for the calculation of the attenuation that ^{60}Co decays by emitting two photons, each with an energy of 1.33 MeV.

3. For which side length of a cube-shaped package do both transport requirements lead to the same shielding requirement?

4. Calculate the minimal thickness (in whole cm) of the lead shielding such that both transport requirements are met.

29. Shielding of mother and daughter (1990-1-2)

An amount of the radioactive nuclide A must be dispatched from a laboratory. One has several ball-shaped containers at one's disposal, as given in the information below. Nuclide A has a radioactive daughter B. The properties are given in the adjacent table.

A technician isolates nuclide A in a pure form. Before transfer, he puts the material successively in a number of containers and determines the ambient dose equivalent rate at 1 m from the surface of the container. He measures 80 μSv h^{-1} for a wall thickness of 50 mm of lead. Although he is aware of the properties of nuclide A and the fact that the transport will take three full days, he sends the material in this container.

Table 1. Properties of nuclides A and B.

property	*nuclide A*	*nuclide B*
$T_{½}$	30 y	3 h
$f_{\text{emission},\beta}$	1	1
$f_{\text{emission},\gamma}$	1	1
$E_{\beta,\max}$ (MeV)	0.5	0.9
E_γ (MeV)	0.6	1.9
h (μSv m^2 MBq^{-1} h^{-1})	0.07	0.23

Given:
- all containers are ball-shaped and have the same external diameter of 40 cm
- all containers have a hollow in the center with a diameter of 2 cm in which the material exactly fits; the radioactive source thus lies in the midpoint
- the containers differ in the thickness of the lead walls: the smallest thickness is 3 cm lead and the following wall thicknesses are 1 cm larger; the influence of the remaining parts of the container on the emitted radiation may be neglected
- the density of lead is 11 350 kg m^{-3}
- the elapsed time between the radiochemical isolation and the measurement may be neglected
- the influence of the β-radiation emitted by nuclides A and B and the associated bremsstrahlung may be neglected for this Problem
- the attenuation in lead of the γ-radiation emitted by nuclides A and B (see Figure 1)
- the ambient dose equivalent requirements during transport are:
  1. less than 2 mSv h^{-1} at the surface of the packaging
  2. less than 0.1 mSv h^{-1} at 1 meter distance from the surface of the packaging

Questions:

1. The technician forgot two things. What are they?

2. Calculate the activity of nuclide A at the time of isolation.

3. Calculate the activity of nuclide B at the moment of delivery of the container.

4. What should the wall thickness have been?

5. Calculate the mass of the lead in the used container and the necessary container.

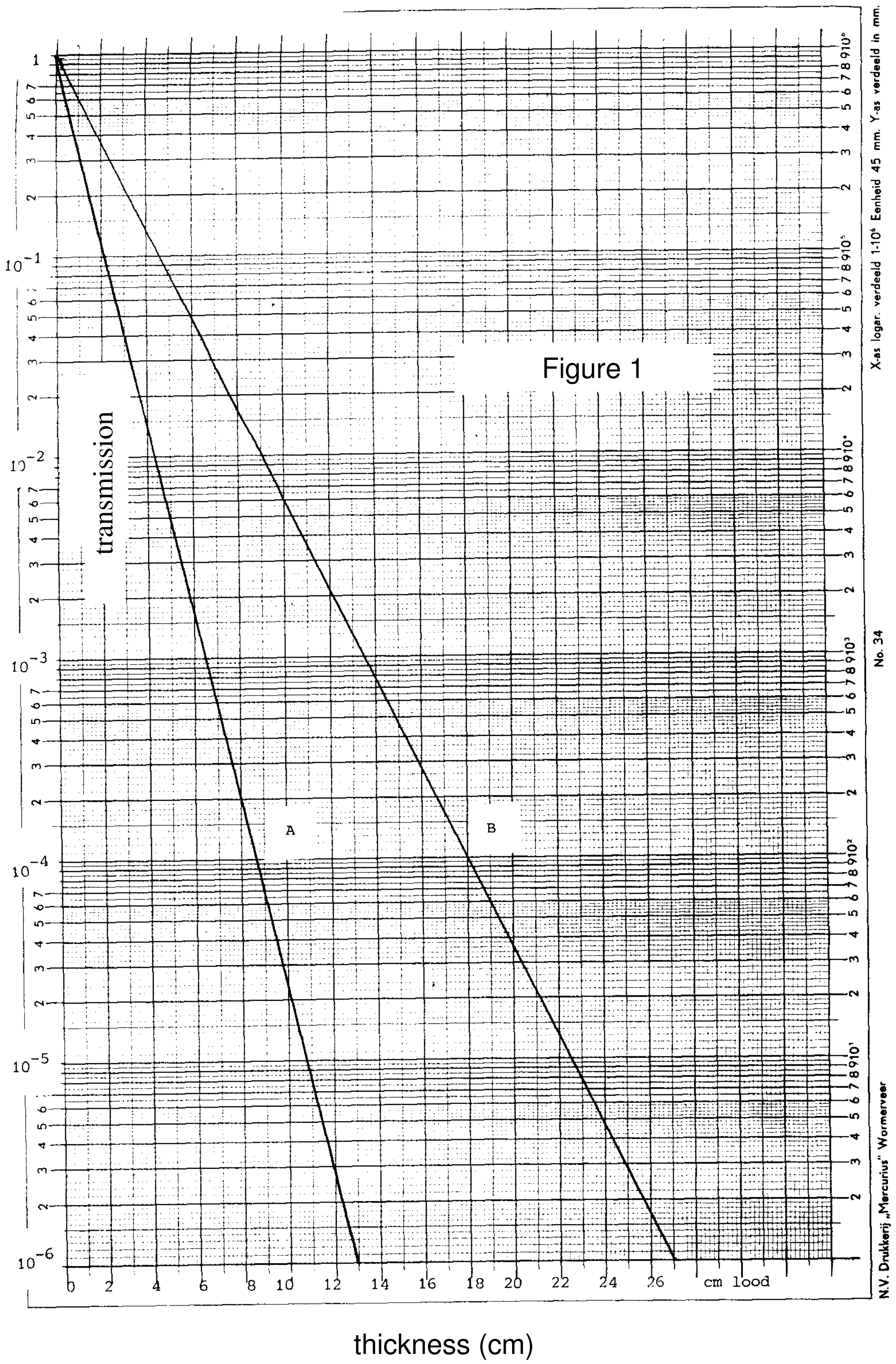


Figure 1 Transmission of γ-radiation of nuclides A and B through lead.

30. Container for storing ^{60}Co (1995-1-3)

For storing ^{60}Co-sources, cylindrical containers must be designed. The cylinders will have a hole parallel to the longitudinal axis with a diameter of 1 cm and a depth of 10 cm. In this hollow, one or more sources are places. The sources may be considered as point sources for the calculations. The bottom and the lid of the containers will be as thick as the side walls.

As a design requirement with regards to the radiation level, the air kerma rate as a result of the γ-radiation at the surface of a container may amount to 50 μGy h^{-1} at the most, if 10 MBq ^{60}Co is places therein.

One has shielding material of lead and depleted uranium at one's disposal. Uranium has the best protection properties but is slightly radioactive. The calculated wall thickness and mass of the containers will both help determine the final choice.

Given:
- the source constant of ^{60}Co for kerma in air is k = 0.305 μGy m^2 MBq^{-1} h^{-1}
- transmission of photons through iron, lead and uranium (see Figure 1)
- the density of lead is 11.35 g cm^{-3}
- the density of uranium is 18.9 gcm^{-3}
- the atomic weight of uranium is 238.03 g mol^{-1}
- the composition of depleted uranium is 99.75% ^{238}U ($T_{½}$ = 4.468×10^9 y) and 0.25% ^{235}U ($T_{½}$ = 7.038×10^8 y)
- the radioactivity of the uranium causes a kerma rate in air of 20 μGy h^{-1} at the surface
- Avogadro's number is 6.02×10^{23} mol^{-1}

Questions:

1. Calculate the minimal necessary wall thickness of the container if this is made from lead (round up to a multiple of a half cm).

Hint: Approximate the desired thickness by trial and error.

2. Calculate the minimal necessary wall thickness of the container if this is made from uranium (round up to a multiple of a half cm).

3. Calculate the mass of a container of lead with a wall thickness as calculated in Question 1 (round up to 0.1 kg).

4. Calculate the mass of a container of uranium with a wall thickness as calculated in Question 2 (round up to 0.1 kg).

5. Calculate the activity of ^{238}U and ^{235}U together, not including the daughter nuclides, for a container of uranium with a mass as calculated in Question 4.

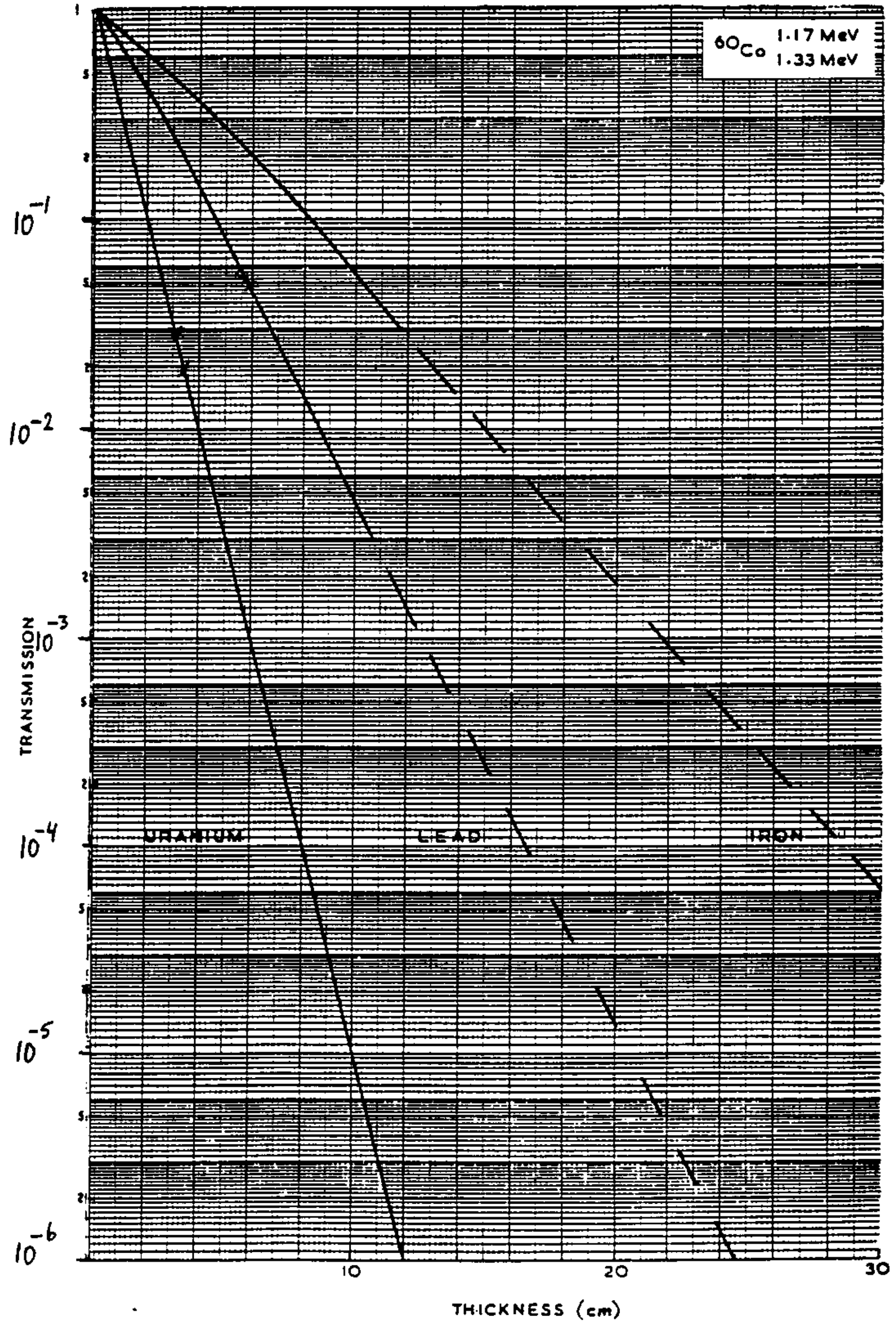


Figure 1. Transmission of broad-beam γ-radiation of ^{60}Co through iron, lead and uranium.

31. Shielding of an ion exchanger (1997-1-1)

The water from the primary cooling system of a nuclear reactor is purified from radioactivity by continuously pumping this water through an ion exchanger. Radioactive materials in this cooling water are more or less retained by this ion exchanger. Several times per year, the ion exchanger must be regenerated.

During the reactor operation, the activity of the cooling water that flows through the ion exchanger is dominated by radionuclides with a relatively short half-life. The activity retained in the ion exchanger makes it necessary to shield the exchanger. For this specific reactor, it appears that the radionuclide ^{24}Na determines the required shielding of the ion exchanger.

The reactor is usually about 110 hours per week in continuous use. Half way in this period, the ^{24}Na-activity in the cooling water has reached its maximal value (= saturation value). At this point, the activity concentration is 40 MBq m^{-3}. As an approximation, you can use this activity concentration of the cooling water for the entire operational week.

Given:
- per hour, 4.0 m^3 water flows through the ion exchanger
- phe capture efficiency of the ion exchanger for Na$^+$-ions is 95%
- a number of radiation protection details for ^{24}Na (see Appendix, Figure 2)
- the transmission of broad-beam γ-radiation from ^{24}Na through some materials (see Figure 1)
- attenuation by the ion exchanger may be neglected.

Questions:

1. Calculate the maximal ^{24}Na-activity that accumulates in the ion exchanger during an operational week. Disregard any activity in the ion exchanger at the beginning of the operational week.

2. Calculate the kerma rate in air at 2 m distance from the ion exchanger assuming that the ^{24}Na-activity that was calculated in Question 1 is present in the ion exchanger. Consider this as a point source.

3. Calculate the thickness of the concrete wall necessary to reduce the kerma rate in air at 2 meters distance from the ion exchanger (calculated in Question 2) to 1 μGy h^{-1}. Perform the calculation for both normal and weighted barite concrete.

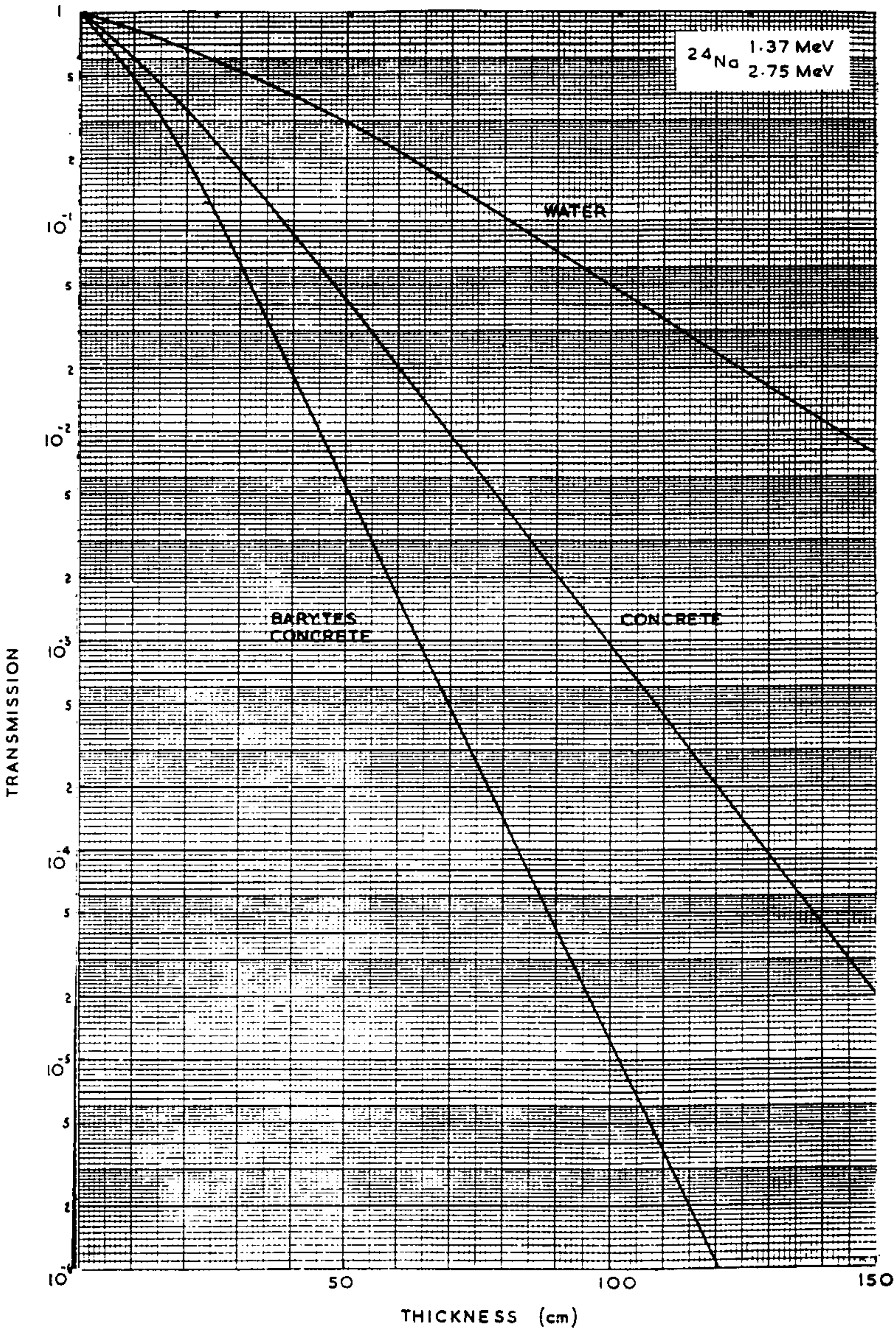


Figure 1. Transmission of broad-beamγ-radiation from ^{24}Na through water, concrete and barite concrete.

32. Shielding of a ^{137}Cs-source (1993-2-2)

A gamma-ray spectrometer is located in a measuring room. The detector is a NaI(Tl)-crystal that is shielded on all sides with 10 cm thick lead. In the room next door, one wants to build an experimental setup in which a sealed point-source of 1 GBq ^{137}Cs will be used. This source must be shielded with lead to fulfill two goals: (1) protecting the worker and (2) reducing the background of the gamma spectrometer.

In connection with goal (2), one sets the requirement that the increase in background of the gamma spectrometer at E_γ = 0.66 MeV (the place of the photopeak in the spectrum of ^{137}Cs) may not exceed 10^{-2} counts per second as a result of the ^{137}Cs-source in the new experimental setup.

Given:
- the energy resolution of the NaI(Tl)-detector at 0.66 MeV is better than 8%
- the distance between the new source and the NaI(Tl)-crystal amounts to 5 m
- the two rooms are separated by a 20 cm thick concrete wall.
- a number of radiation protection details of ^{137}Cs (see Appendix, Figure 21)
- the transmission of broad-beam γ-radiation through lead (see Appendix, Figure 31)
- the densities (in kg m^{-3}) are ρ_{NaI} = 3670, $\rho_{concrete}$ = 2350 and ρ_{lead} = 11 350
- the mass energy absorption coefficient of NaI for an γ-energy of 0.66 MeV is $(\mu/\rho)_{en} = 3.2\times10^{-3}$ m^2 kg^{-1}
- the mass attenuation coefficients (in m^2 kg^{-1}) for an γ-energy of 0.66 MeV are $(\mu/\rho)_{NaI} = 7.6\times10^{-3}$, $(\mu/\rho)_{concrete} = 7.7\times10^{-3}$ and $(\mu/\rho)_{lead} = 10.8\times10^{-3}$
- consider the NaI(Tl)-crystal as a cube with sides of 10 cm and one face turned towards the ^{137}Cs-source in the new setup
- about 100 interactions between the NaI detector and the incoming photons with an energy of 0.66 MeV cause an average of 60 counts in the photopeak

Questions:

1. Calculate the thickness of the lead shielding of the ^{137}Cs-source in order that the free kerma rate in air at 0.5 m from the source amounts to at most 10 μGy h^{-1}.

2. Do the photons from the ^{137}Cs-source which are scattered by the interactions in lead and concrete play a significant role in the counting rate of the spectrometer at the photopeak? Give an argument that supports your answer.

3. Calculate the fluence rate of the 0.66 MeV photons of the ^{137}Cs-source at the location of the NaI(Tl)-crystal, taking into account the attenuation due to the concrete wall and the lead shielding of the NaI(Tl)-detector in the spectrometer. Disregard the shielding of the ^{137}Cs-source calculated in Question 1.

4. Calculate the thickness of the lead shielding of the ^{137}Cs-source such that the above-mentioned requirement for the maximal increase in counting rate of the spectrometer is fulfilled.

33. Shielding of a ^{60}Co-source (1990-1-1)

In a concrete room with a surface area of 8 m × 5 m, an irradiation installation is located and equipped with a ^{60}Co-source of 75 GBq. The source is placed in a lead container. Through the circle-shaped, collimated opening, a beam exits to the outside. The radiation beam has a diameter of 15 cm at 1 m distance from the source.

Given:

- the situation sketch (see Figure 1)
- the source constant of ^{60}Co for kerma in air is k = 0.305 μGy m^2 MBq^{-1} h^{-1}
- the scattering factors for concrete (see Appendix, Figure 44)

Questions:

1. Calculate the kerma rate in air as a result of the direct radiation in point P, if the distance from this point to the source amounts to 5 m.

2. Calculate in the same point P the contribution to the kerma rate in air as a result of the radiation that is backscattered from the wall.

3. What is de maximal distance between the source and the object to be irradiated (point P in Figure 1), if the requirement is set that the contribution of the backscattered radiation with respect to the direct radiation should not be more than 1%?

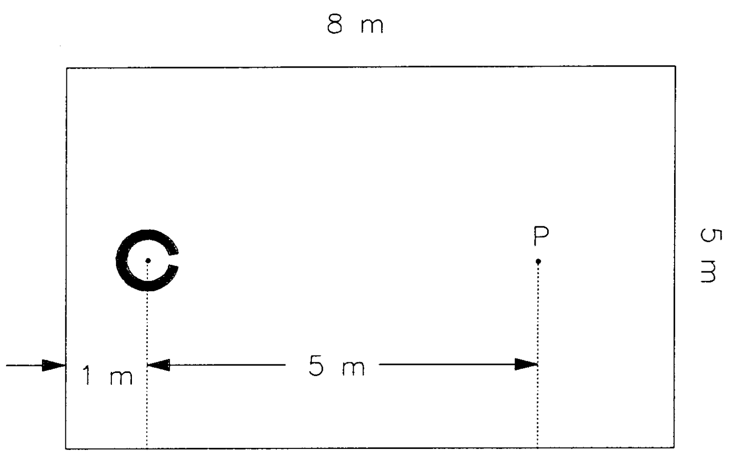


Figure 1. Schematic of the irradiation room. The object to be irradiated is at point P.

34. Shielding of ^{60}Co-activity (1988-1-2)

In a laboratory, metal research is performed on a strongly activated part from a nuclear installation. The activity of the object is 1.5×10^{12} Bq. The object is placed at location P in a lead-shielded chest (see Figure 1). By mistake, the opening of the chest is left partially open. The surface area of this opening is set at 100 cm^2. The researcher is standing at location E.

Given:
- a situation sketch (see Figure 1)
- the source may be considered a point source without self-absorption.
- the wall thickness of the lead chest amounts to 10 cm.
- the source constant of ^{60}Co for kerma in air is k = 0.305 µGy m^2 MBq^{-1} h^{-1}
- the transmission of broad-beam γ-radiation through lead (see Appendix, Figure 31)
- the transmission of broad-beam γ-radiation through concrete (see Appendix, Figure 33)
- the scattering factors for concrete (see Appendix, Figure 44)

Questions:

1. Why may the transmission graph for concrete be used for the radiation that is already attenuated by lead?

2. Calculate the kerma rate in air at location E as a result of the direct radiation.

3. Calculate the kerma rate that reaches point E as a result of the radiation that is emitted via the opening in the lead chest and reflected from the opposite concrete wall.

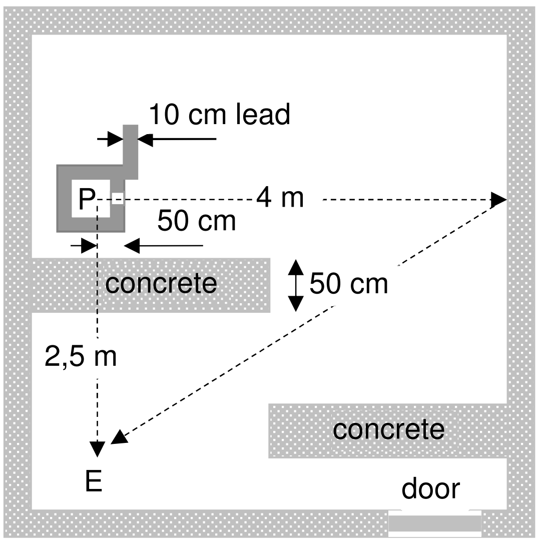


Figure 1. Map of the research room.

35. Shielding of a ^{60}Co- irradiating unit (2000-1-4)

The required shielding for a ^{60}Co-irradiating unit for therapeutic purposes must be calculated. The position of the source in the irradiation room is schematically given in Figure 1. During the irradiation, the source is located at position S and the primary beam is directed along the line SB. The patient is placed in position P. The control panel of the irradiation unit is located at position A. The points A and B lie just on the outside of the concrete walls of the irradiation room.

For the purpose of the irradiation, the source is brought from a completely shielded resting position to the irradiation position S in the shielded head of the device. In the head is a shutter which is only opened when a patient is completely ready to be irradiated. If the source is positioned in the head, the leakage radiation at 1 meter from S causes a dose rate in tissue of 2 mGy h^{-1}.

The source is located at position S for an average of 20 hours per week. Out of this time, approximately one fourth of the time it is used to irradiate patients. During the rest of the time, the shutter is closed. On a yearly basis, the source is in use for 50 work weeks. The field size of the primary radiation beam amounts to 20 cm × 20 cm at the location of the entry surface of the patient at position P.

The requirement for personnel located at positions A and B is that the average effective weekly dose be maximally 0.02 mSv (1 mSv per year, based on a 50 work weeks per year). For these people, an occupancy factor of 1 is adopted.

The wall at point B is also an outside wall of the building. The wall borders a public access area with a fence at 10 m distance from the wall. Outside of this fence is a public parking area which is used both by visitors for the hospital and by neighboring inhabitants.

Given:
- a situation sketch of the interior of the room (see Figure 1)
- the distance SA amounts to 2.1 m
- the unshielded ^{60}Co-source yields a dose rate in tissue at 1 m distance of 100 Gy h^{-1}
- the transmission of broad-beam γ-radiation through concrete (see Appendix, Figure 33)
- the transmission of scattered γ-radiation from ^{60}Co through concrete (see Appendix, Figure 38)
- the scattering factors for concrete (see Appendix, Figure 44); this figure may also be used in this Problem for the scattering from a patient
- assume for the calculations the ratio (effective dose) / (dose in tissue) = 1 Sv Gy^{-1}
- the actual individual dose (AID) is the individual dose (ID) corrected for the actual exposure correction factor (ABC-factor), which is set at 0.01 for parking lots

Questions:

1. Calculate the required thickness of the concrete wall between S and A, taking into account the leakage radiation and the scattered radiation from the patient.

2. Calculate the required thickness of the concrete wall between S and B, taking into account the primary beam and the leakage radiation.

3. Calculate the maximal value for the AID at the parking lot.

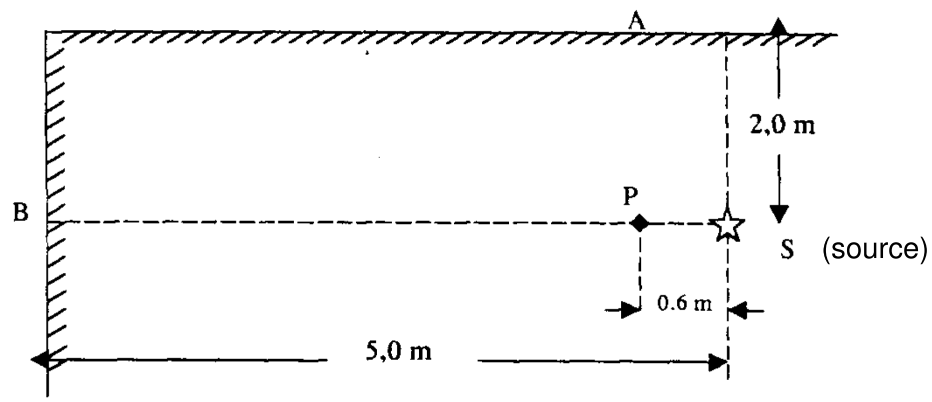


Figure 1. Map of the irradiation room.

36. Shielding of a betatron (1992-2-2)

An electron accelerator (betatron) is used for medical-therapeutic irradiation with either electrons or electron beam-generated bremsstrahlung. The usual settings are 10 MV for irradiation with electrons and 30 MV for irradiation with photons. An average of 200 irradiations per week is performed with an average dose of 4 Gy in air at 1 meter from the target plate.

The irradiation room is surrounded by a shielding wall. To protect personnel, the requirement is set that the outside of the wall at 5 m from the target plate can receive a maximal dose per week of 0.04 mGy in air. The directional factor and occupation factor are both equal to 1.

Given:
- equivalent dose in tissue for irradiation with electrons (see Figure 1)
- range of electrons in water (which is also valid for soft tissue) (see Figure 2)
- bremsstrahlung yield (see Figure 3)
- transmission of broad-beam bremsstrahlung through lead (see Appendix, Figure 39)
- transmission of broad-beam bremsstrahlung through concrete (see Appendix, Figure 40)
- the conversion factor 1 rad = 0.01 Gy
- the density of concrete is 2350 kg m^{-3}
- the density of lead is 11 350 kg m^{-3}

Questions for irradiation with electrons:

1. Determine the range (in cm) of 10 MeV electrons in soft tissue.

2. Calculate the maximal dose equivalent rate in soft tissue as a result of the electron beam for an accelerating voltage of 10 MV, a beam current of 1 nA and a field size 10 cm^2.

3. Suppose, that by a combination of errors, an electron irradiation is performed with an accelerating voltage of 30 MV instead of 10 MV. The remaining settings are as reported in Question 2. What are the range and the maximal dose equivalent rate in this case?

Questions for irradiation with photons:

4. Calculate the required irradiation time to get a dose of 4 Gy in air for an accelerating voltage of 30 MV and a beam current of 1 μA at a distance of 1 m from the target plate.

5. Calculate the required thickness of the shielding for the materials lead and concrete.

6. The maximal permissible load for the portion of the floor where the shielding wall is placed is 10 000 kg m^{-2}. The height of the shielding is 2.7 m. Determine which of the materials named in Question 5 can be used, based on the permissible floor load using calculations.

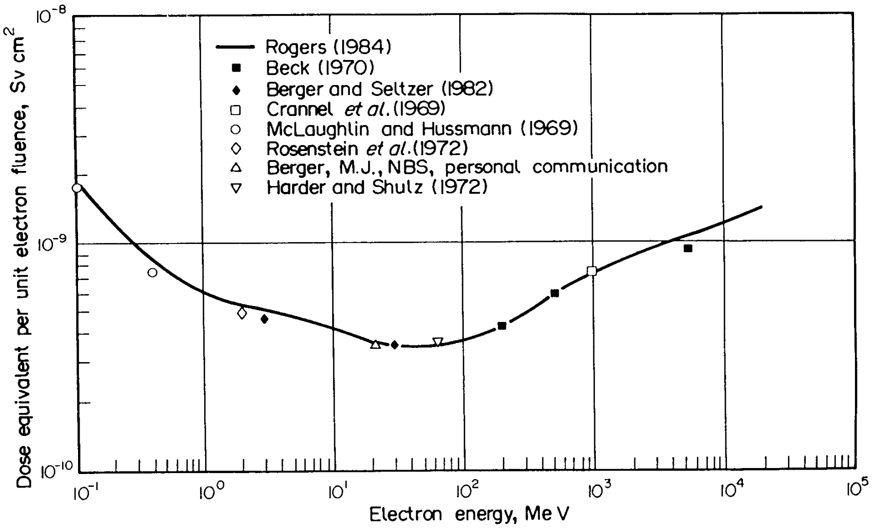


Figure 1. Dose equivalent per unit of fluence for electrons perpendicular to a flat, low, tissue-equivalent material with a thickness of 30 cm.

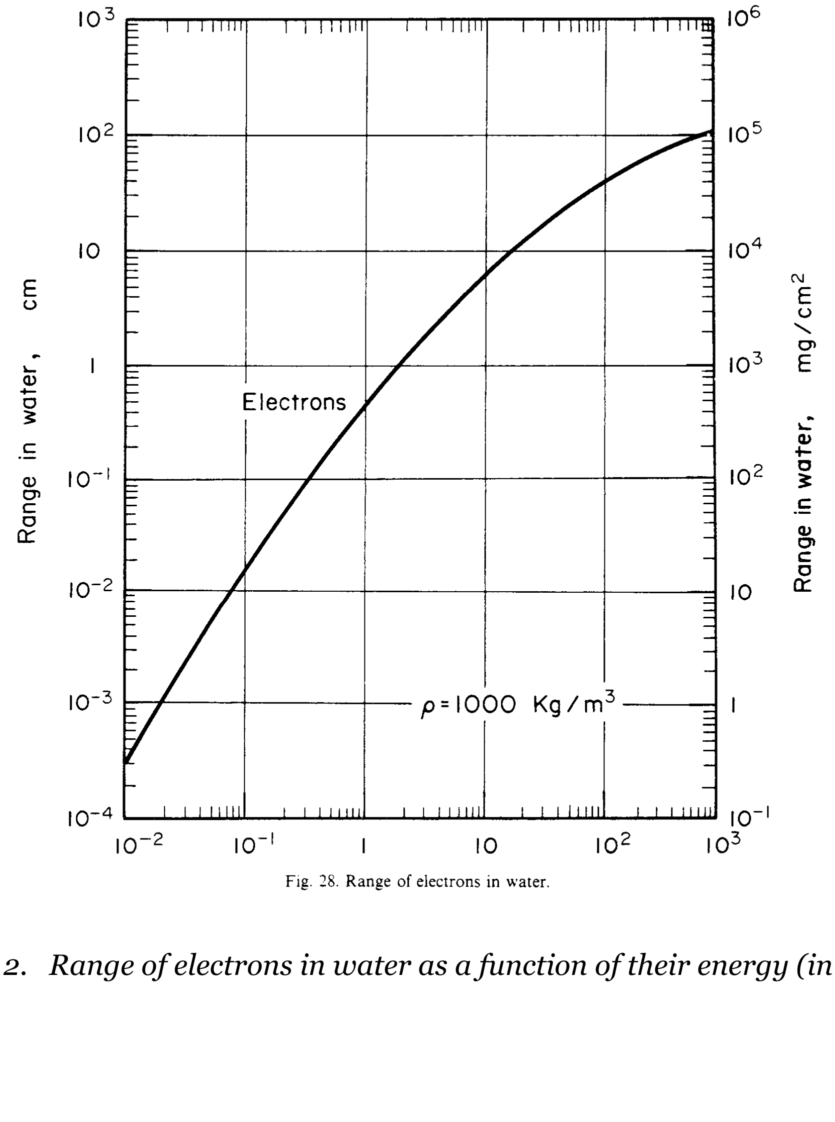


Fig. 28. Range of electrons in water.

Figure 2. Range of electrons in water as a function of their energy (in MeV).

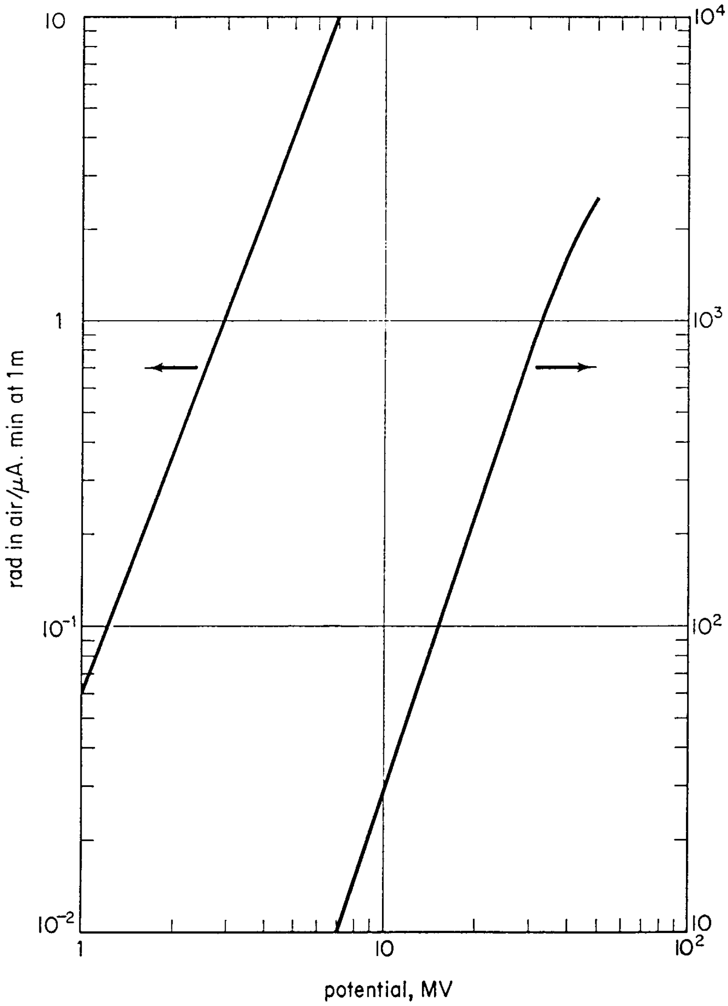


Figure 3. Bremsstrahlung yield at 1 m from the target.

37. Dose for a radiodiagnostic procedure (1993-2-4)

A radiodiagnostic procedure on the abdomen of a female patient consists of a scan using an image enhancer and taking an X-ray photo. During the procedure, the patient is lying on an exmination table. During the scan, the doctor is standing next to the patient.

Given:

- a situation sketch of the installation (see Figure 1)
- the yield of the X-ray tube (see Appendix, Figure 41)
- the total filter contains 2.5 mm Al
- the scan takes 60 s with a tube voltage of 100 kV and a tube current of 0.5 mA
- during the scan, the field size is 30 cm × 20 cm on the skin of the patient and the focus-skin distance (FSD) amounts to 1 m
- while taking the X-ray photo, the tube voltage is 80 kV and the product of the tube current and scan time amounts to 90 mA s
- while taking the X-ray photo, the field size is 30 cm × 40 cm and the focus-skin distance is 85 cm
- scattering factors for tissue (see Table 1)
- the conversion factor C_f = (equivalent organ dose) / (dose free in air) (see Table 2)
- the masses of the target organs (see Appendix, Figure 46)
- the organ weighting factors (see Appendix, Figure 47)
- attenuation by and the scattering to the procedure table may be neglected

Questions:

1. Calculate the scattered dose by scanning at 100 cm from the patient for a FSD = 1 m, for both geometries and for scattering angles of 45°, 90° and 135° (thus for the positions A through F).

2. Calculate the dose free in air D_{air} for a FSD = 85 cm and the conditions under which the X-ray photo is taken.

3. Calculate the effective dose that the patient receives as a result of the X-ray photo. Use the data given in Table 2.

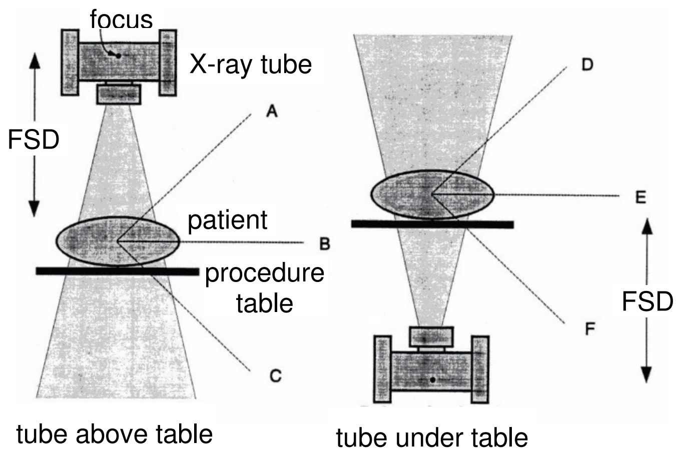


Figure 1. Diagram of the irradiation situation.

Table 1. Percentage of the incoming radiation that is scattered, measured at 1 m from the scattering object for a field size of 400 cm², as a function of the scattering angle.

scattering angle	*accelerating voltage*				
	100 kV	*200 kV*	*300 kV*	*^{60}Co*	*6 MV*
15°	---	---	---	---	0.65
30°	0.02	0.24	0.34	---	0.30
45°	0.03	0.23	0.26	0.18	0.14
60°	0.04	0.19	0.22	0.14	0.08
90°	0.05	0.14	0.19	0.07	0.04
120°	0.12	0.23	0.25	0.05	0.03
135°	0.17	0.30	0.33	0.04	0.03
150°	0.21	0.37	0.48	---	---

Table 2. Conversion factor C_f (in Sv Gy^{-1}) for examination of abdomen (AP-geometry, field size 30 cm × 40 cm, focus-skin distance 85 cm, and tube voltage 80 kV).

organ	*C_f (man)*	*C_f (woman)*
breast tissue	---	0.01
lungs	---	0.02
spleen	0.09	0.13
pancreas	0.18	0.24
stomach wall	0.42	0.53
small intestine	0.35	0.39
large intestine (upper)	0.42	0.45
large intestine (lower)	0.20	0.22
ovaries	---	0.29
uterus	---	0.36
red bone marrow	0.04	0.04
bone surface	0.05	0.06

38. Dosimetry of X-radiation (1995-1-2)

In the radiobiology department, an X-ray device is installed in a new radiation room with walls of concrete. The X-ray device has a 3 mm filter, a maximal tube voltage of 300 kV (half-sine generator), a tungsten reflection anode and a maximal tube current of 10 mA. The radiation level at the control panel, which lies outside of the radiation room, may not be higher in the most unfavorable situation than the legal yearly limit for non-exposed workers.

Given:

- the yield of an X-ray device and transmission of the generated radiation through concrete (see Appendix, Figure 43)
- mass energy transfer and energy absorption coefficients (see Appendix, Figure 26)
- the workload W is 10 000 mA min per week for 50 weeks per year
- the distance from the control panel to the focus amounts to 5 m
- the primary beam is aimed at the control panel during half of the radiation time (use factor U = 0.5)
- the control panel is continuously occupied (occupation factor T = 1)
- consider the dose equivalent in tissue as the norm for the calculation
- assume for the calculation that no changes occurred in the effective energy as a result of the interaction with air and concrete
- the required shielding thickness can be calculated using the formula:

$$k = K_{max} \frac{l^2}{WUT}$$

k = yield of the X-ray device (in mGy m^2 mA^{-1} min^{-1})
K_{max} = maximal permissible kerma (in mGy per year)
l = distance to the focus (in m)
W = workload (in mA min per year)
U = use factor
T = occupation factor

Questions:

1. Determine the maximal dose rate (in mGy min^{-1}) in air without shielding at the control panel.

2. Determine the corresponding absorbed dose rate in tissue.

3. Determine the minimal concrete thickness that is necessary to fulfill the set requirements.

39. Shielding of an X-ray device (1999-1-2)

In a technical scientific research institute, one can use an X-ray device for general purposes. The tube voltage of the device can be adjusted between 50 kV and 100 kV. Filtration of the emitted beam can also be varied. The device is installed in a fixed place.

