Course
Radiation Protection Expert

Simple Exercises

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March 12, 2021

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Reading directions

This collection of simple exercises is intended to provide the student with the opportunity to test his or her own skills. The exercises are basic in nature and cover all the material that the student should be familiar with for the national exam Radiation Protection Expert.

Most exercises are also suitable for students following the course Radiation Protection Officer for applications of dispersible radioactive material;s (TS VRS-C), with the following exceptions:

chapter	*title*	*exercises*
1	Mathematics	5, 12 and 13
2	Compartment systems	all
3	Statistics	6, 7 and 8
4	Atomic and nuclear structure	4
5	Radioactivity	10 and 11
6	Interactions of radiation with matter	1, 2, 3, 9 and 10
7	Basic dosimetry	4
9	Operational dosimetry	3, 4 en 5
10	Dosimetry of internal exposure	
11	Detection of radiation	11
12	Shielding of external radiation	
14	Laws and regulations	
15	Devices	all
16	Sealed sources	3
17	Open sources	2

1 Mathematics

1 Calculate the value of x.
a $2^x = 2^3 \times 2^5$
b $2^x = (2^3)^5$
c $x^2 = 3^2 \times 5^2$

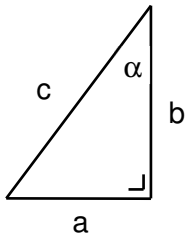
2 Rewrite the following expressions in $^{10}\log(5)$ and $^{10}\log(3)$:
a $^{10}\log(15) - {}^{10}\log(3)$
b $^{10}\log(60)$

3 The following values are given: $^{10}\log(2) = 0.301\,03$, $^{10}\log(3) = 0.477\,12$, and $^{10}\log(5) = 0.698\,97$. Determine the value of x without using a calculator.
a $x = {}^{10}\log(2^3)$
b $x = {}^{10}\log(3^2)$
c $x = {}^{10}\log(2 \times 3)$
d $x = {}^{10}\log(2 / 3)$
e $x = {}^{10}\log(2 + 3)$
f $x = {}^{10}\log(2 - 3)$

4 Determine the value of x using a calculator.
a $x = 1.234^{5.678}$
b $5^x = 625$
c $5^x = 620$

5 Someone deposits € 1000 in a savings account for which he receives 2% interest annually.
a after how many years has his savings been doubled?
hint: solve the equation $1000 \times 1.02^x = 2000$

6 For a right triangle with sides a and b, hypotenuse c, and angle α, the following values apply: $\alpha = 5°$ and $a = 10$ m.
a calculate the angle α in radians
b calculate b and c, accurate to one decimal point



7 Determine x and y for each of the following systems of linear equations:
a $5x + y = 6$
$5x - y = 4$
b $5x + 7y = 18$
$5x + 3y = 12$
c $1.2x + 1.5y = 2.5$
$-2.3x + 3.0y = 0.3$

8 A and B are separated by a distance of 25 km. At exactly 8 o'clock, two hikers depart from A and B simultaneously. The hiker departing from A walks at a pace of 5 km/h, while the hiker from B walks at a pace of 6 km/h.
a at what time do the hikers meet?
b what is the distance from the meeting point to A?

9 The assets of Sean are worth 2.5 times more than those of Pete, while the value of the assets of Pete is € 300 000 less.
a calculate the assets of Sean and Pete

10 One year ago, the assets of Sean were worth 2.5 times more than those of Pete. In that year, Sean's assets have increased by € 300 000, and those of Pete's have increased by € 600 000. Now Sean's assets are only worth 2 times more than those of Pete.
a calculate the current assets of Sean and Pete

11 Determine the roots of the following equations both by factorization and by using the root formula:
a $x^2 - 4x - 5 = 0$
b $x^2 - 5x + 6 = 0$
c $x^2 - 4x + 4 = 0$

12 The concentration of a radioactive substance in a room *C(t)* is given as a function of time *t* (in hours) by the formula:

$$C(t) = 10\, e^{-\lambda t}$$

in which λ is a constant called the ventilation coefficient. In a poorly-ventilated room, $\lambda = 0.5\ h^{-1}$. Calculate the following, accurate to two decimal points:
a the time that it takes before the concentration is halved
b the percent decrease of the concentration per hour
c the concentration after 8 hours

13 On the tenth day of every month, someone deposits a fixed amount into a savings account. On March 1st, 2010, the balance is € 1800. On July 1st, 2010, the balance is € 2500. The balance on the first day of the month *y* is given by $y = y_0 + a\,x$, where y_0 is the balance on January 1st, 2010, *x* is the number of months, and *a* is the amount deposited each month.
a determine *a* and y_0 algebraically
b determine *a* and y_0 graphically

14 Determine the derivatives of the following functions with respect to *x*:
a $y = x^2 - 4x - 5$
b $y = e^{-0.1x}$
c $y = 0.1e^{-0.1x}$
d $y = \ln(0.1x)$

15 Determine the following definite integrals:
a $\int_0^1 e^{-0.1t}\, dt$
b $\int_0^1 e^{-1t}\, dt$
c $\int_0^{10} e^{-0.1t}\, dt$
d $\int_0^{\infty} e^{-0.1t}\, dt$

Answers

1 a $2^x = 2^3 \times 2^5 = 2^{3+5} = 2^8$ $x = 8$
b $2^x = (2^3)^5 = 2^{3\times5} = 2^{15}$ $x = 15$
c $x^2 = 3^2 \times 5^2 = (3 \times 5)^2 = 15^2$ $x = 15$

2 a $^{10}\log(15) - {}^{10}\log(3) = {}^{10}\log(15/3) = {}^{10}\log(5)$
b $^{10}\log(60) = {}^{10}\log(3 \times 20) = {}^{10}\log(3 \times 100/5) = {}^{10}\log(3) + 2 - {}^{10}\log(5)$

3 a $x = {}^{10}\log(2^3) = 3 \times {}^{10}\log(2) = 3 \times 0.301\,03 = 0.903\,09$
b $x = {}^{10}\log(3^2) = 2 \times {}^{10}\log(3) = 2 \times 0.477\,12 = 0.954\,24$
c $x = {}^{10}\log(2 \times 3) = {}^{10}\log(2) + {}^{10}\log(3) = 0.301\,03 + 0.477\,12 = 0.778\,15$
d $x = {}^{10}\log(2 / 3) = {}^{10}\log(2) - {}^{10}\log(3) = 0.301\,03 - 0.477\,12 = -0.176\,09$
e $x = {}^{10}\log(2 + 3) = {}^{10}\log(5) = 0.698\,97$
f $x = {}^{10}\log(2 - 3) = {}^{10}\log(-1)$ undefined!

4 a using the button $\boldsymbol{x^y}$ $x = 1.234^{5.678} = 3.300$
using the buttons **log** and $\mathbf{10^x}$ $\log(x) = 5.678 \times \log(1.234)$
$= 5.678 \times 0.091\,32 = 0.5185$
$x = 10^{0.5185} = 3.300$
b $5^x = 625$ $x \times \log(5) = \log(625)$
$x = \log(625) / \log(5) = 2.7959 / 0.6990 = 4.000$
note that $625 = 25 \times 25 = 5^2 \times 5^2 = 5^4$
c $5^x = 620$ $x \times \log(5) = \log(620)$
$x = \log(620) / \log(5) = 2.7924 / 0.6990 = 3.995$

5 a $1.02^x = 2000 / 1000 = 2$
$x \times {}^{10}\log(1.02) = {}^{10}\log(2)$
$x = {}^{10}\log(2) / {}^{10}\log(1.02) = 0.301\,03 / 0.008\,600\,2 = 35$ years

6 a $\alpha = 5° \times (\pi \text{ rad} / 180°) = 0.0873$ rad
b $b = a / \tan(\alpha) = 10 / 0.087\,49 = 114.3$ m
$c = a / \sin(\alpha) = 10 / 0.087\,16 = 114.7$ m

7 a $5x + y = 6$
$5x - y = 4$ +
$10x = 10$ $x = 1$
$y = 6 - 5x = 6 - (5 \times 1) = 1$
b $5x + 7y = 18$
$5x + 3y = 12$ -
$4y = 6$ $y = 6 / 4 = 1.5$
$5x = 18 - 7y = 18 - (7 \times 1.5) = 7.5$ $x = 7.5 / 5 = 1.5$
c $1.2x + 1.5y = 2.5$ | × 2 | $2.4x + 3.0y = 5.0$
$-2.3x + 3.0y = 0.3$ | × 1 | $-2.3x + 3.0y = 0.3$ -
$4.7x = 4.7$
$x = 4.7 / 4.7 = 1.0$
$3.0y = 0.3 + 2.3x = 0.3 + (2.3 \times 1{,}0) = 2.6$ $y = 2.6 / 3.0 = 0.867$

8 suppose the position of hiker A is defined as x and the position of hiker B is y
choose the origin of the reference frame to coincide with point A
if the time that the two hikers meet is defined as t, then:

a $x = 0 + 5t$ and $y = 25 - 6t$
when the hikers meet, $x = y$, so $5t = 25 - 6t$, which can be written as $11t = 25$
$t = (25 / 11)$ hours = 2.273 hours = 2 hours and 16 minutes.
the hikers will thus meet at 10:16.

b the distance from A is $5t = 5 \times 2.273 = 11.365$ km

9 a define the assets of Sean as x and the assets of Pete as y

$x = 2.5y$

$\underline{x = y + 300\,000}$ -

$0 = 1.5y - 300\,000$ $\quad y = 300\,000 / 1.5 = €\ 200\,000$

$x = 2.5y = 2.5 \times 200\,000 = €\ 500\,000$

10 a define the current assets of Sean as x and the current assets of Pete as y

$x - 300\,000 = 2.5(y - 600\,000)$ $\quad x - 2.5y = -1\,200\,000$

$x = 2y$ $\quad \underline{x - 2y = 0}$ -

$-0.5y = -1\,200\,000$

$y = -1\,200\,000 / -0.5 = €\ 2\,400\,000$

$x = 2y = 2 \times 2\,400\,000 = €\ 4\,800\,000$

11 the root equation is as follows: $x_{1,2} = \{-b \pm \sqrt{(b^2 - 4ac)}\} / 2a$

a	factorization	$x^2 - 4x - 5 = (x - 5)(x + 1) = 0$	$x_1 = 5$	$x_2 = -1$
	root equation	$x_{1,2} = \{+4 \pm \sqrt{(4^2 + 4 \times 1 \times 5)}\} / 2 = 2 \pm 3$	$x_1 = 5$	$x_2 = -1$
b	factorization	$x^2 - 5x + 6 = (x - 3)(x - 2) = 0$	$x_1 = 3$	$x_2 = 2$
	root equation	$x_{1,2} = \{+5 \pm \sqrt{(5^2 - 4 \times 1 \times 6)}\} / 2 = 2.5 \pm 0.5$	$x_1 = 3$	$x_2 = 2$
c	factorization	$x^2 - 4x + 4 = (x - 2)^2 = 0$	$x_1 = x_2 = 2$	
	root equation	$x_{1,2} = \{+4 \pm \sqrt{(4^2 - 4 \times 1 \times 5)}\} / 2 = 2 \pm 0$	$x_1 = 2$	$x_2 = 2$

12 a $\lambda\, t_{½} = \ln\{C(0) / C(t_{½})\} = \ln(2) = 0.69315$
$t_{½} = 0.69315 / \lambda = 0.69315 / 0.5 = 1.39$ hours

b $C(t+1) = 10\, e^{-\lambda(t+1)} = 10\, e^{-\lambda t} \times e^{-\lambda} = C(t) \times e^{-0.5} = 0.607\, C(t)$
$C(t+1) / C(t) = 0{,}607 = 60.7\%$ $\quad \rightarrow$ 39.3% decrease per hour

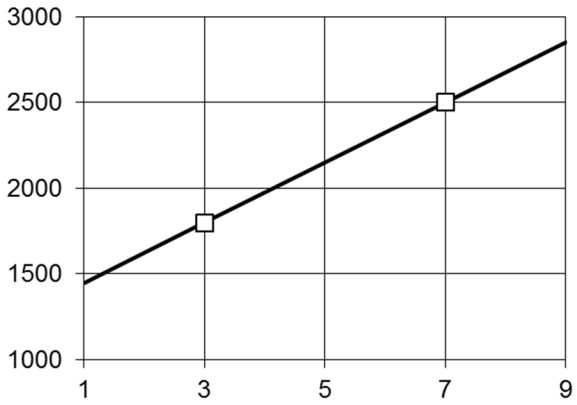
c $C(8) = 10\, e^{-0.5 \times 8} = 10\, e^{-4} = 0.183$

13 a on July 1st $\quad 2500 = y_0 + 6a$
on March 1st $\quad \underline{1800 = y_0 + 2a}$
$700 = 4a$

$a = 700 / 4 = €\ 175$

$y_0 = 2500 - 6a$
$= 2500 - 1050 = €\ 1450$

b see the graph:
slope = 175
intersection y-axis = 1450



14 a $dy/dx = d(x^2)/dx - d(4x)/dx - d(5)/dx = 2x - 4$ (sum rule)

b assume $t = -0.1x$

$dy/dx = d(e^t)/dt \times dt/dx$

$= e^t \times d(-0.1x)/dx = -0.1e^{-0.1x}$ (chain rule)

c $dy/dx = 0.1 \times d(e^{-0.1x})/dx$

$= 0.1 \times (-0.1e^{-0.1x}) = -0.01e^{-0.1x}$ (sum rule + result of b)

d assume $t = 0.1x$

$dy/dx = d(\ln t)/dt \times dt/dx$

$= t^{-1} \times d(0.1x)/dx = (0.1x)^{-1} \times 0.1 = x^{-1}$ (chain rule)

alternative: $y = \ln(0.1x) = \ln(0.1) + \ln(x)$

$dy/dt = 0 + x^{-1} = x^{-1}$ (sum rule)

15 use the definite integral ${}_a\int^b e^{-\mu t}\,dt = (e^{-\mu b} - e^{-\mu a}) / (-\mu)$

entering the coefficients yields the following results:

a ${}_0\int^1 e^{-0.1t}\,dt = (e^{-0.1\times1} - e^{-0.1\times0}) / (-0,1)$

$= 10 \times (1 - e^{-0.1}) = 10 \times (1 - 0.905) = 0.95$

b ${}_0\int^1 e^{-1t}\,dt = (e^{-1\times1} - e^{-1\times0}) / (-1)$

$= (1 - e^{-1}) = 1 - 0.368 = 0.632$

c ${}_0\int^{10} e^{-0.1t}\,dt = (e^{-0.1\times10} - e^{-0.1\times0}) / (-0.1)$

$= 10 \times (1 - e^{-1}) = 10 \times (1 - 0.368) = 6.32$

d ${}_0\int^{\infty} e^{-0.1t}\,dt = (e^{-0.1\times\infty} - e^{-0.1\times0}) / (-0.1)$

$= 10 \times (1 - e^{-\infty}) = 10 \times (1 - 0) = 10$

2 Compartment systems

1 Solve the following differential equations:
- a $y\,(dy/dx) = x$
- b $dy/dx = 3x + 1$
- c $dy/dx = e^{-x}$
- d $y' - xy - y = 0$
- e $y' + 3y = 0$

2 Solve the differential equations with the boundary condition $y = 4$ when $x = 0$:
- a $dy/dx = -2y$

3 The pressure in a gas cylinder P (in atmospheres) as a function time t (in hours) satisfies the differential equation $dP/dt + 0.7P = 0.7$. At time $t = 0$, the pressure in the cylinder $P(0) = 21$ atmospheres.
- a determine the function $P(t)$ which defines the pressure in the cylinder for all values of t
- b calculate the pressure in the cylinder for $t = \infty$ (infinite time after $t = 0$)
- c make a sketch of the pressure against time for the first 10 hours after $t = 0$
  hint: calculate the values for a number of points

4 In a room the air is ventilated with a ventilation rate of eight. This means that per hour an amount of air 8 times the volume of the room is circulated through the room. Due to an accident, chlorine was spilled. At time $t = 0$, 1500 grams of chlorine was present in the 75 m^3 room. The MAC-value of chlorine is 1 ppm, or 3 mg m^{-3}.
- a write down the differential equation governing the concentration of chlorine
- b determine the function which expresses the concentration of chlorine in g m^{-3} as a function of time (so, solve the differential equation)
- c determine the time after which the MAC-value is no longer exceeded
  note: MAC = maximum accepted concentration

5 Two cylindrical barrels with circular bottoms are set up. The first barrel drains into the second barrel through a hole in the bottom of the first barrel. The surface area of the bottom of the first barrel is 5 dm^2, and that of the second is 1 dm^2. The flow rate is proportional to the height of the water level in the barrel, and can be written as $0.2\,h_1(t)$ l min^{-1} (with h_1 in dm). At time $t = 0$, 25 l of water is added to the first barrel.
- a write down the differential equation governing the water level in the first barrel
- b determine the height of the water levels in both barrels as a function of time; plot the resulting functions on single-logarithmic paper (see appendix A1 of these Exercises)
- c at what time is the water level in the first barrel at a height of 1 dm ?

6 Consider three cylindrical barrels with circular bottoms. The first barrel drains into the second barrel through a hole in the bottom of the first barrel, and the second barrel subsequently drains into the third barrel through a hole in the bottom of the second barrel. The surface area of the bottom of the first barrel is 5 dm^2, that of the second barrel is 1 dm^2, and that of the third barrel is 10 dm^2. The flow rate is proportional to the height of the water level in the barrel, and can be written as 0.2 $h_1(t)$ l min^{-1} for the first barrel (with h_1 in dm), and as 1.0 $h_2(t)$ l min^{-1} for the second barrel (with h_2 in dm). The barrels start out empty. At time t = 0, 25 l of water is added to the first barrel.

a determine the water levels in the three barrels as a function of time
b plot these functions on single-logarithmic paper (see Appendix A1 of these Exercises)

7 A 20 l barrel is completely filled with water, after which a saline solution with a concentration of 1.0 g cm^{-3} is added to the barrel with a constant rate of 0.50 l min^{-1}. At time t = 0, the barrel is completely filled with water with a saline concentration of zero.

a determine the concentration of salt in the liquid in this barrel as a function of time t

8 In a 50 m^3 room, 50 mg of ozone was released. Ozone dissociates spontaneously with a half-life of 10 minutes. The room has a ventilation rate of two. The MAC-value of ozone is 0,06 ppm = 0.12 mg m^{-3} as an hourly average.

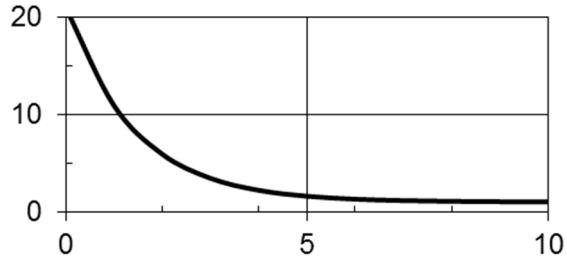
a caluculate the effective half-life of the ozon
b determine the ozon concentration as a function of time
c is the MAC-value exceeded in this room?
d how much ozone is removed from the room in the first hour?

Answers

1 a $y\,dy = x\,dx$ $0.5\,y^2 = 0.5\,x^2 + c$ $y^2 - x^2 = c'$
b $dy = (3x+1)\,dx$ $y = 1.5\,x^2 + x + c$
c $dy/dx = e^{-x}$ $dy = e^{-x}\,dx$ $y = -e^{-x} + c$
d $dy/x = (x+1)\,y$ $dy/y = (x+1)\,dx$ $\ln(y) = 0.5\,x^2 + x + c$
e $dy/dx = -3y$ $dy/y = -3\,dx$ $\ln(y) = -3x + c$ $y = c'\,e^{-3x}$

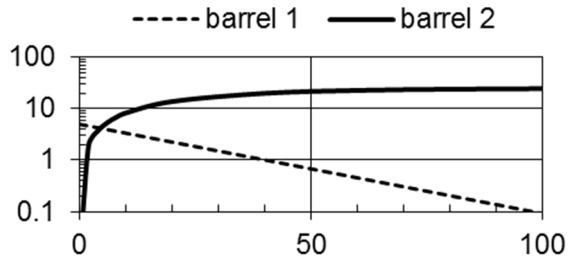
2 a integration gives $\ln(y) = -2x + c$
general solution $y = c'\,e^{-2x}$
entering boundary condition $4 = c'\,e^0 = c'$
$y = 4\,e^{-2x}$

3 a $dP/dt + 0.7P = 0.7$ this is a differential equation of type $dy/dx + ay = k$
the general solution of this is $y = (k/a) + c\,e^{-a\,x}$
$P(t) = 1 + c\,e^{-0,7t}$ atm
entering boundary condition $21\text{ atm} = P(0) = 1 + c\,e^0 = 1 + c \rightarrow c = 20$ atm
$P(t) = 1 + 20\,e^{-0.7t}$ atm
b $P(\infty) = 1 + 20\,e^{-\infty}$
$= 1 + 0 = 1$ atm
c see graph on the right



4 a $d(C_1V_1)/dt = -k_{12}\,C_1V_1$
per hour, $8V_1$ is pumped out
with t in hours, $k_{12} = 8$ per hour
so, $dC_1/dt = -8\,C_1$ (t in hours)
b $C_1(t) = C_1(0)\,e^{-8t}$
$C_1(0) = 1500 / 75 = 20$ g m^{-3} $\rightarrow$ $C_1(t) = 20\,e^{-8t}$ g m^{-3}
c MAC-value = 3 mg m^{-3} = 0.003 g m^{-3}
$0.003 = 20\,e^{-8t}$
$\ln(0.003 / 20) = \ln(1.5 \times 10^{-4}) = -8.8 = -8t$ $\rightarrow$ $t = 1.1$ hours

5 suppose A_i = surface area of the bottom of the ith barrel
a barrel 1: $dV_1/dt = A_1 \times dh_1/dt = -k_{12} = -0,2\,h_1$
$dh_1/dt = -0.2\,h_1 / A_1 = -h_1 \times 0.2$ dm^2 min^{-1} / 5 dm^2 = $-h_1 \times 0.04$ min^{-1}
$dh_1/dt + 0.04\,h_1 = 0$
b barrel 1: $h_1(t) = c\,e^{-0.04t}$
$h_1(0) = 25$ dm^3 / 5 dm^2
$= 5$ dm
$h_1(t) = 5\,e^{-0.04t}$
barrel 2: $V_1 + V_2 = D = 25$ l
$V_1 = h_1 \times A_1$
$= 5\,e^{-0.04t} \times 5 = 25\,e^{-0.04t}$
$V_2 = 25\,(1 - e^{-0.04t})$
$h_2(t) = V_2 / A_2$
$= 25\,(1 - e^{-0.04t}) / 1$
$= 25\,(1 - e^{-0.04t})$
see graph on the right



c $1 = 5\,e^{-0.04t}$ $\rightarrow$ $t = \ln(0.2) / -0.04 = 40$ min

6 suppose A_i = surface area of the bottom of the ith barrel

a barrel 1: $dV_1/dt = -k_{12}$

$A_1 \times dh_1/dt = -0.2\ h_1$

$dh_1/dt = -0.2\ h_1 / A_1 = -h_1 \times 0.2\ dm^2\ min^{-1} / 5\ dm^2 = -h_1 \times 0.04\ min^{-1}$