One of the requirements is that the individual effective yearly dose outside of the radiation room as a consequence of the use of the X-ray device can amount to maximally 1 mSv. No one may be present in the radiation room while the device is in operation. The operator of the control panel is located outside of this radiation room, behind a concrete wall equipped with a lead-glass window and a lead-lined wooden door.

At the wall, indicated by A-B (see Figure 1), the beam spot covers a surface area of 2×10^3 cm^2, with point P as the center. From that place, radiation is scattered back in the direction of the ancillary space where the console is located. Assume that the scattering angle for that direction amounts to 180°.

Given:

- a situation sketch of the radiation room (see Figure 1)
- the yield of the X-ray device and transmission of the radiation generated through lead (see Appendix, Figure 42)
- the (constant) tube voltage is 100 kV
- the workload of the device is 12.5×10^3 mA min per week, for 50 weeks per year
- the beam filtration is 2 mm Al
- the transmission of broad-beam X-radiation through concrete (see Figure 2)
- scattering factors through concrete (see Appendix, Figure 44)
- the effective energy of radiation scattered less than 180° is comparable with that of an X-ray spectrum generated by a voltage of 70 to 75 kV; the transmission graphs corresponding to these tube voltages may be used for this

Questions:

1. Calculate the required thickness of the wall on which the horizontal beam is aimed (A-B in Figure 1). Assume that the beam is aimed at this wall during the full operation time and that the same person stands behind the wall during this time at 0.5 m distance from point P where the beam axis A-B hits the wall.

2. Calculate the required thickness of the wall behind which the operator stands (C-D in Figure 1). Assume that the same person stays at position R during the entire operation time at 1 m distance from point Q where the axis from the scattered beam affects the concrete wall. Assume the same presumptions as in Question 1 with regards to the direction of the primary beam.

3. Calculate the required thickness of the lead layer on the door. The attenuation of the radiation through wood may be neglected. Assume for position R' the same presumption as for position R in Question 2.

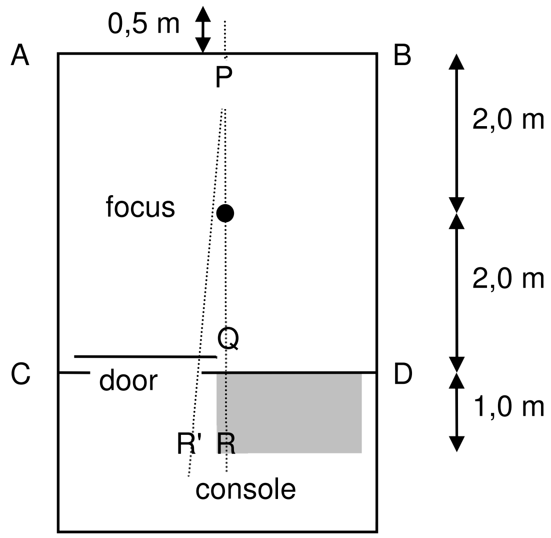


Figure 1. Map of the room with the X-ray device.

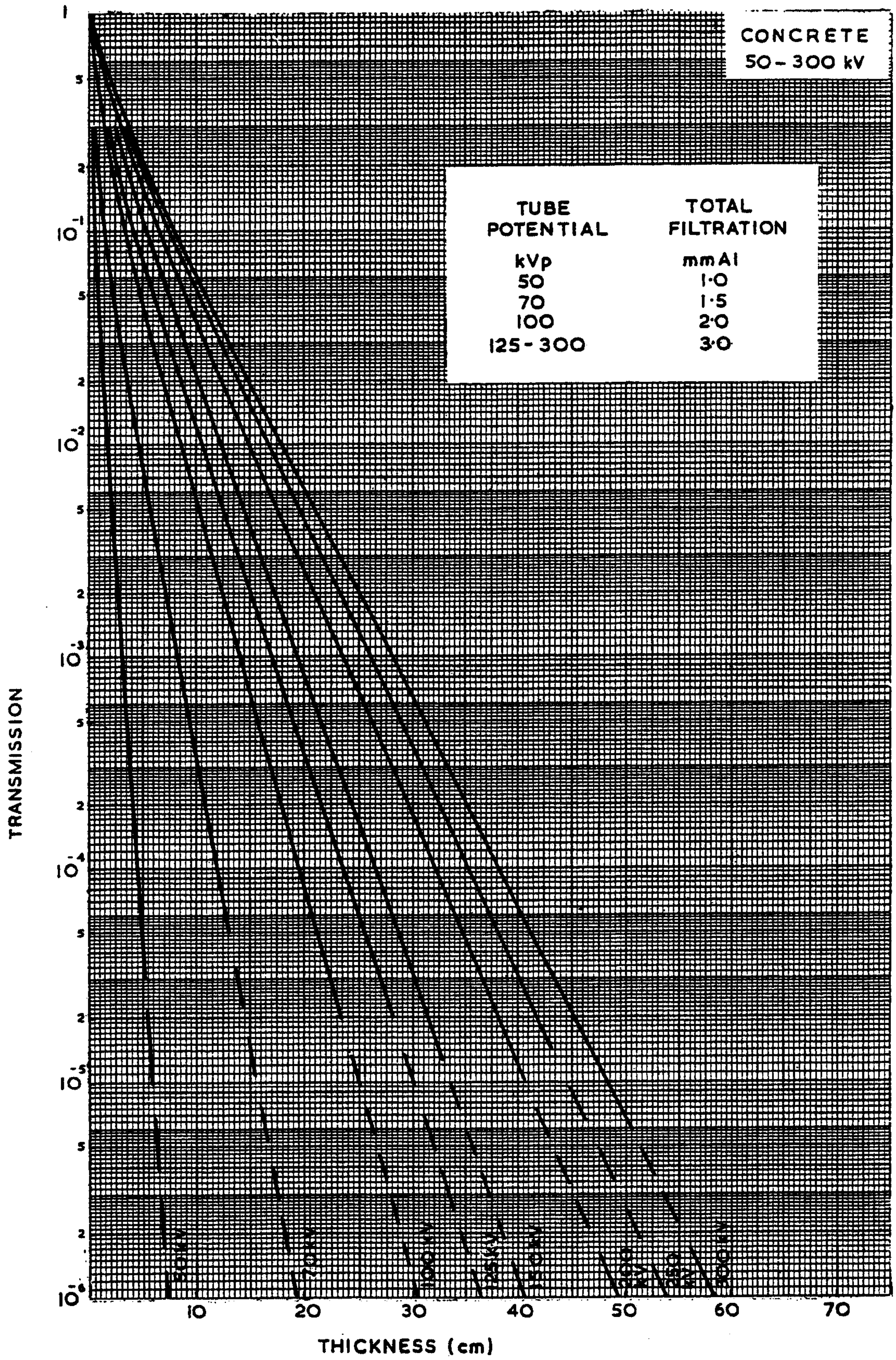


Figure 2 Transmission of broad-beam X-radiation through concrete.

40. Shielding of a neutron generator (2000-2-4)

A research institute wants to purchase a neutron generator. A radiation protection expert is asked to calculate the required shielding. The generator consists of an accelerator that accelerates deuterons (d) to a target of tritium (T). The neutrons are produced according to the nuclear reaction:

$$d + T \rightarrow {}^{4}He + n$$

The neutrons produced are emitted isotropically and have an energy of 14 MeV. The place where the neutrons are generated is so small that the target may be considered as a point source of neutrons. The number of neutrons generated amounts to 1×10^{11} s^{-1}.

The generator is placed in a bunker with 25 cm thick walls of concrete. The bunker is equipped on the outside with an earthen wall. The roof of the bunker is also covered with a layer of dirt.

Given:

- a horizontal cross-section through the bunker (see Figure 1)
- the ambient dose equivalent for mono-energetic neutrons (see Table 1)
- the transmission of neutrons with an energy of 14 MeV through concrete is:

$$T_{\text{concrete}} = 6.6e^{-d/13} \quad \text{(d in cm)}$$

- the transmission of neutrons with an energy of 14 MeV through earth can be described in the same manner as that through concrete, on the understanding that the transmission through *d* cm of concrete is the same as through 2*d* cm of earth

Questions:

1. Calculate the fluence rate in point P at 5 m distance from the target (see Figure 1) for a unshielded generator.

2. Calculate the ambient dose equivalent rate (in μSv h^{-1}) in point P at 5 m distance from the target for an unshielded generator.

3. How thick should the earthen wall be so that the ambient dose equivalent rate in point P at 5 m distance from the target is not larger than 1 μSv h^{-1}. Assume only the contribution from the direct beam (thus no sky shine). Also assume that behind the shielding the most determinant neutron energy still amounts to 14 MeV.

4. In the bunker, operations are carried out on the high-voltage unit and cooling unit. Concrete blocks are available with which a wall of 150 cm thick can be constructed at a distance of 10 cm from the source. This leaves just enough room to perform the operations behind the shielding. The required ambient dose equivalent rate directly behind the shield must not be more than 10 μSv h^{-1}. Does the concrete wall fulfill the requirements?

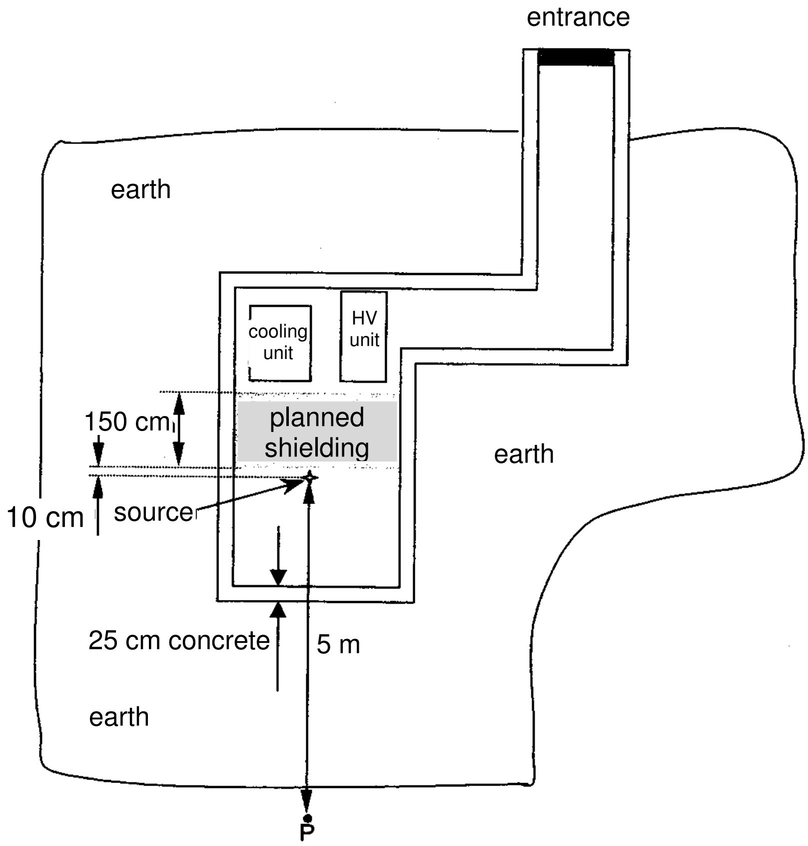


Figure 1. Horizontal cross-section of the bunker with labyrinth.

Table 1. Operational quantities per unit of neutron fluence, expressed in pSv cm², for mono-energetic neutrons (ICRP-74).

Energy (MeV)	$H^*(10)/\Phi$	$H_{p,slab}(10,0°)/\Phi$	$H_{p,slab}(10,15°)/\Phi$	$H_{p,slab}(10,30°)/\Phi$	$H_{p,slab}(10,45°)/\Phi$	$H_{p,slab}(10,60°)/\Phi$	$H_{p,slab}(10,75°)/\Phi$
1.00×10^{-9}	6.60	8.19	7.64	6.57	4.23	2.61	1.13
1.00×10^{-8}	9.00	9.97	9.35	7.90	5.38	3.37	1.50
2.53×10^{-8}	10.6	11.4	10.6	9.11	6.61	4.04	1.73
1.00×10^{-7}	12.9	12.6	11.7	10.3	7.84	4.70	1.94
2.00×10^{-7}	13.5	13.5	12.6	11.1	8.73	5.21	2.12
5.00×10^{-7}	13.6	14.2	13.5	11.8	9.40	5.65	2.31
1.00×10^{-6}	13.3	14.4	13.9	12.0	9.56	5.82	2.40
2.00×10^{-6}	12.9	14.3	14.0	11.9	9.49	5.85	2.46
5.00×10^{-6}	12.0	13.8	13.9	11.5	9.11	5.71	2.48
1.00×10^{-5}	11.3	13.2	13.4	11.0	8.65	5.47	2.44
2.00×10^{-5}	10.6	12.4	12.6	10.4	8.10	5.14	2.35
5.00×10^{-5}	9.90	11.2	11.2	9.42	7.32	4.57	2.16
1.00×10^{-4}	9.40	10.3	9.85	8.64	6.74	4.10	1.99
2.00×10^{-4}	8.90	9.84	9.41	8.22	6.21	3.91	1.83
5.00×10^{-4}	8.30	9.34	8.66	7.66	5.67	3.58	1.68
1.00×10^{-3}	7.90	8.78	8.20	7.29	5.43	3.46	1.66
2.00×10^{-3}	7.70	8.72	8.22	7.27	5.43	3.46	1.67
5.00×10^{-3}	8.00	9.36	8.79	7.46	5.71	3.59	1.69
1.00×10^{-2}	10.5	11.2	10.8	9.18	7.09	4.32	1.77
2.00×10^{-2}	16.6	17.1	17.0	14.6	11.6	6.64	2.11
3.00×10^{-2}	23.7	24.9	24.1	21.3	16.7	9.81	2.85
5.00×10^{-2}	41.1	39.0	36.0	34.4	27.5	16.7	4.78
7.00×10^{-2}	60.0	59.0	55.8	52.6	42.9	27.3	8.10
1.00×10^{-1}	88.0	90.6	87.8	81.3	67.1	44.6	13.7
1.50×10^{-1}	132	139	137	126	106	73.3	24.2
2.00×10^{-1}	170	180	179	166	141	100	35.5
3.00×10^{-1}	233	246	244	232	201	149	58.5
5.00×10^{-1}	322	335	330	326	291	226	102
7.00×10^{-1}	375	386	379	382	348	279	139
9.00×10^{-1}	400	414	407	415	383	317	171
1.00×10^{0}	416	422	416	426	395	332	180
1.20×10^{0}	425	433	427	440	412	355	210
2.00×10^{0}	420	442	438	457	439	402	274
3.00×10^{0}	412	431	429	449	440	412	306
4.00×10^{0}	408	422	421	440	435	409	320
5.00×10^{0}	405	420	418	437	435	409	331
6.00×10^{0}	400	423	422	440	439	414	345
7.00×10^{0}	405	432	432	449	448	425	361
8.00×10^{0}	409	445	445	462	460	440	379
9.00×10^{0}	420	461	462	478	476	458	399
1.00×10^{1}	440	480	481	497	493	480	421
1.20×10^{1}	480	517	519	536	529	523	464
1.40×10^{1}	520	550	552	570	561	562	503
1.50×10^{1}	540	564	565	584	575	579	520
1.60×10^{1}	555	576	577	597	588	593	535
1.80×10^{1}	570	595	593	617	609	615	561
2.00×10^{1}	600	600	595	619	615	619	570
3.00×10^{1}	515	na[a]	na	na	na	na	na[a]
5.00×10^{1}	400	na	na	na	na	na	na
7.50×10^{1}	330	na	na	na	na	na	na
1.00×10^{2}	285	na	na	na	na	na	na
1.25×10^{2}	260	na	na	na	na	na	na
1.50×10^{2}	245	na	na	na	na	na	na
1.75×10^{2}	250	na	na	na	na	na	na
2.01×10^{2}	260	na	na	na	na	na	na

[a]Not available.

Solutions

Problem 21

1. From Figure 27:
   60 keV $\varphi_{60keV} / K_1 = 1.0\times10^7\ m^{-2}\ s^{-1} = 1.0\times10^3$ (photon $cm^{-2}\ s^{-1}$) per $\mu Gy\ h^{-1}$
   $K_1 / \varphi_{60keV} = 1.0\times10^{-3}\ \mu Gy\ h^{-1}$ per (photon $cm^{-2}\ s^{-1}$)
   511 keV $\varphi_{511keV} / K_1 = 1.2\times10^6\ m^{-2}\ s^{-1} = 1.2\times10^2$ (photon $cm^{-2}\ s^{-1}$) per $\mu Gy\ h^{-1}$
   $K_1 / \varphi_{511keV} = 8.3\times10^{-3}\ \mu Gy\ h^{-1}$ per (photon $cm^{-2}\ s^{-1}$)
2. 1 photon of each $1.0\times10^{-3}\ \mu Gy\ h^{-1} + 8.3\times10^{-3}\ \mu Gy\ h^{-1} = 9.3\times10^{-3}\ \mu Gy\ h^{-1}$ per (photon $cm^{-2}\ s^{-1}$)
   for 10 $\mu Gy\ h^{-1}$ there are thus from each energy:
   $\varphi = (10\ \mu Gy\ h^{-1} / 9.3\times10^{-3}\ \mu Gy\ h^{-1}$ per (photon $cm^{-2}\ s^{-1}) \times 1 = 1075\ cm^{-2}\ s^{-1}$
   counting rate = fluence rate × surface area × (1 - transmission)
   mass thickness detector $d \times \rho = 1\times10^{-1}\ cm \times 3.67\ g\ cm^{-3} = 0.367\ g\ cm^{-2}$
   surface area detector $10\ cm^2$
   60 keV transmission = $e^{-(\mu/\rho)(d\times\rho)} = e^{-6.62\times0.367} = 0.088$
   counting rate = $1075\ cm^{-2}\ s^{-1} \times 10\ cm^2 \times (1 - 0.088) = 9804$ cps
   511 keV transmission = $e^{-(\mu/\rho)(d\times\rho)} = e^{-0.0941\times0.367} = 0.966$
   counting rate = $1075\ cm^{-2}\ s^{-1} \times 10\ cm^2 \times (1 - 0.966) = 366$ cps
   total 9804 cps + 366 cps = 10 170 cps
3. $H^* = \varphi \times (K / \varphi) \times (H^* / K)$
   inserting K / φ (see Question 1) and H^* / K (see Figure 28) gives:
   60 keV $K / \varphi = 1.0\times10^{-3}\ \mu Gy\ h^{-1}$ per (photon $cm^{-2}\ s^{-1}$); $H^* / K = 1.75\ Sv\ Gy^{-1}$
   $H^*(10) = 1075\ cm^{-2}\ s^{-1} \times 1.0\times10^{-3}\ \mu Gy\ h^{-1}$ per (photon $cm^{-2}\ s^{-1}) \times 1.75\ Sv\ Gy^{-1}$
   $= 2\ \mu Sv\ h^{-1}$
   511 keV $K / \varphi = 8.3\times10^{-3}\ \mu Gy\ h^{-1}$ per (photon $cm^{-2}\ s^{-1}$); $H^* / K = 1.21\ Sv\ Gy^{-1}$
   $H^*(10) = 1075\ cm^{-2}\ s^{-1} \times 8.3\times10^{-3}\ \mu Gy\ h^{-1}$ per (photon $cm^{-2}\ s^{-1}) \times 1.21\ Sv\ Gy^{-1}$
   $= 11\ \mu Sv\ h^{-1}$
   total $H^*(10) = 2\ \mu Sv\ h^{-1} + 11\ \mu Sv\ h^{-1} = 13\ \mu Sv\ h^{-1}$

Problem 22

1. $E_{\beta,max}(^{42}K) = 3521\ keV = 3.5\ MeV$
   from Figure 25 $R(3.5\ MeV) = 1750\ mg\ cm^{-2}$
   $= 1.75\ g\ cm^{-2} <$ thickness ionization-chamber wall
2. mass of air in ionization chamber $100\ cm^3 \times 1.205\times10^{-3}\ g\ cm^{-3} = 1.205\times10^{-1}\ g$
   $= 1.205\times10^{-4}\ kg$
   X = charge / mass $94.6\times10^{-12}\ C / 1.205\times10^{-4}\ kg = 7.85\times10^{-7}\ C\ kg^{-1}$
   $D = 33.7$ Gy per C $kg^{-1} \times 7.85\times10^{-7}\ C\ kg^{-1} = 2.65\times10^{-5}\ Gy = 26.5\ \mu Gy$
   $dD/dt = 26.5\ \mu Gy / 6\ min = 4.42\ \mu Gy\ min^{-1} = 265\ \mu Gy\ h^{-1}$
   arising from γ-radiation of ^{42}K and ^{51}Cr
3. GM-counter $f_{geom} = 1\ cm^2 / [4\pi \times (50\ cm)^2] = 3.2\times10^{-5}$
   $T_\beta = A(^{42}K) \times f_\beta \times f_{geom} \times f_{det}$
   $= A(^{42}K) \times 1 \times 3.2\times10^{-5} \times 1 = 3.2\times10^{-5}\ A(^{42}K)$
   measured $T_\beta = 3.53\times10^6\ cpm = 5.9\times10^4\ cps$
   activity $A(^{42}K) = 5.9\times10^4\ cps / 3.2\times10^{-5} = 1.8\times10^9\ Bq = 1.8\times10^3\ MBq$
4. contribution of ^{42}K to the kerma rate:
   $0.032\ \mu Gy\ m^2\ MBq^{-1}\ h^{-1} \times 1.8\times10^3\ MBq / (50\times10^{-2}\ m)^2 = 230\ \mu Gy\ h^{-1}$
   contribution of ^{51}Cr to the kerma rate:
   $265\ \mu Gy\ h^{-1} - 230\ \mu Gy\ h^{-1} = 35\ \mu Gy\ h^{-1}$
   activity $A(^{51}Cr) = 35\ \mu Gy\ h^{-1} \times (50\times10^{-2}\ m)^2 / 0.0042\ \mu Gy\ m^2\ MBq^{-1}\ h^{-1}$
   $= 2.1\times10^3\ MBq$

5. 1 cm² skin is reached by a fraction f_{geom} = 1 cm² / [4π × (50 cm)²] = 3.2×10^{-5} of the β-particles according to Figure 6 of the Appendix is $h_{skin} = 7\times10^{-10}$ Sv s^{-1} Bq^{-1} cm²
   $H_{skin} = h_{skin} \times f_{geom} \times A(^{42}\mathrm{K})$
   $= 7\times10^{-10}$ Sv s^{-1} Bq^{-1} cm² × 3.2×10^{-5} per cm² × 1.8×10^{9} Bq = 4.0×10^{-5} Sv s^{-1} = 0.14 Sv h^{-1}
6. setup shielded on all sides with at least R(3.5 MeV) = 1.75 g cm^{-2} artificial materials (for example 1.5 cm perspex)

Problem 23

1. 15 cm from the surface is 15 cm + (30 cm / 2) = 30 cm = 0.3 m from the center
   1 box contains 27 kg × 150 Bq kg^{-1} = 4 050 Bq = 4.05×10^{-3} MBq
   effective density is ρ = 27 kg × 10³ g kg^{-1} / (30 cm)³ = 1.0 g cm^{-3}
   $\mathrm{d}K_1/\mathrm{d}t = B\,\mathrm{e}^{-(\mu/\rho)(d\times\rho)} \times (k\,A / r^2)$
   $= (1 + 0.\ 2 \times 15) \times \mathrm{e}^{-0.085\times(15\times1)} \times 0.077$ μGy m² MBq^{-1} h^{-1} × 4.05×10^{-3} MBq / (0.3 m)²
   $= 3.9\times10^{-3}$ μGy h^{-1}
2. 15 cm from the surface is 15 cm + 30 cm + (30 cm / 2) = 60 cm = 0.6 m from the center of the second box
   $\mathrm{d}K_2/\mathrm{d}t$
   $= (1 + 0.2 \times 45) \times \mathrm{e}^{-0.085\times(45\times1)} \times 0.077$ μGy m² MBq^{-1} h^{-1} × 4.05×10^{-3} MBq / (0.6 m)²
   $= 1.9\times10^{-4}$ μGy h^{-1}
3. emitted energy = $f_\gamma \times E_\gamma$
   = (0.946 × 0.898) × 662 keV per Bq s = 563 keV per Bq s
   emitted energy per kg meat = 150 Bq kg^{-1} × 563 keV per Bq s × 1.6×10^{-16} J keV^{-1}
   = 1.35×10^{-11} J kg^{-1} per s = 1.35×10^{-11} Gy s^{-1}
   $\mathrm{d}K_\gamma/\mathrm{d}t$ = 0.5 × 1.35×10^{-11} Gy s^{-1} = 6.8×10^{-12} Gy s^{-1} = 2.4×10^{-2} μGy h^{-1} = 24 nGy h^{-1}

Problem 24

1. from Figure 1 at 60 keV — TLD($CaSO_4$) / K = 12 000 sd R^{-1} = 1200 sd mGy^{-1}
   TLD($CaSO_4$) = 1200 sd mGy^{-1} × 1 mGy = 1200 sd
   TLD($Li_2B_4O_7$) / K = 900 sd R^{-1} = 90 sd mGy^{-1}
   TLD($Li_2B_4O_7$) = 90 sd mGy^{-1} × 1 mGy = 90 sd
2. from Figure 28 at E = 60 keV — $H_p(10) / K$ = 1.9 mSv mGy^{-1}
   $H_p(10)$ = 1.9 mSv mGy^{-1} × 1 mGy =1.9 mSv
3. person P
   ratio — TLD($CaSO_4$) / TLD($Li_2B_4O_7$) = 85 sd / 85 sd = 1
   from Figure 1 — E_γ > 1 MeV
   TLD($Li_2B_4O_7$) / K = 1000 sd R^{-1} = 100 sd mGy^{-1}
   from Figure 28 at E > 1 MeV — $H_p(10) / K$ = 1.1 Sv Gy^{-1}
   $H_p(10)$ = (85 sd / 100 sd mGy^{-1}) × 1.1 Sv Gy^{-1} = 0.94 mSv
   person Q
   ratio — TLD($CaSO_4$) / TLD($Li_2B_4O_7$) = 315 sd / 35 sd = 9
   from Figure 1 — $E_\gamma \approx$ 85 keV
   TLD($Li_2B_4O_7$) / K = 950 sd R^{-1} = 95 sd mGy^{-1}
   from Figure 28 at E = 85 keV — $H_p(10) / K$ = 1.85 Sv Gy^{-1}
   $H_p(10)$ = (35 sd / 95 sd mGy^{-1}) × 1.85 Sv Gy^{-1} = 0.68 mSv

Problem 25

1. $E_{\beta,max}(^{32}\mathrm{P})$ = 1710 keV = 1.7 MeV
   from Figure 25 — R(1.7 MeV) = 800 mg cm^{-2} = 0.8 g cm^{-2}
   range in air — 0.8 g cm^{-2} / 1.205×10^{-3} g cm^{-3} = 660 cm
   range in water — 0.8 g/cm² / 1.0 g cm^{-3} = 0.8 cm

2. 20 cm 4.67 μGy min^{-1} × (10 cm / 20 cm)^2 = 1.17 μGy min^{-1}
   30 cm 4.67 μGy min^{-1} × (10 cm / 30 cm)^2 = 0.52 μGy min^{-1}
   40 cm 4.67 μGy min^{-1} × (10 cm / 40 cm)^2 = 0.29 μGy min^{-1}
   50 cm 4.67 μGy min^{-1} × (10 cm / 50 cm)^2 = 0.19 μGy min^{-1}
   60 cm 4.67 μGy min^{-1} × (10 cm / 60 cm)^2 = 0.13 μGy min^{-1}
   attenuation apparently does not play a role given the good agreement with the inverse square law
3. half of the emitted β-particles go to the skin, thus
   φ = 1×10^6 Bq cm^{-2} / 2 = 5×10^5 cm^{-2} s^{-1}
   dD_{skin}/dt = 1.602×10^{-10} Gy per MeV g^{-1} × 5×10^5 cm^{-2} s^{-1} × 2 MeV cm^{-2} g^{-1}
   = 1.6×10^{-4} Gy s^{-1} = 0.58 Gy h^{-1}
   for β-particles is w_R = 1 Sv Gy^{-1}
   $dH_{skin}/dt = w_R \times dD_{skin}/dt$ = 1 Sv Gy^{-1} × 0.58 Gy h^{-1} = 0.58 Sv h^{-1} = 580 mSv h^{-1}
   $dH_{skin}/dt = h_{skin} \times A(^{32}P)$
   according to Figure 3 of the Appendix is h_{skin} = 6×10^{-10} Sv s^{-1} Bq^{-1} cm^2
   it follows that dH_{skin}/dt = 6×10^{-10} Sv s^{-1} Bq^{-1} cm^2 × 1×10^6 Bq cm^{-2}
   = 6.0×10^{-4} Sv s^{-1} = 2.16 Sv h^{-1} = 2160 mSv h^{-1}
4. on the basis of formula D_{skin} 500 mSv / 580 Sv h^{-1} = 0.86 h = 52 min
   on the basis of h_{skin} 500 mSv / 2160 Sv h^{-1} = 0.23 h = 14 min

the difference between the result from both approximations is attributable to the fact that the thickness of the skin layer in which the β-energy is deposited, is defined in the direction perpendicular to this layer, whereas the β-particles isotropically are emitted

for β-particles which are emitted at an angle to the normal, the effective layer thickness is proportional to cos(α) and the contribution to the dose is thus proportional $cos^{-1}(\alpha)$

the number of β-particles that are emitted between the angles α and α+dα with the normal is 2π sin(α) dα (this is analogous to the calculation of the formula for the geometry factor; the dose follows now by integrating over α between the limits 0 and α_{max} and normalizing by the full solid angle 4π:

$$\int_0^{\alpha max} \cos^{-1}(\alpha)\, 2\pi \sin(\alpha)\, d\alpha / 4\pi = -0.5 \times \int_{\cos(0)}^{\cos(\alpha max)} \cos^{-1}(\alpha)\, d\cos(\alpha)$$

→ *integral* $= -0.5 \times \ln[\cos(\alpha_{max})]$

the half-thickness is $d_{½} \approx 0.1\, R_{\beta,max} \approx 0.1 \times 0.5\, E_{\beta,max} = 0.05\, E_{\beta,max}$ *cm*
suppose that the skin depth d can not be reached by $d > d_{½} \times \cos(\alpha) / \ln(2)$
→ $\cos(\alpha_{max}) = d \times \ln(2) / d_{½}$
→ *integral* $= 0.5 \times \ln(0.072\, E_{\beta,max} / d)$

take $E_{\beta,max}(^{32}P)$ *= 1.710 MeV and d = 0.07 mm = 0.007 cm (shallow dose)*
→ *integral = 0.5 × ln(0.072 × 1.710 / 0,007) = 0.5×2.9 = 1.45 (= effective solid angle)*

for a skin contaminated with 1 Bq cm^{-2} *is thus*
$h_{skin} = w_R \times 1.602\times10^{-10}$ *Gy per MeV* g^{-1} × *fluence rate × S/ρ × integral*
= *1.602×10^{-10} Sv per MeV* g^{-1} × 1 cm^{-2} s^{-1} × *2 MeV per g* cm^{-2} × 1.45
= *4.6×10^{-10} Sv* s^{-1} *per Bq* cm^{-2}

<u>Problem 26</u>

1. $H^*(10) = h\,A\,t\,/\,r^2$
   without shielding:
   $H^*(10)$
   $= 0.0012\ \text{Sv m}^2\ \text{MBq}^{-1}\ \text{h}^{-1} \times 20\times10^3\ \text{MBq} \times (45\ \text{min} / 60\ \text{min h}^{-1}) / (0.5\ \text{m})^2$
   $= 72\ \mu\text{Sv}$
   with shielding:
   $H^*(10) = 5\times10^{-2} \times 72\ \mu\text{Sv} = 3.6\ \mu\text{Sv}$
2. assume an AP-geometry (from front to back) because this is the most likely geometry and moreover yields the largest conversion factor
   from Figure 29 at $E_\gamma = 84$ keV $= 8.4\times10^{-2}$ MeV $\quad E(\text{AP}) / H^*(10) = 0.85$
   effective dose $\quad E = 0.85 \times 3.6\ \mu\text{Sv} = 3.1\ \mu\text{Sv}$
3. $H_{\text{skin}} = h_{\text{skin}} \times A(^{170}\text{Tm}) \times t$
   $= 5\times10^{-10}\ \text{Sv s}^{-1}\ \text{Bq}^{-1}\ \text{cm}^2 \times 26\times10^3\ \text{Bq cm}^{-2} \times 8\ \text{h} \times 3600\ \text{s h}^{-1} = 0.37\ \text{Sv}$
4. there was a lot wrong
   - the source was not placed in a container after the radiogram was taken
   - the contamination in the hall was cleaned in an unsound manner
   - during the cleanup, the other operations were not stopped
   - the responsible expert was not immediately informed

<u>Problem 27</u>

1. $E_{\beta,\text{max}} = 1390$ keV = 1,39 MeV
   from Figure 25 $\quad R(1.39\ \text{MeV}) = 620\ \text{mg cm}^{-2} = 6.2\ \text{kg m}^{-2}$
   minimal thickness $\quad 6.2\ \text{kg m}^{-2} / 2.7\times10^3\ \text{kg m}^{-3} = 2.3\times10^{-3}\ \text{m}$ = 2,3 mm aluminum
2. $\mathrm{d}K/\mathrm{d}t = \varphi \times (\mu_{en}/\rho) \times E_\gamma$
   $\varphi = 0.999 \times 37\times10^9\ \text{Bq} / [4\pi \times (1\ \text{m})^2] = 2.94\times10^9\ \text{m}^{-2}\ \text{s}^{-1}$
   $\mu_{tr}/\rho = 3.16\times10^{-3}\ \text{m}^{-1} / 1.205\ \text{kg m}^{-3} = 2.62\times10^{-3}\ \text{m}^2\ \text{kg}^{-1}$
   $E_\gamma = 1.37\ \text{MeV}) \times 1.6\times10^{-13}\ \text{J MeV}^{-1} = 2.19\times10^{-13}\ \text{J}$
   $\mathrm{d}K(1.37\ \text{MeV})/\mathrm{d}t = 2.94\times10^9\ \text{m}^{-2}\ \text{s}^{-1} \times 2.62\times10^{-3}\ \text{m}^2\ \text{kg}^{-1} \times 2.19\times10^{-13}\ \text{J}$
   $= 1.69\times10^{-6}\ \text{J kg}^{-1}\ \text{s}^{-1} = 1.69\ \mu\text{Gy s}^{-1}$ at 1 meter
3. $\mathrm{d}K/\mathrm{d}t = \varphi \times (\mu_{en}/\rho) \times E_\gamma$
   $\varphi = 0.999 \times 37\times10^9\ \text{Bq} / [4\pi \times (1\ \text{m})^2] = 2.94\times10^9\ \text{m}^{-2}\ \text{s}^{-1}$
   $\mu_{tr}/\rho = 2.57\times10^{-3}\ \text{m}^{-1} / 1.205\ \text{kg m}^{-3} = 2.13\times10^{-3}\ \text{m}^2\ \text{kg}^{-1}$
   $E_\gamma = 2.75\ \text{MeV} \times 1.6\times10^{-13}\ \text{J MeV}^{-1} = 4.40\times10^{-13}\ \text{J}$
   $\mathrm{d}K(2.75\ \text{MeV})/\mathrm{d}t = 2.94\times10^9\ \text{m}^{-2}\ \text{s}^{-1} \times 2.13\times10^{-3}\ \text{m}^2\ \text{kg}^{-1} \times 4.40\times10^{-13}\ \text{J}$
   $= 2.76\times10^{-6}\ \text{J kg}^{-1}\ \text{s}^{-1} = 2.76\ \mu\text{Gy s}^{-1}$ at 1 meter
4. in both directions, linearly interpolate in Figure 30:
   1,37 MeV $\quad \mu \times d = 6.1\ \text{m}^{-1} \times 2.0\ \text{m} = 12.2$
   $B(12.2) = 29.3$
   attenuation $= B\,e^{-\mu d} = 29.3 \times e^{-12.2} = 1.5\times10^{-4}$
   2,75 MeV $\quad \mu \times d = 4{,}3\ \text{m}^{-1} \times 2.0\ \text{m} = 8.6$
   $B(8.6) = 8.3$
   attenuation $= B\,e^{-\mu d} = 8.3 \times e^{-8.6} = 1.5\times10^{-3}$
   negligible attenuation by air
   total distance to source is 2 m water + 1 m air = 3 m
   $\mathrm{d}K/\mathrm{d}t = 1.5\times10^{-4} \times \mathrm{d}K(1.37\ \text{MeV})/\mathrm{d}t + 1.5\times10^{-3} \times \mathrm{d}K(2.75\ \text{MeV})/\mathrm{d}t$
   $= 1.5\times10^{-4} \times (1.69\ \mu\text{Gy s}^{-1} / 3^2) + 1.5\times10^{-3} \times (2.76\ \mu\text{Gy s}^{-1} / 3^2)$
   $= 2.8\times10^{-5}\ \mu\text{Gy s}^{-1} + 4.6\times10^{-4}\ \mu\text{Gy s}^{-1} = 4.9\times10^{-4}\ \mu\text{Gy s}^{-1} = 1.8\ \mu\text{Gy h}^{-1}$

Problem 28

1. kerma rate = $40{\times}10^{-2} \times A \times k(^{51}Cr) + 60{\times}10^{-2} \times A \times k(^{60}Co)$
   $= (40{\times}10^{-2} \times 0.0042$ µGy m² MBq⁻¹ h⁻¹ $+ 60{\times}10^{-2} \times 0.31$ µGy m² MBq⁻¹ h⁻¹$) \times A$
   $= 0.188\, A$ µGy h⁻¹ per MBq at 1 meter
   measured $dK/dt = 50$ mGy h⁻¹ $= 5.0{\times}10^4$ µGy h⁻¹
   activity $A = 5.0{\times}10^4$ µGy h⁻¹ / 0.188 µGy h⁻¹ $= 2.66{\times}10^5$ MBq = 266 GBq
2. in both directions, linearly interpolate in Figure 30:
   0,32 MeV $\mu \times d = 0.1164$ cm² g⁻¹ × 1 g cm⁻³ × 160 cm = 18.6
   $B(18.6) = 684$
   attenuation $= B\,e^{-\mu d} = 684 \times e^{-18.6} = 5.7{\times}10^{-6}$
   1,33 MeV $\mu \times d = 0.062$ cm² g⁻¹ × 1 g cm⁻³ × 160 cm = 9.9
   $B(9.9) = 22.0$
   attenuation $= B\,e^{-\mu d} = 22.0 \times e^{-9.9} = 1.1{\times}10^{-3}$
   kerma rate at 160 cm = 1.6 m above the water surface:
   $dK_{0,32MeV}/dt$
   $= 40{\times}10^{-2} \times 0.0042$ µGy m² MBq⁻¹ h⁻¹ $\times 2.66{\times}10^5$ MBq $\times 5.7{\times}10^{-6}$ / (1.6 m)²
   $= 1.0{\times}10^{-3}$ µGy h⁻¹
   $dK_{1,33MeV}/dt$
   $= 60{\times}10^{-2} \times 0.31$ µGy m² MBq⁻¹ h⁻¹ $\times 2.66{\times}10^5$ MBq $\times 1.1{\times}10^{-3}$ / (1.6 m)²
   = 21 µGy h⁻¹
   $dK/dt = dK_{0.32MeV}/dt + dK_{1.33MeV}/dt = 1.0{\times}10^{-3}$ µGy h⁻¹ + 21 µGy h⁻¹ = 21 µGy h⁻¹
   fulfills the requirements
3. transport requirement (1) $k\,A\,T / d^2 < 2$ mGy h⁻¹
   $d = \sqrt{(k\,A\,T / 2 \text{ mGy h}^{-1})}$
   transport requirement (2) $k\,A\,T / (d + 100 \text{ cm})^2 < 0.1$ mGy h⁻¹
   $d + 100 \text{ cm} = \sqrt{(k\,A\,T / 0.1 \text{ mGy h}^{-1})}$
   the two equations lead to the same value of d if:
   $(d + 100 \text{ cm}) / d = \sqrt{(2 \text{ mGy/h} / 0.1 \text{ mGy/h})} = \sqrt{20} = 4.47$
   $d + 100 \text{ cm} = 4.47\, d$
   $d = 100 \text{ cm} / (4.47 - 1) = 100 \text{ cm} / 3.47 = 29$ cm
   if the side length is 2 × 29 cm = 58 cm, the two transport requirements lead to the same shielding
4. after 2 weeks, $A(^{51}Cr)$ is decreased with a factor $e^{-0.693\times(2\times7)/27.71} = 0.70$, while $A(^{60}Co)$ is nearly unchanged
   the lead shielding will undoubtedly by determined by ^{60}Co
   the box has a side length of 50 cm
   this is smaller than 58 cm, thus transport requirement (1) is determinant
   at 50 cm / 2 = 25 cm (surface)
   dose rate $60{\times}10^{-2} \times 0.31$ µGy m² MBq⁻¹ h⁻¹ $\times 2.66{\times}10^5$ MBq / (0.25 m)²
   $= 7.9{\times}10^5$ µGy h⁻¹ = 790 mGy h⁻¹
   limit 2 mGy h⁻¹
   required transmission $T = 2$ mGy h⁻¹ / 790 mGy h⁻¹ $= 2.5{\times}10^{-3}$
   from Figure 31 11 cm lead
   the transmission of γ-radiation of ^{137}Cs (0.66 MeV) is about 2 orders of magnitude smaller
   the transmission of γ-radiation of ^{51}Cr (0.32 MeV) will be even much smaller

   control dose rate at 100 cm + (50 cm / 2) = 125 cm (= 1 m from the surface):
   dose rate = (25 cm / 125 cm)² × 2 mGy h⁻¹ = 0.08 mGy h⁻¹ < 0.1 mGy h⁻¹
   fulfills transport requirement (2)