$dh_1/dt + 0.04\ h_1 = 0$

$h_1(t) = c\ e^{-0.04t}$

$h_1(0) = 25\ dm^3 / 5\ dm^2 = 5\ dm \quad \rightarrow \quad h_1(t) = 5\ e^{-0.04t}$

barrel 2: $dV_2/dt = +k_{12} - k_{23}$

$A_2 \times dh_2/dt = +0.2\ h_1 - 1.0\ h_2$

$dh_2/dt = +0.2\ h_1 / A_2 - 1.0\ h_2 / A_2$

$= +0.2 \times 5\ e^{-0.04t} / 1 - 1.0\ h_2 / 1 = +1.0\ e^{-0.04t} - 1.0\ h_2$

$dh_2/dt + 1.0\ h_2 = 1.0\ e^{-0.04t}$

this is a first-order linear differential equation with constant coefficients (type III), with K = 1, a = 1 and b = 0.04

$h_2(t) = (1/0.96)\ e^{-0.04t} + c\ e^{-t}$

$h_2(0) = 0 \quad \rightarrow \quad h_2(t) = 1.04\ (e^{-0.04t} - e^{-t})$

barrel 3: $V_1 + V_2 + V_3 = D = 25\ dm^3$

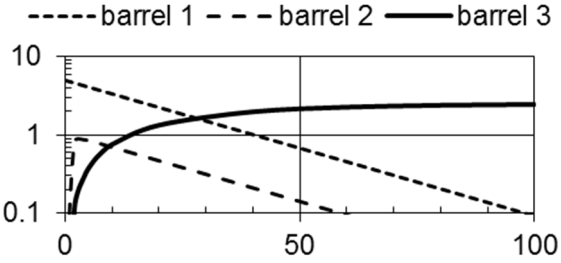
$h_3(t) = V_3 / A_3 = (D - A_1\ h_1 - A_2\ h_2) / A_3$

$= (25 - 5\ h_1 - 1\ h_2) / 10 = 2.5 - 0.5\ h_1(t) - 0.1\ h_2(t)$

filling in h_1 and h_2 yields:

$h_3(t) = 2.5 - 2.5\ e^{-0.04t} - 0{,}104\ (e^{-0.04t} - e^{-t})$

b see graph



7 #1 → #2 → #3

input barrel outflow

C_1= 1 g cm^{-3} dV_1/dt = 0.50 l min^{-1}

V_2 = 20 l = 2×10^4 cm^3

a input $C_1\ dV_1/dt$ = 500 g min^{-1}

outflow $C_2\ dV_2/dt$

note that $dV_1/dt = dV_2/dt$ = 500 cm^3 min^{-1}

$V_2\ (dC_2/dt)$ = input - outflow = 500 - 500 C_2

$2\times10^4\ (dC_2/dt) + 500\ C_2 = 500$

$dC_2/dt + 0.025\ C_2 = 0.025$

this is a differential equation of type $dy/dx + ay = k$

the general solution of this is $y = (k/a) + c\ e^{-ax}$

$C_2(t) = (0.025 / 0.025) + c\ e^{-0.025t} = 1 + c\ e^{-0.025t}$

$C_2(0) = 0 = 1 + c \quad \rightarrow \quad c = -1 \quad \rightarrow \quad C_2(t) = 1 - e^{-0.025t}$

8 a without ventilation $D = 2^{-t/T_{½}} = e^{-\lambda t}$
$T_{½}$ = 10 min = 0.167 hour → $\lambda_{dis} = \ln(2) / T_{½}$ = 4.16 per hour
with ventilation $dD/dt = -\lambda_{dis} D(t) - \lambda_{vent} D(t)$
$= -(4.16 + 2) D(t) = -6.16 D(t) = -\lambda_{eff} D(t)$
$T_{½,eff} = 0{,}693 / \lambda_{eff}$
$= 0{,}693 / 6{,}16$ per hour = 0,112 h = 6,8 min

b $D(t) = D(0) e^{-6.16t}$
concentration $C(t) = D(t) / V$
$C(0) = 50$ mg / 50 m³ = 1 mg m⁻³
$C(t) = e^{-6.16t}$ mg m⁻³

c hourly average concentration
$${}_0\int^T C(t)\,dt / T = {}_0\int^T e^{-6.16t}\,dt / T = (1 - e^{-6.16T}) / (6.16\,T)$$
as the concentration will be highest in the first hour, using T = 1 is sufficient
this gives an average concentration of 0.16 mg/m³ in the first hour
→ MAC-value is exceeded!

d due to the ventilation, per unit time $dD_{removed}(t)/dt = \lambda_{vent} D(t)$ will be removed
$dD_{removed}(t)/dt = 2 \times 50\ m^3 \times C(t) = 100\ e^{-6.16t}$
integration from 0 to t gives:
$D_{removed}(t) = (100 / 6.16)(1 - e^{-6.16t}) = 16.2 (1 - e^{-6.16t})$
→ after one hour, the amount of ozone removed is $D_{removed}(1) = 16.2$ mg

3 Statistics

1 In a static set-up, a detector is used to measure radiation from a radioactive source. One hundred measurements are performed, lasting exactly one minute each. The half-life of the source is very long compared to the measurement time. The measured values x_i are:

5895	5918	5846	5935	5954	5922	5807	5914	5861	5987
5857	5925	5868	5947	5989	5874	5896	5893	5842	5831
5934	5899	5781	5964	5853	6015	5877	5911	5898	6092
5988	5828	5794	5881	5804	5933	6023	5736	5953	6014
5907	5969	5812	6028	5904	5834	5909	6019	5822	6012
5959	5946	5919	5937	5855	5785	5984	5924	5959	5871
5819	5926	5948	5982	6037	5935	5862	6033	5845	5836
5923	6007	5825	6001	5979	6018	5751	5951	6003	5865
5839	5772	5942	5836	5847	6032	5927	5908	5905	5912
6012	5917	5936	5938	5897	5772	5955	5908	5873	5945

Here, $\sum x_i = 591\,113$ and $\sum x_i^2 = 3\,494\,679\,543$

a make a histogram with intervals: 5700-5749, 5750-5799, *etcetera*
b calculate the average $\bar{x}$ of the measured values
c determine the standard deviation σ of the number of detections per minute
d from the histogram, determine the percentage of the measurements which are smaller than $\bar{x}$-σ and the percentage of the measurements which are larger than $\bar{x}$+σ; compare these values to those expected from a normal distribution
e what percentage of the measurements lie in the interval $[\bar{x}-\sigma;\bar{x}+\sigma]$? compare this value to what is expected from a normal distribution
f repeat questions d and e for the interval $[\bar{x}+2\sigma;\ \bar{x}-2\sigma]$
g determine the standard deviation of the average of the measurements
h give the interval within which the actual result should be found with a probability of 95%

2 When measuring a radioactive source, 300 counts are registered in one minute.

a how long should the measurement be performed to achieve an accuracy of 3% within a confidence interval of 67% ?
b how long should the measurement be performed to achieve an accuracy of 1% within a confidence interval of 67% ?
c how long should the measurement be performed to achieve an accuracy of 3% within a confidence interval of 95% ?

3 A measurement of a sample with a small amount of radioactivity gives 244 counts in 10 minutes. A measurement of a non-radioactive control sample gives 184 counts in 10 minutes, under exactly the same circumstances.
- a calculate the gross counting rate and the standard deviation hereof in counts per minute; give the result in the form $T \pm \sigma$ counts per minute
- b repeat the calculation of question a for the control sample
- c repeat the calculation of question a for the net counting rate
- d give the relative error in the net counting rate
- e give the interval within which the actual counting rate should be found with a probability of 95%

4 Two measurements are performed, the first with a sample with a small amount of radioactivity (measurement A), and the second with a non-radioactive control sample (measurement B). Measurement A returns 100 counts in 24 minutes and measurement B returns 100 counts in 50 minutes.
- a calculate the counting rate of measurement A and the standard deviation hereof in counts per minute; give the result in the form $T_A \pm \sigma_A$ counts per minute
- b repeat question a for measurement B; give the result in the form $T_B \pm \sigma_B$ counts per minute
- c calculate the net counting rate of measurement A and the standard deviation hereof; give the result in the form $T \pm \sigma$ counts per minute
- d what would the relative error in the net counting rate have been if both measurements had lasted 60 minutes?
- e determine the minimum measurement time such that the relative error in the net counting rate is 10% with a confidence interval of 95%; assume that the measurement time of measurement B is increased to 200 minutes

5 The shielding properties of an absorber are to be determined. Without the absorber, 1600 counts are measured in 20 minutes (measurement A), and with absorber 480 counts are measured in 20 minutes (measurement B). As background, 80 counts are measured in 50 minutes (measurement C).
- a write the net counting rate without the absorber as $T_A \pm \sigma_A$ counts per minute
- b write the net counting rate with the absorber as $T_B \pm \sigma_B$ counts per minute
- c determine the relative accuracy of the shielding factor $F = T_B / T_A$

6 The radiation expert suspects that an object is radioactively contaminated. Using a GM-counter, he measures $N_A = 1089$ counts in 10 minutes. A background measurement gives $N_B = 1024$ counts in the same time span.
- a determine the probability that the object is not contaminated
  hint: use the one-tailed probability P(k) given in appendix A2 of these Exercises

7 Perform the following calculations and write the result in the scientific notation, leaving out all non-significant digits.
- a 5.31 - 2.3
- b 0.3010 + 0.4771
- c $1.25 \times 10^2 \times 2$
- d 2.718 281 83 / 3.14

8 Two series of measurements are performed on the same radioactive source, each with a different detector. The results of both measurement series are tabulated below.

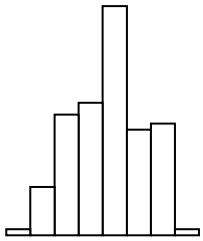
series 1	*series 2*
98	103
100	100
114	105
120	107
85	101
97	103
111	106
119	108
89	102
107	105

a determine for both series the average value $\bar{x}$
b determine for both series the standard deviation σ using the following formula:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$$

c determine for both series the standard deviation using $\sigma = \sqrt{\bar{x}}$
d what can be said about the accuracy, correctness, and precision of both measurement series?

Answers

1 a 

b $\bar{x} = (\sum x_i) / n = 591\,113 / 100 = 5911.13$

c $\sigma_x = \sqrt{[\{\sum (x_i - \bar{x})^2\} / (n - 1)]}$
$= \sqrt{[\{\sum (x_i)^2 - \sum (2x_i\bar{x}) + \sum (\bar{x})^2\} / (n - 1)]} = \sqrt{[\{\sum (x_i)^2 - 2\bar{x}\sum x_i + \sum (\bar{x})^2\} / (n - 1)]}$
$= \sqrt{[\{\sum (x_i)^2 - 2\bar{x}\ (n\bar{x}) + n(\bar{x})^2\} / (n - 1)]} = \sqrt{[\{\sum (x_i)^2 - n(\bar{x})^2\} / (n - 1)]}$
$= \sqrt{[(3\,494\,679\,543 - 100 \times 5911.13^2) / 99]} = 73.4$ cpm

d the 1σ-boundaries are 5837.7 and 5984.5
there are 18 larger outliers (18%) and 18 smaller outliers (18%)

e in the 1σ-interval, there are 64 of the 100 measurements; in a normal distribution, this should be 68%

f the 2σ-boundaries are 5764.3 en 6057.9
in the 2σ-interval, there are 97 of the 100 measurements; in a normal distribution, this should be 95%

g $\sigma_{\bar{x}} = \sigma / \sqrt{n} = 73.4 / \sqrt{100} = 7.3$ cpm

h the interval is $[\bar{x}-2\sigma_{\bar{x}}; \bar{x}+2\sigma_{\bar{x}}] = [5896.5; 5925.7]$