Problem 29

1. - he is not measuring on the surface of the container
   - he is forgetting the ingrowth of the daughter nuclide B
2. from Figure 1 at 5 cm lead and nuclide A:
   transmission $T_A = 5.0\times10^{-3}$
   distance r = 1 m + (0.40 m / 2) = 1.2 m
   $dH_A^*/dt = h\, A_A\, T_A / r^2$
   $= 0{,}07\ \mu Sv\ m^2\ MBq^{-1}\ h^{-1} \times A_A\ MBq \times 5.0\times10^{-3} / (1.2\ m)^2$
   $= 2.4\times10^{-4}\ A_A\ \mu Gy\ h^{-1}$
   measured value 80 $\mu Gy\ h^{-1}$
   activity of A $A_A = 80\ \mu Gy\ h^{-1} / 2.4\times10^{-4}\ \mu Gy\ h^{-1} = 3.3\times10^5$ MBq
3. $T_{½,A} >> 3\ d >> T_{½,B}$
   at the moment of delivery, B is thus in equilibrium with A, while A has barely decayed
   the activity of B $A_B = A_A = 3.3\times10^5$ MBq
4. from Figure 1 at 5 cm lead and nuclide B:
   transmission $T_B = 8.0\times10^{-2}$
   thus H^* almost entirely determined by nuclide B
   without shielding at a distance of 1 m + (0.40 m / 2) = 1.2 m (1 m from the surface):
   $dH_B^*/dt = 0.23\ \mu Sv\ m^2\ MBq^{-1}\ h^{-1} \times 3.3\times10^5\ MBq / (1.2\ m)^2$
   $= 5.3\times10^4\ \mu Gy\ h^{-1} = 53\ mGy\ h^{-1}$
   limit 0.1 mSv/h
   required transmission $T_B = 0.1\ mGy\ h^{-1} / 53\ mGy\ h^{-1} = 1.9\times10^{-3}$
   from Figure 1 at 1.9×10^{-3} and nuclide B wall thickness = 12.2 cm lead
   without shielding at a distance of 0,40 m / 2 = 0,2 m (at the surface):
   $dH_B^*/dt = 0.23\ \mu Sv\ m^2\ MBq^{-1}\ h^{-1} \times 3.3\times10^5\ MBq / (0.2\ m)^2$
   $= 1.9\times10^6\ \mu Gy\ h^{-1} = 1900\ mGy\ h^{-1}$
   required transmission $T_B = 2\ mGy\ h^{-1} / 1900\ mGy\ h^{-1} = 1.1\times10^{-3}$
   from Figure 1 at 1.1×10^{-3} and nuclide B wall thickness = 13.3 cm lead
   thus H^* at the surface is determinant; rounding off to whole centimeters gives 14 cm lead
   from Figure 1 at 14 cm lead and nuclide A transmission = $T_A < 1.0\times10^{-6} << T_B$
   thus the contribution of nuclide A is negligible
5. inner radius of lead = 1 cm
   outer radius of lead = wall thickness + 1 cm
   mass = $(4\pi/3) \times (R_{outer}^3 - R_{inner}^3) \times \rho_{lead}$
   ρ_{lead} = 11 359 kg m^{-3} = 11.35 g cm^{-3}
   used container $(4\pi/3) \times [(6\ cm)^3 - (1\ cm)^3] \times 11.35\ g\ cm^{-3} = 1.0\times10^4\ g = 10\ kg$
   required container $(4\pi/3) \times [(15\ cm)^3 - (1\ cm)^3] \times 11.35\ g\ cm^{-3} = 1.6\times10^5\ g = 160\ kg$

Problem 30

The outer radius of the container with a wall thickness (in m) and a bore of 1 cm = 0.01 m
$r = d + (0.01\ m / 2) = d + 0.005\ m$

1. the wall thickness follows from:
   $dK/dt = k\, A\, T(d) / r^2$
   $= 0.305\ \mu Gy\ m^2\ MBq^{-1}\ h^{-1} \times 10\ MBq \times T(d) / (d + 0.005\ m)^2$
   $\leq 50\ \mu Gy\ h^{-1}$
   $T(d) / (d + 0.005\ m)^2 \leq 50\ \mu Gy\ h^{-1} / (0.305\ \mu Gy\ m^2\ MBq^{-1}\ h^{-1} \times 10\ MBq) = 16.4\ m^{-2}$
   the transmission $T(d)$ follows from Figure 1 for lead:

$d = 0.050$ m
$T(5) = 7.5\times10^{-2}$
$T(5)$ / (0.050 m + 0.005 m)^2 = 7.5×10^{-2} / (0.055 m)^2 = 24.8 m^{-2} > 16.4 m^{-2}
$d = 0.055$ m
$T(5{,}5) = 5.8\times10^{-2}$
$T(5{,}5)$ / (0.055 m + 0.005 m)^2 = 5.8×10^{-2} / (0.060 m)^2 = 16.1 m^{-2} < 16.4 m^{-2}
$d = 0.060$ m
$T(6) = 4.4\times10^{-2}$
$T(6)$ / (0,060 m + 0.005 m)^2 = 4.4×10^{-2} / (0.065 m)^2 = 10.4 m^2 < 16.4 m^{-2}
thus d(Pb) = 5.5 cm is sufficient

2. the kerma rate at the surface of uranium is 20 μGy h^{-1}; the wall thickness follows from:
$\mathrm{d}K/\mathrm{d}t = k\,A\,T(d) / r^2$
= 0.305 μGy m^2 MBq^{-1} h^{-1} × 10 MBq × $T(d)$ / (d + 0.005 m)^2
≤ 50 μGy h^{-1} - 20 μGy h^{-1} = 30 μGy h^{-1}
$T(d)$ / (d + 0.005 m)^2 ≤ 30 μGy/h / (0.305 μGy m^2 MBq^{-1} h^{-1} × 10 MBq) = 9.8 m^{-2}
the transmission $T(d)$ follows from Figure 1 for uranium:
$d = 0.030$ m
$T(3) = 3.1\times10^{-2}$
$T(3)$ / (0.030 m + 0.005 m)^2 = 3.1×10^{-2} / (0.035 m)^2 = 25.3 m^{-2} > 9.8 m^{-2}
$d = 0.035$ m
$T(3{,}5) = 1.7\times10^{-2}$
$T(3.5)$ / (0,.035 m + 0.005 m)^2 = 1.7×10^{-2} / (0.040 m)^2 = 10.6 m^{-2} > 9.8 m^{-2}
$d = 0.040$ m
$T(4) = 9.8\times10^{-3}$
$T(4)$ / (0.040 m + 0.005 m)^2 = 9.8×10^{-3} / (0.045 m)^2 = 4.8 m^{-2} < 9.8 m^{-2}
thus d(U) = 4.0 cm is sufficient

3. volume entire container V_{outside} = π × (d + 0.5 cm)^2 × (10 cm + 2 × d)
volume of the hollow V_{inside} = π × (0.5 cm)^2 × 10 cm = 2.5π cm^3
mass M = ($V_{\mathrm{outside}} - V_{\mathrm{inside}}$) × ρ
lead (d = 5.5 cm) M = π × [(6.0 cm)^2 × 21 cm - 2.5 cm^3] × 11.35 g cm^{-3}
= 26.9×10^3 g = 26.9 kg
4. uranium (d = 4 cm) M = π × [(4.5 cm)^2 × 18 cm - 2.5 cm^3] × 18.9 g cm^{-3}
= 21.5×10^3 g = 21.5 kg
5. $A = \lambda \times N = \lambda$ × (mass / atomic weight) × abundance × N_{Avogadro}
λ(^{238}U) = 0,693 / (4.468×10^9 y × 365 d y^{-1} × 24 h d^{-1} × 3600 s h^{-1}) = 4.9×10^{-18} s^{-1}
A(^{238}U) = 4.9×10^{-18} s^{-1} × (21.5×10^3 g / 238.03 g mol^{-1}) × 99.75×10^{-2} × 6.02×10^{23} mol^{-1}
= 2.66×10^8 Bq = 266 MBq
λ(^{235}U) = 0.693 / (7.038×10^8 y × 365 d y^{-1} × 24 h d^{-1} × 3600 s h^{-1}) = $3{,}1\times10^{-17}$ s^{-1}
A(^{235}U) = 3.1×10^{-17} s^{-1} × (21.5×10^3 g / 238.03 g mol^{-1}) × 0.25×10^{-2} × 6.02×10^{23} mol^{-1}
= 4.21×10^6 Bq = 4 MBq
total activity = 266 MBq + 4 MBq = 270 MBq

Problem 31

1. the capture of $^{24}Na^+$-ions can be described by the differential equation:
$\mathrm{d}A/\mathrm{d}t + \lambda A = P$
$T_{½}$ = 14.96 h = 0.09 week << 1 week, thus after 1 week there is almost complete equilibrium
in the equilibrium situation $\mathrm{d}A/\mathrm{d}t = 0$, thus $\lambda A_{\mathrm{equilibrium}} = P$
P = 4.0 m^3 h^{-1} × 40 MBq m^{-3} × 95×10^{-2} = 152 MBq h^{-1}
λ = 0.693 / 14.96 h = 0,046 h^{-1}
$A_{\mathrm{equilibrium}} = P / \lambda$ = 152 MBq h^{-1} / 0.046 h^{-1} = 3.3×10^3 MBq = 3.3 GBq

2. $dK/dt = 0.43\ \mu Gy\ m^2\ MBq^{-1}\ h^{-1} \times 3.3\times10^3\ MBq\ /\ (2\ m)^2 = 355\ \mu Gy\ h^{-1}$
3. required transmission $T = 1\ \mu Gy/h\ /\ 355\ \mu Gy/h = 2.8\times10^{-3}$
   from Figure 1 86 cm regular concrete, of 55 cm barite concrete

Problem 32

1. $dK/dt = 0.077\ \mu Gy\ m^2\ MBq^{-1}\ h^{-1} \times 1\times10^3\ MBq\ /\ (0.5\ m)^2$
   $= 308\ \mu Gy\ h^{-1} = 3.08\times10^{-4}\ Gy\ h^{-1}$
   required transmission $T = 10\ \mu Gy\ h^{-1}\ /\ 308\ \mu Gy\ h^{-1} = 3.2\times10^{-2}$
   from Figure 31 $d = 3.3$ cm
2. the scattered photons have lost energy and thus do not contribute to the photopeak at 0.66 MeV
   for Question 3, the build-up factor does not need to be taken into account and therefore no transmission graphs may be used
3. $\varphi = A \times f_\gamma \times f_{abs,concrete} \times f_{abs,lead}\ /\ (4\pi\ r^2)$
   concrete $(\mu/\rho) \times (d \times \rho) = 7.7\times10^{-3}\ m^2\ kg^{-1} \times 20\times10^{-2}\ m \times 2350\ kg\ m^{-3} = 3.62$
   $f_{abs,concrete} = e^{-3.62} = 2.7\times10^{-2}$
   lead $(\mu/\rho) \times (d \times \rho) = 10.8\times10^{-3}\ m^2\ kg^{-1} \times 10\times10^{-2}\ m \times 11\ 350\ kg\ m^{-3} = 12.26$
   $f_{abs,concrete} = e^{-12.26} = 4.7\times10^{-6}$
   $\varphi = 1\times10^9\ Bq \times (0.946 \times 0.898) \times 2.7\times10^{-2} \times 4.7\times10^{-6}\ /\ [4\pi \times (5\ m)^2] = 0.34\ m^{-2}\ s^{-1}$
4. surface area of detector $O = 10\ cm \times 10\ cm = 100\ cm^2 = 0.010\ m^2$
   number of photons at detector $dN/dt = \varphi \times O = 0.34\ m^{-2}\ s^{-1} \times 0.010\ m^2 = 3.4\times10^{-3}\ s^{-1}$
   NaI $(\mu/\rho) \times (d \times \rho) = 7.6\times10^{-3}\ m^2\ kg^{-1} \times 10\times10^{-2}\ m \times 3670\ kg\ m^{-3} = 2.79$
   detector efficiency
   ε = (1 - transmission) × (relative photopeak efficiency)
   $= (1 - e^{-2.79}) \times (60\ /\ 100) = 0.56$
   counting rate $T = dN/dt \times \varepsilon = 3.4\times10^{-3}\ s^{-1} \times 0.56 = 1.9\times10^{-3}$ cps $< 10^{-2}$ cps
   there is thus no extra lead shielding necessary

μ

Problem 33

1. $dK_{direct}/dt = k\ A\ /\ r^2$
   $= 0.305\ \mu Gy\ m^2\ MBq^{-1}\ h^{-1} \times 75\times10^3\ MBq\ /\ (5\ m)^2 = 9.15\times10^2\ \mu Gy\ h^{-1}$
2. distance from source to wall 8 m - 1 m = 7 m
   kerma rate at the wall $dK_{wall}/dt = k\ A\ /\ r^2$
   $= 0.305\ \mu Gy\ m^2\ MBq^{-1}\ h^{-1} \times 75\times10^3\ MBq\ /\ (7\ m)^2$
   $= 4.,67\times10^2\ \mu Gy\ h^{-1}$
   beam spot at 1 m $\pi\ r^2 = \pi \times (15\ cm\ /\ 2)^2 = 177\ cm^2$
   beam spot at the wall $177\ cm^2 \times (7\ m\ /\ 1\ m)^2 = 8.7\times10^3\ cm^2$
   from Figure 44 scattering factor = 0.0125% per 100 cm² at 1 m
   distance from the wall 8 m - (1 m + 5 m) = 2 m
   $dK_{scatter}/dt$
   $= dK_{wall}/dt$ × scattering factor × (beam spot at the wall / 100 cm²) × (1 m / r)²
   $= 4.67\times10^2\ \mu Gy\ h^{-1} \times 0.0125\times10^{-2} \times (8.7\times10^3\ cm^2\ /\ 100\ cm^2) \times (1\ m\ /\ 2\ m)^2$
   $= 1.27\ \mu Gy\ h^{-1}$
3. distance from P to the source x
   distance from wall to P $8\ m - (1\ m + x) = 7\ m - x$
   $dK_{direct}/dt = 9.15\times10^2\ \mu Gy\ h^{-1} \times (5\ m\ /\ x)^2 = 2.3\times10^4\ \mu Gy\ m^2\ h^{-1}\ /\ x^2$ (see Question 1)
   $dK_{scatter}/dt = 1.27\ \mu Gy\ h^{-1} \times [\ 2\ m\ /\ (7\ m - x)]^2 = 5.1\ \mu Gy\ m^2\ h^{-1}\ /\ (7\ m - x)^2$ (see Question 2)

   the distance from the source to the wall does not play a role in the calculation of the scatter radiation: although K_{wall} decreases with $1/r^2$, the surface of the beam spot on the wall increases with r^2 and thus $K_{scatter}$ at 1 meter from the wall is independent of r solve now for x in the equation $\mathrm{d}K_{\mathrm{scatter}}/\mathrm{d}t < 10^{-2} \times \mathrm{d}K_{\mathrm{direct}}/\mathrm{d}t$

$5.1 / (7\ \mathrm{m} - x)^2 < 10^{-2} \times 2.3{\times}10^4 / x^2 = 230 / x^2$

$x^2 / (7\ \mathrm{m} - x)^2 < 230 / 5.1 = 45$

$x / (7\ \mathrm{m} - x) < \sqrt{45} = 6.7$

$x < 6.7 \times (7\ \mathrm{m} - x) = 47\ \mathrm{m} - 6.7x$

$x < 47\ \mathrm{m} / (1 + 6.7) = 47\ \mathrm{m} / 7.7 = 6.1\ \mathrm{m}$

Problem 34

1. after transmission through lead, there is relatively little scatter radiation in the beam
   the transmitted spectrum is therefore nearly equal to the primary spectrum of ^{60}Co
2. from Figure 31 at 10 cm lead $T_{\mathrm{lead}} = 4.5{\times}10^{-3}$
   from Figure 33 at 50 cm concrete $T_{\mathrm{concrete}} = 9.0{\times}10^{-3}$
   $\mathrm{d}K/\mathrm{d}t = k\,A\,T_{\mathrm{lead}}\,T_{\mathrm{concrete}} / r^2$
   $= 0.305\ \mu\mathrm{Gy\ m^2\ MBq^{-1}\ h^{-1}} \times 1.5{\times}10^6\ \mathrm{MBq} \times 4.5{\times}10^{-3} \times 9.0{\times}10^{-3} / (2.5\ \mathrm{m})^2$
   $= 2.96\ \mu\mathrm{Gy\ h^{-1}}$
3. distance to wall 4 m
   kerma rate at wall $\mathrm{d}K_{\mathrm{wall}}/\mathrm{d}t = 0.305\ \mu\mathrm{Gy\ m^2\ MBq^{-1}\ h^{-1}} \times 1.5{\times}10^6\ \mathrm{MBq} / (4\ \mathrm{m})^2$
   $= 2.86{\times}10^4\ \mu\mathrm{Gy\ h^{-1}}$
   beam spot at 50 cm 100 cm^2
   beam spot at wall $100\ \mathrm{cm}^2 \times (4\ \mathrm{m} / 0.5\ \mathrm{m})^2 = 6.4{\times}10^3\ \mathrm{cm}^2$
   scattering angle $180° - \arctan(2.5 / 4.0) = 180° - 32° = 148°$
   from Figure 44 scattering factor = 0.012% per 100 cm^2 at 1 m
   distance from the wall $\sqrt{[(4\ \mathrm{m})^2 + (2.5\ \mathrm{m})^2]} = 4.7\ \mathrm{m}$
   $\mathrm{d}K_{\mathrm{scatter}}/\mathrm{d}t$
   $= \mathrm{d}K_{\mathrm{wall}}/\mathrm{d}t \times$ scattering factor $\times$ (beam spot at the wall / 100 cm^2) $\times (1\ \mathrm{m} / r)^2$
   $= 2.86{\times}10^4\ \mu\mathrm{Gy\ h^{-1}} \times 0.012{\times}10^{-2} \times (6.4{\times}10^3\ \mathrm{cm}^2 / 100\ \mathrm{cm}^2) \times (1\ \mathrm{m} / 4.7\ \mathrm{m})^2$
   $= 9.9\ \mu\mathrm{Gy\ h^{-1}}$

Problem 35

1. leakage radiation at r = 2.1 m:
   weekly dose $D_{\mathrm{leak}}(2.1) = \mathrm{d}D_{\mathrm{leak}}(1)/\mathrm{d}t \times t \times (1\ \mathrm{m} / r)^2$
   $= 2\ \mathrm{mGy\ h^{-1}} \times 20\ \mathrm{h/wk} \times (1\ \mathrm{m} / 2.1\ \mathrm{m})^2$
   $= 9.1\ \mathrm{mGy\ wk^{-1}}$
   effective weekly dose $E_{\mathrm{leak}}(2.1) = D_{\mathrm{leak}}(2.1) \times 1\ \mathrm{Sv\ Gy^{-1}} = 9.1\ \mathrm{mSv\ wk^{-1}}$
   required transmission $T = 0.02\ \mathrm{mSv\ wk^{-1}} / 9.1\ \mathrm{mSv\ wk^{-1}} = 2.2{\times}10^{-3}$
   from Figure 33 d = 65 cm concrete
   scatter radiation at r = 2 m:
   distance to patient 0.6 m
   weekly dose at the patient $D(0.6) = \mathrm{d}D(1)/\mathrm{d}t \times t \times (1\ \mathrm{m} / r)^2$
   $= 100\ \mathrm{Gy\ h^{-1}} \times (20 / 4)\ \mathrm{h\ wk^{-1}} \times (1\ \mathrm{m} / 0.6\ \mathrm{m})^2$
   $= 1.4{\times}10^3\ \mathrm{Gy\ wk^{-1}}$
   beam spot 20 cm × 20 cm = 400 cm^2
   from Figure 44 at 90° scattering factor = 0.002% per 100 cm^2 at 1 m
   distance from the patient 2 m
   $D_{\mathrm{scattered}}(2)$
   $= D(0.6) \times$ scattering factor $\times$ (beam spot / 100 cm^2) $\times (1\ \mathrm{m} / r)^2$
   $= 1.4{\times}10^3\ \mathrm{Gy\ wk^{-1}} \times 0.002{\times}10^{-2} \times (400\ \mathrm{cm}^2 / 100\ \mathrm{cm}^2) \times (1\ \mathrm{m} / 2\ \mathrm{m})^2$
   $= 0.028\ \mathrm{Gy\ wk^{-1}}$
   $E_{\mathrm{scattered}}(2) = D_{\mathrm{scattered}}(2) \times 1\ \mathrm{Sv\ Gy^{-1}} = 0.028\ \mathrm{Sv\ wk^{-1}} = 28\ \mathrm{mSv\ wk^{-1}}$
   required transmission $T = 0.02\ \mathrm{mSv\ wk^{-1}} / 28\ \mathrm{mSv\ wk^{-1}} = 7.1{\times}10^{-4}$
   from Figure 38 at 90° d = 42 cm concrete, thus the leakage radiation is determinant

2. direct dose at $r = 5$ m
   - weekly dose $D(5) = \mathrm{d}D(1)/\mathrm{d}t \times t \times (1\ \mathrm{m} / r)^2$
     $= 100\ \mathrm{Gy\ h^{-1}} \times (20 / 4)\ \mathrm{h\ wk^{-1}} \times (1\ \mathrm{m} / 5\ \mathrm{m})^2$
     $= 20\ \mathrm{Gy\ wk^{-1}}$
   - effective weekly dose $E(5) = D(5) \times 1\ \mathrm{Sv\ Gy^{-1}} = 20\ \mathrm{Sv\ wk^{-1}} = 2.0\times10^4\ \mathrm{mSv\ wk^{-1}}$
   - required transmission $T = 0.02\ \mathrm{mSv\ wk^{-1}} / 2.0\times10^4\ \mathrm{mSv\ wk^{-1}} = 1.0\times10^{-6}$
   - from Figure 33 $d = 130$ cm concrete
   - according to Question 1, 65 cm of concrete was sufficient for leakage radiation at 2.1 m thus 130 cm at 5 m is definitely sufficient
3. shortest distance to the parking lot 5 m + 10 m = 15 m
   maximal effective yearly dose:
   ID = (weekly limit at point B) $\times$ 50 wk $\mathrm{y^{-1}} \times (5\ \mathrm{m} / 15\ \mathrm{m})^2$
   $= 0.02\ \mathrm{mSv\ wk^{-1}} \times 50\ \mathrm{wk\ y^{-1}} / 9 = 0.11\ \mathrm{mSv\ y^{-1}}$
   maximal value AID:
   AID = ID $\times$ ABC $= 0.11\ \mathrm{mSv\ y^{-1}} \times 0.01 = 1.1\times10^{-3}\ \mathrm{mSv\ y^{-1}} = 1.1\ \mathrm{\mu Sv\ y^{-1}}$

Problem 36

1. from Figure 2 at 10 MeV 6 cm water
2. current density $1\ \mathrm{nA} / 10\ \mathrm{cm^2} = 1.0\times10^{-10}\ \mathrm{C\ s^{-1}\ cm^{-2}}$
   fluence rate $1.0\times10^{-10}\ \mathrm{C\ s^{-1}\ cm^{-2}} / 1.6\times10^{-19}\ \mathrm{C} = 6.25\times10^8\ \mathrm{cm^{-2}\ s^{-1}}$
   from Figure 1 at 10 MeV $4.2\times10^{-10}\ \mathrm{Sv\ cm^2}$
   equivalent dose rate $6.25\times10^8\ \mathrm{cm^{-2}\ s^{-1}} \times 4.2\times10^{-10}\ \mathrm{Sv\ cm^2} = 0.26\ \mathrm{Sv\ s^{-1}}$
3. from Figure 2 at 30 MeV 17 cm water
   from Figure 1 at 30 MeV $3.4\times10^{-10}\ \mathrm{Sv\ cm^2}$
   equivalent dose rate $6.25\times10^8\ \mathrm{cm^{-2}\ s^{-1}} \times 3.4\times10^{-10}\ \mathrm{Sv\ cm^2} = 0.21\ \mathrm{Sv\ s^{-1}}$
4. from Figure 3 at 30 MV $700\ \mathrm{rad\ \mu A^{-1}\ min^{-1}} = 7\ \mathrm{Gy\ \mu A^{-1}\ min^{-1}}$ op 1 m
   required beam time $4\ \mathrm{Gy} / 7\ \mathrm{Gy\ \mu A^{-1}\ min^{-1}} = 0.57\ \mathrm{\mu A\ min} = 0.57$ min at 1 μA
5. weekly dose 200 times per week $\times$ 4 Gy per time $\times (1\ \mathrm{m} / 5\ \mathrm{m})^2 = 32\ \mathrm{Gy\ wk^{-1}}$
   required transmission $T = 0.04\ \mathrm{mGy\ wk^{-1}} \times 10^{-3}\ \mathrm{Gy\ mGy^{-1}} / 32\ \mathrm{Gy\ wk^{-1}} = 1.25\times10^{-6}$
   from Figure 39 31 cm lead
   from Figure 40 280 cm concrete
6. mass of the wall per $\mathrm{m^2}$ lead $2.7\ \mathrm{m} \times 11\,350\ \mathrm{kg\ m^{-3}} = 30\,645\ \mathrm{kg\ m^{-2}}$
   concrete $2.7\ \mathrm{m} \times 2350\ \mathrm{kg\ m^{-3}} = 6345\ \mathrm{kg\ m^{-2}}$
   floor load with lead is larger than the maximal permissible value of $10\,000\ \mathrm{kg\ m^{-2}}$
   thus use concrete

Problem 37

1. from Figure 41 at 100 kV and 2.5 mm Al 8 mGy per mA min at 1 m
   exposure time 60 s = 1 min
   anode current 0.5 mA
   primary dose 8 mGy per mA min $\times$ 0.5 mA $\times$ 1 min / $(1\ \mathrm{m})^2$ = 4 mGy at 1 m
   beam spot $30\ \mathrm{cm} \times 20\ \mathrm{cm} = 600\ \mathrm{cm^2}$
   scattered dose primary dose $\times$ scattering factor $\times$ (beam spot / 400 $\mathrm{cm^2}$)
   = 4 mGy $\times$ scattering factor $\times$ (600 $\mathrm{cm^2}$ / 400 $\mathrm{cm^2}$)
   = 6 $\times$ scattering factor (in mGy)

position	*angle*	*scattering factor*	*scattered dose (mGy)*
(A,F)	135°	0.0017	0.0102
(B,E)	90°	0.0005	0.0030
(C,D)	45°	0.0003	0.0018

2. from Figure 41 at 80 kV and 2.5 mm Al 5.5 mGy per mA min at 1 m
   exposure 90 mA s = 1.5 mA min
   primary dose D = 5.5 mGy per mA min × 1.5 mA min × (1 m / 0.85 m)^2 = 11.4 mGy
3. divide the weighting factor 0.12 evenly over the 13 organs of the remainder
   divide the weighting factor 0.12 in proportion to the masses of ULI and LLI

organ	w_T *(Sv Gy^{-1})*	$C_{f,T}$	$w_T \times C_{f,T}$ *(Sv Gy^{-1})*
breast tissue	0.12	0.01	0.00120
lungs	0.12	0.02	0.00240
spleen *	0.00923	0.13	0.00120
pancreas *	0.00923	0.24	0.00222
stomach wall	0.12	0.53	0.06360
small intestine *	0.00923	0.39	0.00360
upper large intestine #	0.068	0.45	0.03060
lower large intestine #	0.052	0.22	0.01144
gonads	0.20	0.29	0.05800
uterus *	0.00923	0.36	0.00332
red bone marrow	0.12	0.04	0.00480
bone surface	0.01	0.06	0.00060
total			0.183

* w_T = 0.12 / 13 = 0.00923
# w_T = 0.12 weighted with factor 210 g / 370 g = 0.57 and 160 g / 370 g = 0.43

$E = \sum (w_T \times H_T) = D \times \sum (w_T \times C_{f,T})$ = 11.4 mGy × 0.183 Sv Gy^{-1} = 2.1 mSv

<u>Problem 38</u>

1. from the legend in Figure 43 at 300 kV 20.9 mGy per mA min at 1 m
   tube voltage 10 mA
   distance 5 m
   kerma rate dK_{air}/dt = 20.9 mGy per mA min × 10 mA × (1 m / 5 m)^2
   = 8.4 mGy min^{-1}
   from Figure 26 at 300 keV $(\mu_{en}/\rho)_{air} = (\mu_{tr}/\rho)_{air}$ = 0.00287 m^2 kg^{-1}
   dose rate $dD_{air}/dt = dK_{air}/dt \times (\mu_{en} / \mu_{tr})_{air}$
   = 8.4 mGy min^{-1} × 1 = 8.4 mGy min^{-1}
2. from Figure 26 at 300 keV $(\mu_{en}/\rho)_{tissue}$ = 0.00315 m^2 kg^{-1}
   dose rate $dD_{tissue}/dt = dD_{air}/dt \times (\mu_{en}/\rho)_{tissue} / (\mu_{en}/\rho)_{air}$
   = 8.4 mGy min^{-1} × 0.00315 m^2 kg^{-1} / 0.00287 m^2 kg^{-1}
   = 9.2 mGy min^{-1}
3. For Question 2, the value D_{tissue} = 9.2 mGy is calculated for 10 mA × 1 min = 10 mA min
   work load W = 10 000 mA min wk^{-1} × 50 wk j^{-1} = 5×10^5 mA min
   use factor U = 0.5
   occupancy factor T = 1
   dose $(W\,U\,T$ / 10 mA min$) \times D_{tissue}$
   = (5×10^5 mA min × 0.5 × 1 / 10 mA min) × 9.2 mGy
   = 2.3×10^5 mGy y^{-1}
   legal yearly limit 1 mSv y^{-1} / 1 Sv Gy^{-1} = 1 mGy y^{-1}
   required transmission 1 mGy y^{-1} / 2.3×10^5 mGy y^{-1} = 4.3×10^{-6}
   desired yield 4.3×10^{-6} × 20.9 mGy per mA min = 9.0×10^{-5} mGy per mA min
   from Figure 43 at 300 kV and 9,0×10^{-5} mGy per mA min, it gives 52 cm concrete

Problem 39

1. according to the legend in Figure 42, the yield at 100 kV is 9.6 mGy per mA min at 1 m
   work load per year $W = 12.5\times10^3$ mA min wk^{-1} × 50 wk y^{-1} = 6.25×10^5 mA min
   distance r = 2 m + 0.5 m = 2,5 m
   kerma in air
   K_{air} = 9.6 mGy per mA min × 6.25×10^5 mA min × (1 m / 2.5 m)^2 = 9.6×10^5 mGy
   effective yearly dose $E \approx 9.6\times10^5$ mGy × 1 Sv Gy^{-1} = 9.6×10^5 mSv
   required transmission 1 mSv / 9.6×10^5 mSv = 1.0×10^{-6}
   from Figure 2 at 100 kV, it gives 31 cm concrete (rounded up to whole cm)
2. distance to the wall r = 2 m
   primary kerma
   K_{p} = 9.6 mGy per mA min × 6.25×10^5 mA min × (1 m / 2 m)^2 = 1.5×10^6 mGy
   beam spot $O = 2\times10^3$ cm^2
   from Figure 44 at 180° $C_{scatter} = 0.072\times10^{-2}$ per 100 cm^2 at 1 m
   distance to the wall r = 2 m + 2 m + 1 m = 5 m
   scatter kerma
   $K_{\text{scatter}} = K_{\text{p}} \times C_{\text{scatter}} \times (O$ / 100 cm$^2) \times (1\text{ m} / r)^2$
   = 1.5×10^6 mGy × 0.072×10^{-2} × (2×10^3 cm^2 / 100 cm^2) × (1 m / 5 m)^2 = 8.6×10^2 mGy
   effective yearly dose $E \approx 8.6\times10^2$ mGy × 1 Sv Gy^{-1} = 8.6×10^2 mSv
   required transmission 1 mSv / 8.6×10^2 mSv = 1.2×10^{-3}
   from Figure 2 at 70 kV, it gives 8 cm concrete
3. for the door, the same transmission applies as found in Question 2, but now for lead
   according to the legend in Figure 42, the yield at 75 kV is 6.1 mGy per mA min at 1 m
   desired yield is thus 1.2×10^{-3} × 6.1 mGy per mA min = 7.3×10^{-3} mGy per mA min
   from Figure 42 at 75 keV and 7.3×10^{-3} mGy per mA min, it gives 0.07 cm lead

Problem 40

1. flux 1×10^{11} s^{-1}
   distance to target r = 5 m = 500 cm
   fluence rate = flux density $d\Phi/dt = \varphi$ = flux / $(4\pi\, r^2)$
   = 1×10^{11} s^{-1} / [4π × (500 cm)^2]
   = 3.2×10^4 cm^{-2} s^{-1}
2. from Figure 2 at 14 MeV H^* / Φ = 520 pSv cm^2
   ambient dose equivalent rate dH^*/dt = 520 pSv cm^2 × $d\Phi/dt$ = 520 pSv cm^2 × φ
   = 520 pSv cm^2 × 3.2×10^4 cm^{-2} s^{-1}
   = 1.66×10^7 pSv s^{-1} = 6.0×10^{10} pSv h^{-1} = 6.0×10^4 µSv h^{-1}
3. transmission through concrete $T_{\text{concrete}} = 6.6e^{-d/13}$
   required transmission 1 µSv h^{-1} / 6.0×10^4 µSv h^{-1} = 1.7×10^{-5} = $6.6e^{-d/13}$
   required thickness of concrete d = 13 cm × ln(6.6 / 1.7×10^{-5}) = 13 cm × 12.9 = 168 cm (rounded up to whole cm)
   there is a wall of 25 cm concrete, so what's missing is 168 cm - 25 cm = 143 cm concrete
   this can be replaced by 2 × 143 cm = 286 cm earth
4. transmission through wall $T_{\text{wall}} = 6.6e^{-150/13} = 6.4\times10^{-5}$
   distance to target r = 10 cm + 150 cm = 160 cm
   fluence rate = flux density $d\Phi/dt = \varphi$ = flux × T_{wall} / $(4\pi\, r^2)$
   = 1×10^{11} s^{-1} × 6.4×10^{-5} / [4π × (160 cm)^2]
   = 20 cm^{-2} s^{-1}
   ambient dose equivalent rate
   dH^*/dt = 520 pSv cm^2 × $d\Phi/dt$ = 520 pSv cm^2 × φ = 520 pSv cm^2 × 20 cm^{-2} s^{-1}
   = 1.04×10^4 pSv s^{-1} = 3.7×10^{-5} Sv h^{-1} = 37 µSv h^{-1} > 10 µSv h^{-1}
   the shielding is thus insufficient

INTERNAL EXPOSURE

Formulas used in dosimetry of internal exposure

The retention is described by a sum of exponential functions:

$$R(t) = C_1 e^{-0.693\, t/T_{½,1}} + C_2 e^{-0.693\, t/T_{½,2}} + \ldots + C_n e^{-0.693\, t/T_{½,n}}$$

with $\sum_n C_n = 1$

The first term in this series usually describes the direct excretion into the urine from the transfer compartment.

The number of disintegrations in source organ *S*:

$$U_S = f_1 C_S A_S(0) \int_{t_0}^{t_0+50} e^{-0.693\, t/T_{½}^{eff}} dt \approx f_1 C_S A_S(0) T_{½}^{eff}/0.693 \quad \text{(in Bq s)}$$

In this equation, $A_S(0)$ is the initial activity in source organ *S*. The approximation is valid if the effective half-life is much shorter than 50 years. Note that:

$$\frac{1}{T_{½}^{eff}} = \frac{1}{T_{½}^{biol}} + \frac{1}{T_{½}^{phys}}$$

The specific effective energy that is deposited from source organ *S* into target organ *T* per disintegration is:

$$SEE(T \leftarrow S) = Y \times E \times SAF(T \leftarrow S) \quad \text{(in MeV g}^{-1}\text{)}$$
$$SAF(T \leftarrow S) = AF(T \leftarrow S)/m_T \quad \text{(in g}^{-1}\text{)}$$

With the exception of the gastro-intestinal model and the bone model, we have for α- and β-radiation,:

$$AF(T \leftarrow S) = 1 \quad \text{if } T = S$$
$$AF(T \leftarrow S) = 0 \quad \text{if } T \neq S$$

The equivalent committed dose in target organ *T* is obtained by summing all the source organs *S* and all the radiation types *i*:

$$H_{50,T} = 1.6 \times 10^{-10} \sum_{S,i} U_{S,i} w_{R,i} SEE_i(T \leftarrow S) \quad \text{(in Sv)}$$

The effective committed dose follows from a weighted summation of all the target organs:

$$E_{50} = \sum_T w_T H_{50,T} \quad \text{(in Sv)}$$

41. Equivalent organ dose due to ^{198}Au in the liver

As a result of internal contamination, one finds at a certain moment 1.0 MBq ^{198}Au in the liver.

Given:

- the radioactive decay of ^{198}Au (see Figure 1)
- the masses of source and target organs of the reference man (see Appendix, Figure 46)
- specific absorbed fractions SAF for the source organ liver (see Appendix, Figure 48)
- the biological half-life is 3 d for all organs

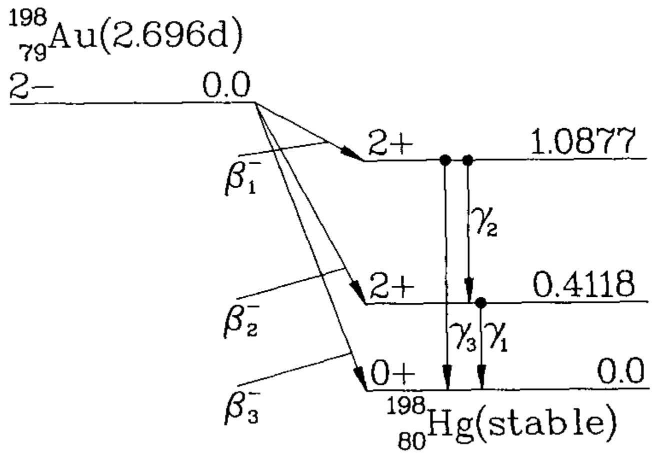
Questions:

1. Calculate the number of disintegrations U_S in the liver (in Bq s).

2. Calculate the average energy that is deposited in the liver per disintegration (in MeV per Bq s).

3. Calculate the specific effective energy *SEE*(liver←liver).

4. Calculate the equivalent committed dose $H_T(50)$ in the liver.



79-GOLD-198

HALFLIFE = 2.696 DAYS 22-DEC-78
DECAY MODE(S): β^-

RADIATION	y(i) $(Bq-s)^{-1}$	E(i) (MeV)	y(i)×E(i)
β^- 1	1.30E-02	7.982E-02*	1.04E-03
β^- 2	9.87E-01	3.150E-01*	3.11E-01
γ 1	9.55E-01	4.118E-01	3.93E-01
ce-K, γ 1	2.88E-02	3.287E-01	9.46E-03
ce-L_1, γ 1	4.07E-03	3.970E-01	1.61E-03
ce-L_2, γ 1	4.29E-03	3.976E-01	1.71E-03
ce-L_3, γ 1	1.84E-03	3.995E-01	7.37E-04
ce-M, γ 1	2.54E-03	4.089E-01*	1.04E-03
γ 2	1.06E-02	6.759E-01	7.16E-03
γ 3	2.29E-03	1.088E 00	2.49E-03
$K\alpha_1$ X-ray	1.38E-02	7.082E-02	9.75E-04
$K\alpha_2$ X-ray	8.10E-03	6.889E-02	5.58E-04

LISTED X, γ AND $\gamma\pm$ RADIATIONS	4.04E-01
OMITTED X, γ AND $\gamma\pm$ RADIATIONS**	6.32E-04
LISTED β, ce AND Auger RADIATIONS	3.26E-01
OMITTED β, ce AND Auger RADIATIONS**	1.02E-03
LISTED RADIATIONS	7.31E-01
OMITTED RADIATIONS**	1.66E-03

* AVERAGE ENERGY (MeV)
** EACH OMITTED TRANSITION CONTRIBUTES <0.100% TO $\Sigma y(i)\times E(i)$ IN ITS CATEGORY.
MERCURY-198 DAUGHTER IS STABLE.

Figure 1. Radioactive decay of ^{198}Au.

42. ^{87}Rb in food (1993-2-1)

The element rubidium appears as a trace element in food. ICRP-23 estimates that the daily intake is 2.2 mg. Rubidium is slightly radioactive as a result of the presence of the long-lived radionuclide ^{87}Rb.

Given:
- a number of radiation protection details of ^{87}Rb (see Appendix, Figure 14)
- to limit the calculations, you may assume that rubidium distributes equally over the entire body from the blood stream
- the atomic weight of Rb is 85,5 g mol^{-1}
- naturally-occurring Rb contains 27,8 atomic% ^{87}Rb
- Avogadro's number is $6{,}02\times10^{23}$ mol^{-1}
- the masses of source and target organs from the reference man (see Appendix, Figure 46)

Questions:

1. Calculate the specific activity of the element Rb (in Bq g^{-1}).

2. Calculate the effective committed dose starting from the yearly intake via ingestion of ^{87}Rb (in Bq).

3. Calculate the effective commited dose starting from the given value of $e_{\text{ing}}(50)$.

4. Calculate the equilibrium activity of ^{87}Rb in the body as a result of the yearly intake.

5. Calculate the number of disintegrations U_S in the body per Bq of intake.

6. Calculate the specific effective energy *SEE*.

7. Calculate $e_{\text{ing}}(50)$ starting from the calculated values of U_S and *SEE* obtained from Questions 5 and 6.

43. Calculating the *e*(50) of ^{35}S for an adult

The radionuclide ^{35}S is widely used in biomedical research.

Given:
- a number of radiation protection details of ^{35}S (see Appendix, Figure 4)
- assume that sulfur is administered as an organic compound
- "all organs/tissues" means the entire body
- the masses of source and target organs for the reference man (see Appendix, Figure 46)

Questions:

1. Calculate the number of disintegrations U_S (in Bq s) per Bq of ingestion.

2. Calculate the specific effective energy *SEE* (in MeV g^{-1} per Bq s).

3. Calculate the effective committed dose E_{50} per Bq of ingestion, starting from the values of U_S and *SEE* calculated in Questions 1 and 2.

4. To what is the difference between E_{50} and $e_{ing}(50)$ attributable?

44. Calculating the $e(50)$ of ^{35}S for a baby (1980-1-3)

Humans absorb the element sulfur via the food chain as a building block for amino acids. For a 6 month-old baby, uptake of this element occurs only via milk. As a result of discharges from nuclear reactors, minimal quantities of the radionuclide ^{35}S may end up in the environment and milk, which therefore increases the risk of internal contamination.

Because the metabolic model for children deviates from that for adults, an estimate for $e_{ing}(50)$ for infants is made in this Problem.

Given:

- $T_{½}(^{35}S)$ = 87.44 d
- ^{35}S emits only β^--particles with an average energy 0.049 MeV
- sulfur distributes itself homogeneously over the entire body
- excretion of sulfur is described by a single exponential function
- according to ICRP-56, f_1 = 1 for a 3-month-old baby; assume for this Problem that this also applies for a baby of 6 months
- for a reference baby: the mass of the body is 7700 g, the sulfur content of the body is 500 mg kg^{-1}, milk consumption is 700 g per day, and the sulfur content of milk is 140 mg kg^{-1} milk
- in this problem, the weight of the baby, the milk consumption and the sulfur uptake are set to be constant

Questions:

1. Calculate the biological half-life of sulfur in the body for this group of infants.

2. Calculate the number of disintegrations U_S in the body per Bq of intake.

3. Calculate the specific effective energy *SEE*.

4. Calculate $e_{ing}(50)$ of ^{35}S for this group of infants, starting with the calculated values of U_S and *SEE* from Questions 2 and 3. Compare the result with the effective dose coefficient for adults (see Appendix, Figure 4).