2 a for a relative error of 3%, $(1 / 0.03)^2 = 1111$ counts are necessary
the time necessary is 1111 / 300 cpm = 3,7 minutes

b for a relative error of 1%, $(1 / 0.01)^2 = 10\,000$ counts are necessary
the time necessary is 10 000 / 300 cpm = 33.3 minutes

c a confidence interval of 95% corresponds to 2σ-boundaries, so σ_{rel} is 1.5%
for a relative error of 1.5%, $(1 / 0.015)^2 = 4444$ counts are necessary
t = 4444 / 300 cpm = 14.8 min

3 a $T_1 = 244 / 10 = 24.4$ cpm $\quad \sigma_1 = \sqrt{244} / 10 = 15.6 / 10 = 1.6$ cpm
$T_1 \pm \sigma_1 = 24.4 \pm 1.6$ cpm

b $T_2 = 184 / 10 = 18.4$ cpm $\quad \sigma_2 = \sqrt{184} / 10 = 13.6 / 10 = 1.4$ cpm
$T_2 \pm \sigma_2 = 18.4 \pm 1.4$ cpm

c $T = T_1 - T_2 = 24.4 - 18.4 = 6.0$ cpm
$\sigma = \sqrt{(\sigma_1^2 + \sigma_2^2)} = \sqrt{(1.6^2 + 1.4^2)} = \sqrt{(2.56 + 1.96)} = \sqrt{4.5} = 2.1$ cpm
$T \pm \sigma = 6.0 \pm 2.1$ cpm

d the relative error is 2.1 / 6.0 = 35%

e a confidence interval of 95% corresponds to $2\sigma = 4.2$ cpm
thus, the interval is [6.0-4.2; 6.0+4.2] = [1.8; 10.2] cpm

4 a $T_A = 100 / 24 = 4.17$ cpm $\quad \sigma_A = \sqrt{100} / 24 = 10 / 24 = 0.42$ cpm
$T_A \pm \sigma_A = 4.17 \pm 0.42$ cpm

b $T_B = 100 / 50 = 2.00$ cpm $\quad \sigma_B = \sqrt{100} / 50 = 10 / 50 = 0.20$ cpm
$T_B \pm \sigma_B = 2.00 \pm 0.20$ cpm

c $T = T_A - T_B = 4.17 - 2.00 = 2.17$ cpm
$\sigma = \sqrt{(\sigma_A^2 + \sigma_B^2)} = \sqrt{(0.42^2 + 0.20^2)} = \sqrt{(0.176 + 0.040)} = \sqrt{0.216} = 0.46$ cpm
$T \pm \sigma = 2.17 \pm 0.47$ cpm

d $\sigma_{gross} = \sqrt{(24 / 60)} \times 0.42 = 0.27$ cpm
$\sigma_{control} = \sqrt{(50 / 60)} \times 0.20 = 0.18$ cpm
$\sigma_{net} = \sqrt{(\sigma_{gross}^2 + \sigma_{control}^2)} = \sqrt{(0.0729 + 0.0324)} = \sqrt{0.1053} = 0.32$ cpm
the relative error is $0.32 / 2.17 = 15\%$

e $\sigma_{control} = \sqrt{(50 / 200)} \times 0.20 = 0.10$ cpm
a confidence interval of 95% corresponds to 2σ
a relative error of 10% is demanded, so $2\sigma_{net} = 0.1 \times 2.17 = 0.217$ cpm
thus, $\sigma_{net} = 0.1085$ cpm
$\sigma_{gross} = \sqrt{(\sigma_{net}^2 - \sigma_{control}^2)} = \sqrt{(0.1085^2 - 0.10^2)} = \sqrt{0.0018} = 0.042$ cpm
the measurement time should be $(0.42 / 0.042)^2 \times 24 = 2400$ min = 40 hours

5 a $T_A = T_{A,gross} - T_C = (1600 / 20) - (80 / 50) = 80.0 - 1.6 = 78.4$ cpm
$\sigma_{A,gross} = \sqrt{1600} / 20 = 2.0$ cpm
$\sigma_C = \sqrt{80} / 50 = 0.18$ cpm
$\sigma_A = \sqrt{(\sigma_{A,gross}^2 + \sigma_C^2)} = \sqrt{(4.00 + 0.03)} = \sqrt{4.03} = 2.0$ cpm
$T_A \pm \sigma_A = 78.4 \pm 2.0$ cpm

b $T_B = T_{B,gross} - T_C = (480 / 20) - (80 / 50) = 24.0 - 1.6 = 22.4$ cpm
$\sigma_{B,gross} = \sqrt{480} / 20 = 1.1$ cpm
$\sigma_C = \sqrt{80} / 50 = 0.18$ cpm
$\sigma_B = \sqrt{(\sigma_{B,gross}^2 + \sigma_C^2)} = \sqrt{(1.21 + 0.03)} = \sqrt{1.24} = 1.1$ cpm
$T_B \pm \sigma_B = 22.4 \pm 1.1$ cpm

c $F = T_B / T_A = 22.4 / 78.4 = 0.286$
the relative errors of T_A and T_B should be added quadratically
$\sigma_F / F = \sqrt{[(\sigma_A / T_A)^2 + (\sigma_B / T_B)^2]}$
$= \sqrt{[(2.0 / 78.1)^2 + (1.1 / 22.4)^2]}$
$= \sqrt{(0.000\,65 + 0.002\,41)} = \sqrt{0.003\,06} = 0.055$

6 a the net number of counts is $N_C = N_A - N_B = 1089 - 1024 = 65$
the standard deviation is $\sigma_C = \sqrt{(1089 + 1024)} = \sqrt{2113} = 46$
the difference is $k = 65 / 46 = 1.4$ standard deviations
the one-tailed probability is $P(1.4) = 0.081$
the probability that the object is not contaminated is therefore 8.1%

7 a $3.01 \rightarrow 3.0\times10^{0}$
b $0.7781 \rightarrow 7.781\times10^{-1}$
c $2.50\times10^{2} \rightarrow 3\times10^{2}$
d $0.865\,694\,85 \rightarrow 8.66\times10^{-1}$

8
a series 1 $\bar{x}$ = 104.0
series 2 $\bar{x}$ = 104.0
b series 1 σ = 12.1
series 2 σ = 2.6
c series 1 σ = 10.2
series 2 σ = 10.2
d series 1 spread of the measurement results matches that of a normal distribution
accuracy, correctness, and precision of the average value are (most probably) good
series 2 spread of the measurements is much smaller than statistically expected
the precision seems high, but the detector is most likely malfunctioning
thus, the accuracy and correctness are (most probably) poor

4 Atomic and nuclear structure

1 Determine the proton number Z, the neutron number N, and the ratio N/Z for the following nuclides:

a $^{1}_{1}H$
b $^{3}_{1}H$
c $^{6}_{3}Li$
d $^{60}_{27}Co$
e $^{137}_{55}Cs$
f $^{241}_{95}Am$

2 The atomic mass of sodium and chlorine are 22.99 and 35.45, respectively. Avogadro's constant is 6.02×10^{23} mol^{-1}.

a calculate the number of molecules in 1 gram of kitchen salt (NaCl)

3 The binding energy of the K, L, M, and N-electrons of lead 88.01 keV, 15.86 keV, 3.85 keV, and 0.90 keV, are respectively. Determine the minimum energy of:

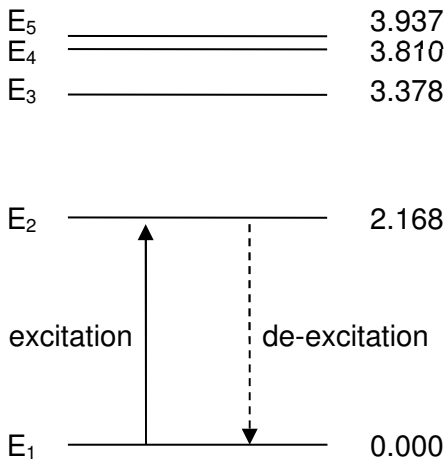
a characteristic K X-ray photons of lead
b characteristic L X-ray photons of lead
c characteristic M X-ray photons of lead
d characteristic N X-ray photons of lead

4 When a vacancy in the K-shell is filled, either an Auger electron or a characteristic X-ray photon is emitted.

a determine the ratio of the number of emitted X-ray photons N_X and the number of emitted Auger electrons N_{Auger} caused by a vacancy in the K-shell of an iron atom (Z = 26)
hint: use the data in Appendix A3 of these Exercises

5 In the figure on the right, the energy states (in MeV) of the nuclide ^{38}Cl are given.

a determine the photon energies for the transitions between the first three energy states



Answers

1	a	Z = 1	N = 1 - 1 = 0	N / Z = 0
	b	Z = 1	N = 3 - 1 = 2	N / Z = 2.00
	c	Z = 3	N = 6 - 3 = 3	N / Z = 1.00
	d	Z = 27	N = 60 - 27 = 33	N / Z = 1.22
	e	Z = 55	N = 137 - 55 = 82	N / Z = 1.49
	f	Z = 95	N = 241 - 95 = 146	N / Z = 1.54

2 a molecular mass 22.99 + 35.45 = 58.44
number of molecules in 1 gram $(1 / 58.44) \times 6.02\times10^{23} = 1.0\times10^{22}$

3 a $E_{K\text{-}X}$ = 88.01 - 15.86 = 72.15 keV
b $E_{L\text{-}X}$ = 15.86 - 3.85 = 12.01 keV
c $E_{M\text{-}X}$ = 3.85 - 0.90 = 2.95 keV
d $E_{N\text{-}X}$ = 0.90 - 0.0 = 0.90 keV

4 a from Appendix A3 of these Exercises, the K-fluorescence yield = ω = 0.29
$N_X / N_{Auger} = \omega / (1 - \omega) = 0.29 / 0.71 = 0.41$

5 a $E3 - E1$ = 3.378 - 0 = 3.378 MeV
$E2 - E1$ = 2.168 - 0 = 2.168 MeV
$E3 - E2$ = 3.378 – 2.168 = 1.210 MeV

5 Radioactivity

1 The net counting rate resulting from a radioactive source is 11500 counts per minute (cpm) at 9:00 hours and 3200 cpm at 15:30 hours.
- a calculate the half-life
- b determine the net counting rate at 12:00 hours
- c verify the answer found for b using a graphical method

2 A calibrated amount of ^{133}Xe ($T_{½}$ = 5.25 d) has an activity of 100 MBq on Monday morning at 9:00 hours.
- a determine analytically at which time the activity has decreased to 75 MBq
- b determine graphically at which time the activity has decreased to 75 MBq
- c using both methods, determine the activity on the previous Friday at 15:00 hours

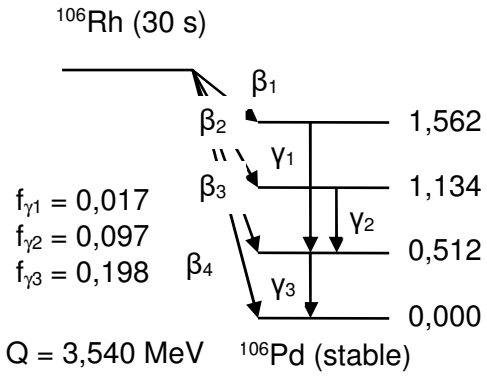
3 A carrier-free source of NaI with a strength of 37 kBq contains iodine atoms exclusively consisting of the radionuclide ^{131}I ($T_{½}$ = 8.05 d). The mass number of sodium is A = 23. Avogadro's constant is equal to 6.02×10^{23} mol^{-1}.
- a determine the mass of this radioactive substance

4 The old unit of radioactivity is the curie. This is defined as the activity of one gram of radium.
- a determine the activity (in Bq) of 1.0 gram ^{226}Ra ($T_{½}$ = 1600 y)

5 Tritium (^{3}H) is radioactive and decays through emission of a β^--particle to the ground state of a stable helium isotope. The maximum β^--energy is 18.6 keV. The half-life is 12.33 years.
- a how large is the energy difference between the initial and the final state?
- b draw the decay scheme with all relevant data

6 The radionuclide ^{13}N decays through emission of a positron to the ground state of the stable nuclide ^{13}C. The maximum β^+-energy is 1.19 MeV. The half-life is 10.0 minutes.
- a how large is the energy difference between the initial and the final state?
- b draw the decay scheme with all relevant data

7 The decay scheme of the nuclide ^{106}Rh is given. There is no internal conversion.
- a give the maximum energy for all β-transitions
- b give the emission probability for all β-transitions
- c how many β-particles per second are emitted by 1.0 kBq ^{106}Rh ?
- d how many γ-photons per second are emitted by 1.0 kBq ^{106}Rh ?



8 The radionuclide ^{125}I decays for 100% to an isomeric level of ^{125}Te at 35.46 keV. During the decay of this isomeric level, internal conversion occurs in 93.33% of the cases, consisting of 80.30% K-electrons, 10.47% L-electrons, 2.09% M-electrons, and 0.50% N-electrons.
   a determine α_{tot}, α_K, α_L, α_M, and α_N

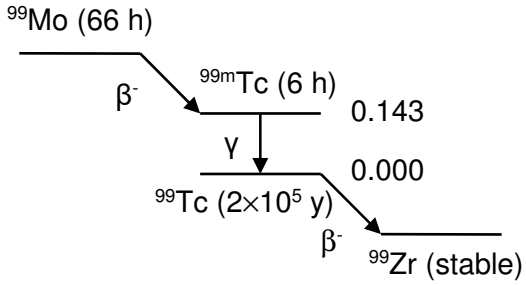
9 The radionuclide ^{137}Cs decays to ^{137m}Ba through emission of a β^--particle with $E_{\beta 1,max}$ = 0.514 MeV with an emission probability of $f_{\beta 1}$ = 0.944, and in the rest of the cases it decays directly to the ground state of ^{137}Ba. The energy of the isomeric level ^{137m}Ba is 662 keV, and the conversion coefficient of the isomeric transition is α = 0.110.
   a determine the energy $E_{\beta 2,\,max}$ of the β^--transition to the ground state of ^{137}Ba
   b determine the probability of emission of the γ-photon
   c draw the decay scheme with all relevant data

10 At 9:00 hours, an amount of ^{99m}Tc is brought into a laboratory. One hour later, the activity of the technetium is determined. Every hour afterwards, the activity is determined again (see the Table below).

time t *(h)*	*activity A* *(Bq)*
10:00	2.00×10^6
11:00	1.78×10^6
12:00	1.59×10^6
13:00	1.42×10^6
14:00	1.26×10^6
15:00	1.13×10^6
16:00	1.00×10^6
17:00	0.89×10^6

   a plot the measurements on single-logarithmic graphing paper (plot the activity on the *y*-axis and the time on the *x*-axis)
   b what was the activity at the moment the technetium was brought into the laboratory?
   c how long does in take for the activity to reduce by half?
   d give the activity *A* as a function of time *t* (use the exponential function; take 9:00 hours as *t* = 0, 10:00 hours as *t* = 1, *etcetera*)
   e how many disintegrations occur between 10:00 hours and 17:00 hours?
   f give the total number of disintegrations since 9:00 hours as a function of *t*
   g how many radioactive nuclei did the technetium contain when it was brought into the laboratory?

11 The radionuclide ^{99}Mo decays through the short-lived isomeric state ^{99m}Tc to the ground state of ^{99}Tc. This radionuclide has a very long half-life, and in turn decays to stable ^{99}Zr. An activity of 1.0 GBq pure ^{99}Mo is present at time t = 0.



a what are the activities of ^{99}Mo and ^{99m}Tc at time t = 6 h ?

b what are the activities of ^{99}Mo and ^{99m}Tc at time t = 66 h ?

c what is the activity of ^{99}Tc at time t = 660 h ?

d what is the activity of ^{99}Tc at time $t = 2\times10^5$ y ?

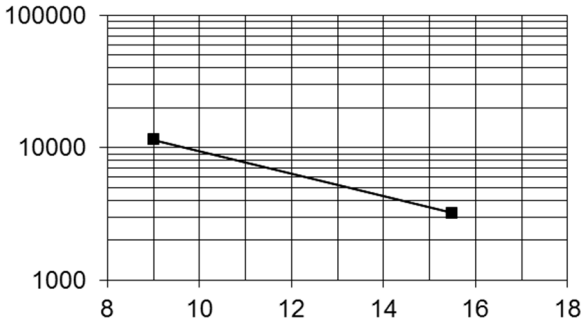
Answers

1 $N(t) = N(0)\, e^{-0.693\, t/T_{½}}$, $N(0) = 11\,500$

a between 9:00 and 15:30 are 6.5 h:
$N(6.5) = 11\,500\, e^{-0.693\times 6.5/T_{½}} = 3200$
$0.693 \times 6.5 / T_{½} = \ln(11\,500 / 3200)$
$= \ln(3.59) = 1.28$
$T_{½} = 0.693 \times 6.5 / 1.28 = 3.52$ hours

b between 9:00 and 12:00 are 3.0 h:
$N(3.0) = 11\,500\, e^{-0.693\times 3/3.52}$
$= 11\,500 \times 0.554 = 6370$ cpm

c use single-logarithmic paper

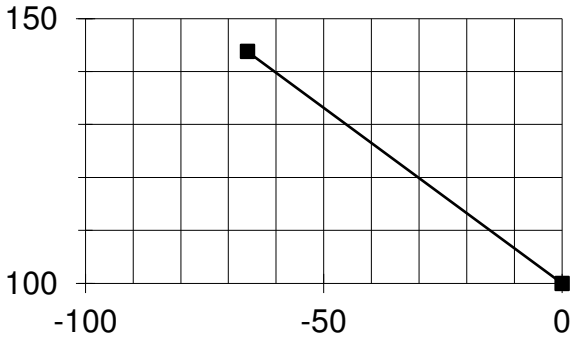


2 $T_{½} = 5.25 \times 24 = 126$ hours

a $e^{-0.693\, t/126} = 75 / 100 = 0{,}75$
$-0{,}693t / 126 = \ln(0.75) = -0.288$
$t = 0.288 \times 126 / 0.693 = 52.4$ hours
so, Wednesday afternoon at 13:24 hours

b use single-logarithmic paper

c between Friday 15:00 and Monday 9:00 are 66 hours:
$A(-66) = 100\, e^{-0.693\times(-66)/126}$
$= 100 \times 1.44 = 144$ MBq

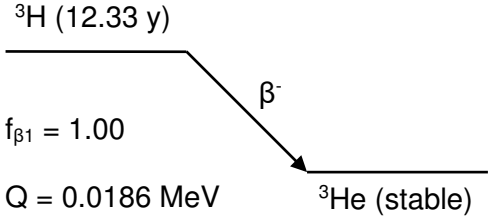


3 a $\lambda(^{131}I) = \ln(2) / (8.05 \times 24 \times 3600)\ s^{-1} = 9.97\times10^{-7}\ s^{-1}$
number of ^{131}I atoms is $N = A / \lambda = 37\times10^{3} / 9.97\times10^{-7} = 3.7\times10^{10}$
number of gram atoms is $N / N_{Avo} = 3.7\times10^{10} / 6.02\times10^{23} = 6.1\times10^{-14}$
the mass of $Na^{131}I$ is $6.1\times10^{-14} \times (23 + 131) = 9.4\times10^{-12}$ g = 9.4 pg

4 a 1 gram ^{226}Ra (= 1 / 226 mol) contains $6.02\times10^{23} / 226 = 2.664\times10^{21}$ atoms
$\lambda(^{226}Ra) = 0.693 / (1600 \times 365 \times 24 \times 3600) = 1.373\times10^{-11}\ s^{-1}$
$A = \lambda N = 2.664\times10^{21} \times 1.373\times10^{-11} = 3.66\times10^{10}$ Bq = 1.0 Ci

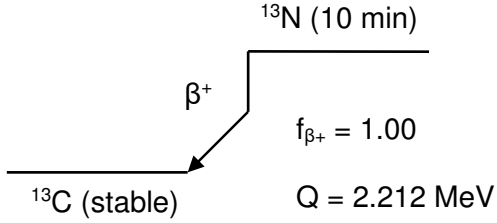
5 a $Q = E_{\beta,max} = 18.6$ keV = 0.0186 MeV

b see figure



6 a $Q = E_{\beta,max} + 1.022 = 1.19 + 1.022$
$= 2.212$ MeV

b see figure



7 a $E_{\beta 1,max} = 3.540 - 1.562 = 1.978$ MeV
$E_{\beta 2,max} = 3.540 - 1.134 = 2.406$ MeV
$E_{\beta 3,max} = 3.540 - 0.512 = 3.028$ MeV
$E_{\beta 4,max} = 3.540 - 0.000 = 3.540$ MeV

b $f_{\beta 1} = f_{\gamma 1} = 0.017$
$f_{\beta 2} = f_{\gamma 2} = 0.097$
$f_{\beta 3} = f_{\gamma 3} - f_{\gamma 1} - f_{\gamma 2} = 0.198 - 0.017 - 0.097 = 0.084$
$f_{\beta 4} = 1 - f_{\gamma 3} = 1 - 0.198 = 0.802$

c a β-particle is always emitted; at 1 kBq, this gives 1000 β-particles per second

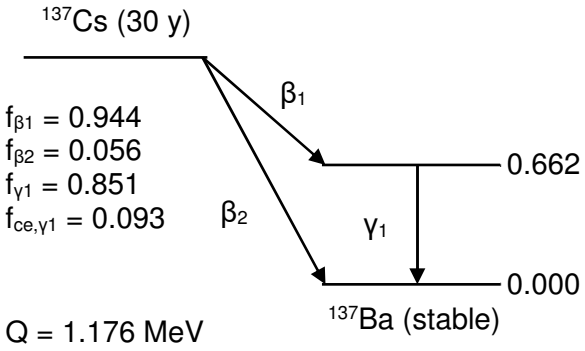
d the number of γ-photons is $1000 \times (f_{\gamma 1} + f_{\gamma 2} + f_{\gamma 3}) = 1000 \times (0.017 + 0.097 + 0.198) =$ 312 per second

8 a $f_\gamma = 100\% - 93.33\% = 6.67\%$
$\alpha = N_{ce} / N_\gamma$
$\alpha_{tot} = N_{ce,tot} / N_\gamma = 93.33 / 6.67 = 13.99$
$\alpha_K = N_{ce,K} / N_\gamma = 80.30 / 6.67 = 12.04$
$\alpha_L = N_{ce,L} / N_\gamma = 10.47 / 6.67 = 1.57$
$\alpha_M = N_{ce,M} / N_\gamma = 2.09 / 6.67 = 0.31$
$\alpha_N = N_{ce,N} / N_\gamma = 0.50 / 6.67 = 0.07$

9 a $E_{\beta 2,max} = 0.514 + 0.662$
$= 1.176$ MeV $= Q$

b $f_{\gamma 1} = f_{\beta 1} \times N_{\gamma 1} / (N_{\gamma 1} + N_{ce,\gamma 1})$
$= f_{\beta 1} / (1 + N_{ce,\gamma 1} / N_{\gamma 1})$
$= f_{\beta 1} / (1 + \alpha)$
$= 0.944 / 1.110 = 0.85$

c $f_{\beta 2} = 1 - f_{\beta 1} = 1 - 0.944 = 0.056$
$f_{ce,\gamma 1} = \alpha \times f_{\gamma 1} = 0.110 \times 0.85 = 0.0935$