45. Calculating the *e*(50) of ^3H for an adult

The radionuclide ^3H is widely used in biomedical research.

Given:

- a number of radiation protection details of ^3H (see Appendix, Figure 1)
- "all organs/tissues" refers to the entire body
- the masses of source and target organs of the reference man (see Appendix, Figure 46)

Questions:

1. Calculate the number of disintegrations U_S per Bq of inhalation.

2. Calculate the specific effective energy *SEE*.

3. Calculate $e_{inh}(50)$ starting from the values of U_S and *SEE* calculated in Questions 1 and 2.

46. Calculating the *e*(50) of ^{3}H for a child (1991-2-4)

To determine the dose of the general public as a consequence of the discharge of radioactive materials into air and water, it is necessary to know the effective dose coefficients for people of different ages. Several models were developed in ICRP-56, including one for a reference child of 1 year old.

Given:
- $T_{½}(^3H)$ = 12.35 y
- ^{3}H emits only β^--particles with an average energy of 0.0057 MeV
- tritium oxide distributes homogeneously almost immediately throughout the entire body
- the metabolic model for a one-year-old child consists of two compartments which both encompass the entire body; the distribution to the compartments is as follows: 97% with a biological half-life of 3.5 d and 3% with a biological half-life of 15 d
- the mass of a one-year-old reference child amounts to 9800 g

Questions:

1. Calculate the number of disintegrations U_S in the body of a one-year-old child per Bq of ingestion.

2. Calculate the specific effective energy *SEE*.

3. Calculate $e_{ing}(50)$ for a one-year-old child, starting from the values of U_S and *SEE* determined in Questions 1 and 2. Compare the result with the effective dose coefficient for adults (see Appendix, Figure 1).

47. Inhalation of tritiated water vapor

Water vapor containing 30 MBq ^3H is discharged per hour from the hall of a pool reactor.

Given:

- the flow rate of the ventilation system amounts to 2000 m^3 per hour
- assume for this Problem that the breathing rate is 1.2 $m^3\ h^{-1}$
- for a breathing rate of 1.2 $m^3\ h^{-1}$, the effective uptake is 50% larger than the inhaled activity as a result of the uptake of tritium through the skin
- the water balance of the reference man is:
  - 1.4 $l\ d^{-1}$ urine
  - 0.65 $l\ d^{-1}$ sweat
  - 0.95 $l\ d^{-1}$ other bodily fluids
- the effective dose coefficient for inhalation is $e_{inh}(50) = 1{,}8\times10^{-11}$ Sv Bq^{-1}

Questions:

1. Calculate the effective commited dose of an employee who works for 2000 hours per year in the hall.

2. Calculate the activity concentration of tritium in the urine of this employee.

48. Internal contamination with ^3H (1987-2-2)

During testing of urine for internal contamination by tritium, an exposed worker is found to have an increased concentration of tritium. Further investigation determined that this worker wears a watch that has tritium-containing luminous paint.

The counting samples contain 8 ml of urine. The counting efficiency of the measuring device amounts to 40%. The urine analysis yields a gross counting rate of 14.0 counts per minute (cpm). A measurement using 8 ml of distilled water yields a counting rate of 1.2 cpm.

Subsequently, the watch is removed and stored. After the removal of the watch, the gross counting rates are:

time (d)	*gross counting rate (cpm)*
7	9.6
14	6.8
21	5.0
28	3.4
63	1.4

Given:

- $T_{½}(^3H) = 12.35$ y
- the standard human contains 42 l body liquid
- the water balance of the reference man is:
  1.4 l d^{-1} urine
  0.65 l d^{-1} sweat
  0.95 l d^{-1} other bodily fluids
- the effective dose coefficient is $e(50) = 1.8{\times}10^{-11}$ Sv Bq^{-1}

Questions:

1. Calculate the activity concentration in Bq ml^{-1}. Plot these values on single-logarithmic graph paper and determine the effective half-life.

2. Calculate the annual effective commited dose befor the removal of the watch, assuming that the equilibrium state had occurred before the watch was removed.

3. Calculate the effective committed dose in the case that this measurement was related to a one-time intake just before the production of the first urine sample.

49. Tritium oxide in the air (1985-2-3)

Tritium compounds in animals are for the most part catabolized, after which the tritium is released as tritiated water. The expert from a C-laboratory with animal facilities tries to understand the potential internal exposure of the animal caretaker due to breathing contaminated air, and therefore measures tritium from the air and from the urine of this worker. The animal facility is kept at 24 °C with a relative humidity of 80%.

The tritium concentration in air is determined by freezing water vapor on a cold surface. Counting vials are filled with 1.0 ml of this water, and then filled with counting fluid. These samples yield an average counting rate of 80 counts per minute (cpm). The urine samples yield an average counting rate of 50 cpm from 10 ml urine.

Given:

- at 24 °C, saturated air contains 22 g water per m^3 air
- the liquid scintillation counter has a zero effect in the tritium channel of 20 cpm
- the counting efficiency for tritium amounts to 25%
- assume for this Problem that the breathing rate is 1.2 m^3 h^{-1}
- for a breathing rate of 1.2 m^3 h^{-1}, the effective intake is 50% larger than the inhaled activity as a result of intake of tritium through the skin
- the reference man contains 42 l of body fluids
- the effective dose coefficient for inhalation is $e_{inh}(50) = 1.8\times10^{-11}$ Sv Bq^{-1}
- for continuous intake of tritium and a body activity of 1 Bq, the effective committed dose amounts to 4.4×10^{-10} Sv y^{-1}

Questions:

1. Calculate the activity concentration in the water that had been frozen (in Bq ml^{-1}).

2. Calculate the activity concentration in the air (in Bq m^{-3}).

3. Calculate the effective committed dose that the animal caretaker accumulates if he works for 2000 hours per year in the animal facility.

4. Calculate the average tritium concentration in the urine of this worker.

5. Calculate the total tritium activity in the body of this worker.

6. Calculate the annual effective commited dose assuming a continuous intake of tritium.

50. Internal contamination with ^{32}P

A student reports an incident during a synthesis with ^{32}P. The expert asks him to collect his urine during every 24 hours after the incident and also to collect all the faeces that he excretes in the first five days. Because it was an easily dissolvable phosphate compound, it is classified as class F. Furthermore, an AMAD of 1 µm is assumed.

The urine testing yields 1980 Bq for the first day, 820 Bq for the second day and 436 Bq for the third day. The activity in the faeces amounts to 500 Bq.

Following this incident, the expert decides to check the internal exposure as a result of inhalation of ^{32}P by measuring a urine sample of each worker at the beginning of each month. The minimal detectable activity concentration is 5 Bq l^{-1}.

Given:
- a number of radiation protection details of ^{32}P (see Appendix, Figure 3)
- the lung deposition fractions for a normal nose breather (see Appendix, Figure 50)
- the urine production of the reference man amounts to 1.4 l per day

Questions:

1. Give the retention formula.

2. Calculate the effective committed dose as a result of inhalation on the basis of the urine measurements.

3. Calculate the effective committed dose as a result of inhalation on the basis of the faeces measurement.

4. Calculate the maximal committed dose that can be received per year.

51. Urine testing after a contamination with $H^{36}Cl$

After an incident with $H^{36}Cl$, the radiation expert decides to analyze the urine of the exposed worker. He asks the worker to collect his urine during the next 24 hours, which is repeated 14 days later. Each sample taken contains 8 ml urine and is counted in a liquid scintillation counter. The measured net counting rate amounts to 11 520 and 5130 counts per minute (cpm), respectively.

Given:
- the counting efficiency of the liquid scintillation counter is 80%
- a number of radiation protection details of ^{36}Cl (see Appendix, Figure 5)
- for this question, assume that 48% of the inhaled activity remains in the lungs
- chlorine is taken up completely by the blood within a few hours
- the urine production of the reference man amounts to 1.4 l per day

Questions:

1. Calculate the biological half-life of HCl starting from the measured activity concentrations in the urine.

2. Calculate the amount of activity that is inhaled.

3. Calculate the effective committed dose.

52. Accidents with ^{51}Cr-powder (1997-2-4)

During a clean-up, the contents of a bottle containing ^{51}Cr-powder were released into the air by accident. A lung measurement was taken 1 hour after the incident, and it was determined that a worker is contaminated with ^{51}Cr. A test with an air particle meter gives the result that the AMAD of the powder amounts to 5 μm. The chemical composition is actually unknown.

Because the compound is unknown, the lung measurement is repeated several times. For the lung measurement, only the activity in the lungs and the lymph glands under the sternum are measured. The results of the measurements are:

date	*activity (kBq)*
08-01-96	1.64
09-01-96	1.33
11-01-96	1.30
10-02-96	0.48

Given:
- a number of radiation protection details of ^{51}Cr (see Appendix, Figure 9)
- the lung deposition fractions for a normal nose breather (see Appendix, Figure 50)

Questions:

1. Determine the class (F, M or S) of the relevant compound based on the lung measurements.

2. Calculate the intake of activity.

3. Calculate the effective committed dose.

53. Injection with ^{67}Ga-citrate (1997-1-2)

In the nuclear medicine department, patients are injected with ^{67}Ga-citrate to detect growing tumors. The amount of activity injected into the bloodstream for a normal test is 200 MBq.

After several days, there is sufficient gallium taken up by the tumor to take an image using a gamma camera. The measurement using the gamma camera occurred 72 hours after administration of the gallium.

One day, the nurse drops the syringe in such a way that it lands on the plunger and therefore the radioactive contents are released into the work room in the form of aerosols. One day after this event, the nurse undergoes a total body count. From this measurement, it appears that a total of 8500 Bq ^{67}Ga is present in her body.

Given:
- a number of radiation protection details of ^{67}Ga (see Appendix, Figure 12)

Questions:

1. Make an estimate of the effective committed dose that an adult normally receives during a gallium procedure.

2. Which activity is still present in the patient at the time of the scan?

3. Make an estimate of the effective committed dose for the nurse.

54. Administration of ^{99m}Tc-phosphonate (1999-1-3)

It is suspected that there is metastasis from an unknown primary tumor in an adult kidney patient. A bone scan is requested from the department of nuclear medicine. The bone scan is performed on a day that this patient is already present in the hospital to undergo dialysis.

The patient will first receive an injection of 600 MBq ^{99m}Tc-phosphonate, a material that will be taken up partially in the bone tissue. Afterwards, the patient will go to the dialysis department where waste materials will be removed from his blood. After the kidney dialysis, the patient goes back to the department of nuclear medicine, where the bone scan will be performed.

The particular patient produced no urine by himself. For such patients, 70% of the administered radiopharmaceutical is taken up by the bone with a half-life of 15 minutes and stays there permanently. The effective half-life will therefore be different than that for a normal patient.

Given:
- the next kidney dialysis will take place in 2 days
- $T_{½}(^{99m}\mathrm{Tc}) = 6.006$ h
- for this problem, the effective half-life for the body of this patient as a whole is set at 2.8 h
- the effective dose coefficient for intravenous administration is $e(50) = 6.0 \times 10^{-12}$ Sv Bq^{-1}

Questions:

1. Calculate the effective committed dose as a result of a bone scan for ^{99m}Tc for a patient with a normal kidney function.

2. Present arguments as to whether the effective committed dose for the dialysis patient is higher or lower when the bone test, including injection, takes place just after the dialysis, in contrast to the abovementioned protocol.

55. Ingestion of ^{137}Cs (1987-1-4)

A group of adults ingest the same quantity of ^{137}Cs every day for one year. After one year, the average activity in their bodies is 520 Bq.

Given:
- a number of radiation protection details of ^{137}Cs (see Appendix, Figure 21)
- for this problem, the excretion is described by a single exponential function with a half-life of 110 d

Questions:

1. Show that after one year, 90% of the saturation concentration is reached.

2. Calculate the daily intake starting with the measured ^{137}Cs-activity in the body.

3. What is the effective committed dose as a result of a year-long daily intake?

56. Internal contamination with ^{195m}Pt (1991-1-2)

At the end of a brief radiochemical process using the radionuclide ^{195m}Pt, it appears that a technician has sustained an external contamination. After the man had taken a shower, one decides to check him for internal contamination. The urine from the technician is thus collected for 24 hours following the contamination. In total, 1.4 liters are collected with a concentration of 25 Bq l^{-1}.

Given:

- $T_{½}(^{195m}Pt) = 4.02$ d
- for this problem, the AMAD is set at 1 µm.
- the retention formula is $R(t) = 0.20\ e^{-0.693 \times t/0.25} + 0.76\ e^{-0.693 \times t/8} + 0.04\ e^{-0.693 \times t/200}$ (all biological half-lives are in d)
- for all compounds, $f_1 = 0.01$
- all compounds belong to class F
- the lung deposition fractions for a normal nose breather (see Appendix, Figure 50)
- the effective dose coefficients are $e_{\text{ing}}(50) = 6.3 \times 10^{-10}$ Sv Bq^{-1} and $e_{\text{inh}}(50) = 1.9 \times 10^{-10}$ Sv Bq^{-1}

Questions:

1. Make an estimate of the effective committed dose if the intake was a result of ingestion.

2. Make an estimate of the effective committed dose if the intake was a result of inhalation.

57. Incident with a ^{241}Am-source (2000-1-3)

The radioactive ^{241}Am-source in a liquid level meter in a brewery must be replaced by a new one. The technician performs the work in the cargo compartment of his truck. While disassembling the device, it appears that the source is stuck due to corrosion of the source holder. Using a screw driver, the technician pries the source loose and transfers it to the transport container.

The technician drives first to his home for lunch and afterwards delivers the source as radioactive waste to the receiving station. At the station, it is discovered that the container and the truck are considerably contaminated.

It is decided that the urine from the technician should be collected for several days. The following activities are found:

time (d)	*activity (Bq d^{-1})*
1	0.22
2	0.16
3	0.11

Given:

- a number of radiation protection details of ^{241}Am (see Appendix, Figure 24)

Questions:

1. Make an estimate of the effective committed dose if the intake was a result of ingestion.

2. Make an estimate of the effective committed dose if the intake was a result of inhalation.

58. Determination of ^{241}Am in the urine

After working with ^{241}Am, urine is collected for 48 hours. The activity in the urine turns out to be 0.15 Bq l^{-1} for a volume of 2.8 l.

Given:
- a number of radiation protection details of ^{241}Am (see Appendix, Figure 24)
- according to the metabolic model for americium, 10% is excreted from the transfer compartment directly to the urine
- lung deposition fractions for a normal nose breather (see Appendix, Figure 50)

Questions:

1. Make an estimate of the intake and the effective committed dose for ingestion.

2. Make an estimate of the intake and the effective committed dose for inhalation starting with an AMAD of 1 µm.

3. Make an estimate of the intake and the effective committed dose for inhalation starting with an AMAD of 5 µm.

59. Leaking cylinder with ^{85}Kr

In a storage room of 500 m^3 with a ventilation rate of 1 time per hour, a cylinder filled with the noble gas isotope ^{85}Kr is leaking. The leakage rate is estimated at 40 MBq h^{-1}.

Given:
- a number of radiation protection details of ^{85}Kr (see Appendix, Figure 13)

Question:

1. Calculate the ambient dose equivalent rate in this room.

60. ^{85}Kr-concentration in the outside air (1989-1-4)

In nuclear reactors processing plants, the noble gas isotope ^{85}Kr is released in the atmosphere. In order to determine the exposure of the general public as a result of this discharge, the ^{85}Kr-concentration in the outside air is measured. This occurs by freezing the krypton out of the air.

After distillation, a sample of pure krypton is obtained, from which the activity can be determined using a γ-spectrometer. The measured net counting rate amounts to 89 counts per hour.

Given:
- a number of radiation protection details of ^{85}Kr (see Appendix, Figure 13)
- the outside air contains 4.2 mg krypton per m^3
- the mass of the krypton sample amounts to 8.0 g
- the counting efficiency in the photopeak amounts to 2.5×10^{-3} counts per disintegration
- the organ weighting factors (see Appendix, Figure 47)
- according to the submersion model, the equivalent dose rate as a result of a semi-infinite radioactive gas cloud is given by the formula:

$$H_{submersion} = 2.5\times10^{-10}\ g \times E \times C$$

$H_{submersion}$	equivalent dose rate (in Sv h^{-1})
g	fraction of the radiation that is absorbed in the body
E	effective energy per disintegration (in MeV per Bq s)
C	activity concentration in the gas cloud (in Bq m^{-3})

Questions:

1. Calculate the ^{85}Kr-concentration in the outside air.

2. Calculate the effective dose for people outside for 2000 hours per year, using the effective dose coefficient for submersion.

3. Calculate the effective dose for people outside for 2000 hours per year, using the formula given above for $H_{submersion}$. Explain the difference from the result calculated in Question 2.

4. Make an estimate of the equivalent skin dose for people that stay for 2000 hours per year in the outside air.

Solutions

<u>Question 41</u>

1. $1 / T_{½,\,\mathrm{eff}} = 1 / T_{½,\,\mathrm{phys}} + 1 / T_{½,\,\mathrm{biol}}$
   $= (1 / 2.696\ \mathrm{d}) + (1 / 3\ \mathrm{d}) = 0.704\ \mathrm{d}^{-1}$
   $T_{½,\,\mathrm{eff}} = 1.42\ \mathrm{d} = 1.23{\times}10^{5}\ \mathrm{s}$
   $U_S = \mathrm{A} \times T_{½,\,\mathrm{eff}} / 0.693$
   $= 1{\times}10^{6}\ \mathrm{Bq} \times 1.23{\times}10^{5}\ \mathrm{s} / 0.693 = 1.77{\times}10^{11}\ \mathrm{Bq\ s}$
2. according to Appendix, Figure 46 $\quad m_{\mathrm{liver}} = 1800\ \mathrm{g}$
   $\langle E \rangle = \sum Y \times E \times AF(\mathrm{liver} \leftarrow \mathrm{liver})$
   $AF(\mathrm{liver} \leftarrow \mathrm{liver}) = SAF(\mathrm{liver} \leftarrow \mathrm{liver}) \times m_{\mathrm{liver}}$
   electrons: $AF(\mathrm{liver} \leftarrow \mathrm{liver}) = 1$
   according to Figure 1, "listed radiations" is $\sum Y_{\mathrm{i}} \times E_{\mathrm{i}} = 3.26{\times}10^{-1}$ MeV per Bq s
   $\langle E_\beta \rangle = 3.26{\times}10^{-1}$ MeV per Bq s × 1 = 0.326 MeV per Bq s
   photons: according to Figure 1
   $E_{\gamma 1} = 0.4118$ MeV $\quad Y_{\gamma 1} \times E_{\gamma 1} = 3.93{\times}10^{-1}$ MeV per Bq s
   $E_{\gamma 2} = 0.6759$ MeV $\quad Y_{\gamma 2} \times E_{\gamma 2} = 7.16{\times}10^{-3}$ MeV per Bq s
   $E_{\gamma 3} = 1.088$ MeV $\quad Y_{\gamma 3} \times E_{\gamma 3} = 2.49{\times}10^{-3}$ MeV per Bq s
   linear interpolation in Appendix, Figure48
   412 keV $\quad SAF(\mathrm{liver} \leftarrow \mathrm{liver}) = 8.84{\times}10^{-5}\ \mathrm{g}^{-1}$
   $AF = 8.84{\times}10^{-5}\ \mathrm{g}^{-1} \times 1800\ \mathrm{g} = 0.159$
   676 keV $\quad SAF(\mathrm{liver} \leftarrow \mathrm{liver}) = 8.58{\times}10^{-5}\ \mathrm{g}^{-1}$
   $AF = 8.58{\times}10^{-5}\ \mathrm{g}^{-1} \times 1800\ \mathrm{g} = 0.154$
   1088 keV $\quad SAF(\mathrm{liver} \leftarrow \mathrm{liver}) = 7.97{\times}10^{-5}\ \mathrm{g}^{-1}$
   $AF = 7.97{\times}10^{-5}\ \mathrm{g}^{-1} \times 1800\ \mathrm{g} = 0.143$
   $\langle E_\gamma \rangle = \sum Y \times E \times AF$
   $= 3.93{\times}10^{-1}$ MeV per Bq s × 0.159 +
   $7.16{\times}10^{-3}$ MeV per Bq s × 0.154 +
   $2.49{\times}10^{-3}$ MeV per Bq s × 0.143 = 0.064 MeV per Bq s
   total $\quad \langle E \rangle = \langle E_\beta \rangle + \langle E_\gamma \rangle$ = 0.326 MeV per Bq s + 0.064 MeV per Bq s
   = 0.390 MeV per Bq s
3. $SEE = \langle E \rangle / m_{\mathrm{liver}}$
   = 1 × 0.390 MeV per Bq s / 1800 g = $2.22{\times}10^{-4}$ MeV g^{-1} per Bq s
4. $H_{50,\mathrm{T}} = 1.6{\times}10^{-10} \times U_S \times w_{\mathrm{R}} \times SEE$
   = $1.6{\times}10^{-10}$ J kg^{-1} per MeV g^{-1} × $1.77{\times}10^{11}$ Bq s × 1 Sv Gy^{-1} × $2.22{\times}10^{-4}$ MeV g^{-1} per Bq s
   = $6.3{\times}10^{-3}$ Sv = 6.3 mSv

<u>Question 42</u>

1. decay constant $\quad \lambda = 0.693 / T_{½}$
   $= 0.693 / (4.7{\times}10^{10}\ \mathrm{y} \times 365\ \mathrm{d\ y}^{-1} \times 24\ \mathrm{h\ d}^{-1} \times 3600\ \mathrm{s\ h}^{-1})$
   $= 4.7{\times}10^{-19}\ \mathrm{s}^{-1}$
   number atoms per gram $\quad N$ = (mass × abundance / atomic weight) × $\mathrm{N_{Avogadro}}$
   = (1 g × $27.8{\times}10^{-2}$ / 85.5 g mol^{-1}) × $6.02{\times}10^{23}$ mol^{-1}
   = $2.0{\times}10^{21}$ per gram naturally-occurring rubidium
   specific activity $\quad \lambda \times N = 4.7{\times}10^{-19}\ \mathrm{s}^{-1} \times 2.0{\times}10^{21}\ \mathrm{g}^{-1}$
   $= 9.4{\times}10^{2}\ \mathrm{Bq\ g}^{-1} = 0.94\ \mathrm{Bq\ mg}^{-1}$
2. yearly intake $\quad A = 2.2\ \mathrm{mg\ d}^{-1} \times 365\ \mathrm{d\ y}^{-1} \times 0.94\ \mathrm{Bq\ mg}^{-1} = 7.5{\times}10^{2}\ \mathrm{Bq\ y}^{-1}$
3. $E_{50} = A \times e_{\mathrm{ing}}(50) = 7.5{\times}10^{2}\ \mathrm{Bq} \times 1.5{\times}10^{-9}\ \mathrm{Sv\ Bq}^{-1} = 1.1{\times}10^{-6}\ \mathrm{Sv} = 1.1\ \mu\mathrm{Sv}$

4. the exchange of rubidium is described by the differential equation
   $dM/dt + \lambda M = P$
   in the equilibrium situation, $dM/dt = 0$, thus $\lambda M = P$
   intake of rubidium $P = 2.2$ mg d^{-1}
   $T_{½,\,eff} >> T_{½,\,biol}$ $T_{½,\,eff} \approx T_{½,\,biol} = 44$ d
   $\lambda = 0.693 / T_{½,\,eff} = 0.693 / 44\ d = 0.016\ d^{-1}$
   quantity of rubidium in the body $M = P / \lambda = 2.2$ mg d^{-1} / 0.016 d^{-1} = 138 mg
   activity in the body $A = 138$ mg × 0.94 Bq mg^{-1} = 130 Bq
5. $U_S = A \times f_1 \times T_{½,\,eff} / 0.693$ = 1 Bq × 1 × 44 d / 0.693 = 63,5 Bq d = 5.5×10^6 Bq s
6. according to Appendix, Figure46 $m_{total\ body}$ = 70 000 g
   $SEE = E_{eff} \times AF / m_{total\ body}$
   = 0.112 MeV per Bq s × 1 / 70 000 g = 1.6×10^{-6} MeV g^{-1} per Bq s
7. $e_{ing}(50)$ = 1.6×10^{-10} J kg^{-1} per MeV g^{-1} × $U_S \times w_R \times SEE$
   = 1.6×10^{-10} J kg^{-1} per MeV g^{-1} × 5.5×10^6 Bq s × 1 Sv Gy^{-1} × 1.6×10^{-6} MeV g^{-1} per Bq s
   = 1.4×10^{-9} Sv Bq^{-1}

Question 43
1. the effective half-life is:
   $1 / T_{½,\,eff} = (1 / 87.44\ d) + (1 / 140\ d) = 0{,}0186\ d^{-1}$ $\rightarrow T_{½,\,eff} = 54$ d
   $U_S = A \times f_1 \times T_{½,\,eff} / 0.693$ = 1 Bq × 1 × 54 d / 0.693 = 78 Bq d = 6.7×10^6 Bq s
2. according to Appendix, Figure46 $m_{total\ body}$ = 70 000 g
   specific effective energy $SEE = E_{eff} / m_{total\ body}$
   = 0.049 MeV per Bq s / 70 000 g
   = 7.0×10^{-7} MeV g^{-1} per Bq s
3. E_{50} = 1.6×10^{-10} J kg^{-1} per MeV g^{-1} × $U_S \times w_R \times SEE$
   = 1.6×10^{-10} J kg^{-1} per MeV g^{-1} × 6.7×10^6 Bq s × 1 Sv Gy^{-1} × 7.0×10^{-7} MeV g^{-1} per Bq s
   = 7.5×10^{-10} Sv (per Bq intake)
4. e(50) - E_{50} = 7.7×10^{-10} Sv Bq^{-1} - 7.5×10^{-10} Sv Bq^{-1} = 0.2×10^{-10} Sv Bq^{-1}
   the difference is attributable to rounding errors

Question 44
1. the exchange of sulfur is described by the differential equation
   $dM/dt + \lambda M = P$
   in the equilibrium situation, $dM/dt = 0$, thus $\lambda M = P$
   amount of sulfur that goes in P = 700 g d^{-1} × 10^{-3} kg g^{-1} × 140 mg kg^{-1} = 98 mg d^{-1}
   amount of sulfur that goes out $\lambda M = \lambda$ × 7700 g × 10^{-3} kg g^{-1} × 500 mg kg^{-1}
   = 3.85×10^3 λ mg
   $\lambda = P / M$ = 98 mg d^{-1} / 3.85×10^3 mg = 0.0255 d^{-1}
   $T_{½,\,biol} = 0.693 / \lambda = 0.693 / 0.0255\ d^{-1} = 27$ d
2. the effective half-life is:
   $1 / T_{½,\,eff} = (1 / 87.44\ d) + (1 / 27\ d) = 0.0485\ d^{-1}$ $\rightarrow T_{½,\,eff} = 21$ d
   $U_S = A \times f_1 \times T_{½,\,eff} / 0.693$ = 1 Bq × 1 × 21 d / 0.693 = 30 Bq d = 2.6×10^6 Bq s
3. $SEE = E_{eff} / m$ = 0.049 MeV per Bq s / 7700 g = 6.4×10^{-6} MeV g^{-1} per Bq s
4. $e_{ing}(50)$ = 1.6×10^{-10} J kg^{-1} per MeV g^{-1} × $U_S \times w_R \times SEE$
   = 1.6×10^{-10} J kg^{-1} per MeV g^{-1} × 2.6×10^6 Bq s × 1 Sv Gy^{-1} × 6.4×10^{-6} MeV g^{-1} per Bq s
   = 2.7×10^{-9} Sv Bq^{-1}
   this is a factor of 2.7×10^{-9} Sv Bq^{-1} / 7.7×10^{-10} Sv Bq^{-1} ≈ 3,5 greater than for an adult
   this is due to on the one hand 70 000 g / 7700 g ≈ 9 times smaller body mass (makes the committed dose larger) and on the other hand 44 d / 21 d ≈ 2 times shorter effective half-life (makes the committed dose smaller)

Question 45

1. $T_{½,\text{phys}} >> T_{½,\text{biol}}$, dus $T_{½,\text{eff}} \approx T_{½,\text{biol}}$
   $U_S = A \times f_1 \times (0.97 \times T_{½,\text{eff},1} + 0.03 \times T_{½,\text{eff},2}) / 0.693$
   $= 1$ Bq × 1 × (0.97 × 10 d + 0.03 × 40 d) / 0.693 = 15,7 Bq d = 1.4×10^{6} Bq s
2. according to Appendix, Figure46 $m_{\text{total body}}$= 70 000 g
   $SEE = E_{\text{eff}} / m_{\text{total body}}$
   = 0.0057 MeV per Bq s / 70 000 g = 8.1×10^{-8} MeV g^{-1} per Bq s
3. $e_{\text{ing}}(50) = 1.6\times10^{-10}$ J kg^{-1} per MeV g^{-1} × $U_S \times w_R \times SEE$
   = 1.6×10^{-10} J kg^{-1} per MeV g^{-1} × 1.4×10^{6} Bq s × 1 Sv Gy^{-1} × 8.1×10^{-8} MeV g^{-1} per Bq s
   = 1.8×10^{-11} Sv Bq^{-1}

Question 46

1. $T_{½,\text{phys}} >> T_{½,\text{biol}}$, dus $T_{½,\text{eff}} \approx T_{½,\text{biol}}$
   $U_S = A \times f_1 \times (0.97 \times T_{½,\text{eff},1} + 0.03 \times T_{½,\text{eff},2}) / 0.693$
   = 1 Bq × 1 × (0.97 × 3.5 d + 0.03 × 15 d) / 0.693 = 5.55 Bq d = 4.8×10^{5} Bq s
2. $SEE = E_{\text{eff}} / m$
   = 0.0057 MeV per Bq s / 9800 (g) = 5.8×10^{-7} MeV g^{-1} per Bq s
3. $e_{\text{ing}}(50) = 1.6\times10^{-10}$ J kg^{-1} per MeV g^{-1} × $U_S \times w_R \times SEE$
   = 1.6×10^{-10} J kg^{-1} per MeV g^{-1} × 4.8×10^{5} Bq s × 1 Sv Gy^{-1} × 5.8×10^{-7} MeV g^{-1} per Bq s
   = 4.5×10^{-11} Sv Bq^{-1}

   this is a factor of 4.5×10^{-11} Sv Bq^{-1} / 1.8×10^{-11} Sv Bq^{-1} ≈ 2,5 greater than that for an adult

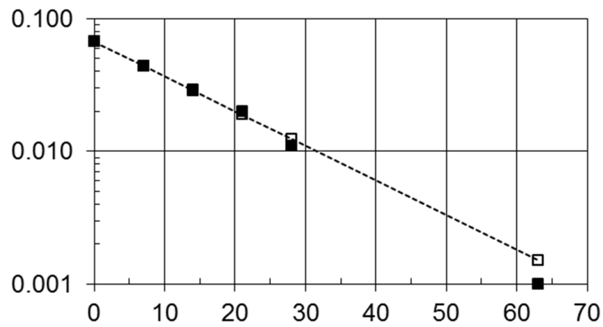
Question 47

1. in the equilibrium situation, the activity that escapes per hour from the basin to the air is discharged per hour
   the activity concentration is thus 30 MBq / 2000 m^3 = 1.5×10^{4} Bq m^{-3}
   in 2000 hours, the amount inhaled is 2000 h × 1.2 m^3 h^{-1} × 1.5×10^{4} Bq m^{-3} = 3.6×10^{7} Bq
   effective intake $A = (1 + 50\times10^{-2}) \times 3.6\times10^{7}$ Bq = 5.4×10^{7} Bq
   $E_{50} = A \times e(50) = 5.4\times10^{7}$ Bq × 1.8×10^{-11} Sv Bq^{-1} = 9.7×10^{-4} Sv = 0.97 mSv
2. activity intake per day (8 h d^{-1} / 2000 h) × 5.4×10^{7} Bq = 2.2×10^{5} Bq d^{-1}
   total water exchange per day 1.4 l d^{-1} + 0.65 l d^{-1} + 0.95 l d^{-1} = 3.0 l d^{-1} = 3.0×10^{3} ml d^{-1}
   activity concentration in excreted water (thus also in the urine):
   2.2×10^{5} Bq d^{-1} / 3.0×10^{3} ml d^{-1} = 73 Bq ml^{-1}

Question 48

1. activity follows from $N_{\text{net}} = N_{\text{gross}} - N_{\text{blank}}$
   $= A \times$ counting efficiency × counting time
   $= A \times 40\times10^{-2} \times 1$ min × 60 s min^{-1} = 24 A
   $A = N_{\text{net}} / 24$
   activity concentration a = A / 8 ml = N_{net} / 192 ml
   substitute details in spreadsheet + linear regression yields $T_{½,\text{biol}}$ = 11.5(2) d

t (d)	*N_{gross}* (cpm)	*N_{net}* (cpm)	*a* (Bq ml^{-1})
0	14.0	12.8	0.067
7	9.6	8.4	0.044
14	6.8	5.6	0.029
21	5.0	3.8	0.020
28	3.4	2.2	0.011
63	1.4	0.2	0.001



2. activity concentration for removal $0.067\ \text{Bq ml}^{-1}$
   total water exchange per day $1.4\ \text{l d}^{-1} + 0.65\ \text{l d}^{-1} + 0.95\ \text{l d}^{-1} = 3.0\ \text{l d}^{-1} = 3000\ \text{ml d}^{-1}$
   activity exchange $A = 3000\ \text{ml d}^{-1} \times 0.067\ \text{Bq ml}^{-1} = 201\ \text{Bq d}^{-1} = 7.3{\times}10^{4}\ \text{Bq y}^{-1}$
   $E_{50} = A \times e(50) = 7.3{\times}10^{4}\ \text{Bq} \times 1.8{\times}10^{-11}\ \text{Sv Bq}^{-1} = 1.3{\times}10^{-6}\ \text{Sv} = 1.3\ \mu\text{Sv}$
3. after one-time intake, body contains 42 l water with activity concentration of $0.067\ \text{Bq ml}^{-1}$
   $A = 42\ \text{l} \times 10^{3}\ \text{ml l}^{-1} \times 0.067\ \text{Bq ml}^{-1} = 2.8{\times}10^{3}\ \text{Bq}$
   $E_{50} = A \times e(50) = 2.8{\times}10^{3}\ \text{Bq} \times 1.8{\times}10^{-11}\ \text{Sv Bq}^{-1} = 5.0{\times}10^{-8}\ \text{Sv} = 0.05\ \mu\text{Sv}$

Question 49

1. net counting rate for 1 ml water $80\ \text{cpm ml}^{-1} - 20\ \text{cpm ml}^{-1} = 60\ \text{cpm ml}^{-1} = 1.0\ \text{cps ml}^{-1}$
   activity concentration in water $1.0\ \text{cps ml}^{-1} / 25{\times}10^{-2} = 4.0\ \text{Bq ml}^{-1} = 4.0\ \text{Bq g}^{-1}$
2. for a relative humidity of 80%, the air contains:
   $80{\times}10^{-2} \times 22\ \text{g m}^{-3} = 17.6\ \text{g m}^{-3}$ water
   activity concentration in the air $4.0\ \text{Bq g}^{-1} \times 17.6\ \text{g m}^{-3} = 70\ \text{Bq m}^{-3}$
3. inhaled activity $2000\ \text{h} \times 1.2\ \text{m}^{3}\ \text{h}^{-1} \times 70\ \text{Bq m}^{-3} = 1.7{\times}10^{5}\ \text{Bq}$
   effective intake $A = (1 + 50{\times}10^{-2}) \times 1.7{\times}10^{5}\ \text{Bq} = 2.6{\times}10^{5}\ \text{Bq}$
   effective committed dose $A \times e(50) = 2.6{\times}10^{5}\ \text{Bq} \times 1.8{\times}10^{-11}\ \text{Sv Bq}^{-1} = 4.7{\times}10^{-6}\ \text{Sv} = 4.7\ \mu\text{Sv}$
4. net counting rate $50\ \text{cpm} - 20\ \text{cpm} = 30\ \text{cpm} = 0.50\ \text{cps}$ per 10 ml
   activity concentration in urine 0.50 cps per 10 ml $/ 25{\times}10^{-2} = 2.0$ Bq per 10 ml $= 200\ \text{Bq l}^{-1}$
5. the activity concentration in body fluids is equal to that in the urine
   total body activity $200\ \text{Bq l}^{-1} \times 42\ \text{l} = 8.4{\times}10^{3}\ \text{Bq}$
6. effective committed dose $8.4{\times}10^{3}\ \text{Bq} \times 4.4{\times}10^{-10}\ \text{Sv y}^{-1}$ per Bq $= 3.7{\times}10^{-6}\ \text{Sv y}^{-1} = 3.7\ \mu\text{Sv y}^{-1}$

Question 50

1. according to Appendix, Figure 3
   $R(t) = 0.15\ \text{e}^{-0.693 \times t/0.5} + 0.15\ \text{e}^{-0.693 \times t/2} + 0.40\ \text{e}^{-0.693 \times t/19} + 0.30$
   (all biological half-lives in d)
2. AMAD = 1 ET_1 does not apply
   $ET_2 = 0.21$
   $BB + bb + AI = 0.0066 + 0.0058 + 0.0084 + 0.0081 + 0.11 = 0.14$
   for class F 50% of ET_2 goes directly to TC
   50% of ET_2 goes directly to the gastro-intestinal tract, where $f_1 = 0.8$ to TC
   100% of BB + bb + AI goes to the TC
   total to TC $50{\times}10^{-2} \times 0.21 + 50{\times}10^{-2} \times 0.21 \times 0.8 + 100{\times}10^{-2} \times 0.14 = 0.33$
   retention formula $R(0) = 1$, $R(1) = 0.8293$, $R(2) = 0.7563$, $R(3) = 0.7139$
   excretion first day $R(0) - R(1) = 1 - 0.8293 = 0{,}171$
   excretion second day $R(1) - R(2) = 0.8293 - 0.7563 = 0.073$
   excretion third day $R(2) - R(3) = 0.7563 - 0.7139 = 0.042$
   during excretion, the activity decays according to $C(t) = \text{e}^{-0.693 \times t/14.29}$
   substitute decay correction $C(1) = 0.953$, $C(2) = 0.908$, $C(3) = 0.865$
   first day $0.33 \times 0.171 \times 0.953 \times \text{intake} = 0.054 \times \text{intake} = 1980\ \text{Bq}$
   intake $= 1980\ \text{Bq} / 0.054 = 3.67 \times 10^{4}\ \text{Bq}$
   second day $0.33 \times 0.073 \times 0.908 \times \text{intake} = 0.022 \times \text{intake} = 820\ \text{Bq}$
   intake $= 820\ \text{Bq} / 0.022 = 3.73{\times}10^{4}\ \text{Bq}$

third day — $0.33 \times 0.042 \times 0.865 \times \text{intake} = 0.012 \times \text{intake} = 436$ Bq
intake = 436 Bq / 0.012 = 3.63×10^4 Bq
average inhalation — $\langle A_{\text{inh}} \rangle = (3.67\times10^4 + 3.73\times10^4 + 3.63\times10^4)$ Bq / 3 = 3.7×10^4 Bq
effective committed dose — $E_{50} = \langle A_{\text{inh}} \rangle \times e(50)_{\text{inh}}$
$= 3.7\times10^4$ Bq $\times 1.1\times10^{-9}$ Sv Bq^{-1} = 4.1×10^{-5} Sv = 41 μSv

3. 50% of ET_2 goes to gastro-intestinal tract, where $1 - f_1 = 0.2$ via feces is excreted
   substitute decay correction $C(5) = 0.785$
   activity in faeces:
   $50\times10^{-2} \times 0.21 \times 0.2 \times 0.785 \times \text{intake} = 0.0165 \times \text{intake} = 500$ Bq
   intake = 500 Bq / 0.0165 = 3.0×10^4 Bq
   effective committed dose — intake $\times\, e(50) = 3.0\times10^4$ Bq $\times 1.1\times10^{-9}$ Sv Bq^{-1}
   $= 3.3\times10^{-5}$ Sv = 33 μSv
4. total to TC — 0.33
   in the worst case, the intake occurs on the first day of the month
   retention formula — $R(29) = 0.4389$, $R(30) = 0.4339$ (only last 2 terms)
   excretion — $R(29) - R(30) = 0.4389 - 0.4339 = 0.005$
   decay correction — $C(30) = 0.233$
   activity — $0.33 \times 0.005 \times 0.233 \times \text{intake} = 0.0004 \times \text{intake}$
   detection limit — 5 Bq/l × 1.4 l d^{-1} × 12 d y^{-1} = 84 Bq y^{-1} (12 times per year)
   maximal intake — 84 Bq y^{-1} / 0.0004 = 2.1×10^5 Bq y^{-1}
   maximal committed dose — 2.1×10^5 Bq $\times 1.1\times10^{-9}$ Sv Bq^{-1} = 2.3×10^{-4} Sv = 0.23 mSv

<u>Question 51</u>

1. $T_{½,\text{ phys}} >> T_{½,\text{ biol}}$, dus $T_{½,\text{ eff}} \approx T_{½,\text{ biol}}$
   excretion is proportional to measured net counting rate
   $T(14) = T(0) \times e^{-0.693\times14/T_{½,\text{biol}}}$
   $T_{½,\text{ biol}} = 0.693 \times 14 \text{ d} / \ln[T(0) / T(14)]$
   $= 0.693 \times 14$ d / ln(11 520 cpm / 5130 cpm) = 0.693×14 d / 0.809 = 12 d
2. counting rate (in cpm) = activity (in Bq) × counting efficiency × count time (in s)
   $= A(\text{t}) \times 80\times10^{-2} \times 60 \text{ s} = 48\, A(\text{t})$
   activity in 8 ml urine — $A(0)$ = 11 520 cpm / 48 = 240 Bq
   activity in 1.4 l urine — 240 (Bq) × (1.4 l × 10^3 ml l^{-1} / 8 ml) = 4.2×10^4 Bq
   retention formula — $R(0) = 1$, $R(1) = e^{-0.693\times1/12} = 0.944$
   excretion first day — $R(0) - R(1) = 1 - 0.944 = 0.056$
   activity in body — 4.2×10^4 Bq / 0.056 = 7.5×10^5 Bq
   for a class F compound and $f_1 = 1$, all the deposited activity is taken up in the TC
   intake — 7.5×10^5 Bq / lung deposition = 7.5×10^5 Bq / 48×10^{-2} = 1.6×10^6 Bq
3. effective committed dose — $E_{50} = A(0) \times e(50)$
   $= 1.6\times10^6$ Bq $\times 4.9\times10^{-10}$ Sv Bq^{-1} = 7.8×10^{-4} Sv = 0.8 mSv