10 a see graph

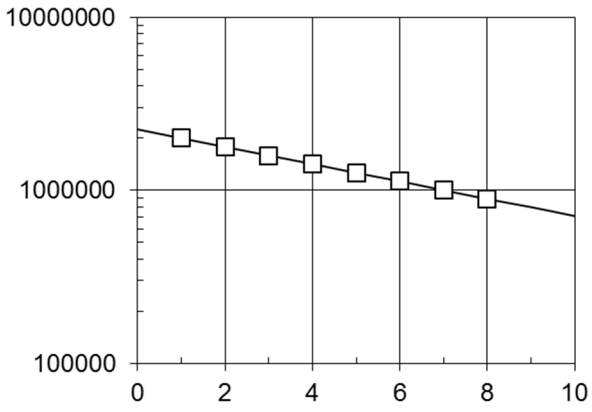
b extrapolate the graph to 9:00 hours and read: 2.25×10^6 disintegrations per second

c from the graph: about 6 hours (for instance, compare the activities at 10:00 hours and at 16:00 hours)

d a function which is linear on single-logarithmic paper can be described by an exponential function:

$$A(t) = A(0)e^{-\lambda t}$$

in which $A(0)$ and λ are constants
for $t = 0$ $A(0) = 2.25 \times 10^6$ s^{-1}
for $t = 6$ $A = 0.5\,A(0)$
entering this data gives that $\lambda = 0.115$ per hour (the time axis is given in hours)



e the total number of decayed nuclei is determined by integrating over the considered time span:

$$N = \int_{t=1}^{t=8} A(t)\,dt = A(0)\int_1^8 e^{-\lambda t}\,dt = \frac{A(0)}{-\lambda} e^{-\lambda t}\Big|_1^8 = \frac{A(0)}{-\lambda}(e^{-8\lambda} - e^{-\lambda})$$

here, the unit of N is equal to (disintegrations / second) × hours, as the unit of A is disintegrations per second and that of λ is per hour
to obtain the total number of disintegrations, it is necessary to multiply by 3600 seconds per hour:

$$N = \frac{3600\,A(0)}{\lambda}(e^{-\lambda} - e^{-8\lambda})$$

entering $A(0)$ and λ $N = 3.47\times10^{10}$ disintegrations

f N as a function of t is obtained by setting the lower integration boundary to 0 and the upper integration boundary to t:

$$N = \int_0^t A(t)\,dt = A(0)\int_0^t e^{-\lambda t}\,dt = \frac{3600\,A(0)}{-\lambda} e^{-\lambda t}\Big|_0^t = \frac{3600\,A(0)}{\lambda}(1 - e^{-\lambda t})$$

g the number of nuclei at time $t = 0$ is equal to the number of disintegrations between times $t = 0$ and $t = \infty$ (see also the solution to question e):

$$N = \int_0^\infty A(t)\,dt = A(0)\int_0^\infty e^{-\lambda t}\,dt = \frac{3600\,A(0)}{-\lambda} e^{-\lambda t}\Big|_0^\infty = \frac{3600\,A(0)}{\lambda}$$

entering $A(0)$ and λ $N = 7.04 \times 10^{10}$ disintegrations
alternatively: $A = \lambda \times N$

$$N = \lambda / A = 2.25\times10^{6}\ s^{-1} \times 3600\ s\ h^{-1} / 0.115\ h^{-1} = 7.04\times10^{10}$$

11 ^{99}Mo decays with $T_{½}$ = 66 h
^{99m}Tc first grows with $T_{½}$ = 6 h and subsequently decays with ^{99}Mo with $T_{½}$ = 66 h
^{99}Tc first grows with $T_{½}$ = 66 h and subsequently decays with $T_{½} = 2\times10^{5}$ y
note that with a mother-daughter relationship, the ingrowth always occurs with the shorter half-life, and the decay always occurs with the longer half-life

a ^{99}Mo has slightly decayed and ^{99m}Tc has grown in by half:
$A(^{99}\text{Mo}, t{=}6\text{ h}) = e^{-0.693\times6/66} \times A(^{99}\text{Mo}, t{=}0) = 0.9 \times 1.0\text{ GBq} = 0.9\text{ GBq}$
$A(^{99m}\text{Tc}, t{=}6\text{ h}) \approx 0.5 \times A(^{99}\text{Mo}, t{=}6\text{ h}) = 0.45\text{ GBq}$

b ^{99}Mo has decayed by half and ^{99m}Tc is in equilibrium with it:
$A(^{99}\text{Mo}, t{=}66\text{ h}) = 0.5 \times A(^{99}\text{Mo}, t{=}0) = 0.5 \times 1.0\text{ GBq} = 0.5\text{ GBq}$
$A(^{99m}\text{Tc}, t{=}66\text{ h}) \approx A(^{99}\text{Mo}, t{=}66\text{ h}) = 0.5\text{ GBq}$

c ^{99}Mo and ^{99m}Tc have mostly decayed and there are as many ^{99}Tc-atoms as there were ^{99}Mo-atoms at time $t = 0$
consider that $A = \lambda N = 0.693 \times N / T_{½}$
$A(^{99}\text{Tc}, t{=}660\text{ h}) / A(^{99}\text{Mo}, t{=}0) = T_{½}(^{99}\text{Mo}) / T_{½}(^{99}\text{Tc}) = 66\text{ h} / 2\times10^{5}\text{ y} = 4\times10^{-8}$
$A(^{99}\text{Tc}, t{=}660\text{ h}) = 4\times10^{-8} \times A(^{99}\text{Mo}, t{=}0) = 4\times10^{-8} \times 1.0\text{ GBq} = 40\text{ Bq}$

d there is no more trace of ^{99}Mo or ^{99m}Tc, and the formed ^{99}Tc has decayed by half:
$A(^{99}\text{Tc}, t{=}2\times10^{5}\text{ y}) = 0.5 \times A(^{99}\text{Tc}, t{=}660\text{ h}) = 0.5 \times 40\text{ Bq} = 20\text{ Bq}$

6 Interactions of radiation with matter

1 A radioactive point source of 1 MBq emits 1 γ-photon per disintegration.
a determine the fluence rate and the flux density at 1 m from the source

2 What is the missing reaction product in the shown nuclear reactions?
a $^{4}_{2}\mathrm{He} + {}^{9}_{4}\mathrm{Be} \rightarrow\ ?\ + \mathrm{n}$
b $^{2}_{1}\mathrm{H} + {}^{12}_{6}\mathrm{C} \rightarrow {}^{13}_{7}\mathrm{N} + \ ?$
c $^{6}_{3}\mathrm{Li} + \mathrm{n} \rightarrow\ ?\ + \alpha$
d $^{9}_{4}\mathrm{Be} + \gamma \rightarrow\ ?\ + 2\alpha$

3 The following formula for the mass range of an α-particle is given:

$$\mathrm{R}_{\alpha}(\mathrm{E})\rho = 3{,}2 \times 10^{-4}\ \sqrt{\mathrm{A}}\mathrm{R}_{\alpha,\mathrm{L}}(\mathrm{E})$$

In this formula, E (in MeV) is the energy of the α-particle, A is the (effective) mass number of the matter, and $R_{\alpha,\mathrm{L}}$ (in cm) is the linear range in air.
a determine the linear range of α-particles with an energy of 5 MeV in water
hint: use the rule of thumb $R_L = 0.3\ E^{3/2}$

4 A spherical, air-filled ionization chamber is to be constructed. In the center, a radioactive source will be placed which emits α-particles with an energy of 8 MeV.
a what should be the minimum radius, such that the α-particles transmit all their energy to the air in the ionization chamber?
hint: use the rule of thumb $R_L = 0.3\ E^{3/2}$

5 An α-detector consists of a ZnS-scintillator with a photomultiplier tube. The scintillator is covered with aluminum foil with a thickness of 1.5 mg cm^{-2}. Between the foil and the source is 0.5 cm of air. The atomic mass of aluminum is A = 27, the density of aluminum is ρ_{Al} = 2.7 g cm^{-3}, and the density of air is ρ_{air} = 1.2 mg cm^{-3}.
a determine the minimum energy of the α-particles, such that they can reach the ZnS-scintillator
hint: use the rule of thumb $R_L = 0.3\ E^{3/2}$

6 A β-source is placed in the center of a spherical ionization chamber with a radius of 5 cm. The inert gas is argon, of which the density is ρ_{Ar} = 1.784 mg cm^{-3} at 0° C and 1 atm. What should the minimum pressure in the chamber be such that all the β-energy is transmitted to the inert gas, in the case that the source is:
a ^{3}H ($E_{\beta,\mathrm{max}}$ = 18 keV)
b ^{63}Ni ($E_{\beta,\mathrm{max}}$ = 67 keV)
c ^{14}C ($E_{\beta,\mathrm{max}}$ = 156 keV)
hint: use the rule of thumb $\rho\ R_{\beta,\mathrm{max}} = 0.5\ E_{\beta,\mathrm{max}}$

7 Determine the conversion factor g for bremsstrahlung in the case that the β-radiation of the radionuclide ^{32}P ($E_{\beta,max}$ = 1.71 MeV) is placed in:
   a aluminum (Z = 13)
   b copper (Z = 29)
   c lead (Z = 82)

8 A naturally occurring radionuclide, ^{208}Tl, emits a γ-photon with an energy of 2.6 MeV.
   a determine the relative contributions of the photoelectric effect, Compton scattering, and pair production to the attenuation of this γ-radiation in lead
   hint: use the data in Appendix A5 of these Exercises

9 A photon with an energy of 10 MeV is scattered over an angle θ.
   a determine the energy of the scattered photon when θ = 10°
   b determine the energy of the scattered photon when θ = 90°
   c determine the energy of the scattered photon when θ = 180°

10 For the production of ^{60}Co, 10 g of cobalt is irradiated with thermal neutrons. The neutron flux density is $\varphi = 2\times10^{14}$ cm^{-2} s^{-1} and the effective cross-section for neutron activation is σ = 38 b. Avogadro's constant is 6.02×10^{23} mol^{-1}. The half-life of ^{60}Co is $T_{½}$ = 5.27 y. Natural cobalt consists for 100% out of the isotope ^{59}Co.
   a determine the formed activity after 1 day
   b determine the formed activity after 1 month
   c determine the formed activity after 1 year

Answers

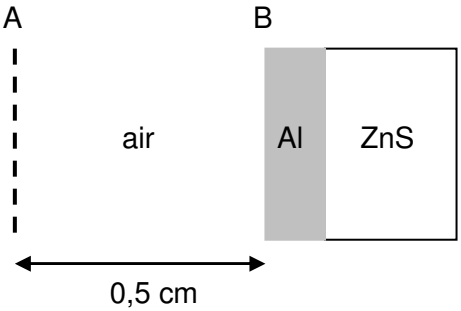
1 a $\varphi = A f_\gamma / (4\pi r^2) = 1\times10^6 \times 1 / (4\pi \times 1^2) = 8.0\times10^4$ m^{-2} s^{-1}

2 a $^{12}_{6}C$
b n
c $^{3}_{1}H$
d n

3 a $1 / \sqrt{A_{eff}} = (2/18) / \sqrt{1} + (16/18)/ \sqrt{16} = 0.11 + 0.22 = 0.33$
$A_{eff} = (1 / 0.33)^2 = 9.2$
$R_{\alpha,L} = 0.3\ E^{3/2} = 0.3 \times 5^{3/2} = 3.35$ cm
$R_\alpha\ \rho = 3.2\times10^{-4} \times \sqrt{9.2} \times 3.35 = 3.3\times10^{-3}$ g cm^{-1}
$R_\alpha = 3.3\times10^{-3}$ g cm^{-1} / 1 g cm^{-3} $= 3.3\times10^{-3}$ cm $= 33$ µm

4 a the radius must be equal to the range of the α-particles in air
$R_L = 0.3\ E^{3/2} = 0.3 \times 8^{3/2} = 6.8$ cm