<u>Question 52</u>

1. the decrease in the lung activity during the first day is about 20%
   - for class F, there is a 100% fast discharge to TC
     the compound thus can not be of class F
   - for class M, there is a 10% fast discharge to TC
     in addition, the fast component BB_{fast}+bb_{fast} of the mechanial lung cleaning discharges a portion via ET_2 into the gastro-intestinal tract
     it could be of class M
   - for class S, there is a 0.1% fast discharge to TC plus the fast mechanial lung cleaning
     thus it could be of class S as well

according to the last two measurements, the activity in the lungs in 30 decays decreased with a factor of:

$e^{-0.693\times 30/T_{½,\mathrm{eff}}} = 0.48\ \mathrm{kBq} / 1.30\ \mathrm{kBq} = 1 / 2.71$

$T_{½,\,\mathrm{eff}} = 0.693 \times 30\ \mathrm{d} / \ln(2.71) = 21\ \mathrm{d}$

$1 / T_{½,\,\mathrm{biol}} = 1 / T_{½,\,\mathrm{eff}} - 1 / T_{½,\,\mathrm{phys}} = (1 / 21\ \mathrm{d}) - (1 / 27.71\ \mathrm{d}) = 0.0115\ \mathrm{d}^{-1}$

$T_{½,\,\mathrm{biol}} = 1 / 0.0115\ \mathrm{d}^{-1} = 87\ \mathrm{d}$

this is in reasonable agreement with the slower removal time for class M (140 d), but does not agree with class S (7000 d); it therefore must be a compound of class M

2. AMAD = 5 BB + bb + AI = 0.012 + 0.0059 + 0,0066 + 0.0044 + 0.053 = 0.082
   after 1 hour, only the slower component of 90% remains
   according to the first measurement, the intake is thus about
   $A = 1.64\ \mathrm{kBq} / (90\times10^{-2} \times 0.082) = 22\ \mathrm{kBq} = 2.2\times10^{4}\ \mathrm{Bq}$
3. effective committed dose $E_{50} = A \times e(50)$
   $= 2.2\times10^{4}\ \mathrm{Bq} \times 3.4\times10^{-11}\ \mathrm{Sv\ Bq^{-1}} = 7.5\times10^{-7}\ \mathrm{Sv} = 0.75\ \mu\mathrm{Sv}$

Question 53

1. given is the effective dose coefficient for wound contamination $e(50) = 8.4\times10^{-11}\ \mathrm{Sv\ Bq^{-1}}$
   injected activity $A(0) = 200\ \mathrm{MBq} = 2.0\times10^{8}\ \mathrm{Bq}$
   effective committed dose $E_{50} = A(0) \times e_{\mathrm{wound}}(50)$
   $= 2.0\times10^{8}\ \mathrm{Bq} \times 8.4\times10^{-11}\ \mathrm{Sv\ Bq^{-1}} = 1.7\times10^{-2}\ \mathrm{Sv} = 17\ \mathrm{mSv}$
2. the retention formula $R(t) = 0.3e^{-0.693\times t/1} + 0.7e^{-0.693\times t/50}$ (half-life in d)
   $T_{½,\,\mathrm{phys}} = 78.23\ \mathrm{h} = 3{,}26\ \mathrm{d}$
   remaining fraction $0.3\ e^{-0.693\times 3/1} + 0{,}7\ e^{-0.693\times 3/50} = 0.709$
   meanwhile activity dacays according to $C(3) = e^{-0.693\times 3/3.26} = 0.528$
   remaining activity $A(3) = R(3) \times C(3) \times A(0)$
   $= 0.709 \times 0.528 \times 200\ \mathrm{MBq} = 75\ \mathrm{MBq}$
3. according to the data, gallium citrate belongs to class F
   for this class, $e_{\mathrm{inh}}(50) = 1.1\times10^{-10}\ \mathrm{Sv\ Bq^{-1}}$ and a fraction 4.3×10^{-1} of the inhaled activity is present in the body 1 day after inhalation
   measured activity 8500 Bq
   inhalation $A = 8500\ \mathrm{Bq} / 4.3\times10^{-1} = 2.0\times10^{4}\ \mathrm{Bq}$
   effective committed dose $E_{50} = A \times e_{\mathrm{inh}}(50)$
   $= 2.0\times10^{4}\ \mathrm{Bq} \times 1.1\times10^{-10}\ \mathrm{Sv\ Bq^{-1}} = 2.2\times10^{-6}\ \mathrm{Sv} = 2.2\ \mu\mathrm{Sv}$

Question 54

1. effective committed dose $E_{50} = A \times e_{\mathrm{injection}}(50)$
   $= 600\times10^{6}\ \mathrm{Bq} \times 6.0\times10^{-12}\ \mathrm{Sv\ Bq^{-1}} = 3.6\times10^{-3}\ \mathrm{Sv} = 3.6\ \mathrm{mSv}$
2. compare the two situations
   - for a patient who does not produce any urine himself, the blood will not be purified of waste materials, such that the activity that is not taken up by the bone will only be excreted 2 days later during the next kidney dialysis
     the administered activity will not (biologically) leave the body and decays with the physical half-life of 6.0 h
   - during the dialysis, the blood will be purified and the activity in the kidney patient will decrease with an effective half-life of 2.8 h

   conclusion: the same activity ^{99m}Tc will cause a higher effective dose if administered after dialysis than if administered just before dialysis

<u>Question 55</u>

1. the exchange of cesium is described by the differential equation:
   $dA/dt + \lambda A = P$
   P is the intake, λ is the biological decay time
   the solution is $A(t) = (P / \lambda) \times (1 - e^{-\lambda t})$
   $\lambda = 0.693 / T_{½,\,biol} = 0.693 / 110\ d = 6.3\times10^{-3}\ d^{-1} = 2.3\ y^{-1}$
   saturation activity ($t = \infty$) $A(\infty) = P / \lambda$
   activity after 1 year $A(1\ y) = A(\infty) \times (1 - e^{-2.3\times1}) = A(\infty) \times (1 - 0.10) = 0.90\ A(\infty)$
   $A(\infty) = A(1\ y) / 0.90 = 520\ Bq / 0.90 = 578\ Bq$
2. in the equilibrium situation, $dA/dt = 0$, thus $\lambda A(\infty) = P$
   daily intake cesium $P = \lambda A(\infty) = 6.3\times10^{-3}\ d^{-1} \times 578\ Bq = 3.64\ Bq\ d^{-1}$
3. annual intake cesium $365\ d \times 3.64\ Bq\ d^{-1} = 1.3\times10^{3}\ Bq$
   effective committed dose $E_{50} = A \times e_{ing}(50)$
   $= 1.3\times10^{3}\ Bq \times 1.3\times10^{-8}\ Sv\ Bq^{-1}$
   $= 1.7\times10^{-5}\ Sv = 17\ \mu Sv$

<u>Question 56</u>

1. $R(t) = 0.20\ e^{-0.693\times t/0.25} + 0.76\ e^{-0.693\times t/8} + 0{,}04\ e^{-0.693\times t/200}$
   (alle biologische halveringstijden in d)
   retention formula $R(0) = 1$ en $R(1) = 0.75$
   excretion first day $R(0) - R(1) = 1 - 0.75 = 0.37$
   during excretion, the activity decays according to $C(t) = e^{-0.693\times t/4.02}$
   decay correction $C(1) = 0.84$
   excreted activity $A_{ing} \times f_1 \times [R(0) - R(1)] \times C(1) = A_{ing} \times 0.01 \times 0.25 \times 0.84$
   $= 0.0021\ A_{ing}$
   $= 1.4\ l \times 25\ Bq\ l^{-1} = 35\ Bq$
   intake $A_{ing} = 35\ Bq / 0.0021 = 17\times10^{3}\ Bq$
   effective committed dose $E_{50} = A_{ing} \times e_{ing}(50)$
   $= 17\times10^{3}\ Bq \times 6.3\times10^{-10}\ Sv\ Bq^{-1} = 1.1\times10^{-5}\ Sv = 11\ \mu Sv$
2. AMAD = 1 ET_1 does not apply
   $ET_2 = 0{,}21$
   BB + bb + AI = 0.0066 + 0.0058 + 0.0084 + 0.0081 + 0.11 = 0.139
   class F from ET_2, 50% goes to the TC and 50% goes to the gastro-intestinal tract
   (for both processes, the half-life is 10 min)
   from the gastro-intestinal tract, $f_1 = 0.01$ goes still to the TC
   from BB + bb + AI, 100% goes to the TC
   total TC $50\times10^{-2} \times 0.21 + 50\times10^{-2} \times 0.21 \times 0.01 + 100\times10^{-2} \times 0.139 = 0.245$
   excreted activity $A_{inh} \times 0.245 \times [R(0) - R(1)] \times C(1) = A_{inh} \times 0.245 \times 0.25 \times 0.84$
   $= 0.051\ A_{inh}$
   $= 35\ Bq$
   intake $A_{inh} = 35\ Bq / 0.051 = 0.69\times10^{3}\ Bq$
   effective committed dose $E_{50} = A_{inh} \times e_{inh}(50)$
   $= 0.69\times10^{3}\ Bq \times 1.9\times10^{-10}\ Sv\ Bq^{-1} = 1.3\times10^{-7}\ Sv = 0.13\ \mu Sv$

Question 57

1. use the activity concentration in the urine after ingestion (see excretion details)
   it follows that ingestion = measured activity / concentration
   1 d concentration = 3.0×10^{-5} Bq d^{-1} per Bq
   ingestion = 0.22 Bq d^{-1} / 3.0×10^{-5} Bq d^{-1} per Bq = 0.7×10^{4} Bq
   2 d concentration = 4.8×10^{-6} Bq d^{-1} per Bq
   ingestion = 0.16 Bq d^{-1} / 4.8×10^{-6} Bq d^{-1} per Bq = 3.3×10^{4} Bq
   3 d concentration = 2.2×10^{-6} Bq d^{-1} per Bq
   ingestion = 0.11 Bq d^{-1} / 2.2×10^{-6} Bq d^{-1} per Bq = 5.0×10^{4} Bq
   average value $\langle A_{\mathrm{ing}}\rangle = (0.7 + 3.3 + 5.0)\times10^{4}$ Bq / 3 = 3.0×10^{4} Bq
   effective committed dose $E_{50} = \langle A_{\mathrm{ing}}\rangle \times e_{\mathrm{ing}}(50)$
   $= 3.0\times10^{4}$ Bq $\times\ 2.0\times10^{-7}$ Sv Bq^{-1} = 6.0×10^{-3} Sv = 6 mSv
2. use the activity concentration in the urine after inhalation (see excretion details)
   it therefore follows that inhalation = measured activity / concentration
   1 d concentration = 1.8×10^{-3} Bq d^{-1} per Bq
   inhalation = 0.22 Bq d^{-1} / 1.8×10^{-3} Bq d^{-1} per Bq = 1.2×10^{2} Bq
   2 d concentration = 2.3×10^{-4} Bq d^{-1} per Bq
   inhalation = 0.16 Bq d^{-1} / 2.3×10^{-4} Bq d^{-1} per Bq = 7.0×10^{2} Bq
   3 d concentration = 1.3×10^{-4} Bq d^{-1} per Bq
   inhalation = 0.11 Bq d^{-1} / 1.3×10^{-4} Bq d^{-1} per Bq = 8.5×10^{2} Bq
   average value $\langle A_{\mathrm{inh}}\rangle = (1.2 + 7.0 + 8.5)\times10^{2}$ Bq / 3 = 5.6×10^{2} Bq
   effective committed dose $E_{50} = \langle A_{\mathrm{inh}}\rangle \times e_{\mathrm{inh}}(50)$
   $= 5.6\times10^{2}$ Bq $\times\ 2.7\times10^{-5}$ Sv Bq^{-1} = 1.5×10^{-2} Sv = 15 mSv

Question 58

1. excreted activity $A_{\mathrm{ing}} \times f_1 \times 10\times10^{-2} = A_{\mathrm{ing}} \times 5\times10^{-4} \times 10\times10^{-2} = 5\times10^{-5} A_{\mathrm{ing}}$
   = 2.8 l × 0.15 Bq l^{-1} = 0.42 Bq
   intake A_{ing} = 0.42 Bq / 5×10^{-5} = 8.4×10^{3} Bq
   effective committed dose $E_{50} = A_{\mathrm{ing}} \times e_{\mathrm{ing}}(50)$
   $= 8.4\times10^{3}$ Bq $\times\ 2.0\times10^{-7}$ Sv Bq^{-1} = 1.7×10^{-3} Sv = 1.7 mSv

   please note: for the calculation of the $e_{inh}(50)(w)$ for workers, an AMAD = 5 is assumed; for the calculation of the $e_{inh}(50)(b)$ for the general population, an AMAD = 1 is used

2. AMAD = 1 ET_1 does not apply
   ET_2 = 0.21
   BB + bb + AI = 0.0066 + 0.0058 + 0.0084 + 0.0081 + 0.11 = 0.139
   type M from ET_2, half of the 10% goes to the TC and the other half goes to the gastro-intestinal tract (fast uptake in the blood and mechanical cleansing both have a half-life of 10 min), and 90% goes entirely to the gastro-intestinal tract (mechanical cleansing will win over the slow uptake in the blood)
   from the gastro-intestinal tract, $f_1 = 5\times10^{-4}$ still goes to the TC
   from BB+bb+AI, 10% goes to the TC
   total TC $0.21 \times [10\times10^{-2} \times 0.5 \times (1+ 5\times10^{-4}) + 90\times10^{-2} \times 5\times10^{-4}] + 0.139 \times 10\times10^{-2}$
   = 0.0245
   excreted activity $A_{\mathrm{inh}} \times 0.0245 \times 10\times10^{-2} = 2.45\times10^{-3} A_{\mathrm{inh}}$
   = 0.42 Bq
   intake A_{inh} = 0.42 Bq / 2.45×10^{-3} = 1.7×10^{2} Bq
   effective committed dose $E_{50} = A_{\mathrm{inh}} \times e_{\mathrm{inh}}(50)$
   $= 1.7\times10^{2}$ Bq $\times\ 3.9\times10^{-5}$ Sv Bq^{-1} = 6.6×10^{-3} Sv = 6.6 mSv

3. AMAD = 5 ET_1 does not apply
ET_2 = 0.40
BB + bb + AI = 0.012 + 0.0059 + 0.0066 + 0.0044 + 0.053 = 0.082
total TC $0.40 \times [10\times10^{-2} \times 0.5 \times (1 + 5\times10^{-4}) + 90\times10^{-2}\times 5\times10^{-4}] + 0.082 \times 10\times10^{-2}$
$= 0.0282$
excreted activity 0.42 Bq $= A_{\text{inh}} \times 0.0282 \times 10\times10^{-2} = 2.82\times10^{-3}\, A_{\text{inh}}$
intake $A_{\text{inh}} = 0.42$ Bq / 2.82×10^{-3} = 149 Bq
effective committed dose $E_{50} = A_{\text{inh}} \times e_{\text{inh}}(50)$
$= 149$ Bq $\times 2.7\times10^{-5}$ Sv Bq^{-1} = 4.0×10^{-3} Sv = 4.0 mSv

Question 59

1. the exchange of krypton with the outside world is described by the differential equation:
$dA/dt + \lambda A = P$
A (in Bq) = activity concentration (in Bq m^{-3}) × room volume (in m^3)
λ = ventilation rate = room volumes per hour (in h^{-1}) = 1 h^{-1}
P = leakage = 40 MBq h^{-1} = 40×10^6 Bq h^{-1}
in equilibrium, $dA/dt = 0$ $A = P / \lambda = 40\times10^6$ Bq h^{-1} / 1 h^{-1} = 40×10^6 Bq
activity concentration $a = 40\times10^6$ Bq / 500 m^3 = 8×10^4 Bq m^{-3}
equivalent dose rate $dH/dt = a \times e$
$= 8\times10^4$ Bq m^{-3} × 9.2×10^{-13} Sv h^{-1} per Bq m^{-3}
$= 7.4\times10^{-8}$ Sv h^{-1} = 74 nSv h^{-1}

Question 60

1. number of counts $N = A \times$ emission probability × counting efficiency × t
$= A \times 0.43\times10^{-2} \times 2.5\times10^{-3} \times 3600\ \text{s} = 0.0387\, A$
= 89 counts
measured activity $A = 89 / 0.0387 = 2.3\times10^3$ Bq
sampled volume $V = (8.0\ \text{g} \times 10^3\ \text{g mg}^{-1}) / 4.2\ \text{mg m}^{-3} = 1.9\times10^3$ m^3 air
activity concentration $C = A / V = 2.3\times10^3$ Bq / 1.9×10^3 m^3 = 1.2 Bq m^{-3}
2. effective yearly dose $E = C \times e \times t$
= 1.2 Bq m^{-3} × 9.2×10^{-13} Sv h^{-1} per Bq m^{-3} × 2000 h y^{-1}
$= 2.2\times10^{-9}$ Sv y^{-1} = 2.2 nSv y^{-1}
3. energy per Bq s $f_\beta E_\beta + f_\gamma E_\gamma = 0.996 \times 0.251$ MeV + 0.0043 × 0.514 MeV
= 0.250 MeV + 0.002 MeV
equivalent dose rate $dH/dt = 2.5\times10^{-10}\, g\, C\, E$
$= 2.5\times10^{-10} \times 1.2$ Bq m^{-3} × (g_β × 0.250 MeV + g_γ × 0.002 MeV)
$= (7.6\times10^{-11}\, g_\beta + 6.0\times10^{-13}\, g_\gamma)$ Sv h^{-1}
effective yearly rate $E = 2000$ h y^{-1} × $(7.6\times10^{-11}\, g_\beta + 6.0\times10^{-13}\, g_\gamma)$ Sv h^{-1}
$= (1.5\times10^{-7}\, g_\beta + 1.2\times10^{-7}\, g_\gamma)$ Sv y^{-1} = $(150\, g_\beta + 1.2\, g_\gamma)$ nSv y^{-1}
the difference with the result from Question 2 can be understood as follows:
- the effective dose is determined by the penetrating γ-radiation, for which $g_\gamma \approx 0.7$ (see the values of AF for E_γ = 0.514 MeV), but the γ-radiation contributes only about 1% to the energy deposition
- the skin dose is mostly determined by the non-penetrating β-radiation, for which $g_\beta \approx 1$, but the skin contributes only w_{skin} = 1% to the effective dose

4. set $g_\beta = 1.0$ for β-radiation:
   then the skin dose is $H_{skin} = 1.0 \times 150$ nSv y^{-1} = 150 nSv y^{-1}
   contribution of β-radiation to E $w_{skin} \times H_{skin} = 0.01 \times 150$ nSv y^{-1} = 1.5 nSv y^{-1}
   contribution of γ-radiation to E 2.2 nSv y^{-1} - 1.5 nSv y^{-1} = 0.7 nSv y^{-1}
   set $g_\gamma = 0.7$ for γ-radiation:
   contribution of γ-radiation to E 0.7×1.2 nSv y^{-1} = 0.84 nSv y^{-1}
   contribution of β-radiation E 2.2 nSv y^{-1} - 0.84 nSv y^{-1} = 1.36 nSv y^{-1}
   both analyses agree reasonably with each other

   please note: the (older) DAC-values yield an effective dose of 1.2 nSv y^{-1} for the body and an equivalent organ dose of 120 nSv y^{-1} for the critical organ (= skin)

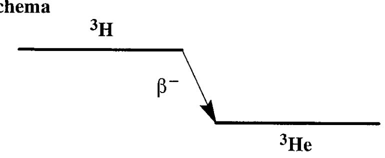
APPENDIX

^{3}H Z = 1   N = 2 ^{3}H

Halveringstijd en vervalconstante

$T_{1/2} = 12{,}35$ j $= 3{,}90\times10^{8}$ s $\lambda = 1{,}78\times10^{-9}\ s^{-1}$

Vervalschema



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)
β^{-}	1,000	5,7 | 18,6

Diversen

Specifieke activiteit	A_{sp}	$= 3{,}57\times10^{14}$ Bq/g
Vrijstellingsgrenzen	C_v	$= 10^{6}$ Bq/g en $A_v = 10^{9}$ Bq
Huidbesmetting	H_{huid}	$< 10^{-14}$ Sv/s per Bq/cm^2
Wondbesmetting; Injectie	$e(50)$	$= 1{,}8\times10^{-11}$ Sv/Bq (water)
Wondbesmetting; Injectie	$e(50)$	$= 4{,}1\times10^{-11}$ Sv/Bq (organisch)
Vervoer	A_1	$= 40$ TBq
	A_2	$= 40$ TBq

Productie en toepassingen

Tritium wordt geproduceerd door bestraling van lithium met neutronen: $^{6}Li(n,\alpha)^{3}H$. Tritium ontstaat ook op natuurlijke wijze. Het wordt gevormd in de buitenste lagen van de atmosfeer, door interactie van kosmische straling met stikstof, voornamelijk via de reactie $^{14}N(n,^{3}H)^{12}C$. Zodoende komt tritium voor in de biosfeer: de tritium-concentratie in zeewater ten gevolge van het natuurlijke tritium bedraagt 0,1–1 Bq/l. De tritiuminventaris van de gehele aarde wordt geschat op 1–2 EBq. Door proeven met thermonucleaire explosies in de atmosfeer is hieraan inmiddels ongeveer 200 EBq toegevoegd. Elk persoon bevat hierdoor 100 Bq tritium.
Van de vele toepassingen van tritium zijn de volgende het belangrijkst:
- tritium-houdende trefplaat voor neutronengenerator via D,T-reactie;
- als lichtbron (o.a. EXIT-bord en horloge): β-light;
- als grondstof voor thermonucleaire reactie (waterstofbom)
- als merker van biologische verbindingen, o.a. voor geneesmiddelenonderzoek
- als merker bij geologische onderzoekingen, o.a. bij olie-exploratie
- als bron in een electroncapture-detector.

Metabool model

Voor stralingshygiënische doeleinden wordt aangenomen dat tritium bij inhalatie en ingestie volledig en instantaan in het lichaam wordt opgenomen. Verder wordt het ook via de intacte huid opgenomen.
De biologische halveringstijd voor alle organen/weefsels wordt gesteld op:

Water	$T_{1/2}$	Organisch	$T_{1/2}$
97%	10 d	50%	10 d
3%	40 d	50%	40 d

Ingestie- en longzuiveringsklassen

Ingestie	
Alle verbindingen	$f_1 = 1$
Inhalatie	
Waterdamp	SR-2
Organisch	SR-2

Voor waterdamp geldt een extra inname van 0,6 Bq/h per Bq/m^3 ten gevolge van opname door de huid.

Dosisconversiecoëfficiënt en radiotoxiciteitsequivalent zowel voor werknemers als voor leden van de bevolking

	Ingestie en inhalatie Water(damp)	Ingestie en inhalatie Organisch	
$e(50)$	$1{,}8\times10^{-11}$	$4{,}1\times10^{-11}$	Sv/Bq
A_{Re}	$5{,}6\times10^{10}$	$2{,}4\times10^{10}$	Bq

Gegevens voor urine-analyse

Na eenmalige inname

Tijd (d)	Urineconcentratie (Bq/l per Bq inname)	Urine-uitscheidingstempo (Bq/d per Bq inname)
1	$2{,}3\times10^{-2}$	$1{,}3\times10^{-2}$
2	$2{,}1\times10^{-2}$	$2{,}3\times10^{-2}$
3	$2{,}0\times10^{-2}$	$2{,}2\times10^{-2}$
5	$1{,}7\times10^{-2}$	$2{,}0\times10^{-2}$
7	$1{,}5\times10^{-2}$	$1{,}8\times10^{-2}$

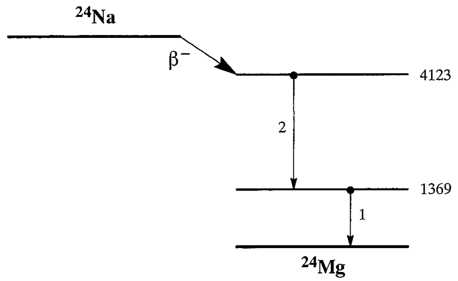
Figure 1. Radiation protection details of the nuclide ^{3}H

^{24}Na Z = 11 N = 13 ^{24}Na

Halveringstijd en vervalconstante

$T_{1/2}$ = 14,96 h = 5,39×10^4 s λ = 1,29×10^{-5} s^{-1}

Vervalschema (vereenvoudigd)



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)
β^-	0,999	554 | 1390
γ_1	1,000	1369
γ_2	0,999	2754

Bronconstanten

Kermatempo in lucht	k = 0,43 µGy/h per MBq/m^2
Omgevingsdosisequivalenttempo	h = 0,49 µSv/h per MBq/m^2

Diversen

Specifieke activiteit	A_{sp} = 3,22×10^{17} Bq/g
Vrijstellingsgrenzen	C_v = 10^1 Bq/g en A_v = 10^5 Bq
Huidbesmetting	H_{huid} = 4×10^{-10} Sv/s per Bq/cm^2
Wondbesmetting; Injectie	$e(50)$ = 3,1×10^{-10} Sv/Bq
Vervoer	A_1 = 0,2 TBq
	A_2 = 0,2 TBq

Productie en toepassingen

Het nuclide wordt gevormd in een reactor door de vangst van thermische neutronen in natrium (^{23}Na). Het is dus een activeringsproduct. Toepassingen liggen op het gebied van biologisch onderzoek, nucleaire-activeringsanalyse en dosimetrie van personen na overbestraling met neutronen.

Metabool model

Voor stralingshygiënische doeleinden wordt aangenomen dat natrium zich vanuit het bloed als volgt verdeelt: 30% naar bot en 70% verdeeld over de overige organen/weefsels.
De biologische halveringstijden in het botweefsel zijn: 10 dagen (99%) en 500 dagen (1%). De biologische halveringstijd voor de overige organen/weefsels wordt gesteld op 10 dagen.

Ingestie- en longzuiveringsklassen

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

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

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

Gegevens voor totale-lichaamstelling

Na eenmalige inname

Tijd (d)	Lichaamsactiviteit (Bq per Bq inname)	
0,25	7,6×10^{-1}	5,6×10^{-1}
1	3,2×10^{-1}	1,9×10^{-1}
2	9,9×10^{-2}	5,2×10^{-2}
3	3,1×10^{-2}	1,5×10^{-2}
5	2,9×10^{-3}	1,4×10^{-3}
7	2,7×10^{-4}	1,3×10^{-4}

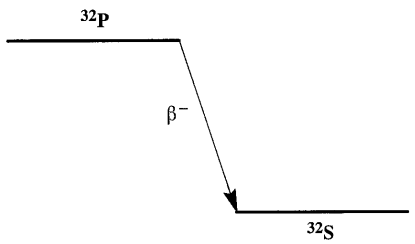
Figure 2. Radiation protection details of the nuclide ^{24}Na

^{32}P Z = 15 N = 17 ^{32}P

Halveringstijd en vervalconstante

$T_{1/2}$ = 14,29 d = 1,23×10^{6} s λ = 5,61×10^{-7} s^{-1}

Vervalschema (vereenvoudigd)



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)
β^-	1,000	695 | 1710

Diversen

Specifieke activiteit	A_{sp}	= 1,06×10^{16} Bq/g
Vrijstellingsgrenzen	C_v	= 10^{3} Bq/g en A_v = 10^{5} Bq
Huidbesmetting	H_{huid}	= 6×10^{-10} Sv/s per Bq/cm^{2}
Wondbesmetting; Injectie	$e(50)$	= 2,2×10^{-9} Sv/Bq
Vervoer	A_1	= 0,5 TBq
	A_2	= 0,5 TBq

Productie en toepassingen

Het radionuclide ^{32}P is een activeringsproduct. Het nuclide wordt toegepast bij medisch-biologisch onderzoek als merker.

Metabool model

Voor stralingshygiënische doeleinden wordt aangenomen dat fosfor zich vanuit het bloed als volgt verdeelt: 15% directe uitscheiding, 15% naar intracellulaire vloeistof, 40% naar zacht weefsel en 30% naar bot. De aangenomen biologische halveringstijden zijn:

Bloed	0,5 d
Intracellulair	2 d
Zachte weefsel	19 d
Bot	oneindig

Ingestie- en longzuiveringsklassen

Ingestie		
Alle verbindingen	f_1 = 0,8	
Inhalatie		
Fosfaat van Zn, Sn, Mg, Fe, Bi, lantaniden	f_1 = 0,8	Klasse M
Overige verbindingen	f_1 = 0,8	Klasse F

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

	Ingestie	Inhalatie	Inhalatie	
	f_1 = 0,8	F	M	
$e(50)$(w)	2,4×10^{-9}	1,1×10^{-9}	2,9×10^{-9}	Sv/Bq
A_{Re}(w)	4,2×10^{8}	9,1×10^{8}	3,4×10^{8}	Bq
$e(50)$(b)	2,4×10^{-9}	8,0×10^{-10}	3,2×10^{-9}	Sv/Bq
A_{Re}(b)	4,2×10^{8}	1,3×10^{9}	3,1×10^{8}	Bq

Gegevens voor urine-analyse

Na eenmalige inname

Tijd (d)	Urine-uitscheidingstempo (Bq/d per Bq inname)		
1	8,5×10^{-2}	4,9×10^{-2}	3,6×10^{-2}
2	5,2×10^{-2}	2,8×10^{-2}	2,3×10^{-2}
3	3,1×10^{-2}	1,7×10^{-2}	1,4×10^{-2}
5	1,6×10^{-2}	8,9×10^{-3}	7,2×10^{-3}
7	1,0×10^{-2}	5,6×10^{-3}	4,5×10^{-3}

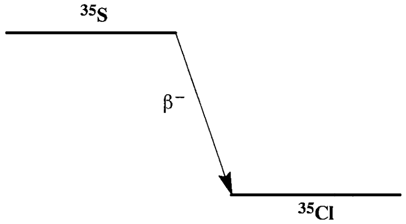
Figure 3. Radiation protection details of the nuclide ^{32}P

^{35}S Z = 16 N = 19 ^{35}S

Halveringstijd en vervalconstante

$T_{1/2}$ = 87,44 d = 7,55×10^{6} s λ = 9,17×10^{-8} s^{-1}

Vervalschema (vereenvoudigd)



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)
β^-	1,000	49 | 167

Diversen

Specifieke activiteit	A_{sp}	= 1,58×10^{15} Bq/g
Vrijstellingsgrenzen	C_v	= 10^{6} Bq/g en A_v = 10^{9} Bq (damp)
	C_v	= 10^{5} Bq/g en A_v = 10^{8} Bq(overig)
Huidbesmetting	H_{huid}	= 3×10^{-11} Sv/s per Bq/cm^{2}
Wondbesmetting; Injectie	$e(50)$	= 7,7×10^{-10} Sv/Bq (organisch)
	$e(50)$	= 1,2×10^{-10} Sv/Bq (anorganisch)
Vervoer	A_1	= 40 TBq
	A_2	= 3 TBq

Productie en toepassingen

Het radionuclide ^{35}S is een activeringsproduct. Het nuclide wordt toegepast bij medisch-biologisch onderzoek als merker.

Metabool model

Organisch zwavel
Voor stralingshygiënische doeleinden wordt aangenomen dat organisch zwavel zich homogeen over het lichaam verdeelt en met een biologische halveringstijd van 140 dagen wordt uitgescheiden.

Ingestie		
Zwavel in voedsel	f_1 = 1	$e(50)$ = 7,7×10^{-10} Sv/Bq
Inhalatie		
CS_2, H_2S, COS	SR-1	$e(50)$ = 7,0×10^{-10} Sv/Bq

Anorganisch zwavel
Voor stralingshygiënische doeleinden wordt aangenomen dat anorganisch zwavel zich vanuit het bloed als volgt verdeelt: 80% directe uitscheiding en 20% verdeeld over alle organen/weefsels.
De biologische halveringstijden voor de alle organen/weefsels wordt gesteld op:

Fractie	$T_{1/2}$	Fractie	$T_{1/2}$
0,75	20 d	0,25	2000 d

Ingestie- en longzuiveringsklassen

Ingestie		
Elementair zwavel	f_1 = 0,1	
Overige anorg. verbindingen	f_1 = 0,8	
Inhalatie		
Elementair zwavel, de meeste sulfiden	f_1 = 0,8	Klasse M
Overige anorganische verbindingen	f_1 = 0,8	Klasse F
SO_2	Gas	Klasse SR-1, 85% depositie

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

	Ingestie f_1 = 0,1	Ingestie f_1 = 0,8	Inhalatie F	Inhalatie M	Inhalatie SO_2	
$e(50)$(w)	1,9×10^{-10}	1,4×10^{-10}	8,0×10^{-11}	1,1×10^{-9}	1,1×10^{-10}	Sv/Bq
A_{Re}(w)	5,3×10^{9}	7,1×10^{9}	1,2×10^{10}	9,1×10^{8}	9,1×10^{9}	Bq
$e(50)$(b)	1,9×10^{-10}	1,4×10^{-10}	5,3×10^{-11}	1,3×10^{-9}	1,1×10^{-10}	Sv/Bq
A_{Re}(b)	5,3×10^{9}	7,1×10^{9}	1,9×10^{10}	7,7×10^{8}	9,1×10^{9}	Bq

Gegevens voor urine-analyse

Tijd (d)	Urine-uitscheidingstempo (Bq/d per Bq inname)				
1	6,1×10^{-2}	5,2×10^{-1}	2,9×10^{-1}	2,2×10^{-1}	4,9×10^{-1}
2	1,1×10^{-2}	5,7×10^{-2}	2,8×10^{-2}	2,7×10^{-2}	4,6×10^{-2}
3	1,1×10^{-3}	6,8×10^{-3}	3,5×10^{-3}	3,7×10^{-3}	5,8×10^{-3}
5	4,0×10^{-4}	3,2×10^{-3}	1,7×10^{-3}	1,9×10^{-3}	2,9×10^{-3}
7	3,6×10^{-4}	2,9×10^{-3}	1,6×10^{-3}	1,7×10^{-3}	2,7×10^{-3}

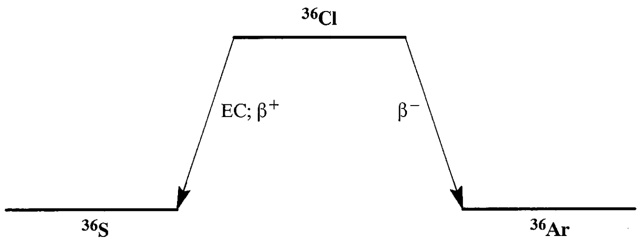
Figure 4. Radiation protection details of the nuclide ^{35}S

^{36}Cl Z = 17 N = 19 ^{36}Cl

Halveringstijd en vervalconstante

$T_{1/2} = 3{,}01 \times 10^{5}$ j $= 9{,}50 \times 10^{12}$ s $\lambda = 7{,}30 \times 10^{-14}\ s^{-1}$

Vervalschema (vereenvoudigd)



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)
β^-	0,981	279 | 710

Bronconstanten

Kermatempo in lucht	k = 0,0 μGy/h per MBq/m^2
Omgevingsdosisequivalenttempo	h = 0,0 μSv/h per MBq/m^2

Diversen

Specifieke activiteit	$A_{sp} = 1{,}22 \times 10^{9}$ Bq/g
Vrijstellingsgrenzen	$C_v = 10^{4}$ Bq/g en $A_v = 10^{6}$ Bq
Huidbesmetting	$H_{huid} = 5 \times 10^{-11}$ Sv/s per Bq/cm^2
Wondbesmetting; Injectie	$e(50) = 8{,}2 \times 10^{-10}$ Sv/Bq
Vervoer	A_1 = 10 TBq
	A_2 = 0,6 TBq

Productie en toepassingen

Het radionuclide ^{36}Cl wordt geproduceerd door vangst van thermische neutronen in chloor. Het nuclide wordt toegepast als beta-ijkbron. Een speciale toepassing werd gevonden bij de reconstructie van de neutronenfluentie ten gevolge van de kern-explosies in Hiroshima en Nagasaki.

Metabool model

Voor stralingshygiënische doeleinden wordt aangenomen dat chloor zich vanuit het bloed homogeen over alle organen/weefsels verdeelt.
De biologische halveringstijden voor de alle organen/weefsels wordt gesteld op 10 dagen.

Ingestie- en longzuiveringsklassen

Ingestie		
Alle verbindingen	$f_1 = 1$	
Inhalatie		
Chloride van H, Li, Na, K, Rb en Cs	$f_1 = 1$	Klasse F
Overige chloriden	$f_1 = 1$	Klasse M

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

	Ingestie	Inhalatie	Inhalatie	
	$f_1 = 1$	F	M	
$e(50)(w)$	$9{,}3 \times 10^{-10}$	$4{,}9 \times 10^{-10}$	$5{,}1 \times 10^{-9}$	Sv/Bq
$A_{Re}(w)$	$1{,}1 \times 10^{9}$	$2{,}0 \times 10^{9}$	$2{,}0 \times 10^{8}$	Bq
$e(50)(b)$	$9{,}3 \times 10^{-10}$	$3{,}4 \times 10^{-10}$	$6{,}9 \times 10^{-9}$	Sv/Bq
$A_{Re}(b)$	$1{,}1 \times 10^{9}$	$2{,}9 \times 10^{9}$	$1{,}4 \times 10^{8}$	Bq

Gegevens voor urine-analyse

Na eenmalige inname

Tijd (d)	Urine-uitscheidingstempo (Bq/d per Bq inname)		
1	$6{,}8 \times 10^{-2}$	$1{,}9 \times 10^{-2}$	$1{,}5 \times 10^{-2}$
2	$6{,}3 \times 10^{-2}$	$3{,}0 \times 10^{-2}$	$2{,}6 \times 10^{-2}$
3	$5{,}7 \times 10^{-2}$	$2{,}9 \times 10^{-2}$	$2{,}5 \times 10^{-2}$
5	$5{,}0 \times 10^{-2}$	$2{,}5 \times 10^{-2}$	$2{,}2 \times 10^{-2}$
7	$4{,}3 \times 10^{-2}$	$2{,}2 \times 10^{-2}$	$2{,}0 \times 10^{-2}$

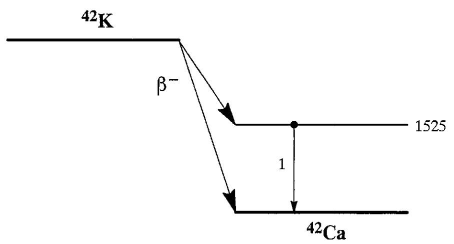
Figure 5. Radiation protection details of the nuclide ^{36}Cl

^{42}K Z = 19 N = 23 ^{42}K

Halveringstijd en vervalconstante

$T_{1/2}$ = 12,36 h = $4{,}45\times10^{4}$ s $\lambda = 1{,}56\times10^{-5}\ s^{-1}$

Vervalschema (vereenvoudigd)



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)
β^-	0,175	822 | 1996
β^-	0,821	1564 | 3521
γ_1	0,179	1525

Bronconstanten

Kermatempo in lucht	k = 0,032 µGy/h per MBq/m^2
Omgevingsdosisequivalenttempo	h = 0,037 µSv/h per MBq/m^2

Diversen

Specifieke activiteit	A_{sp} = $2{,}24\times10^{17}$ Bq/g
Vrijstellingsgrenzen	C_v = 10^2 Bq/g en $A_v = 10^6$ Bq
Huidbesmetting	H_{huid} = 7×10^{-10} Sv/s per Bq/cm^2
Wondbesmetting; Injectie	$e(50)$ = $2{,}3\times10^{-10}$ Sv/Bq
Vervoer	A_1 = 0,2 TBq
	A_2 = 0,2 TBq

Productie en toepassingen

Het radionuclide ^{42}K is een activeringsproduct. Het nuclide wordt onder meer gebruikt als merker 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 radiotoxiciteitsequivalent voor werknemers (w) en voor leden van de bevolking (b)

	Ingestie	Inhalatie	
	$f_1 = 1$	F	
$e(50)$(w)	$4{,}3\times10^{-10}$	$2{,}0\times10^{-10}$	Sv/Bq
A_{Re}(w)	$2{,}3\times10^{9}$	$5{,}0\times10^{9}$	Bq
$e(50)$(b)	$4{,}3\times10^{-10}$	$1{,}3\times10^{-10}$	Sv/Bq
A_{Re}(b)	$2{,}3\times10^{9}$	$7{,}7\times10^{9}$	Bq

Gegevens voor totale-lichaamstelling

Na eenmalige inname

Tijd (d)	Lichaamsactiviteit (Bq per Bq inname)	
0,25	$7{,}1\times10^{-1}$	$5{,}3\times10^{-1}$
1	$2{,}6\times10^{-1}$	$1{,}6\times10^{-1}$
2	$6{,}5\times10^{-2}$	$3{,}5\times10^{-2}$
3	$1{,}6\times10^{-2}$	$8{,}4\times10^{-3}$
5	$1{,}1\times10^{-3}$	$5{,}3\times10^{-4}$
7	$6{,}9\times10^{-5}$	$3{,}4\times10^{-5}$

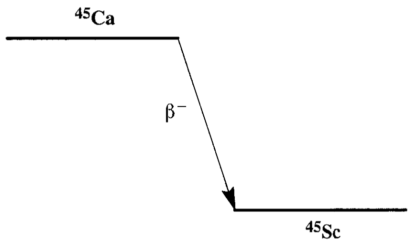
Figure 6. Radiation protection details of the nuclide ^{42}K

^{45}Ca Z = 20 N = 25 ^{45}Ca

Halveringstijd en vervalconstante

$T_{1/2}$ = 163 d = 1,41×10^{7} s λ = 4,92×10^{-8} s^{-1}

Vervalschema (vereenvoudigd)



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)
β^{-}	1,000	77 | 256

Diversen

Specifieke activiteit	A_{sp}	= 6,58×10^{14} Bq/g
Vrijstellingsgrenzen	C_v	= 10^{4} Bq/g en A_v = 10^{7} Bq
Huidbesmetting	H_{huid}	= 2×10^{-10} Sv/s per Bq/cm^{2}
Wondbesmetting; Injectie	$e(50)$	= 1,8×10^{-9} Sv/Bq
Vervoer	A_1	= 40 TBq
	A_2	= 1 TBq

Productie en toepassingen

Het radionuclide ^{45}Ca is een activeringsproduct. Het nuclide wordt onder meer gebruikt als merker bij medisch-biologisch onderzoek.

Metabool model

Voor stralingshygiënische doeleinden wordt aangenomen dat calcium zich vanuit het bloed verdeelt naar bot en zacht weefsel. Een speciaal model is gepresenteerd in ICRP-20. Als benadering kan de volgende verdeling met bijbehorende biologische halveringstijden worden aangenomen:

Sponsachtig bot (32%)		Compact bot (33%)		Zacht weefsel (35%)	
Fractie	$T_{1/2}$	Fractie	$T_{1/2}$	Fractie	$T_{1/2}$
0,34	10 d	0,30	10 d	0,37	1,5 d
0,16	700 d	0,15	1100 d	0,29	45 d
0,50	2900 d	0,55	10500 d	0,14	100 d

Ingestie- en longzuiveringsklassen

Ingestie		
Alle verbindingen	f_1 = 0,3	
Inhalatie		
Alle verbindingen	f_1 = 0,3	Klasse M

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

	Ingestie	Inhalatie	
	f_1 = 0,3	M	
$e(50)$(w)	7,6×10^{-10}	2,3×10^{-9}	Sv/Bq
A_{Re}(w)	1,3×10^{9}	4,3×10^{8}	Bq
$e(50)$(b)	7,6×10^{-10}	2,7×10^{-9}	Sv/Bq
A_{Re}(b)	1,3×10^{9}	3,7×10^{8}	Bq

Gegevens voor totale-lichaamstelling

Na eenmalige inname

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

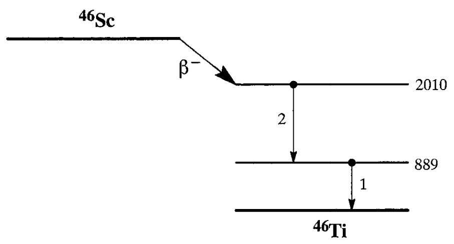
Figure 7. Radiation protection details of the nuclide ^{45}Ca

^{46}Sc Z = 21 N = 25 ^{46}Sc

Halveringstijd en vervalconstante

$T_{1/2}$ = 83,80 d = 7,24×10^{6} s λ = 9,57×10^{-8} s^{-1}

Vervalschema (vereenvoudigd)



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)
β^-	1,000	112 ¦ 357
γ_1	1,000	889
γ_2	1,000	1121

Bronconstanten

Kermatempo in lucht	k = 0,26 µGy/h per MBq/m^2
Omgevingsdosisequivalenttempo	h = 0,30 µSv/h per MBq/m^2

Diversen

Specifieke activiteit	A_{sp} = 1,25×10^{15} Bq/g
Vrijstellingsgrenzen	C_v = 10^{1} Bq/g en A_v = 10^{6} Bq
Huidbesmetting	H_{huid} = 3×10^{-10} Sv/s per Bq/cm^2
Wondbesmetting; Injectie	$e(50)$ = 2,3×10^{-8} Sv/Bq
Vervoer	A_1 = 0,5 TBq
	A_2 = 0,5 TBq

Productie en toepassingen

Het radionuclide ^{46}Sc is een activeringsproduct.

Metabool model

Voor stralingshygiënische doeleinden wordt aangenomen dat scandium zich vanuit het bloed als volgt verdeelt: 40% naar bot, 30% naar lever, 10% naar milt en de rest homogeen verdeeld over de overige organen/weefsels. De biologische halveringstijden zijn:

Fractie	$T_{1/2}$
0,1	5 d
0,9	1500 d

Ingestie- en longzuiveringsklassen

Ingestie		
Alle verbindingen	f_1 = 1×10^{-4}	
Inhalatie		
Alle verbindingen	f_1 = 1×10^{-4}	Klasse S

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

	Ingestie	Inhalatie	
	f_1 = 1×10^{-4}	S	
$e(50)$(w)	1,5×10^{-9}	4,8×10^{-9}	Sv/Bq
A_{Re}(w)	6,7×10^{8}	2,1×10^{8}	Bq
$e(50)$(b)	1,5×10^{-9}	6,4×10^{-9}	Sv/Bq
A_{Re}(b)	6,7×10^{8}	1,6×10^{8}	Bq

Gegevens voor totale-lichaamstelling

Na eenmalige inname

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

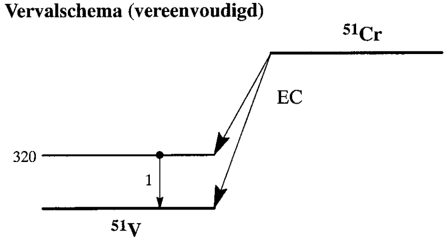
Figure 8. Radiation protection details of the nuclide ^{46}Sc

^{51}Cr Z = 24 N = 27 ^{51}Cr

Halveringstijd en vervalconstante

$T_{1/2}$ = 27,71 d = 2,39×10^6 s λ = 2,90×10^{-7} s^{-1}

Vervalschema (vereenvoudigd)



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)
γ_1	0,098	320
K_α	0,200	5
KLL	0,558	4
KLX	0,113	5

Bronconstanten

Kermatempo in lucht k = 0,0042 µGy/h per MBq/m^2
Omgevingsdosisequivalenttempo h = 0,0054 µSv/h per MBq/m^2

Diversen

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

Productie en toepassingen

Het radionuclide ^{51}Cr is een bijzonder activeringsproduct: het zendt geen beta's uit en wordt zodoende niet waargenomen door de gebruikelijke besmettingsmeters. Voor de detectie van ^{51}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 gesteld op:

Bloed		0,5 d
Bot		1000 d
Rest	0,62	6 d
	0,38	80 d

Ingestie- en longzuiveringsklassen

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

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

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

Gegevens voor totale-lichaamstelling

Na eenmalige inname

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

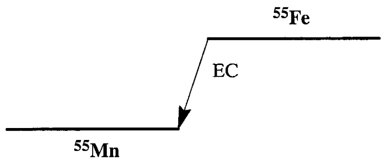
Figure 9. Radiation protection details of the nuclide ^{51}Cr

^{55}Fe Z = 26 N = 29 ^{55}Fe

Halveringstijd en vervalconstante

$T_{1/2}$ = 985,4 d = $8{,}51\times10^{7}$ s $\lambda = 8{,}14\times10^{-9}\ s^{-1}$

Vervalschema (vereenvoudigd)



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)
K_{α}	0,250	6
K_{β}	0,033	6
KLL	0,495	5
KLX	0,112	6

Bronconstanten

Kermatempo in lucht	k = 0,000 µGy/h per MBq/m^2
Omgevingsdosisequivalenttempo	h = 0,000 µSv/h per MBq/m^2

Diversen

Specifieke activiteit	$A_{sp} = 8{,}91\times10^{13}$ Bq/g
Vrijstellingsgrenzen	$C_v = 10^4$ Bq/g en $A_v = 10^6$ Bq
Huidbesmetting	$H_{huid} = 1\times10^{-12}$ Sv/s per Bq/cm^2
Wondbesmetting; Injectie	$e(50) = 3{,}0\times10^{-9}$ Sv/Bq
Vervoer	A_1 = 40 TBq
	A_2 = 40 TBq

Productie en toepassingen

Het radionuclide ^{55}Fe is een activeringsproduct dat ontstaat uit de reactie: ^{54}Fe(n,γ)^{55}Fe. Het nuclide zendt alleen karakteristieke röntgenstraling uit. Daarom is voor detectie een speciale detector ontwikkeld (zgn. Fe-55-detector). Het nuclide wordt gebruikt in een electroncapture-detector en bij röntgen-fluorescentie.

Metabool model

Het model wordt beschreven in ICRP-69. Het model bevat 17 compartimenten en 21 transportconstanten. Het gedrag van ijzer in het lichaam wordt voornamelijk bepaald door opname in het haemoglobine.

Ingestie- en longzuiveringsklassen

Ingestie		
Alle verbindingen	f_1 = 0,1	
Inhalatie		
Oxide, hydroxide, halogenide	f_1 = 0,1	Klasse M
Overige verbindingen	f_1 = 0,1	Klasse F

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

	Ingestie	Inhalatie	Inhalatie	
	f_1 = 0,1	F	M	
$e(50)(w)$	$3{,}3\times10^{-10}$	$9{,}2\times10^{-10}$	$3{,}3\times10^{-10}$	Sv/Bq
$A_{Re}(w)$	$3{,}0\times10^{9}$	$1{,}1\times10^{9}$	$3{,}0\times10^{9}$	Bq
$e(50)(b)$	$3{,}3\times10^{-10}$	$7{,}7\times10^{-10}$	$3{,}7\times10^{-10}$	Sv/Bq
$A_{Re}(b)$	$3{,}0\times10^{9}$	$1{,}3\times10^{9}$	$2{,}7\times10^{9}$	Bq

Gegevens voor urine–analyse

Na eenmalige inname

Tijd (d)	Urine–uitscheidingstempo (Bq/d per Bq inname)		
1	$2{,}0\times10^{-4}$	$6{,}1\times10^{-4}$	$1{,}3\times10^{-4}$
2	$2{,}1\times10^{-5}$	$5{,}4\times10^{-5}$	$1{,}4\times10^{-5}$
3	$1{,}2\times10^{-5}$	$3{,}5\times10^{-5}$	$9{,}0\times10^{-6}$
5	$6{,}2\times10^{-6}$	$1{,}8\times10^{-5}$	$4{,}9\times10^{-6}$
7	$3{,}8\times10^{-6}$	$1{,}1\times10^{-5}$	$3{,}4\times10^{-6}$

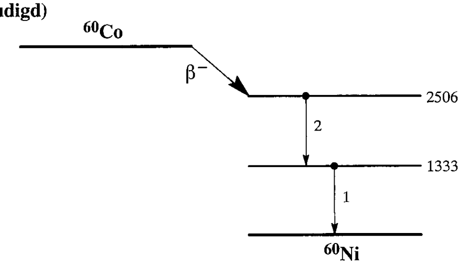
Figure 10. Radiation protection details of the nuclide ^{55}Fe

^{60}Co Z = 27 N = 33 ^{60}Co

Halveringstijd en vervalconstante

$T_{1/2}$ = 5,272 j = 1,66×10^{8} s λ = 4,17×10^{-9} s^{-1}

Vervalschema (vereenvoudigd)



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)
β^-	0,999	96 | 318
γ_1	1,000	1333
γ_2	0,999	1173

Bronconstanten

Kermatempo in lucht	k = 0,31 μGy/h per MBq/m^2
Omgevingsdosisequivalenttempo	h = 0,36 μSv/h per MBq/m^2

Diversen

Specifieke activiteit	A_{sp} = 4,18×10^{13} Bq/g
Vrijstellingsgrenzen	C_v = 10^0 = 1 Bq/g !!
	A_v = 10^5 Bq
Huidbesmetting	H_{huid} = 3×10^{-10} Sv/s per Bq/cm^2
Wondbesmetting; Injectie	$e(50)$ = 1,9×10^{-8} Sv/Bq
Vervoer	A_1 = 0,4 TBq
	A_2 = 0,4 TBq

Productie en toepassingen

Het radionuclide ^{60}Co is een activeringsproduct. Het komt voor als bijproduct in reactoren ten gevolge van de activering van staal. Daarnaast wordt het op velerlei terreinen toegepast. Voorbeelden zijn: radiotherapie, gammagrafie, doorstraling, ijking, demonstratie.

Metabool model

Voor stralingshygiënische doeleinden wordt aangenomen dat kobalt zich vanuit het bloed als volgt verdeelt: 50% directe uitscheiding, 5% naar lever en 45% naar de rest van het lichaam, met een biologische halveringstijd van 0,5 dag.
De biologische halveringstijden voor de organen zijn:

Fractie	$T_{1/2}$
0,6	6 d
0,2	60 d
0,2	800 d

Ingestie- en longzuiveringsklassen

Ingestie		
Oxide, hydroxide en anorganisch	f_1 = 0,05	
Overige verbindingen	f_1 = 0,1	
Inhalatie		
Oxide, hydroxide, halogenide, nitraat	f_1 = 0,05	Klasse S
Overige	f_1 = 0,1	Klasse M

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

	Ingestie	Ingestie	Inhalatie	Inhalatie	
	f_1 = 0,05	f_1 = 0,1	M	S	
$e(50)$(w)	2,5×10^{-9}	3,4×10^{-9}	7,1×10^{-9}	1,7×10^{-8}	Sv/Bq
A_{Re}(w)	4,0×10^{8}	2,9×10^{8}	1,4×10^{8}	5,9×10^{7}	Bq
$e(50)$(b)	2,5×10^{-9}	3,4×10^{-9}	9,6×10^{-9}	2,9×10^{-8}	Sv/Bq
A_{Re}(b)	4,0×10^{8}	2,9×10^{8}	1,0×10^{8}	3,4×10^{7}	Bq

Gegevens voor totale-lichaamstelling

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

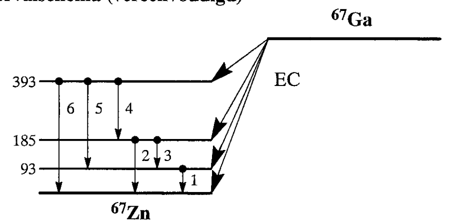
Figure 11. Radiation protection details of the nuclide ^{60}Co

^{67}Ga Z = 31 N = 36 ^{67}Ga

Halveringstijd en vervalconstante

$T_{1/2}$ = 78,23 h = 2,82×10^{5} s λ = 2,46×10^{-6} s^{-1}

Vervalschema (vereenvoudigd)



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)	Straling	y (Bq·s)$^{-1}$	E (keV)
γ_1	0,383	93	ce K γ_1	0,287	84
γ_2	0,209	185	K_α	0,495	9
γ_3	0,031	91	KLL	0,467	7
γ_4	0,024	209	KLX	0,133	8
γ_5	0,168	300			
γ_6	0,047	393			

Bronconstanten

Kermatempo in lucht	k = 0,018 μGy/h per MBq/m^2
Omgevingsdosisequivalenttempo	h = 0,025 μSv/h per MBq/m^2

Diversen

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

Productie en toepassingen

Het radionuclide ^{67}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		
Alle verbindingen	f_1 = 0,001	
Inhalatie		
Oxide, hydroxide, carbide, halogenide, nitraat	f_1 = 0,001	Klasse M
Overige	f_1 = 0,001	Klasse F

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

	Ingestie	Inhalatie	Inhalatie	
	f_1 = 0,001	F	M	
$e(50)$(w)	1,9×10^{-10}	1,1×10^{-10}	2,8×10^{-10}	Sv/Bq
A_{Re}(w)	5,3×10^{9}	9,1×10^{9}	3,6×10^{9}	Bq
$e(50)$(b)	1,9×10^{-10}	6,8×10^{-11}	2,3×10^{-10}	Sv/Bq
A_{Re}(b)	5,3×10^{9}	1,5×10^{10}	4,3×10^{9}	Bq

Gegevens voor totale-lichaamstelling

Na eenmalige inname

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

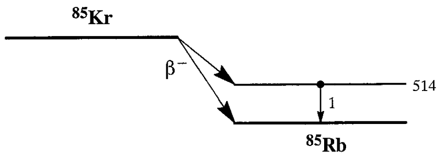
Figure 12. Radiation protection details of the nuclide ^{67}Ga

^{85}Kr Z = 36 N = 49 ^{85}Kr

Halveringstijd en vervalconstante

$T_{1/2}$ = 10,70 j = 3,38×10^{8} s λ = 2,05×10^{-9} s^{-1}

Vervalschema (vereenvoudigd)



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)
β^{-}	0,996	251 | 687
γ_1	0,0043	514

Bronconstanten

Kermatempo in lucht	k = 3,0×10^{-4} μGy/h per MBq/m^2
Omgevingsdosisequivalenttempo	h = 3,7×10^{-4} μSv/h per MBq/m^2

Diversen

Specifieke activiteit	A_{sp} = 1,45×10^{13} Bq/g
Vrijstellingsgrenzen	C_v = 10^{5} Bq/g
	A_v = 10^{4} Bq
	A_v = 10^{10} Bq (gebruiksartikelen zoals lampen en starters)
Huidbesmetting	H_{huid} = 5×10^{-10} Sv/s per Bq/cm^2
Wondbesmetting; Injectie	Niet van toepassing
Vervoer	A_1 = 10 TBq
	A_2 = 10 TBq

Productie en toepassingen

Het radionuclide ^{85}Kr is een splijtingsproduct dat vrijkomt bij de verwerking van gebruikte splijtstof. Hierdoor komt het voor in de atmosfeer met een concentratie van ongeveer 1 Bq·m^{-3}. Het wordt gebruikt onder andere in een vulhoogtemeter (als gammastraler) of in een diktemeter (als betastraler). Omdat krypton een edelgas is, kan bij een ongeval met de bron geen oppervlaktebesmetting plaatsvinden.

Dosisconversiecoëfficiënt klasse SR-0

e = 9,2×10^{-13} Sv/h per Bq/m^3

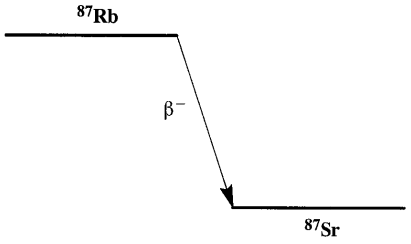
Figure 13. Radiation protection details of the nuclide ^{85}Kr

^{87}Rb Z = 37 N = 50 ^{87}Rb

Halveringstijd en vervalconstante

$T_{1/2} = 4{,}7\times10^{10}$ j = $1{,}5\times10^{18}$ s $\lambda = 4{,}7\times10^{-19}\ s^{-1}$

Vervalschema (vereenvoudigd)



Belangrijkste uitgezonden straling

Straling	$y\ (Bq\cdot s)^{-1}$	E (keV)
β^-	1,000	112 | 273

Diversen

Specifieke activiteit	A_{sp}	= $3{,}2\times10^{3}$ Bq/g
Vrijstellingsgrenzen	C_v	= 10^4 Bq/g
	A_v	= 10^7 Bq
Huidbesmetting	H_{huid}	= 3×10^{-10} Sv/s per Bq/cm²
Wondbesmetting; Injectie	$e(50)$	= $1{,}3\times10^{-9}$ Sv/Bq
Vervoer	A_1	= Onbeperkt
	A_2	= Onbeperkt

Productie en toepassingen

Het radionuclide ^{87}Rb is van primordiale oorsprong. Het komt in geringe mate voor in de natuur: de referentiemens bevat ongeveer 500 Bq ^{87}Rb.

Metabool model

Voor stralingshygiënische doeleinden wordt aangenomen dat rubidium zich vanuit het bloed als volgt verdeelt: 25% naar het skelet en 75% naar alle overige organen. De biologische halveringstijd voor alle organen is gesteld op 44 dagen.

Ingestie- en longzuiveringsklassen

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

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

	Ingestie	Inhalatie	
	$f_1 = 1$	F	
$e(50)(w)$	$1{,}5\times10^{-9}$	$7{,}6\times10^{-10}$	Sv/Bq
$A_{Re}(w)$	$6{,}7\times10^{8}$	$1{,}3\times10^{9}$	Bq
$e(50)(b)$	$1{,}5\times10^{-9}$	$5{,}1\times10^{-10}$	Sv/Bq
$A_{Re}(b)$	$6{,}7\times10^{8}$	$2{,}0\times10^{9}$	Bq

Gegevens voor totale-lichaamstelling

Na eenmalige inname

Tijd (d)	Lichaamsactiviteit (Bq per Bq inname)	
0,25	$1{,}0\times10^{-0}$	$7{,}4\times10^{-1}$
1	$9{,}9\times10^{-1}$	$6{,}0\times10^{-1}$
2	$9{,}7\times10^{-1}$	$5{,}2\times10^{-1}$
3	$9{,}6\times10^{-1}$	$4{,}8\times10^{-1}$
5	$9{,}3\times10^{-1}$	$4{,}5\times10^{-1}$
7	$9{,}0\times10^{-1}$	$4{,}4\times10^{-1}$

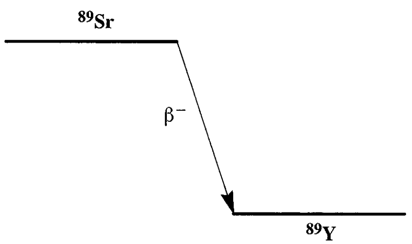
Figure 14. Radiation protection details of the nuclide ^{87}Rb

^{89}Sr Z = 38 N = 51 ^{89}Sr

Halveringstijd en vervalconstante

$T_{1/2}$ = 50,5 d = $4{,}36\times10^{6}$ s $\lambda = 1{,}59\times10^{-7}\ s^{-1}$

Vervalschema



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)
β⁻	1,000	583 | 1491

Diversen

Specifieke activiteit	A_{sp}	= $1{,}07\times10^{15}$ Bq/g
Vrijstellingsgrenzen	C_v	= 10^{3} Bq/g en $A_v = 10^{6}$ Bq
Huidbesmetting	H_{huid}	= 4×10^{-10} Sv/s per Bq/cm^2
Wondbesmetting; Injectie	$e(50)$	= $3{,}1\times10^{-9}$ Sv/Bq
Vervoer	A_1	= 0,6 TBq
	A_2	= 0,6 TBq

Productie en toepassingen

Het radionuclide ^{89}Sr is een splijtingsproduct.

Metabool model

De stofwisseling van de botzoeker strontium is uitgebreid beschreven in ICRP-67.

Ingestie- en longzuiveringsklassen

Ingestie		
Sr-titanaat	$f_1 = 0{,}01$	
Overige verbindingen	$f_1 = 0{,}3$	
Inhalatie		
Titanaat	$f_1 = 0{,}01$	Klasse S
Overige	$f_1 = 0{,}3$	Klasse F

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

	Ingestie	Ingestie	Inhalatie	Inhalatie	
	$f_1 = 0{,}01$	$f_1 = 0{,}3$	F	S	
$e(50)$(w)	$2{,}3\times10^{-9}$	$2{,}6\times10^{-9}$	$1{,}4\times10^{-9}$	$5{,}6\times10^{-9}$	Sv/Bq
A_{Re}(w)	$4{,}3\times10^{8}$	$3{,}8\times10^{8}$	$7{,}1\times10^{8}$	$1{,}8\times10^{8}$	Bq
$e(50)$(b)	$2{,}3\times10^{-9}$	$2{,}6\times10^{-9}$	$1{,}0\times10^{-9}$	$7{,}5\times10^{-9}$	Sv/Bq
A_{Re}(b)	$4{,}3\times10^{8}$	$3{,}8\times10^{8}$	$1{,}0\times10^{9}$	$1{,}3\times10^{8}$	Bq

Gegevens voor urine-analyse

Na eenmalige inname

Tijd (d)	Urine-uitscheidingstempo (Bq/d per Bq inname)			
1	$1{,}8\times10^{-3}$	$5{,}6\times10^{-2}$	$6{,}7\times10^{-2}$	$8{,}0\times10^{-4}$
2	$7{,}4\times10^{-4}$	$2{,}1\times10^{-2}$	$2{,}3\times10^{-2}$	$3{,}3\times10^{-4}$
3	$4{,}7\times10^{-4}$	$1{,}4\times10^{-2}$	$1{,}5\times10^{-2}$	$2{,}1\times10^{-4}$
5	$2{,}6\times10^{-4}$	$7{,}8\times10^{-3}$	$8{,}6\times10^{-3}$	$1{,}2\times10^{-4}$
7	$1{,}7\times10^{-4}$	$5{,}1\times10^{-3}$	$5{,}7\times10^{-3}$	$8{,}2\times10^{-5}$

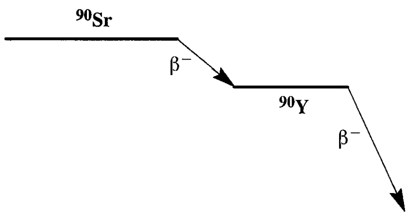
Figure 15. Radiation protection details of the nuclide ^{89}Sr

^{90}Sr Z = 38 N = 52 ^{90}Sr

Halveringstijd en vervalconstante

$T_{1/2}$ = 28,7 j = 9,06×10^8 s λ = 7,65×10^{-10} s^{-1}

Vervalschema



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)
β⁻	1,000	196 | 546

Van dochter ^{90}Y ($T_{1/2}$ = 64 h):

Straling	y (Bq·s)$^{-1}$	E (keV)
β⁻	1,000	935 | 2284

Diversen

Specifieke activiteit	A_{sp} = 5,12×10^{12} Bq/g
Vrijstellingsgrenzen	C_v = 10^2 Bq/g en A_v = 10^4 Bq
Huidbesmetting	H_{huid} = 5×10^{-10} Sv/s per Bq/cm^2
Wondbesmetting; Injectie	$e(50)$ = 8,8×10^{-8} Sv/Bq
Vervoer	A_1 = 0,3 TBq
	A_2 = 0,3 TBq

Productie en toepassingen

Het radionuclide ^{90}Sr is een splijtingsproduct dat door bovengrondse kernexplosies in de atmosfeer is gebracht. Door zijn lange halveringstijd en zijn chemische eigenschappen (botzoeker) is ^{90}Sr een belangrijke contaminant.
Het wordt gebruikt, vanwege de hoge beta-energie van dochter ^{90}Y, als beta-standaard, bron voor diktemeting, bij brachytherapie en in een ophtalmisch applicator.

Metabool model

De stofwisseling van de botzoeker strontium is uitgebreid beschreven in ICRP-67.

Ingestie- en longzuiveringsklassen

Ingestie		
Sr-titanaat	f_1 = 0,01	
Overige verbindingen	f_1 = 0,3	
Inhalatie		
Titanaat	f_1 = 0,01	Klasse S
Overige	f_1 = 0,3	Klasse F

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

	Ingestie f_1 = 0,01	Ingestie f_1 = 0,3	Inhalatie F	Inhalatie S	
$e(50)$(w)	2,7×10^{-9}	2,8×10^{-8}	3,0×10^{-8}	7,7×10^{-8}	Sv/Bq
A_{Re}(w)	3,7×10^8	3,6×10^7	3,3×10^7	1,3×10^7	Bq
$e(50)$(b)	2,7×10^{-9}	2,8×10^{-8}	2,4×10^{-8}	1,5×10^{-7}	Sv/Bq
A_{Re}(b)	3,7×10^8	3,6×10^7	4,2×10^7	6,7×10^6	Bq

Gegevens voor urine-analyse

Na eenmalige inname

Tijd (d)	Urine-uitscheidingstempo (Bq/d per Bq inname)			
1	1,8×10^{-3}	5,6×10^{-2}	6,8×10^{-2}	8,1×10^{-4}
2	7,6×10^{-4}	2,2×10^{-2}	2,3×10^{-2}	3,4×10^{-4}
3	4,9×10^{-4}	1,4×10^{-2}	1,6×10^{-2}	2,2×10^{-4}
5	2,8×10^{-4}	8,3×10^{-3}	9,2×10^{-3}	1,3×10^{-4}
7	1,9×10^{-4}	5,7×10^{-3}	6,3×10^{-3}	9,0×10^{-5}

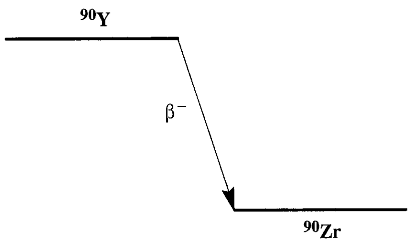
Figure 16. Radiation protection details of the nuclide ^{90}Sr

^{90}Y Z = 39 N = 51 ^{90}Y

Halveringstijd en vervalconstante

$T_{1/2}$ = 64,1 h = 2,31×10^5 s λ = 3,00×10^{-6} s^{-1}

Vervalschema



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)
β$^-$	1,000	935 | 2284

Diversen

Specifieke activiteit	A_{sp}	= 2,01×10^{16} Bq/g
Vrijstellingsgrenzen	C_v	= 10^3 Bq/g en A_v = 10^5 Bq
Huidbesmetting	H_{huid}	= 4×10^{-10} Sv/s per Bq/cm^2
Wondbesmetting; Injectie	$e(50)$	= 1,2×10^{-9} Sv/Bq
Vervoer	A_1	= 0,3 TBq
	A_2	= 0,3 TBq

Productie en toepassingen

Het radionuclide ^{90}Y is de dochter van ^{90}Sr. De toepassingen van de combinatie ^{90}Sr/Y zijn aangegeven bij het moedernuclide.

Metabool model

Voor stralingshygiënische doeleinden wordt aangenomen dat yttrium zich vanuit het bloed als volgt verdeelt: 25% directe uitscheiding, 50% naar het skelet, 15% naar de lever en 10% verdeeld over de overige organen/weefsels.
De biologische halveringstijd wordt oneindig verondersteld. Omdat er geen langlevende yttrium-isotopen zijn, is deze rekenwijze voor de stralingshygiëne verantwoord.

Ingestie- en longzuiveringsklassen

Ingestie		
Alle verbindingen	f_1 = 1×10^{-4}	
Inhalatie		
Oxide, hydroxide	f_1 = 1×10^{-4}	Klasse S
Overige verbindingen	f_1 = 1×10^{-4}	Klasse M

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

	Ingestie	Inhalatie	Inhalatie	
	f_1 = 1×10^{-4}	M	S	
$e(50)$(w)	2,7×10^{-9}	1,6×10^{-9}	1,7×10^{-9}	Sv/Bq
A_{Re}(w)	3,7×10^8	6,3×10^8	5,9×10^8	Bq
$e(50)$(b)	2,7×10^{-9}	1,4×10^{-9}	1,5×10^{-9}	Sv/Bq
A_{Re}(b)	3,7×10^8	7,1×10^8	6,7×10^8	Bq

Gegevens voor urine-analyse

Na eenmalige inname

Tijd (d)	Urine-uitscheidingsconcentratie (Bq/d per Bq inname)		
1	8,0×10^{-6}	2,5×10^{-3}	2,9×10^{-5}
2	1,1×10^{-6}	1,8×10^{-4}	2,6×10^{-6}
3	5,7×10^{-8}	2,4×10^{-5}	4,7×10^{-7}
5	1,3×10^{-10}	9,3×10^{-6}	2,1×10^{-7}
7	3,1×10^{-13}	5,3×10^{-6}	1,2×10^{-7}

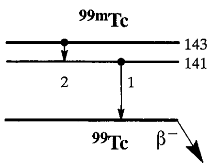
Figure 17. Radiation protection details of the nuclide ^{90}Y

^{99m}Tc   Z = 43   N = 56 ^{99m}Tc

Halveringstijd en vervalconstante

$T_{1/2}$ = 6,006 h = 2,17×10^4 s λ = 3,21×10^{-5} s^{-1}

Vervalschema (vereenvoudigd)



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)
γ_1	0,889	141
ce M γ_2	0,914	2
ce N γ_2	0,076	2
K$_\alpha$	0,062	18
LMX	0,102	2

Bronconstanten

Kermatempo in lucht	k = 0,018 µGy/h per MBq/m^2
Omgevingsdosisequivalenttempo	h = 0,023 µSv/h per MBq/m^2

Diversen

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

Productie en toepassingen

Het radionuclide ^{99m}Tc is de dochter van ^{99}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		
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 radiotoxiciteitsequivalent voor werknemers (w) en voor leden van de bevolking (b)

	Ingestie f_1 = 0,8	Inhalatie F	Inhalatie M	
$e(50)$(w)	2,2×10^{-11}	2,0×10^{-11}	2,9×10^{-11}	Sv/Bq
A_{Re}(w)	4,5×10^{10}	5,0×10^{10}	3,4×10^{10}	Bq
$e(50)$(b)	2,2×10^{-11}	1,2×10^{-11}	1,9×10^{-11}	Sv/Bq
A_{Re}(b)	4,5×10^{10}	8,3×10^{10}	5,3×10^{10}	Bq

Gegevens voor totale-lichaamstelling

Na eenmalige inname

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

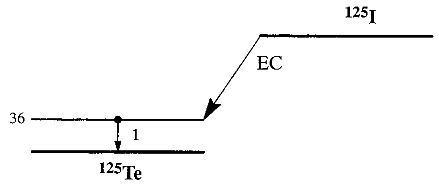
Figure 18. Radiation protection details of the nuclide ^{99m}Tc

^{125}I Z = 53   N = 72 ^{125}I

Halveringstijd en vervalconstante

$T_{1/2}$ = 59,39 d = 5,13×10^{6} s λ = 1,35×10^{-7} s^{-1}

Vervalschema (vereenvoudigd)



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)	Straling	y (Bq·s)$^{-1}$	E (keV)
γ_1	0,067	35	L_α	0,061	4
ce K γ_1	0,803	4	L_β	0,059	4
ce L γ_1	0,105	31	KLL	0,132	23
K_α	1,140	27	KLX	0,060	26
K_β	0,255	31	LMM	1,010	3
			LXY	0,590	4

Bronconstanten

Kermatempo in lucht k = 0,034 μGy/h per MBq/m^2
Omgevingsdosisequivalenttempo h = 0,034 μSv/h per MBq/m^2

Diversen

Specifieke activiteit A_{sp} = 6,51×10^{14} Bq/g
Vrijstellingsgrenzen C_v = 10^3 Bq/g en A_v = 10^6 Bq
Huidbesmetting H_{huid} = 4×10^{-12} Sv/s per Bq/cm^2
Wondbesmetting; Injectie $e(50)$ = 1,5×10^{-8} Sv/Bq
Vervoer A_1 = 20 TBq
A_2 = 3 TBq

Productie en toepassingen

Het radionuclide ^{125}I is een cyclotronproduct. Het wordt toegepast in de nucleaire geneeskunde, onder meer bij brachytherapie. Het vindt tevens toepassing als gamma-referentiebron.

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 verblijf in andere organen/weefsels dan de schildklier geschiedt 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 (CH_3I)	f_1 = 1	Klasse SR-1 70% depositie
Overige verbindingen	f_1 = 1	Klasse F

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

	Ingestie	Inhalatie	Inhalatie	Inhalatie	
	f_1 = 1	F	I_2	CH_3I	
$e(50)$(w)	1,5×10^{-8}	7,3×10^{-9}	1,4×10^{-8}	1,1×10^{-8}	Sv/Bq
A_{Re}(w)	6,7×10^{7}	1,4×10^{8}	7,1×10^{7}	9,1×10^{7}	Bq
$e(50)$(b)	1,5×10^{-8}	5,3×10^{-9}	1,4×10^{-8}	1,1×10^{-8}	Sv/Bq
A_{Re}(b)	6,7×10^{7}	1,9×10^{8}	7,1×10^{7}	9,1×10^{7}	Bq

Gegevens voor schildkliertelling (na eenmalige inname)

Tijd (d)	Activiteit in schildklier (Bq per Bq inname)			
	f_1 = 1	F	I_2	CH_3I
0,25	6,1×10^{-2}	5,3×10^{-2}	1,1×10^{-1}	1,1×10^{-1}
1	2,6×10^{-1}	1,3×10^{-1}	2,4×10^{-1}	1,9×10^{-1}
2	2,9×10^{-1}	1,4×10^{-1}	2,6×10^{-1}	2,0×10^{-1}
3	2,8×10^{-1}	1,4×10^{-1}	2,6×10^{-1}	2,0×10^{-1}
5	2,7×10^{-1}	1,3×10^{-1}	2,5×10^{-1}	1,9×10^{-1}
7	2,6×10^{-1}	1,3×10^{-1}	2,4×10^{-1}	1,8×10^{-1}

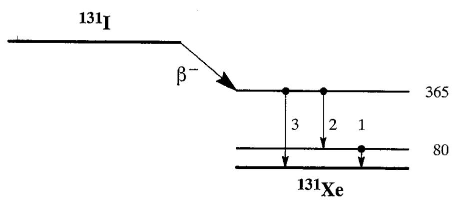
Figure 19. Radiation protection details of the nuclide ^{125}I

^{131}I Z = 53 N = 78 ^{131}I

Halveringstijd en vervalconstante

$T_{1/2}$ = 8,021 d = 6,93×10^5 s λ = 1,00×10^{-6} s^{-1}

Vervalschema (vereenvoudigd)



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)
β^-	0,894	192 | 606
γ_1	0,026	80
ce K γ_1	0,036	46
γ_2	0,061	284
γ_3	0,812	365

Bronconstanten

Kermatempo in lucht	k = 0,052 μGy/h per MBq/m^2
Omgevingsdosisequivalenttempo	h = 0,066 μSv/h per MBq/m^2

Diversen

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

Productie en toepassingen

Het radionuclide ^{131}I is een belangrijk splijtingsproduct. 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 verblijf in andere organen/weefsels dan de schildklier geschiedt 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 (CH_3I)	f_1 = 1	Klasse SR-1 70% depositie
Overige verbindingen	f_1 = 1	Klasse F

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

	Ingestie	Inhalatie	Inhalatie	Inhalatie	
	f_1 = 1	F	I_2	CH_3I	
$e(50)$(w)	2,2×10^{-8}	1,1×10^{-8}	2,0×10^{-8}	1,5×10^{-8}	Sv/Bq
A_{Re}(w)	4,5×10^7	9,1×10^7	5,0×10^7	6,7×10^7	Bq
$e(50)$(b)	2,2×10^{-8}	7,6×10^{-9}	2,0×10^{-8}	1,5×10^{-8}	Sv/Bq
A_{Re}(b)	4,5×10^7	1,3×10^8	5,0×10^7	6,7×10^7	Bq

Gegevens voor schildkliertelling (na eenmalige inname)

Tijd (d)	Activiteit in schildklier (Bq per Bq inname)			
	f_1 = 1	F	I_2	CH_3I
0,25	6,0×10^{-2}	5,2×10^{-2}	1,1×10^{-1}	1,0×10^{-1}
1	2,4×10^{-1}	1,2×10^{-1}	2,3×10^{-1}	1,8×10^{-1}
2	2,5×10^{-1}	1,2×10^{-1}	2,2×10^{-1}	1,7×10^{-1}
3	2,3×10^{-1}	1,1×10^{-1}	2,0×10^{-1}	1,6×10^{-1}
5	1,9×10^{-1}	9,0×10^{-2}	1,7×10^{-1}	1,3×10^{-1}
7	1,6×10^{-1}	7,5×10^{-2}	1,4×10^{-1}	1,1×10^{-1}

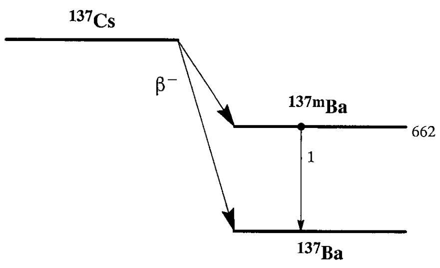
Figure 20. Radiation protection details of the nuclide ^{131}I

^{137}Cs Z = 55 N = 82 ^{137}Cs

Halveringstijd en vervalconstante

$T_{1/2}$ = 30,25 j = 9,55×10⁸ s $\lambda = 7{,}26\times10^{-10}\ s^{-1}$

Vervalschema (vereenvoudigd)



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)
β⁻	0,946	173 | 512
β⁻	0,054	425 | 1173

Van ^{137m}Ba ($T_{1/2}$ = 2,55 m; y = 0,946):

Straling	y (Bq·s)$^{-1}$	E (keV)
γ_1	0,898	662
ce K γ_1	0,083	624

Bronconstanten (van dochter ^{137m}Ba in evenwicht met ^{137}Cs)

Kermatempo in lucht	k = 0,077 μGy/h per MBq/m²
Omgevingsdosisequivalenttempo	h = 0,093 μSv/h per MBq/m²

Diversen

Specifieke activiteit	A_{sp} = 3,19×10¹² Bq/g
Vrijstellingsgrenzen	C_v = 10¹ Bq/g en A_v = 10⁴ Bq
Huidbesmetting	H_{huid} = 5×10⁻¹⁰ Sv/s per Bq/cm² (incl. ^{137m}Ba)
Wondbesmetting; Injectie	$e(50)$ = 1,4×10⁻⁸ Sv/Bq (incl. ^{137m}Ba)
Vervoer	A_1 = 2 TBq
	A_2 = 0,6 TBq

Productie en toepassingen

Het radionuclide ^{137}Cs is een belangrijk splijtingsproduct. Het wordt onder meer gebruikt als gamma-referentiebron en als bron bij brachytherapie.

Metabool model

Voor stralingshygiënische doeleinden wordt aangenomen dat cesium zich vanuit het bloed homogeen over alle organen/weefsels verdeelt.
De biologische halveringstijden zijn:

Fractie	$T_{1/2}$
0,1	2 d
0,9	110 d

Ingestie- en longzuiveringsklassen

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

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

	Ingestie f_1 = 1	Inhalatie F	
$e(50)$(w)	1,3×10⁻⁸	6,7×10⁻⁹	Sv/Bq
A_{Re}(w)	7,7×10⁷	1,5×10⁸	Bq
$e(50)$(b)	1,3×10⁻⁸	4,8×10⁻⁹	Sv/Bq
A_{Re}(b)	7,7×10⁷	2,1×10⁸	Bq

Gegevens voor totale-lichaamstelling

Na eenmalige inname

Tijd (d)	Lichaamsactiviteit (Bq per Bq inname)	
0,25	1,0×10⁰	7,4×10⁻¹
1	9,9×10⁻¹	6,0×10⁻¹
2	9,6×10⁻¹	5,1×10⁻¹
3	9,4×10⁻¹	4,7×10⁻¹
5	9,0×10⁻¹	4,4×10⁻¹
7	8,8×10⁻¹	4,2×10⁻¹

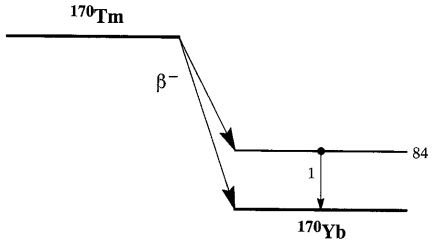
Figure 21. Radiation protection details of the nuclide ^{137}Cs

^{170}Tm Z = 69 N = 101 ^{170}Tm

Halveringstijd en vervalconstante

$T_{1/2}$ = 128,6 d = 1,11×10^7 s λ = 6,24×10^{-8} s^{-1}

Vervalschema (vereenvoudigd)



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)	Straling	y (Bq·s)$^{-1}$	E (keV)
β^-_1	0,240	298 | 884	K_α	0,035	52
β^-_2	0,759	323 | 968	LMM	0,073	6
γ_1	0,033	84	LMX	0,045	8
ce K γ_1	0,047	23	MXY	0,259	2
ce L γ_1	0,122	74			

Bronconstanten

Kermatempo in lucht	k = 0,0007 µGy/h per MBq/m^2
Omgevingsdosisequivalenttempo	h = 0,0012 µSv/h per MBq/m^2

Diversen

Specifieke activiteit	A_{sp} = 2,21×10^{14} Bq/g
Vrijstellingsgrenzen	C_v = 10^3 Bq/g en A_v = 10^6 Bq
Huidbesmetting	H_{huid} = 5×10^{-10} Sv/s per Bq/cm^2
Wondbesmetting; Injectie	$e(50)$ = 1,4×10^{-8} Sv/Bq
Vervoer	A_1 = 3 TBq
	A_2 = 0,6 TBq

Productie en toepassingen

Het radionuclide ^{170}Tm is een activeringsproduct. Het wordt toegepast als bron voor gammagrafie.

Metabool model

Voor stralingshygiënische doeleinden wordt aangenomen dat thulium zich vanuit het bloed als volgt verdeelt: 21% directe uitscheiding, 65% naar bot, 4% naar lever, 10% naar de overige organen/weefsels.
De biologische halveringstijd voor alle organen/weefsels wordt gesteld op 3500 dagen.