5 a thickness aluminum
1.5×10^{-3} g cm^{-2} / 2.7 g cm^{-3} $= 0.56\times10^{-3}$ cm
in point B, the range in aluminum must be at least 0.56×10^{-3} cm
$R_{Al} = 3.2\times10^{-4}\ (\sqrt{A} / \rho)\ R_L$ (see Exercise 3)
$= 3.2\times10^{-4} \times (\sqrt{27} / 2.7)\ R_L$
$= 6.16\times10^{-4}\ R_L$
$= 0.56\times10^{-3}$ cm
$R_L = 0.56\times10^{-3} / 6.16\times10^{-4} = 0.9$ cm
in point A, the range in air must be at least 0.5 + 0.9 = 1.4 cm
$E_\alpha = (1.4 / 0.3)^{2/3} = 2.8$ MeV



6 mass radius ionization chamber $R\rho = 5$ cm × 1.784 mg cm^{-3} = 8.9 mg cm^{-2} (0° C, 1 atm)
a $R\rho = 0.5 \times 0.018 = 9\times10^{-3}$ g cm^{-2} = 9 mg cm^{-2}
minimum pressure = 1 atm × (9 mg cm^{-2} / 8.9 mg cm^{-2}) = 1.0 atm at 0° C
b $R\rho = 0.5 \times 0.067 = 34\times10^{-3}$ g cm^{-2} = 34 mg cm^{-2}
minimum pressure = 1 atm × (34 mg cm^{-2} / 8.9 mg cm^{-2}) = 3.8 atm at 0° C
c $R\rho = 0.5 \times 0.156 = 78\times10^{-3}$ g cm^{-2} = 78 mg cm^{-2}
minimum pressure = 1 atm × (78 mg cm^{-2} / 8.9 mg cm^{-2}) = 8.8 atm at 0° C

7 $g = 2\times10^{-4}\ Z E_{max}$
a $2\times10^{-4} \times 13 \times 1.71 = 0.004$
b $2\times10^{-4} \times 29 \times 1.71 = 0.010$
c $2\times10^{-4} \times 82 \times 1.71 = 0.028$

8 a according to equation (6.10) of the syllabus, the attenuation (= the number of interactions) is proportional to µ
from Appendix A5 of these Exercises:

photoelectric effect	$\mu_f/\rho = 0.0035$ cm^2 g^{-1}	$\mu_f / \sum\mu = 0.084 = 8.4\%$
Compton-scattering	$\mu_c/\rho = 0.030$ cm^2 g^{-1}	$\mu_c / \sum\mu = 0.723 = 72.3\%$
pair production	$\mu_p/\rho = 0.008$ cm^2 g^{-1}	$\mu_p / \sum\mu = 0.193 = 19.3\%$
total	$\sum\mu/\rho = 0.0415$ cm^2 g^{-1}	

9 the Compton equation is as follows:

$$E_f' = \frac{E_f}{1 + \frac{E_f}{0.511}[1 - \cos(\theta)]}$$

a $\theta = 10°$ $\cos(10°) = 0.985$
$E' = 10 \text{ MeV} / [1 + (10 / 0.511)(1 - 0.985)] = 7.73 \text{ MeV}$

b $\theta = 90°$ $\cos(90°) = 0$
$E' = 10 \text{ MeV} / [1 + (10 / 0.511)(1 - 0)] = 0.49 \text{ MeV}$

c $\theta = 180°$ $\cos(180°) = -1$
$E' = 10 \text{ MeV} / [1 + (10 / 0.511)(1 + 1)] = 0.25 \text{ MeV}$

10 activity $A = \sigma\, n\, \varphi\, (1 - e^{-\lambda t}) \approx \sigma\, n\, \varphi\, \lambda\, t$
effective cross-section $\sigma = 38 \text{ b} = 38\times10^{-24} \text{ cm}^2$
number of cobalt atoms $n = (10 \text{ g} / 59 \text{ g mol}^{-1}) \times 6.022\times10^{23} \text{ mol}^{-1} = 1.0\times10^{23}$
decay constant $\lambda = 0.693 / 5.272 \text{ y} = 0.13 \text{ y}^{-1} = 0.011 \text{ mnd}^{-1} = 0.000\ 36 \text{ d}^{-1}$

a $\lambda t = 0.000\ 36$
$A \approx 38\times10^{-24} \text{ cm}^2 \times 1.0\times10^{23} \times 2\times10^{14} \text{ cm}^{-2} \text{ s}^{-1} \times 0.000\ 36 = 2.7\times10^{11} \text{ Bq} = 0.3 \text{ TBq}$

b $\lambda t = 0.011$
$A \approx 38\times10^{-24} \text{ cm}^2 \times 1.0\times10^{23} \times 2\times10^{14} \text{ cm}^{-2} \text{ s}^{-1} \times 0.011 = 8.4\times10^{12} \text{ Bq} = 8 \text{ TBq}$

c $\lambda t = 0.13$
$A \approx 38\times10^{-24} \text{ cm}^2 \times 1.0\times10^{23} \times 2\times10^{14} \text{ cm}^{-2} \text{ s}^{-1} \times 0.13 = 1.0\times10^{14} \text{ Bq} = 100 \text{ TBq}$

7 Basic dosimetry

1 To form one ion in air, on average an energy of 33.7 eV is necessary.
   a show, through calculation, that an exposure of 1 R corresponds with and absorbed dose of 8.695 mGy in air

2 In an ionization chamber with a volume of 500 ml, an ionization current of 10 pA is flowing. The density of air at room temperature is 0.0012 g cm^{-3}.
   a determine the exposure rate, using the conversion factor:
      1 R $\rightarrow$ 2.58×10^{-4} C kg^{-1}
   b determine the absorbed dose rate; assume that the entire ionization chamber is evenly irradiated

3 In the following exercises, R stands for röntgen and A stands for ampere. The following conversion factors are given:
   1 R $\rightarrow$ 2.58×10^{-4} C kg^{-1}
   1 R $\rightarrow$ 8.695 mGy
   1 Ci = 3.7×10^{10} Bq.
   a express 1 R m^2 Ci^{-1} h^{-1} in the unit Sv m^2 Bq^{-1} h^{-1}.
   b express 1 Sv m^2 Bq^{-1} h^{-1} in the unit A m^2 Bq^{-1} kg^{-1}

4 In a photon field (E = 0.5 MeV), the kerma in air is 1.0 mGy. Determine:
   a the absorbed dose in air
   b the kerma in muscle tissue
   c the absorbed dose in bone
   hint: use the data in appendix A4 of these Exercises

5 A radioactive source emits a γ-photon with an energy of 2.6 MeV and an emission probability of 100%.
   a make an estimate of the source constant (in μGy h^{-1} MBq^{-1} m^2)
   hint: use the rule of thumb $d_\gamma = E_\gamma / 7$

Answers

1 a 1 R / electron charge = 2.58×10^{-4} C kg^{-1} / 1.6×10^{-19} C = 1.6125×10^{15} ions per kg
energy per mass E / M = 1.6125×10^{15} kg^{-1} × 33.7 eV × 1.6×10^{-19} J eV^{-1}
= 8.695×10^{-3} J kg^{-1} = 8.695 mGy

2 a charge per unit time dQ/dt = 10 pA = 10×10^{-12} C s^{-1}
mass M = 500 ml × 0.0012 g ml^{-1} = 0.6 g = 0.6×10^{-3} kg
exposure rate dX/dt = dQ/dt / M
= 10×10^{-12} C s^{-1} / [0.6×10^{-3} kg × 2.58×10^{-4} C kg^{-1} per R]
= 6.46×10^{-5} R s^{-1} = 0.23 R h^{-1}

b charge per unit time 10 pA = 10×10^{-12} C s^{-1}
ions per unit time 10×10^{-12} C s^{-1} / 1.6×10^{-19} C = 6.25×10^{7} s^{-1}
energy per unit time dE/dt = 6.25×10^{7} s^{-1} × 33.7 eV × 1.6×10^{-19} J eV^{-1}
= 3.37×10^{-10} J s^{-1}
mass M = 500 ml × 0.0012 g ml^{-1} = 0.6 g = 0.6×10^{-3} kg
absorbed dose rate dD/dt = dE/dt / M
= 3.37×10^{-10} J s^{-1} / 0.6×10^{-3} kg
= 5.62×10^{-7} Gy s^{-1} = 2.0 mGy h^{-1}
so, 6.46×10^{-5} R s^{-1} corresponds to 5.62×10^{-7} Gy s^{-1}, or 1 R corresponds to 8.7 mGy

3 a 1 R m^2 Ci^{-1} h^{-1} = 1 R m^2 Ci^{-1} h^{-1} × 0.008 695 Gy R^{-1} × 1 Sv Gy^{-1} / 3.7×10^{10} Bq Ci^{-1}
= 2.35×10^{-13} Sv m^2 Bq^{-1} h^{-1}

b 1 Sv m^2 Bq^{-1} h^{-1} = 1 Sv m^2 Bq^{-1} h^{-1} × 1 Gy Sv^{-1} / [0.008 695 Gy R^{-1} × 3600 (s h^{-1})]
= 0.03195 R s^{-1} m^2 Bq^{-1}
= 0.03195 R s^{-1} m^2 Bq^{-1} × 2.58×10^{-4} C kg^{-1} per R
= 8.24×10^{-6} C kg^{-1} s^{-1} m^2 Bq^{-1}
= 8.24×10^{-6} A m^2 Bq^{-1} kg^{-1}

4 kerma is proportional to μ_{tr}/ρ
absorbed dose is proportional to μ_{en}/ρ
a absorbed dose in air = 1.0 mGy × (0.0296 / 0.0296) = 1.0 mGy
b kerma in muscle tissue = 1.0 mGy × (0.0328 / 0.0296) = 1.11 mGy
c absorbed dose in bone = 1.0 mGy × (0.0317 / 0.0296) = 1.07 mGy

5 a d_γ = 2,6 / 7 = 0.36 µGy h^{-1} MBq^{-1} m^2

9 Operational dosimetry

1 In a mixed radiation field, an employee receives an exposure of 70 mR due to γ-photons and an absorbed dose of 0.5 mGy from neutron radiation. The radiation weighting factor of the neutrons is 8 Sv Gy^{-1}. Assume that the entire body is evenly irradiated. Use the conversion factor:

1 R $\rightarrow$ 0.01 Gy

a determine the effective dose

2 The contribution to the effective dose as a result of irradiation of the lungs by the α-emitter radon is 0.90 mSv per year. The radiation weighting factor for α-radiation is 20 and the tissue weighting factor for the lungs is 0.12.

a determine the equivalent lung dose per year

b determine the absorbed yearly dose of the lungs

3 During an isotropic irradiation with 100 keV photons an effective dose of 10 mSv is received. What would the effective dose be if irradiation occurred from:

a the front

b the rear

c the left

d the right

hint: use the data in Appendix A6 of these Exercises

4 In a field of 20 keV photons, the fluence rate is $\varphi = 1.0 \times 10^9$ cm^{-2} s^{-1}. The photons only approach from the front.

a determine the kerma rate in air

b determine the ambient dose equivalent

c determine the effective dose

hint: use the data in Appendix A7 of these Exercises

5 In a field of thermal neutrons with an energy E_n = 25 meV, the kerma in air is equal to 1 mGy. The neutrons only approach from the front.

a determine the ambient dose equivalent

b determine the effective dose

hint: use the data in Appendix A8 of these Exercises

Answers

1 as the entire body is evenly irradiated, equivalent dose = effective dose

a contribution γ-radiation

radiation weighting factor w_R = 1 Sv Gy^{-1}

effective dose 1 Sv Gy^{-1} × 70 mR × 0.01 Gy R^{-1} = 0.70 mSv

contribution neutron radiation

radiation weighting factor w_R = 8 Sv Gy^{-1}

effective dose 8 Sv Gy^{-1} × 0.5 mGy = 4.0 mSv

total effective dose E = 0.7 mSv + 4.0 mSv = 4.7 mSv

2 a equivalent lung dose $H_{lung} = E / w_{lung}$
= 0.90 mSv y^{-1} / 0.12 = 7.5 mSv y^{-1}

b radiation weighting factor α-radiation w_R = 20 Sv Gy^{-1}

absorbed yearly dose $D_{lung} = H_{lung} / w_R$
= 7.5 mSv j^{-1} / 20 Sv Gy^{-1} = 0.38 mGy