Ingestie- en longzuiveringsklassen

Ingestie		
Alle verbindingen	f_1 = 5×10^{-4}	
Inhalatie		
Alle verbindingen	f_1 = 5×10^{-4}	Klasse M

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

	Ingestie	Inhalatie	
	f_1 = 5×10^{-4}	M	
$e(50)$(w)	1,3×10^{-9}	5,2×10^{-9}	Sv/Bq
A_{Re}(w)	7,7×10^8	1,9×10^8	Bq
$e(50)$(b)	1,3×10^{-9}	6,6×10^{-9}	Sv/Bq
A_{Re}(b)	7,7×10^8	1,5×10^8	Bq

Gegevens voor totale-lichaamstelling

Na eenmalige inname

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

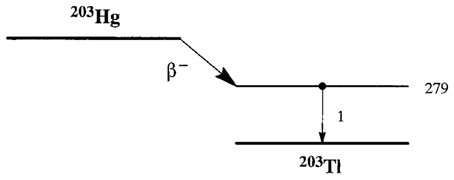
Figure 22. Radiation protection details of the nuclide ^{170}Tm

^{203}Hg   Z = 80   N = 123 ^{203}Hg

Halveringstijd en vervalconstante

$T_{1/2}$ = 46,61 d = 4,03×10^{6} s λ = 1,72×10^{-7} s^{-1}

Vervalschema (vereenvoudigd)



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)
β^-	1,000	58 | 212
γ_1	0,815	279
ce K γ_1	0,138	194
$K_{\alpha 1}$	0,066	73
$K_{\alpha 2}$	0,039	71

Bronconstanten

Kermatempo in lucht	k = 0,044 µGy/h per MBq/m^2
Omgevingsdosisequivalenttempo	h = 0,040 µSv/h per MBq/m^2

Diversen

Specifieke activiteit	A_{sp} = 5,10×10^{14} Bq/g
Vrijstellingsgrenzen	C_v = 10^2 Bq/g en A_v = 10^5 Bq
Huidbesmetting	H_{huid} = 3×10^{-10} Sv/s per Bq/cm^2
Wondbesmetting; Injectie	$e(50)$ = 1,7×10^{-9} Sv/Bq
Vervoer	A_1 = 5 TBq
	A_2 = 1 TBq

Productie en toepassingen

Het radionuclide ^{203}Hg is een activeringsproduct. Het nuclide wordt onder meer toegepast als gamma-ijkbron.

Metabool model

Voor stralingshygiënische doeleinden wordt aangenomen dat anorganisch kwik zich vanuit het bloed als volgt verdeelt: 8% naar nieren en 92% verdeeld over de overige organen/weefsels. Van organisch kwik wordt aangenomen dat 5% naar de nieren gaat, 20% naar de hersens en de rest uniform over de overige organen/weefsels verdeeld is. De aangenomen biologische halveringstijden zijn:

Anorganisch kwik		Organisch kwik	
Fractie	$T_{1/2}$	Fractie	$T_{1/2}$
0,95	40 d	0,95	80 d
0,05	10000 d	0,05	10000 d

Ingestie- en longzuiveringsklassen

Ingestie		
Anorganisch kwik	f_1 = 0,02	
Organische kwik	f_1 = 0,4, behalve	
Methyl-kwik	f_1 = 1	
Inhalatie		
Kwikdamp	f_1 = 0,02	Klasse SR-1, 70% depositie
Oxide, hydroxide, halogenide, nitraat, sulfide	f_1 = 0,02	Klasse M
Organisch kwik	f_1 = 1	Klasse F
Overige verbindingen	f_1 = 0,02	Klasse F

Dosisconversiecoëfficiënt en radiotoxiciteitsequivalent voor werknemers (w) en voor leden van de bevolking (b), na inwendige besmetting met kwik

Anorganisch	Ingestie	Inhalatie	Inhalatie	Inhalatie	
	f_1 = 0,02	F	M	SR-1	
$e(50)$(w)	5,4×10^{-10}	5,9×10^{-10}	1,9×10^{-9}	7,0×10^{-9}	Sv/Bq
A_{Re}(w)	1,9×10^{9}	1,7×10^{9}	5,3×10^{8}	1,4×10^{8}	Bq
$e(50)$(b)	5,4×10^{-10}	4,7×10^{-10}	2,3×10^{-9}	7,0×10^{-9}	Sv/Bq
A_{Re}(b)	1,9×10^{9}	2,1×10^{9}	4,3×10^{8}	1,4×10^{8}	Bq

Organisch	Ingestie	Ingestie	Inhalatie
	f_1 = 0,4	f_1 = 1	F
$e(50)$(w)	1,1×10^{-9}	1,9×10^{-9}	7,5×10^{-10}
A_{Re}(w)	9,1×10^{8}	5,3×10^{8}	1,3×10^{9}
$e(50)$(b)	1,1×10^{-9}	1,9×10^{-9}	5,7×10^{-10}
A_{Re}(b)	9,1×10^{8}	5,3×10^{8}	1,8×10^{9}

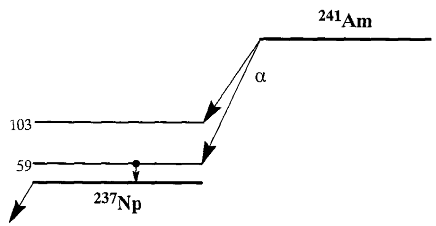
Figure 23. Radiation protection details of the nuclide ^{203}Hg

^{241}Am Z = 95 N = 146 ^{241}Am

Halveringstijd en vervalconstante

$T_{1/2} = 432{,}0$ j $= 1{,}36 \times 10^{10}$ s $\lambda = 5{,}08 \times 10^{-11}$ s^{-1}

Vervalschema (vereenvoudigd)



Belangrijkste uitgezonden straling

Straling	y (Bq·s)$^{-1}$	E (keV)	Straling	y (Bq·s)$^{-1}$	E (keV)
α_1	0,852	5486	γ_1	0,357	60
$\alpha_{terugstoot}$	0,852	93	ce-L γ_1	0,308	39
α_2	0,128	5443	ce-M γ_1	0,076	55
$\alpha_{terugstoot}$	0,128	92			
L_α	0,244	14	L_β	0,305	18

Bronconstanten

Kermatempo in lucht	k = 0,048 µGy/h per MBq/m^2
Omgevingsdosisequivalenttempo	h = 0,017 µSv/h per MBq/m^2

Diversen

Specifieke activiteit	$A_{sp} = 1{,}27 \times 10^{11}$ Bq/g
Vrijstellingsgrenzen	$C_v = 10^0 = 1$ Bq/g
	$A_v = 10^4$ Bq
Huidbesmetting	$H_{huid} = 5 \times 10^{-12}$ Sv/s per Bq/cm^2
Wondbesmetting; Injectie	$e(50) = 4{,}0 \times 10^{-4}$ Sv/Bq
Vervoer	$A_1 = 10$ TBq
	$A_2 = 0{,}001$ TBq

Productie en toepassingen

Het radionuclide ^{241}Am wordt geproduceerd in een kernreactor. Het nuclide wordt toegepast in brandmelders (ionisatiekamer), als ijkbron voor alfa- en gammastraling en in een neutronenbron (Am/Be-bron).

Metabool model

Het gedetailleerde metabole model voor americium wordt beschreven in ICRP-67.

Ingestie- en longzuiveringsklassen

Ingestie		
Alle verbindingen	$f_1 = 5 \times 10^{-4}$	
Inhalatie		
Alle verbindingen	$f_1 = 5 \times 10^{-4}$	Klasse M

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

	Ingestie	Inhalatie	
	$f_1 = 5 \times 10^{-4}$	M	
$e(50)$(w)	$2{,}0 \times 10^{-7}$	$2{,}7 \times 10^{-5}$	Sv/Bq
A_{Re}(w)	$5{,}0 \times 10^{6}$	$3{,}7 \times 10^{4}$	Bq
$e(50)$(b)	$2{,}0 \times 10^{-7}$	$3{,}9 \times 10^{-5}$	Sv/Bq
A_{Re}(b)	$5{,}0 \times 10^{6}$	$2{,}6 \times 10^{4}$	Bq

Gegevens voor urine-analyse

Na eenmalige inname

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

Figure 24. Radiation protection details of the nuclide ^{241}Am

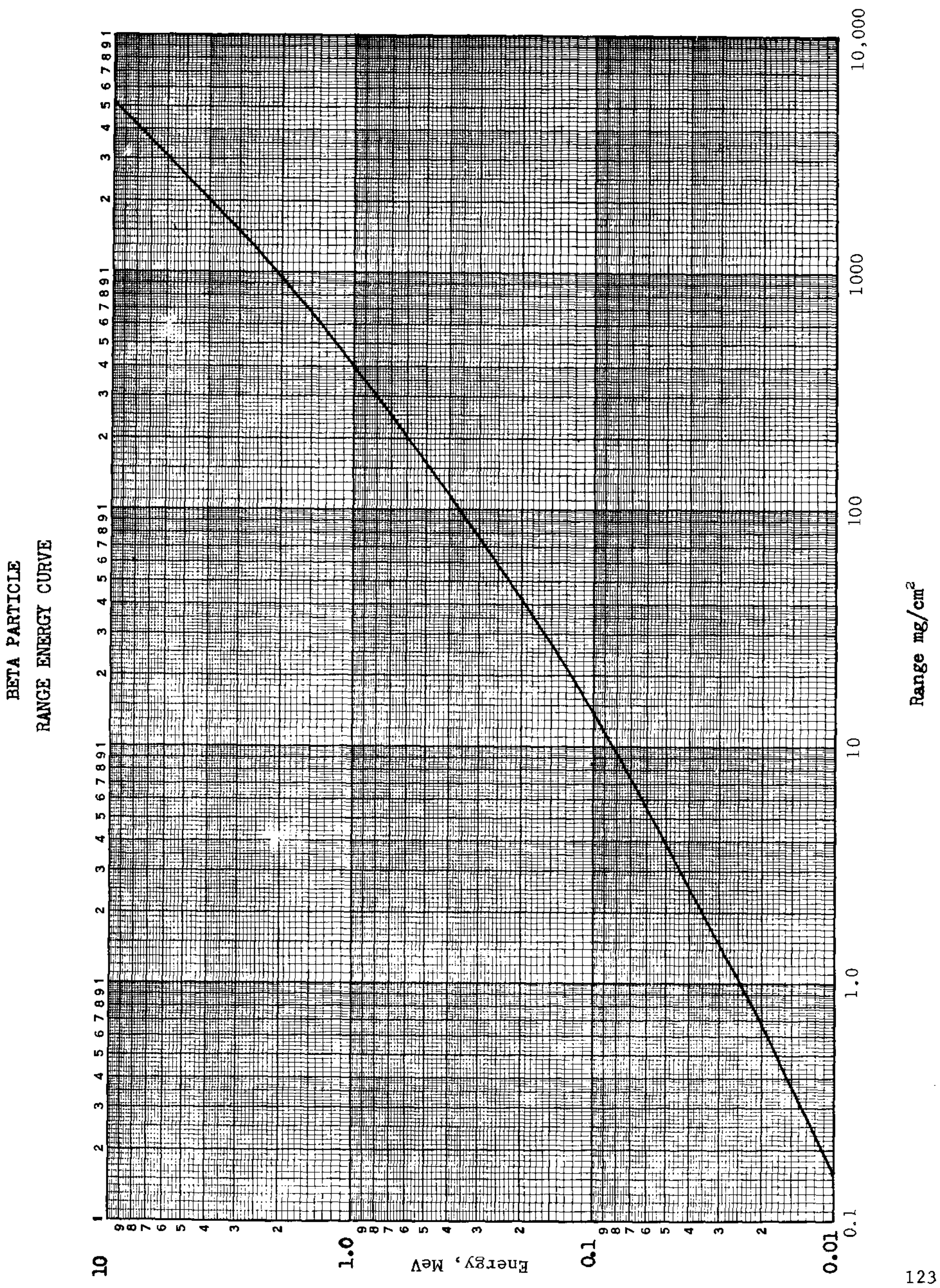


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Figure 25. Reduced range of β-particles as a function of the end point energy

E_{photon} (MeV)	air		water		tissue		bone	
	μ_{tr}/ρ	μ_{en}/ρ	μ_{tr}/ρ	μ_{en}/ρ	μ_{tr}/ρ	μ_{en}/ρ	μ_{tr}/ρ	μ_{en}/ρ
0.100	0.00227	0.00227	0.00248	0.00248	0.00244	0.00244	0.00439	0.00439
0.125	0.00238	0.00237	0.00262	0.00262	0.00259	0.00259	0.00358	0.00358
0.150	0.00247	0.00247	0.00275	0.00275	0.00272	0.00271	0.00316	0.00315
0.175	0.00257	0.00257	0.00286	0.00285	0.00282	0.00282	0.00307	0.00306
0.200	0.00266	0.00266	0.00295	0.00295	0.00292	0.00292	0.00301	0.00301
0.250	0.00277	0.00277	0.00308	0.00308	0.00305	0.00305	0.00304	0.00303
0.300	0.00287	0.00287	0.00319	0.00319	0.00316	0.00315	0.00307	0.00306

Figure 26. Mass energy transfer and mass energy absorption coefficients μ_{tr}/ρ and μ_{en}/ρ (in $m^2\ kg^{-1}$) for different materials

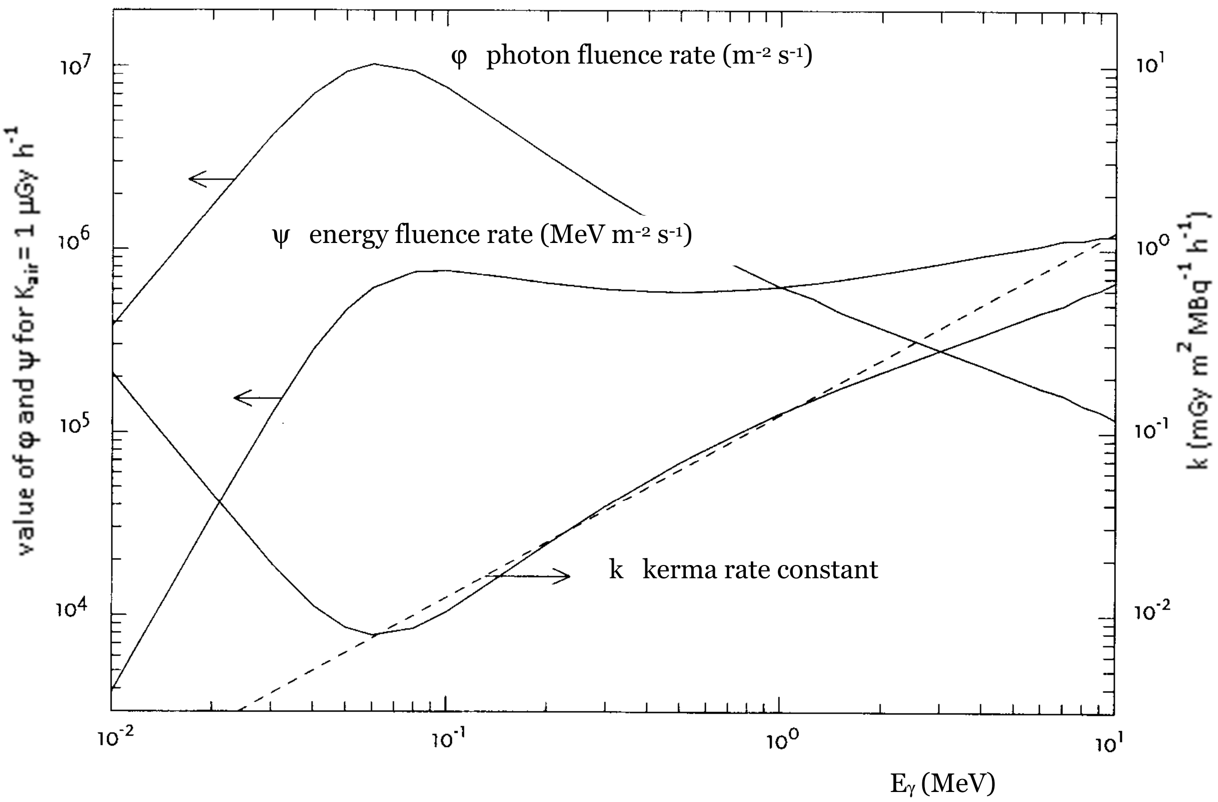

Figure 27. Fluence rate and energy fluence rate of photons compared with a kerma rate in air of 1 μGy/h. Also displayed is the kerma rate constant for a point source that emits energy E_γ per disintegration of 1 photon (the dashed line gives the approximation $\Gamma \approx E_{photon} / 8$)

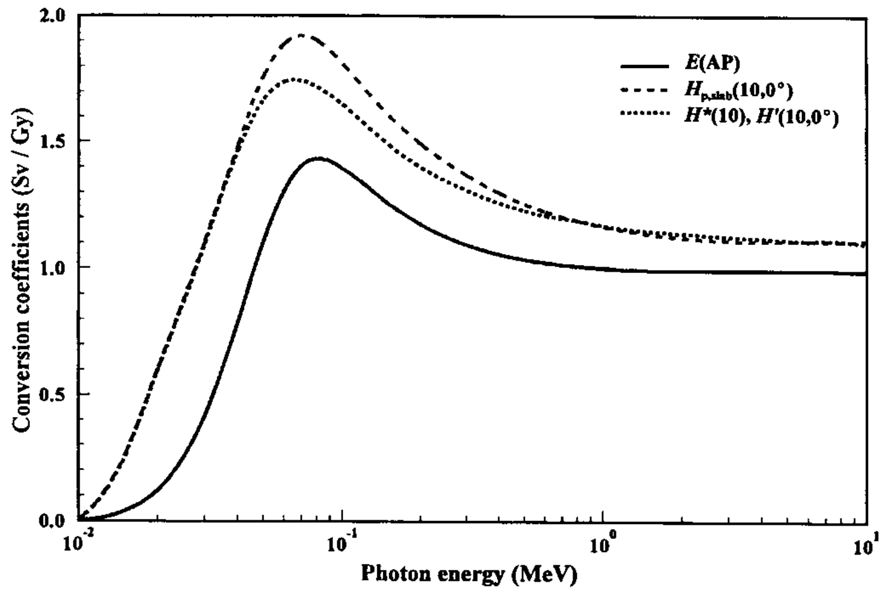

Figure 28. Conversion coefficients of air kerma K_a to ambient dose equivalent H(10), effective dose E(AP) in a phantom of an adult in the anterior-posterior geometry, and personal dose equivalent $H_{p,slab}(10)$ in an ICRU-slab*

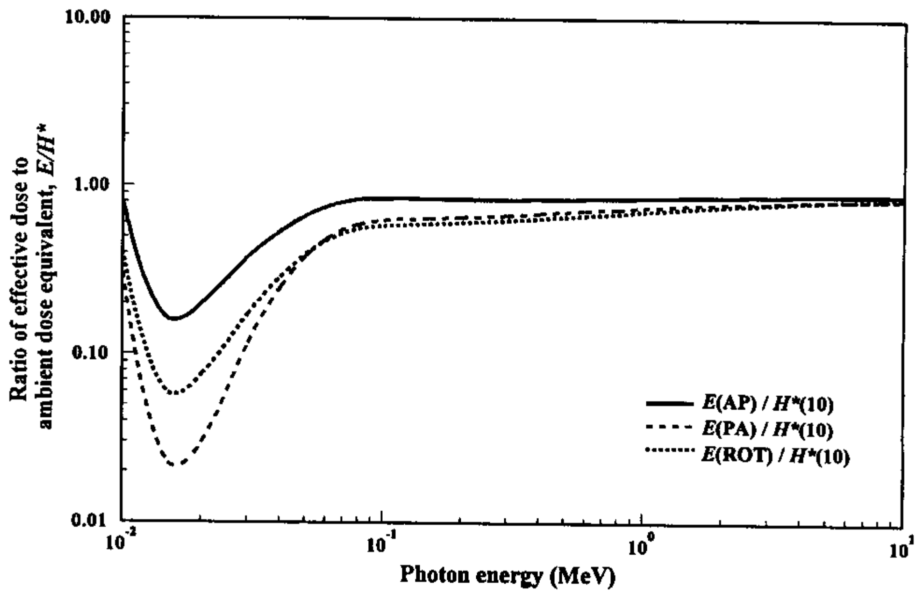

Figure 29. Ratio of effective dose and ambient dose equivalent as a function of the photon energy at different radiation geometries (AP = anterior-posterior, PA = posterior-anterior and ROT = rotating)

material	*E (MeV)*	*μd*						
		1	*2*	*4*	*7*	*10*	*15*	*20*
water	0.25	3.09	7.14	23.0	72.9	166	456	982
	0.5	2.52	5.14	14.3	38.8	77.6	178	334
	1.0	2.13	3.71	7.68	16.2	27.1	50.4	82.2
	2.0	1.83	2.77	4.88	8.46	12.4	19.5	27.7
	3.0	1.69	2.42	3.91	6.23	8.63	12.8	17.0
	4.0	1.58	2.17	3.34	5.13	6.94	9.97	12.9
	6.0	1.46	1.91	2.76	3.99	5.18	7.09	8.85
	8.0	1.38	1.74	2.40	3.34	4.25	5.66	6.95
concrete	0.5	2.18	3.66	7.72	16.5	29.1	58.1	98.3
	1.0	1.95	2.60	5.98	11.6	18.7	33.1	50.6
	2.0	1.75	2.52	4.38	7.65	11.4	18.2	25.7
	3.0							
	4.0							
	6.0							
	8.0							
iron	0.5	1.98	3.09	5.98	11.7	19.2	35.4	55.6
	1.0	1.87	2.89	5.39	10.2	16.2	28.3	42.7
	2.0	1.76	2.43	4.13	7.25	10.9	17.6	25.1
	3.0	1.55	2.15	3.51	5.85	8.51	13.5	19.1
	4.0	1.45	1.94	3.03	4.91	7.11	11.2	16.0
	6.0	1.34	1.72	2.58	4.14	6.02	9.89	14.7
	8.0	1.27	1.56	2.23	3.49	5.07	8.50	13.0
lead	0.5	1.24	1.42	1.69	2.00	2.27	2.65	2.73
	1.0	1.36	1.69	2.26	3.02	3.74	4.81	5.86
	2.0	1.39	1.76	2.51	3.66	4.84	6.87	9.00
	3.0	1.34	1.68	2.43	3.75	5.30	8.44	12.3
	4.0	1.27	1.56	2.25	3.61	5.44	9.80	16.3
	6.0	1.18	1.40	1.97	3.34	5.69	13.8	32.7
	8.0	1.14	1.30	1.74	2.89	5.07	14.1	44.6

Figure 30. Dose build-up factors for an isotropic point source and different materials as a function of the thickness of the shielding and the energy of the photons

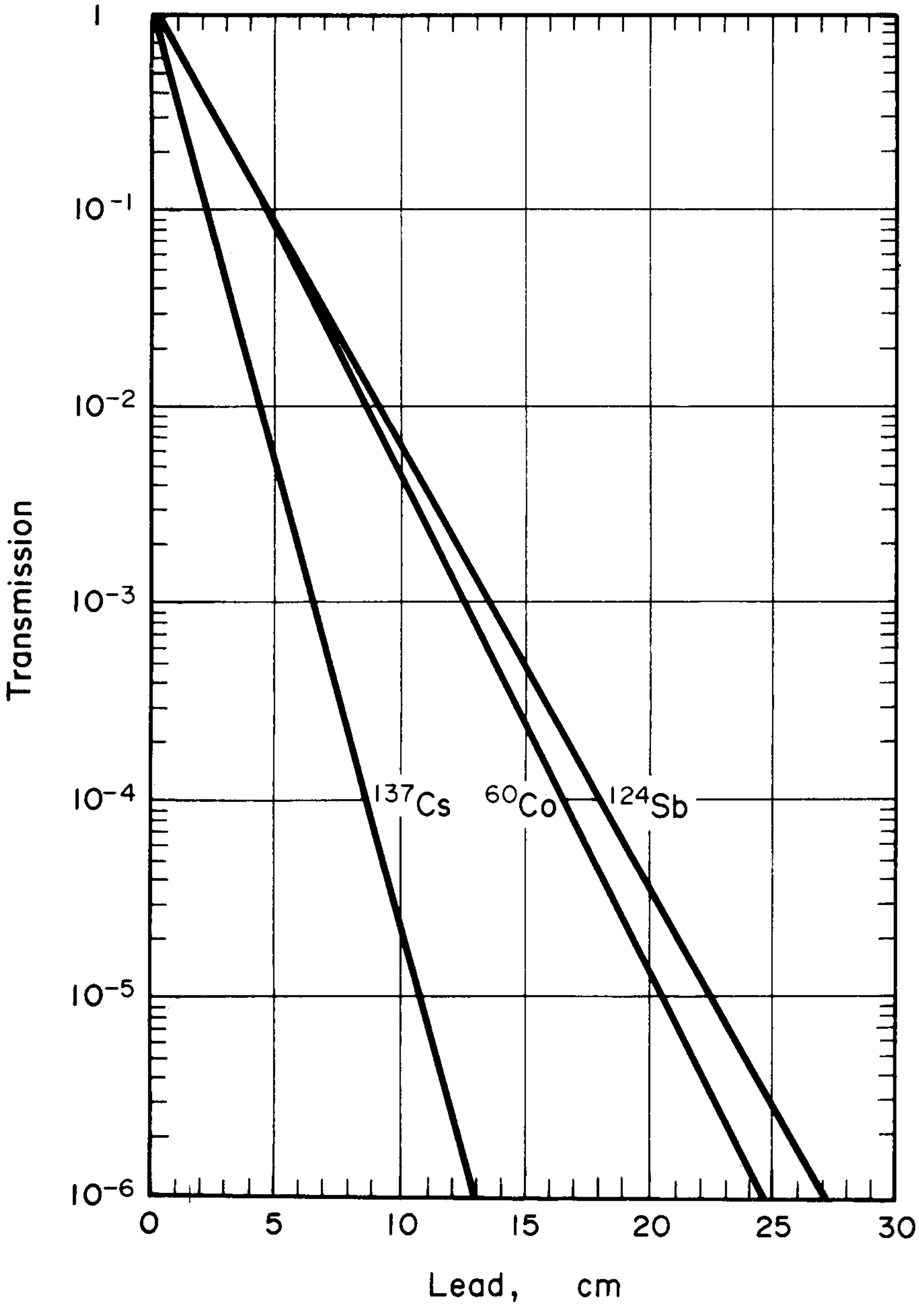

Figure 31. Transmission of broad-beam γ-radiation through lead

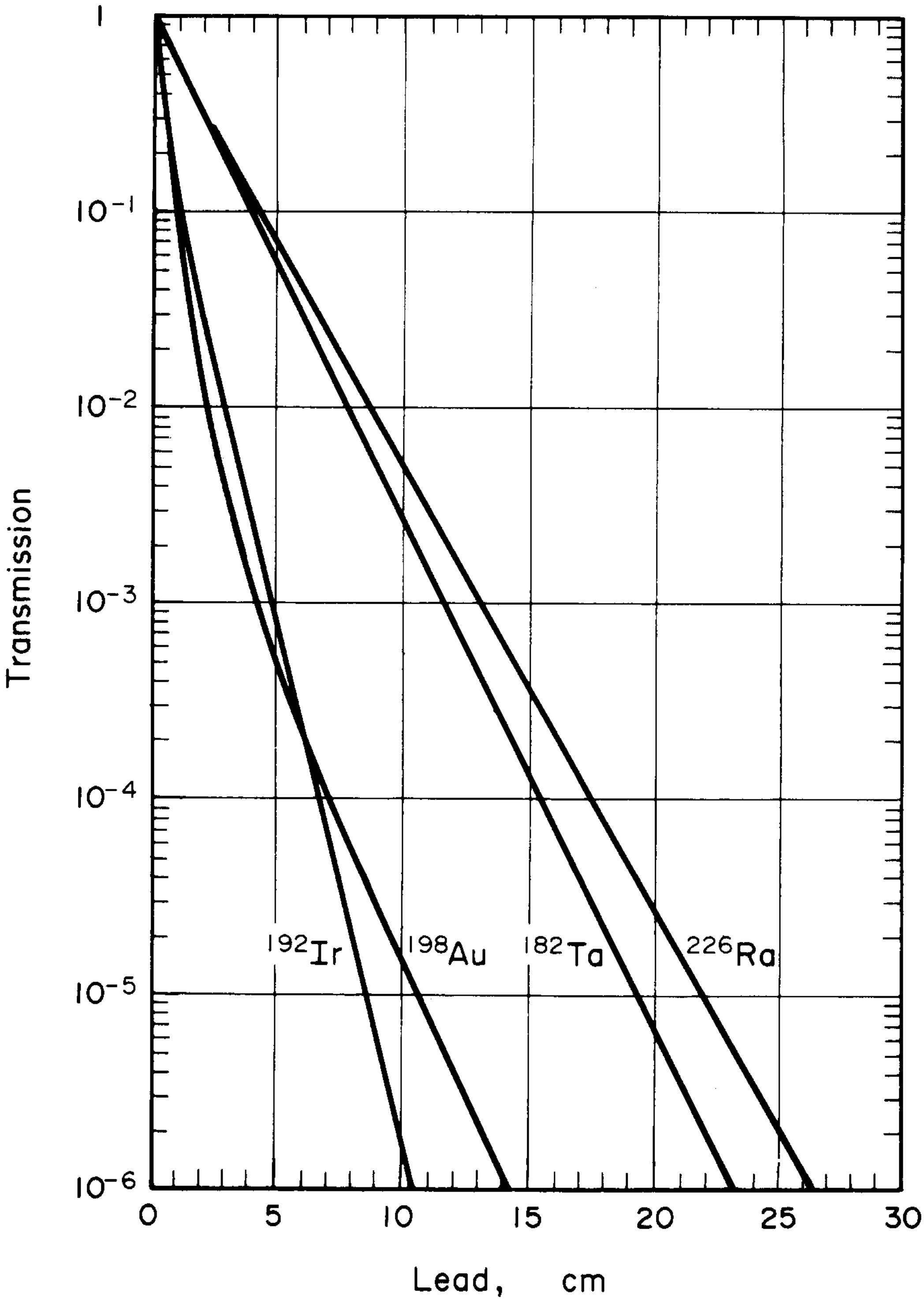

Figure 32. Transmission of broad-beam γ-radiation through lead

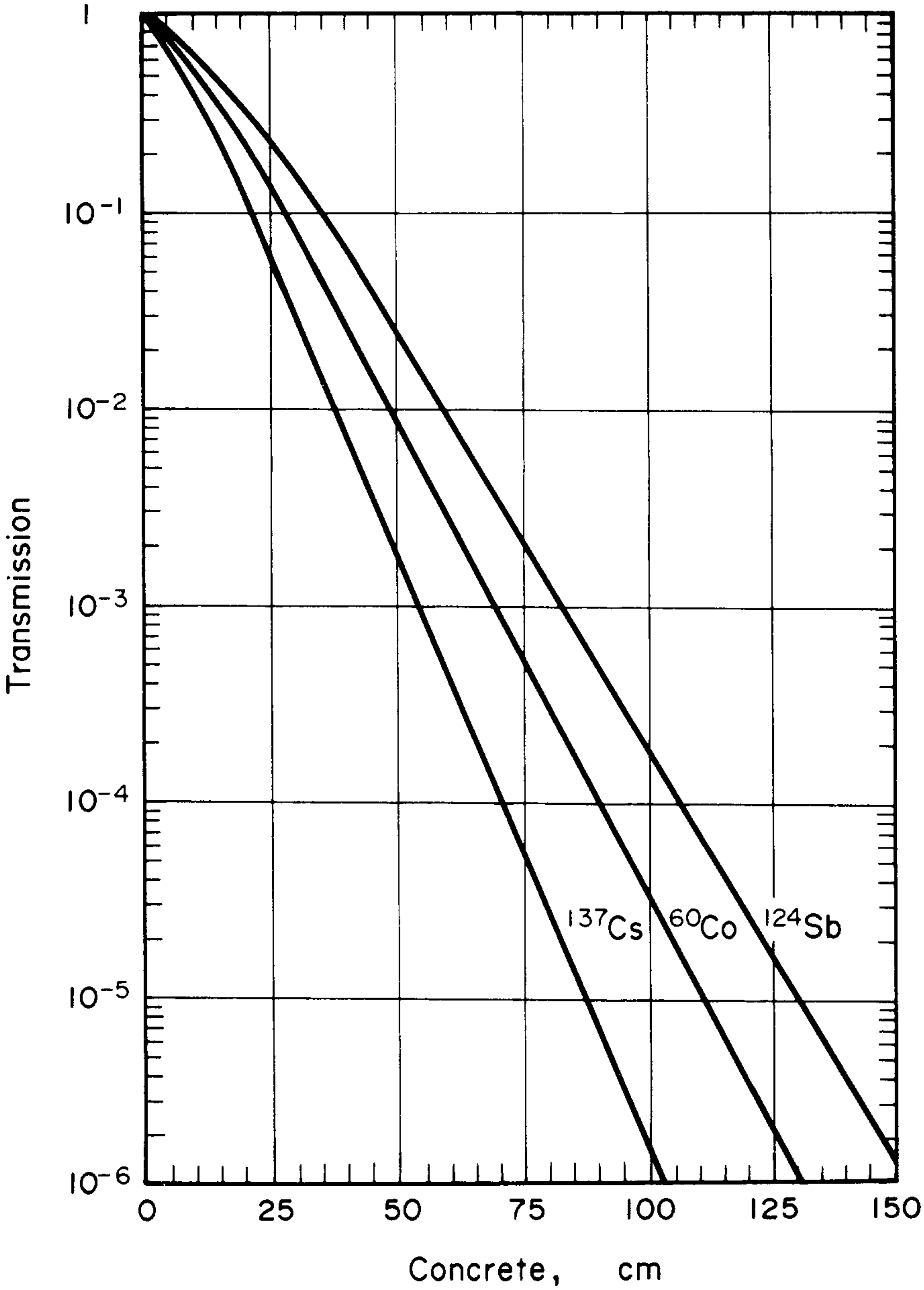

Figure 33. Transmission of broad beam γ-radiation through concrete

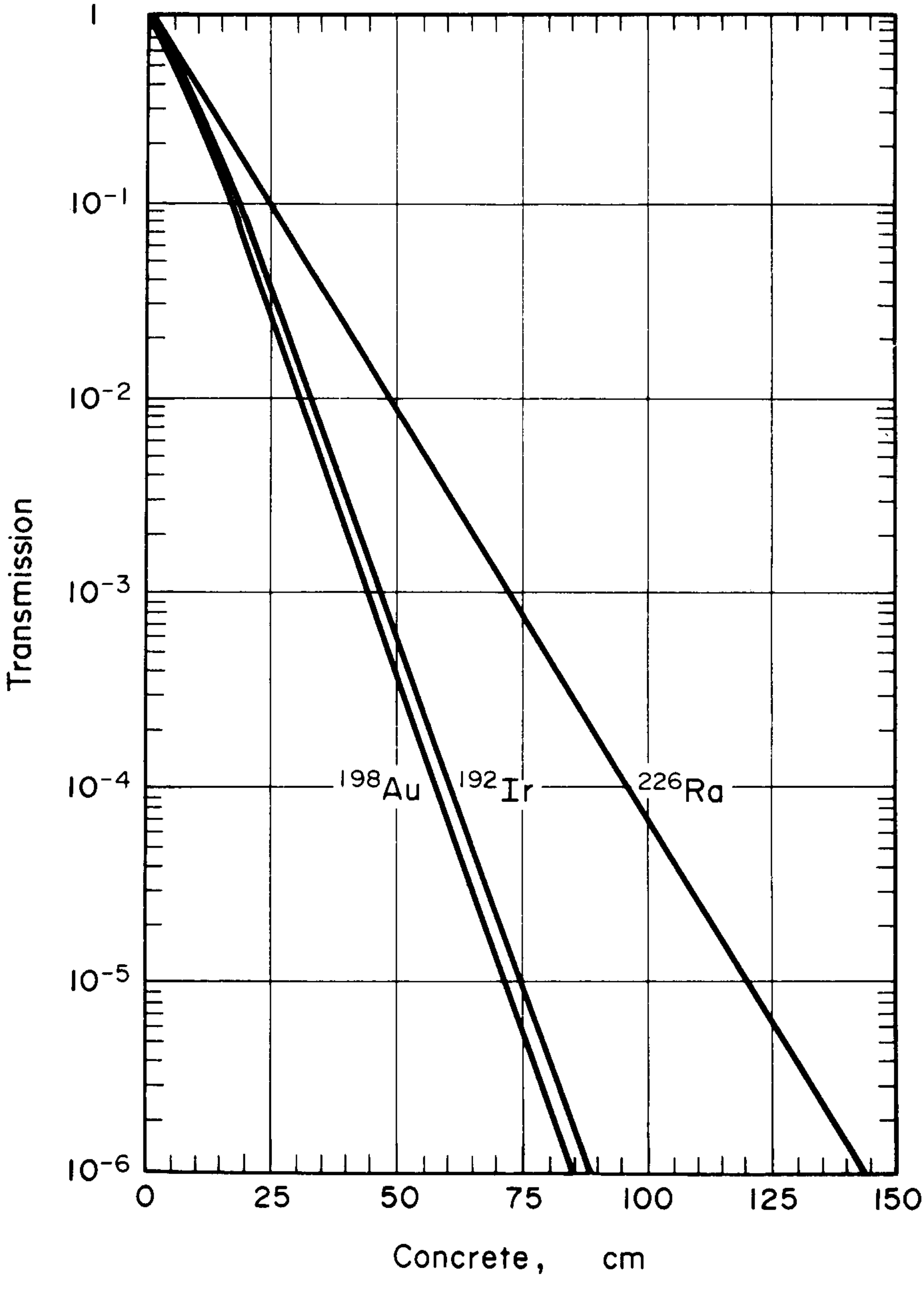

Figure 34. Transmission of broad-beam γ-radiation through concrete

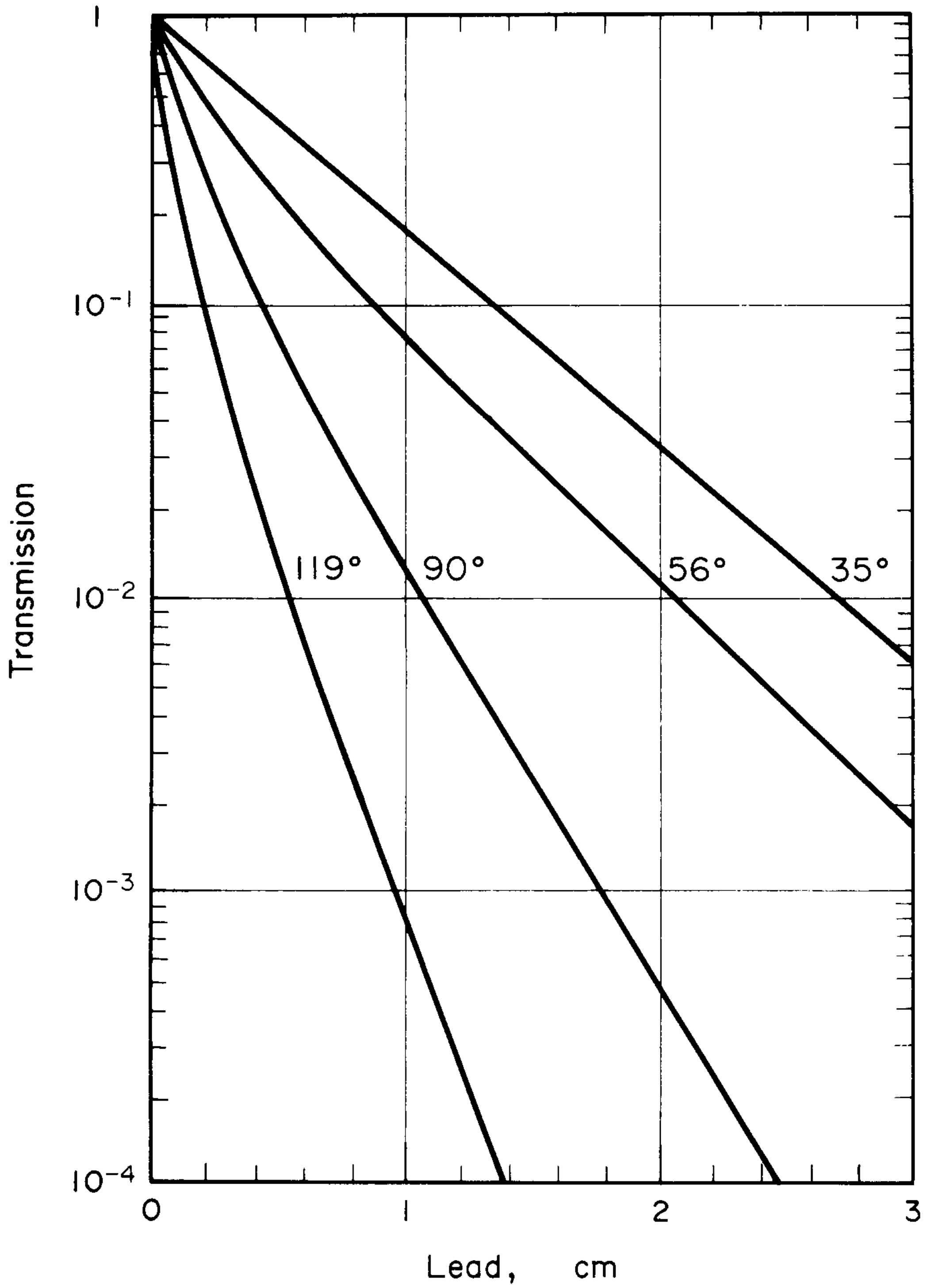

Figure 35. Transmission of concrete-scattered γ-radiation of ¹³⁷Cs through lead

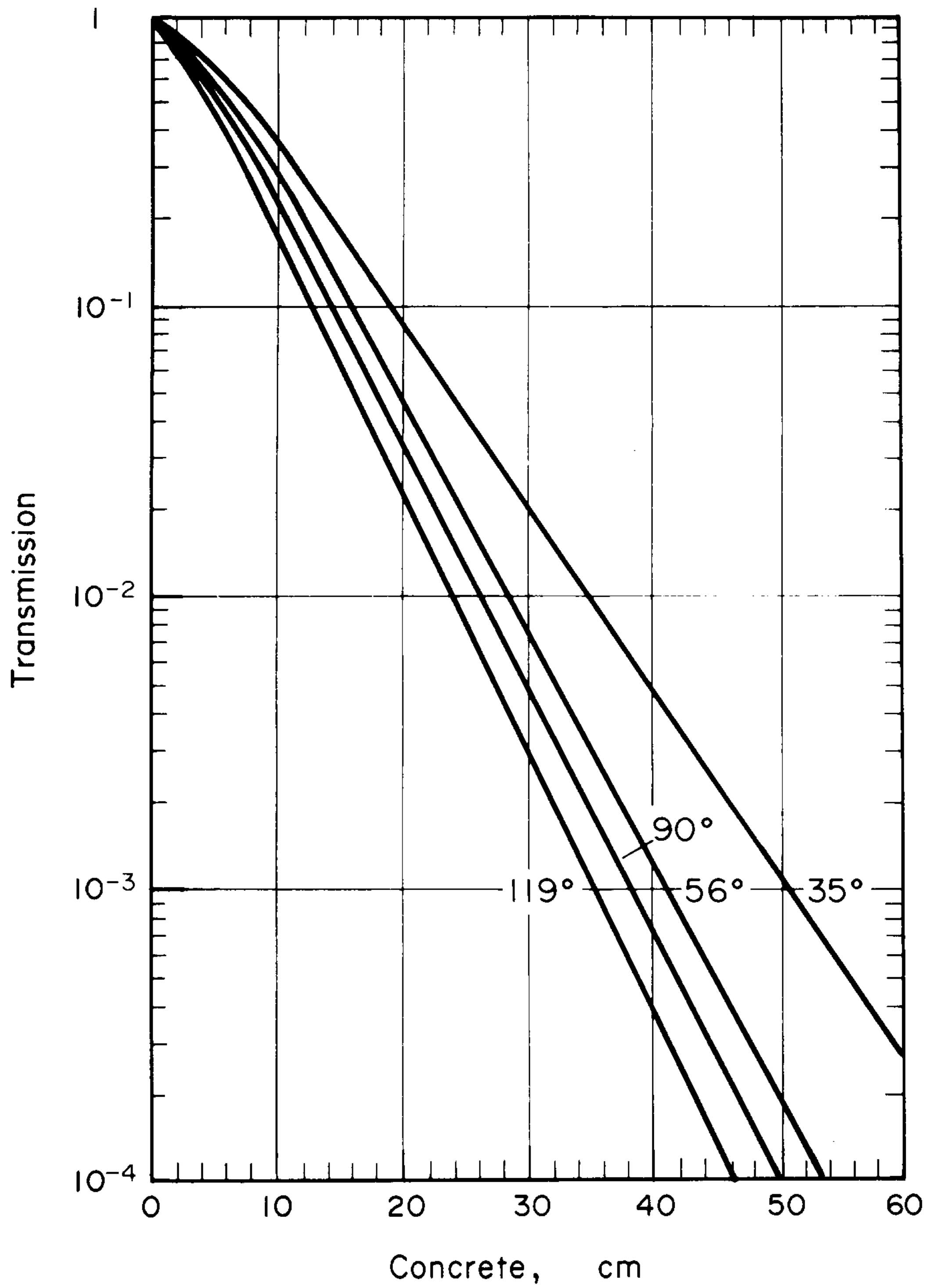

Figure 36. Transmission of concrete-scattered γ-radiation of ^{137}Cs through concrete

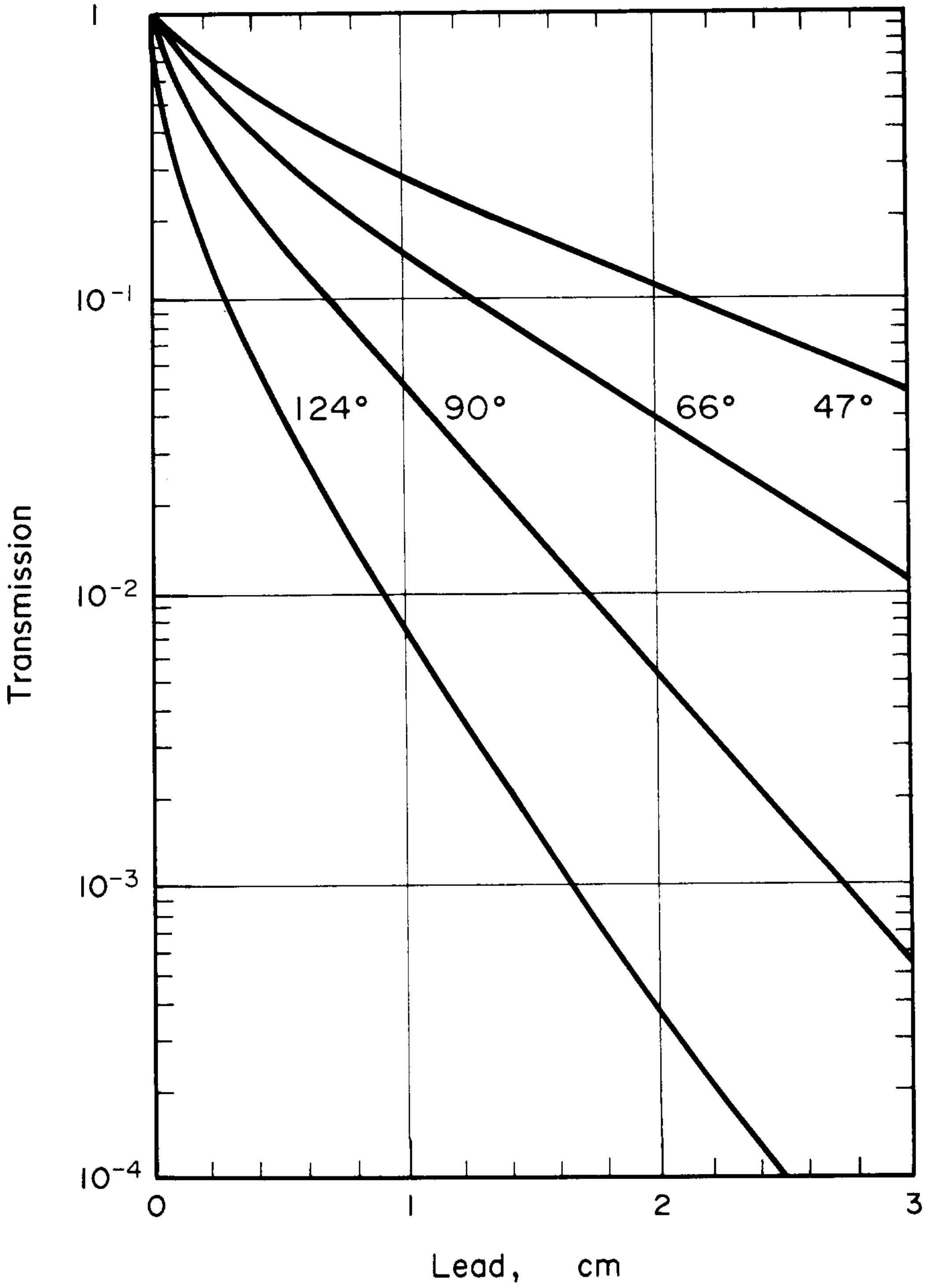

Figure 37. Transmission of phantom-scattered γ-radiation of ^{60}Co through lead

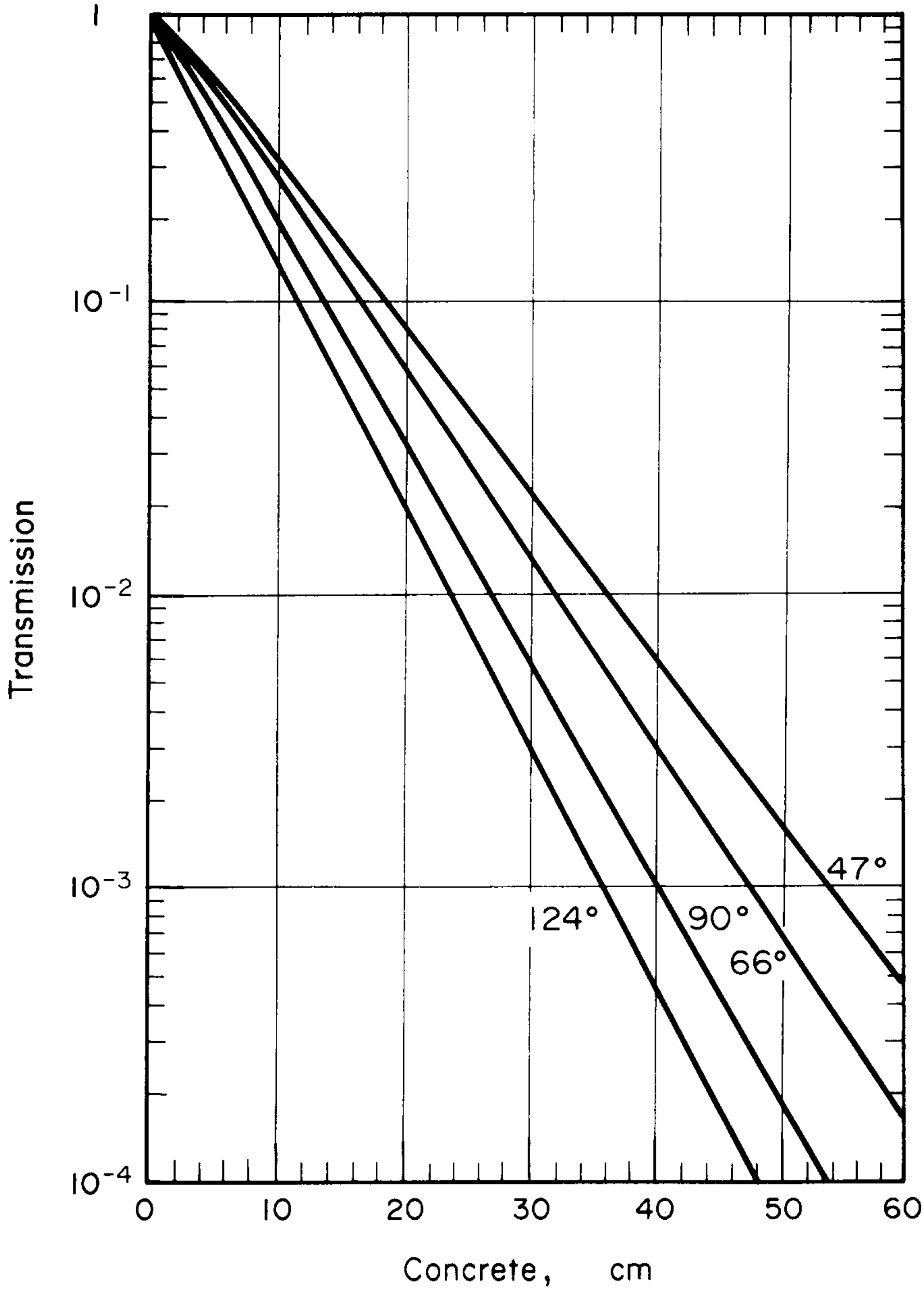

Figure 38. Transmission of phantom-scattered γ-radiation of ^{60}Co through concrete

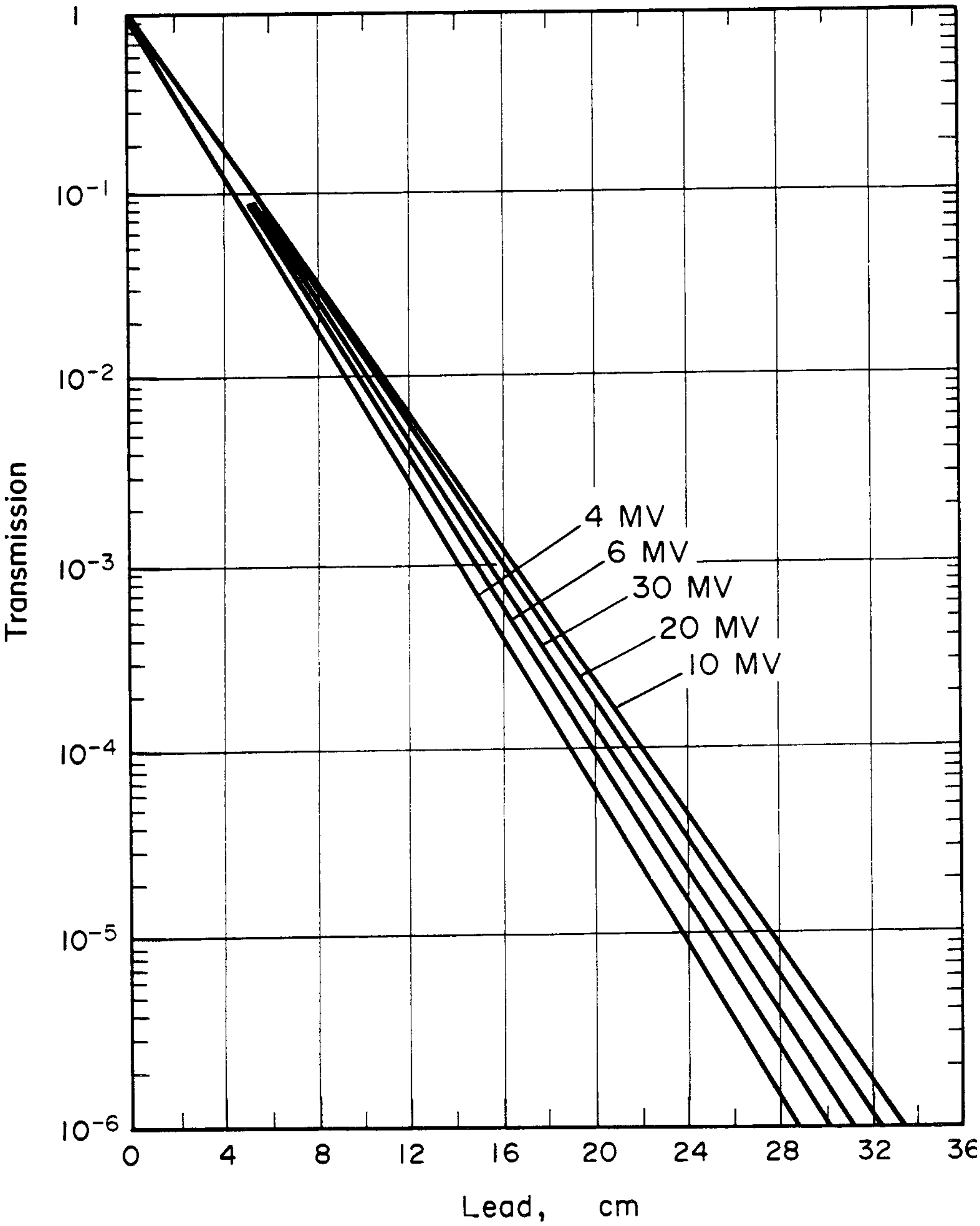

Figure 39. Transmission of broad-beam X-rays through lead

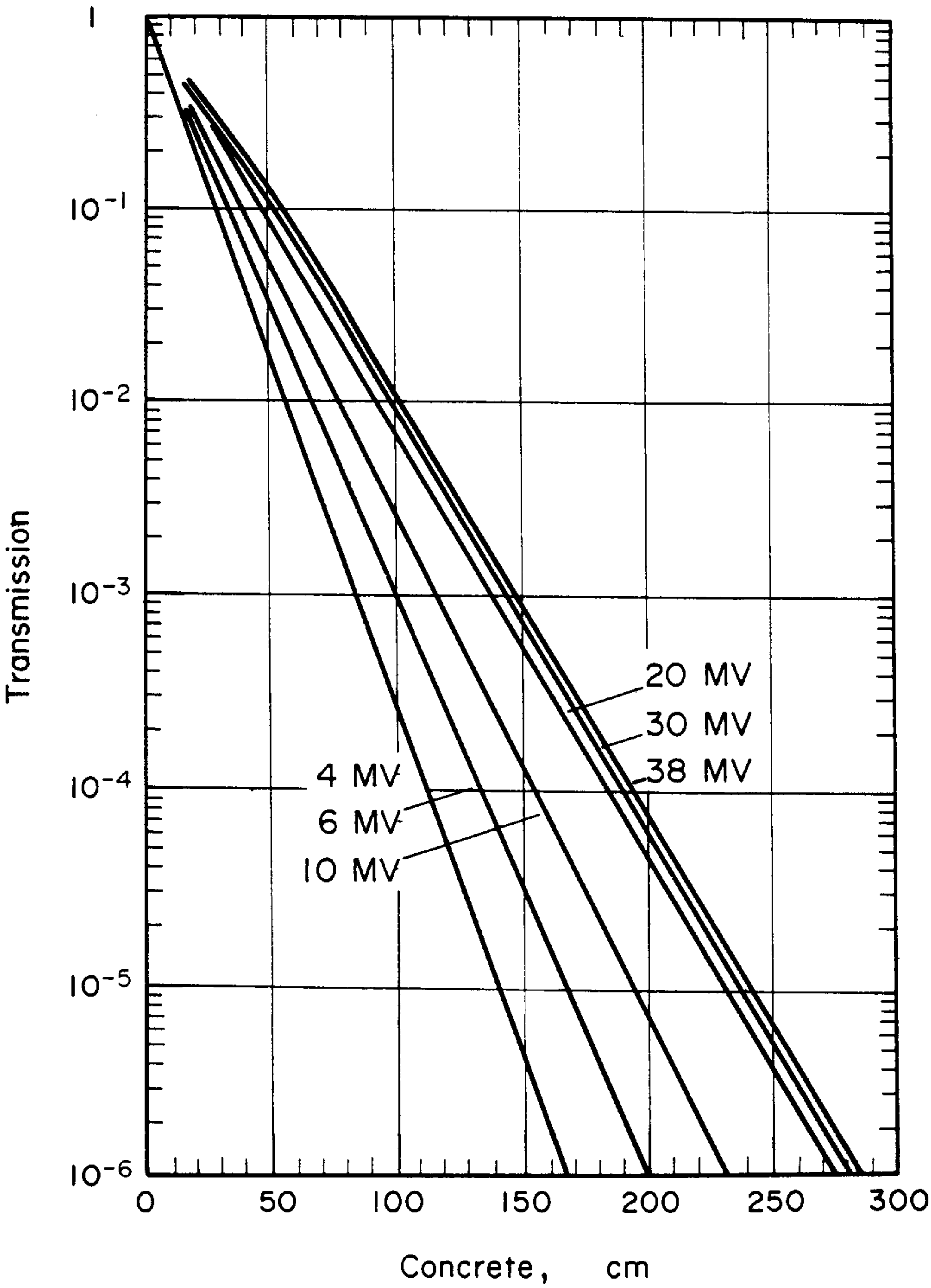

Figure 40. Transmission of broad-beam X-rays through concrete

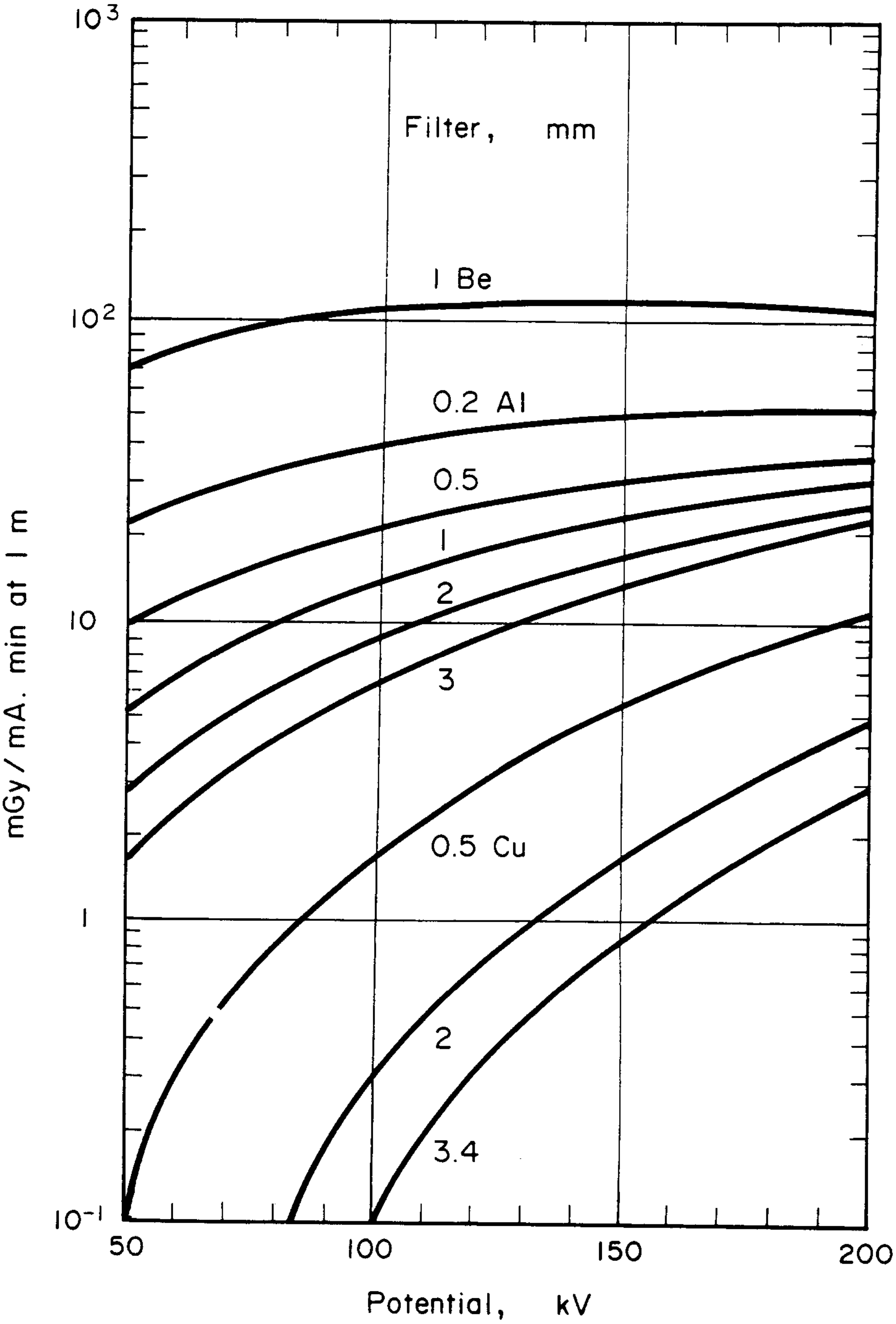

Figure 41. Kerma rate for different filters

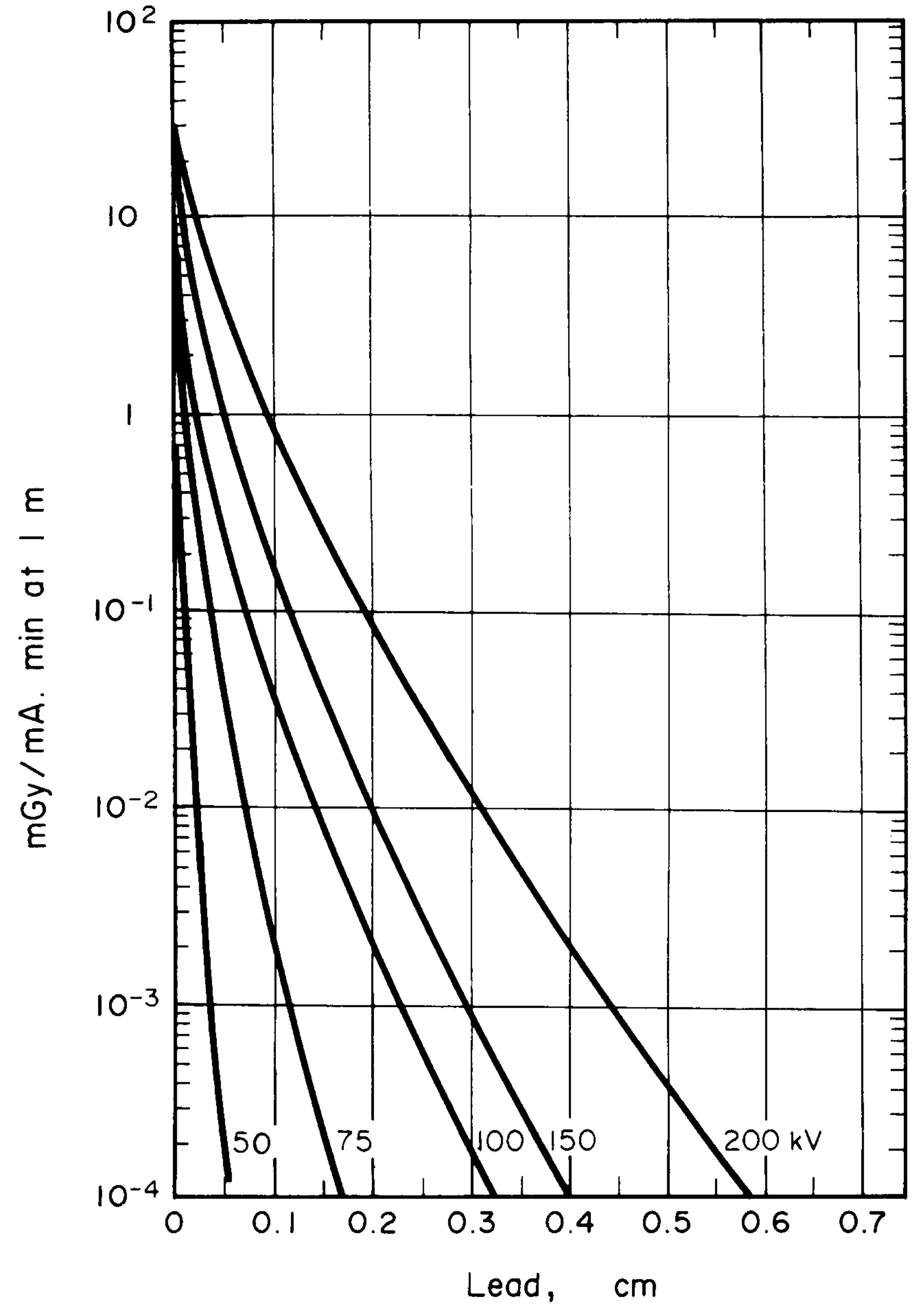

Figure 42. Kerma rate and transmission of X-radiation through lead (DC, anode of tungsten and filter of 2 mm aluminum; the intensity for 0 cm lead is 28,7 at 200 kV, 18,3 at 150 kV, 9,6 at 100 kV, 6,1 at 75 kV and 2,6 at 50 kV)

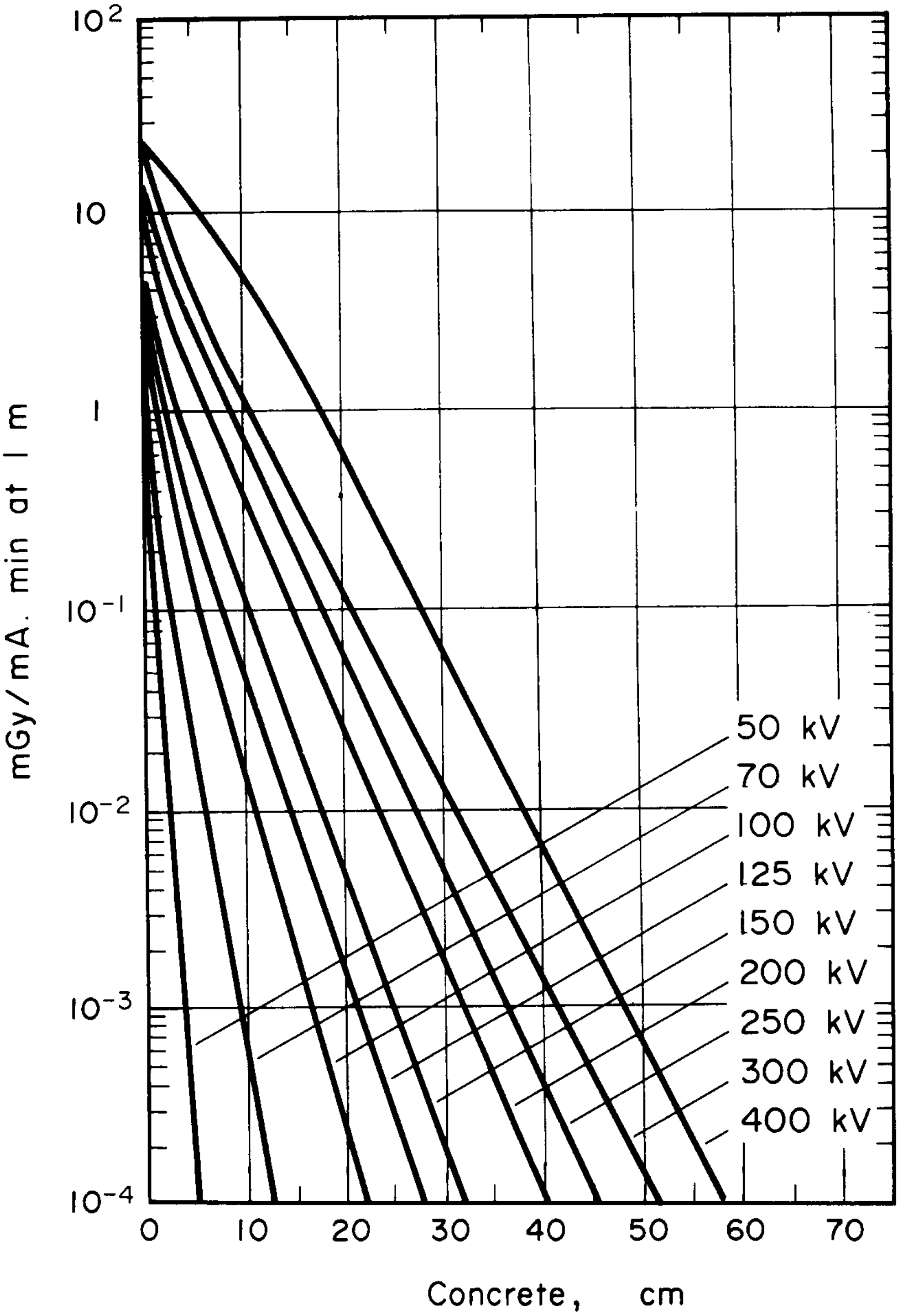

Figure 43. Kerma rate and transmission of X-radiation through concrete (50-300 kV: half-sine wave, anode of tungsten and filter of 1 mm aluminum at 50 kV, 1,5 mm aluminum at 70 kV, 2 mm aluminum at 100 kV and 3 mm aluminum at 125-300 kV; 400 kV: DC, anode of gold and filter of 3 mm copper; the intensity at 0 cm concrete amounts to 23,5 at 400 kV, 20,9 at 300 kV, 13,9 at 250 kV, 8,9 at 200 kV, 5,2 at 150 kV, 3,9 at 125 kV, 2,8 at 100 kV, 2,1 at 70 kV and 1,7 at 50 kV)

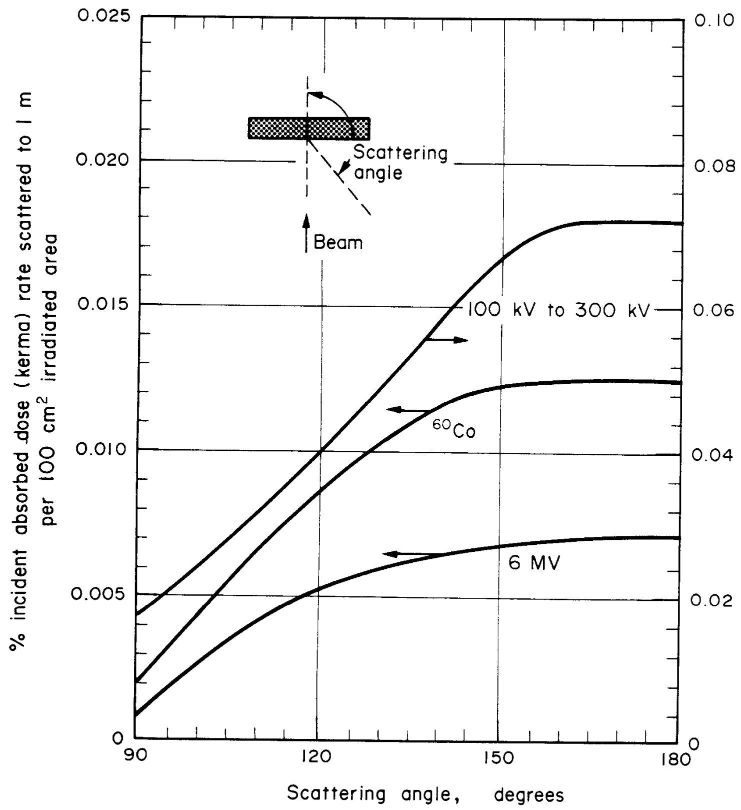

Figure 44. Scattering of X-radiation from concrete as a function of the scatter angle for perpendicular incidence

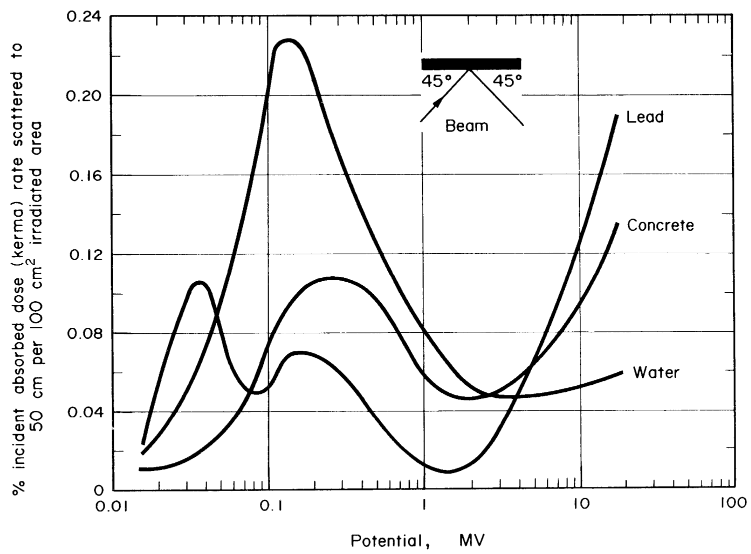

Figure 45. Scattering of X-radiation from water, concrete and lead as a function of the tube voltage (incident angle = exit angle = 45°)

source organ	*mass (g)*	*target organ*	*mass (g)*
ovaries	11	ovaries	11
testes	35	testes	35
muscle tissue	28 000	muscle tissue	28 000
red bone marrow	1500	red bone marrow	1500
compact bone	4000	bone surface	120
spongy bone	1000		
lungs	1000	lungs	1000
thyroid	20	thyroid	20
stomach contents	250	stomach wall	150
small intestine contents	400	small intestine wall	640
large intestine contents (upper)	220	large intestine wall (upper)	210
large intestine contents (lower)	135	large intestine wall (lower)	160
kidneys	310	kidneys	310
liver	1800	liver	1800
pancreas	100	pancreas	100
skin	2600	skin	2600
spleen	180	spleen	180
adrenal glands	14	adrenal glands	14
bladder contents	200	bladder wall	45
		thymus	20
		uterus	80
		brain	1400
soft tissue	63 000		
body fluids	42 000		
total body	70 000		

Figure 46. Masses of source and target organs of reference man

organ (T)	w_T
large intestine	0.12
lungs	0.12
stomach	0.12
red bone marrow	0.12
breast tissue	0.12
gonads	0.08
bladder	0.04
liver	0.04
thyroid	0.04
oesophagus	0.04
bone surface	0.01
brains	0.01
skin	0.01
salivary glands	0.01
13 other organs *	0.12

* pancreas, uterus+cervix / prostate, adrenals, small intestine, extra thoracic portions of the air ways, gall bladder, hearth, lymph nodes, spleen, oral mucosa, kidneys, muscle tissue, and thymus

Figure 47. Tissue weighting factors w_T

target organ	*photon energy (keV)*						
	50	*100*	*200*	*500*	*1000*	*1500*	*2000*
bladder wall	2.04E-7	6.16E-7	5.60E-7	1.21E-7	5.80E-7	8.48E-7	9.02E-7
stomach wall	8.90E-6	7.07E-6	6.96E-6	6.50E-6	6.44E-6	6.00E-6	6.11E-6
kidneys	1.95E-5	1.58E-5	1.36E-5	1.29E-5	1.18E-5	1.14E-5	1.10E-5
liver	1.52E-4	9.14E-5	8.82E-5	8.85E-5	8.07E-5	7.48E-5	6.86E-5
lungs	1.45E-5	9.92E-6	8.84E-6	8.23E-6	7.90E-6	7.72E-6	6.96E-6
ovaries	1.51E-6	1.63E-6	1.80E-6	6.53E-7	2.49E-6	3.44E-6	2.22E-6
pancreas	2.18E-5	1.77E-5	1.35E-5	1.66E-5	1.36E-5	1.21E-5	9.99E-6
bone surface	7.80E-6	4.93E-6	3.17E-6	2.53E-6	2.30E-6	2.26E-6	2.20E-6
bone marrow	9.33E-6	7.14E-6	4.64E-6	3.72E-6	3.21E-6	3.26E-6	3.17E-6
spleen	2.93E-6	3.56E-6	3.34E-6	3.44E-6	3.81E-6	2.95E-6	3.14E-6
testes	3.42E-8	1.90E-7	3.05E-7	3.92E-7	8.76E-7	4.70E-7	4.79E-7
thyroid	8.81E-8	3.80E-7	8.23E-7	6.32E-7	6.81E-7	6.87E-7	6.90E-7
uterus	9.07E-7	1.51E-6	1.40E-6	1.52E-6	1.28E-6	2.07E-6	1.81E-6
whole body	9.48E-6	6.54E-6	5.94E-6	5.86E-6	5.49E-6	5.16E-6	4.86E-6

Figure 48. Specific absorbed fractions SAF (in g^{-1}) for source organ liver

target organ	*photon energy (keV)*						
	50	*100*	*200*	*500*	*1000*	*1500*	*2000*
bladder wall	2.28E-7	3.15E-7	6.27E-7	4.52E-7	1.25E-6	8.91E-7	9.65E-7
stomach wall	5.86E-5	4.09E-5	3.36E-5	3.39E-5	2.93E-5	3.14E-5	2.65E-5
kidneys	5.30E-5	3.61E-5	3.14E-5	2.93E-5	2.59E-5	2.55E-5	2.33E-5
liverl	2.93E-6	3.78E-6	3.67E-6	3.69E-6	3.53E-6	3.45E-6	3.27E-6
lungs	1.23E-5	8.97E-6	7.91E-6	7.56E-6	6.87E-6	6.21E-6	6.38E-6
ovaries	1.19E-6	1.14E-6	2.05E-6	3.70E-7	1.70E-6	2.17E-6	3.46E-6
pancreas	1.23E-4	7.35E-5	6.58E-5	6.70E-5	5.80E-5	5.13E-5	4.94E-5
bone surface	8.30E-6	5.06E-6	3.25E-6	2.65E-6	2.48E-6	2.36E-6	2.18E-6
bone marrow	1.05E-5	7.47E-6	5.04E-6	3.90E-6	3.64E-6	3.35E-6	3.19E-6
spleen	7.24E-4	4.21E-4	4.32E-4	4.49E-4	4.10E-4	3.77E-4	3.55E-4
testes	2.09E-8	1.42E-7	2.45E-7	3.30E-7	3.88E-7	4.14E-7	4.26E-7
thyroid	5.15E-8	2.70E-7	4.16E-7	5.10E-7	5.68E-7	5.83E-7	5.88E-7
uterus	6.87E-7	1.61E-6	1.42E-6	1.61E-6	2.11E-6	6.25E-7	1.76E-6
whole body	9.47E-6	6.52E-6	5.93E-6	5.82E-6	5.46E-6	5.16E-6	4.81E-6

Figure 49. Specific absorbed fractions SAF (in g^{-1}) for source organ spleen

AMAD (μm)	*ET_1*	*ET_2*	*$BB_{fast+seq}$*	*BB_{slow}*	*$bb_{fast+seq}$*	*bb_{slow}*	*AI*	*total*
0.0006	0.45	0.44	0.030	0.030	0.020	0.020	0.00029	0.99
0.001	0.40	0.40	0.039	0.039	0.048	0.048	0.0037	0.99
0.002	0.30	0.32	0.042	0.042	0.11	0.11	0.043	0.96
0.005	0.16	0.18	0.025	0.025	0.13	0.13	0.27	0.92
0.01	0.087	0.098	0.014	0.014	0.095	0.095	0.47	0.88
0.02	0.053	0.059	0.0081	0.0081	0.063	0.063	0.49	0.74
0.05	0.032	0.034	0.0047	0.0047	0.036	0.036	0.31	0.46
0.1	0.032	0.032	0.0034	0.0034	0.024	0.024	0.21	0.33
0.2	0.055	0.061	0.0032	0.0032	0.015	0.015	0.15	0.30
0.5	0.089	0.11	0.0040	0.0039	0.011	0.011	0.12	0.35
0.7	0.12	0.15	0.0051	0.0048	0.0094	0.0092	0.11	0.42
1	0.17	0.21	0.0066	0.0058	0.0084	0.0081	0.11	0.51
2	0.25	0.32	0.0099	0.0074	0.0080	0.0068	0.092	0.70
3	0.30	0.37	0.011	0.0073	0.0077	0.0060	0.077	0.78
5	0.34	0.40	0.012	0.0059	0.0066	0.0044	0.053	0.82
7	0.35	0.40	0.011	0.0046	0.0055	0.0032	0.038	0.81
10	0.35	0.38	0.0095	0.0031	0.0042	0.0021	0.024	0.77
15	0.34	0.36	0.0072	0.0018	0.0027	0.0011	0.012	0.71
20	0.32	0.33	0.0055	0.0011	0.00066	0.0018	0.0072	0.67

Figure 50. Lung deposition fractions for nose breather (breathing rate = 1.2 m^3 h^{-1})

AMAD (μm)	*ET_1*	*ET_2*	*$BB_{fast+seq}$*	*BB_{slow}*	*$bb_{fast+seq}$*	*bb_{slow}*	*AI*	*total*
0.0006	0.20	0.58	0.060	0.060	0.040	0.040	0.00061	0.99
0.001	0.18	0.49	0.066	0.066	0.081	0.081	0.0062	0.98
0.002	0.14	0.35	0.058	0.058	0.14	0.14	0.058	0.95
0.005	0.075	0.18	0.031	0.031	0.15	0.15	0.30	0.91
0.01	0.042	0.099	0.016	0.016	0.10	0.10	0.50	0.87
0.02	0.026	0.060	0.0091	0.0091	0.065	0.065	0.50	0.73
0.05	0.015	0.034	0.0052	0.0052	0.037	0.037	0.32	0.45
0.1	0.012	0.024	0.0038	0.0038	0.024	0.024	0.21	0.30
0.2	0.015	0.025	0.0040	0.0039	0.016	0.016	0.15	0.23
0.5	0.024	0.037	0.0066	0.0059	0.013	0.012	0.14	0.24
0.7	0.033	0.055	0.011	0.0086	0.013	0.012	0.14	0.28
1	0.047	0.083	0.017	0.012	0.014	0.012	0.16	0.34
2	0.082	0.17	0.039	0.020	0.020	0.014	0.17	0.52
3	0.10	0.24	0.054	0.023	0.024	0.014	0.17	0.62
5	0.12	0.32	0.068	0.021	0.026	0.012	0.13	0.71
7	0.13	0.37	0.071	0.018	0.024	0.0099	0.11	0.73
10	0.14	0.41	0.066	0.013	0.019	0.0070	0.073	0.72
15	0.14	0.43	0.054	0.0083	0.014	0.0041	0.042	0.69
20	0.13	0.43	0.043	0.0053	0.0095	0.0025	0.026	0.65

Figure 51. Lung deposition fractions for mouth breather (breathing rate = 1.2 m^3 h^{-1})

RECENT EXAMS