3 from Appendix A6 of these Exercises, at 0.1 MeV, E(ISO) / H^*(10) = 0.46

a E(AP) / H^*(10) = 0.85 → E(AP) = (0.85 / 0.46) × 10 mSv = 18.5 mSv

b E(PA) / H^*(10) = 0.63 → E(AP) = (0.63 / 0.46) × 10 mSv = 13.7 mSv

c E(LLA) / H^*(10) = 0.40 → E(AP) = (0.40 / 0.46) × 10 mSv = 8.7 mSv

d E(RLA) / H^*(10) = 0.35 → E(AP) = (0.35 / 0.46) × 10 mSv = 7.6 mSv

4 from Appendix A7 of these Exercises, at 0.02 MeV:

a K_a = 1.3 pGy cm² × φ
= 1.3×10^{-12} Gy cm² × 1.0×10^9 cm^{-2} s^{-1} = 1.3×10^{-3} Gy s^{-1} = 1.3 mGy s^{-1}

b H^*(10) = 1.0 pSv cm² × φ
= 1.0×10^{-12} Sv cm² × 1.0×10^9 cm^{-2} s^{-1} = 1.0×10^{-3} Sv s^{-1} = 1.0 mSv s^{-1}

c E(AP) = 0.2 pSv cm² × φ
= 0.2×10^{-12} Sv cm² × 1.0×10^9 cm^{-2} s^{-1} = 0.2×10^{-3} Sv s^{-1} = 0.2 mSv s^{-1}

5 from Appendix A8 of these Exercises, at 0,025 eV, K_a = 0,2 pGy cm²

a H^*(10) = 10 pSv cm² → H^* = (10 pSv cm² / 0.2 pGy cm²) × 1 mGy = 50 mSv

b E(AP) = 7 pSv cm² → H^* = (7 pSv cm² / 0.2 pGy cm²) × 1 mGy = 35 mSv

10 Dosimetry of internal exposure

1 A laboratory technician is contaminated with ^{111}In ($T_{½}$ = 2,8 d) through ingestion. The next day, the stool turn out to have an activity of 80 kBq. During the next days, no measurable amount of activity is observed in the stool. According to data from the ICRP, f_1 = 0.02 for all indium compounds, and all activity is transferred from the blood to the organs, where it decays completely. The dose conversion coefficient of ^{111}In for ingestion is $e(50)_{ing} = 2.9\times10^{-10}$ Sv Bq^{-1}.

a determine the ingested activity
b determine the effective committed dose
c how much activity would be found in the urine which is collected during the first 24 hours after ingestion?

2 During an incident in the hall of a nuclear power plant, ^{38}Cl ($T_{½}$ = 37.2 min) is released. All employees who are present in the hall at that moment are asked to forcefully blow their nose for further investigation. For one of the employees, the activity in the mucus turns out to be 40 kBq ^{38}Cl. The measurement was performed 60 minutes after the incident. The dose conversion coefficient for inhalation of ^{38}Cl is $e(50)_{inh} = 4.6\times10^{-11}$ Sv Bq^{-1}.

a determine the effective committed dose in the case that AMAD = 0.1 µm
b determine the effective committed dose in the case that AMAD = 1 µm
c determine the effective committed dose in the case that AMAD = 10 µm
hint: use the data in Appendix A9 of these Exercises

3 During maintenance in the active area of a nuclear power plant, the employees are checked daily after work for internal contamination using a total body counter. One day, an activity of 1.0 kBq ^{60}Co is measured in an employee. The dose conversion coefficient for inhalation is $e(50)_{inh} = 1.7\times10^{-8}$ Sv Bq^{-1}. According to data from the ICRP, 74% of the inhaled activity is still present in the body after 6 hours.

a determine the inhaled activity
b determine the effective committed dose as a result of this incident

4 The urine of the employees of a plutonium factory is regularly checked for radioactive contamination. On a bad day, 10 Bq of ^{239}Pu is found in the urine from the previous day of one of the employees. The dose conversion coefficient for inhalation is $e(50)_{inh} = 8.3\times10^{-6}$ Sv Bq^{-1}. According to data from the ICRP, 1.7×10^{-5} Bq per becquerel of inhaled activity ends up in urinary excretion during the first day after contamination.

a determine the activity inhaled by the employee
b determine the effective committed dose
c what is the probability that this employee will not survive due to bone cancer?

5 The radionuclide ^{85}Kr is a fission product which occurs in the atmosphere with a concentration of 1 Bq m^{-3}. The dose conversion coefficient of ^{85}Kr for submersion is $e = 2.2 \times 10^{-11}$ Sv d^{-1} per Bq m^{-3}.

a determine the effective dose per hour as a result of submersion

b determine the effective yearly dose as a result of submersion

Answers

1 a a fraction $1 - f_1 = 1 - 0.02 = 0.98$ of the activity is excreted through stool
after decay a fraction $e^{-0.693t/T½} = e^{-0.693\times1.0/2.8} = 0.78$ of the activity remains
ingestion $A_{ing} = 80$ kBq / (0.98 × 0.78) = 105 kBq = 105×10^3 Bq

b effective committed dose $E(50) = e(50)_{ing} \times A_{ing}$
$= 2.9\times10^{-10}$ Sv Bq^{-1} × 105×10^3 Bq
$= 3.0\times10^{-5}$ Sv = 30 µSv

c all activity is passed to the organs and body tissue, where it completely decays
thus, no activity is excreted through urine on the first day

2 a AMAD = 0.1 µm
deposited fraction $ET_1 = 0.03$
decay correction $e^{-0.693t/T½} = e^{-0.693\times60/37.2} = 0.33$
inhalation $A_{inh} = 40$ kBq / (0.03 × 0.33)
$= 4.0\times10^3$ kB = 4.0×10^6 Bq
effective committed dose $E(50) = e(50)_{inh} \times A_{inh}$
$= 4.6\times10^{-11}$ Sv Bq^{-1} × 4.0×10^6 Bq
$= 0.18\times10^{-3}$ Sv = 180 µSv

b AMAD = 1 µm
deposited fraction $ET_1 = 0.17$
inhalation $A_{inh} = 40$ kBq / (0.17 × 0.33)
$= 0.71\times10^3$ kB = 0.71×10^6 Bq
effective committed dose $E(50) = e(50)_{inh} \times A_{inh}$
$= 4.6\times10^{-11}$ Sv Bq^{-1} × 0.71×10^6 Bq
$= 3.3\times10^{-5}$ Sv = 33 µSv

c AMAD = 10 µm
deposited fraction $ET_1 = 0{,}35$
inhalation $A_{inh} = 40$ kBq / (0.35 × 0.33)
$= 0.35\times10^3$ kB = 0.35×10^6 Bq
effective committed dose $E(50) = e(50)_{inh} \times A_{inh}$
$= 4.6\times10^{-11}$ Sv Bq^{-1} × 0.35×10^6 Bq
$= 1.6\times10^{-5}$ Sv = 16 µSv

3 a after 6 hours, 74% of the inhaled activity remains.
inhalation $A_{inh} = 1.0$ kBq / 0.74 = 1.4 kBq = 1.4×10^3 Bq

b effective committed dose $E(50) = e(50)_{inh} \times A_{inh}$
$= 1.7\times10^{-8}$ Sv Bq^{-1} × 1.4×10^3 Bq
$= 2.4\times10^{-5}$ Sv = 24 µSv

4 a inhaled activity $A_{inh} = 10$ Bq d^{-1} / 1.7×10^{-5} Bq d^{-1} per Bq = 6×10^5 Bq

b effective committed dose $E(50) = e(50)_{inh} \times A_{inh}$
$= 8.3\times10^{-6}$ Sv Bq^{-1} × 6×10^5 Bq = 5 Sv

c according to the ICRP, the risk factor is 5% per sievert
for plutonium, this risk predominantly manifests itself in the form of bone cancer
probability of bone cancer 5 Sv × 5% per Sv = 25%

5 a $dE/dt = 2.2\times10^{-11}$ Sv d^{-1} per Bq m^{13} × 1 Bq m^{-3} = 2.2×10^{-11} Sv d^{-1}
$= 2.2\times10^{-11}$ Sv d^{-1} / 24 h d^{-1} = 9.2×10^{-13} Sv h^{-1}

b $E = 2.2\times10^{-11}$ Sv d^{-1} × 365 d y^{-1} = 8.0×10^{-9} Sv y^{-1} = 8.0 nSv y^{-1}

11 Detection of radiation

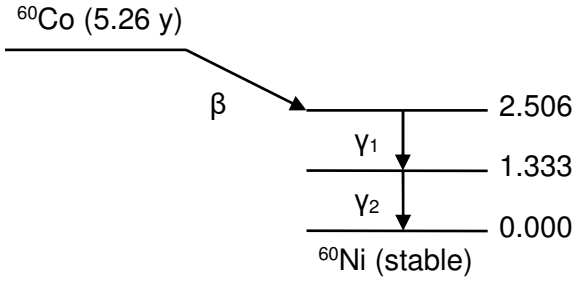
1 Through homogenous irradiation of the inert gas in an ionization chamber by γ-radiation, 3.6×10^4 ions are formed per minute. Per ionization, 33.7 eV of energy is released. The mass of the inert gas is 120 mg.
- a what is the formed negative charge in coulombs per minute?
- b what is the formed positive charge in coulombs per minute?
- c what is the resulting current (in ampere) through the ionization chamber?

2 A sample of the α-emitter ^{210}Po with an activity of 10 kBq is mounted in an ionization chamber. The α-particles have an energy of 5.5 MeV and are completely stopped by the inert gas. Per ionization, 33.7 eV is dissipated in the gas.
- a determine the number of ions which are being formed per second
- b determine the current through the chamber when this acts in the ionization-chamber region
- c determine the current through the chamber if this acts in the proportional region and the gas amplification is 16

3 For a measurement on a β-sample, a Geiger counter is used. The counter gives a counting rate of 6.0×10^4 counts per minute.
- a determine the true counting rate if the dead time of the counter is 180 μs
- b what would the true counting rate have been if the measurement was done with a proportional counter with a dead time of 15 μs ?

4 The effective thickness of the gas layer in an argon-filled proportional counter is 35 mm. The density of argon is 1.66 mg cm^{-3}. The mass attenuation coefficients of argon to the K_α-line of copper (8 keV) and the K_α-line of molybdenum (13 keV) are 112 cm^2 g^{-1} and 27.5 cm^2 g^{-1} respectively.
- a determine the detector efficiency at 8 keV
- b determine the detector efficiency at 13 keV

5 The decay scheme of the nuclide ^{60}Co is given. At 65 cm from a point ^{60}Co source, a photon flux density of 1400 cm^{-2} s^{-1} is measured.
- a determine the source activity



6 The radionuclide ^{32}P emits one high-energy β-particle per disintegration. Self-absorption within the source and absorption in air may be neglected.
- a determine the flux density at a distance of 50 cm from a 37 MBq ^{32}P source
- b determine the counting rate (in counts per second) if a detector with a 1 cm^2 window is placed perpendicular to the incoming radiation at 50 cm from the source

  hint: assume the counting efficiency of the detector is 100%

7 A cylindrical detector has a diameter of r = 40 mm. The distance between the source and the front of the detector is h = 6 cm. Also, $R^2 = r^2 + h^2$.

a determine the geometry factor using the formula:

$$f_{geometry} = \frac{1}{2}(1 - \cos\alpha) = \frac{1}{2}\left(1 - \frac{h}{\sqrt{h^2 + r^2}}\right)$$

b determine the geometry factor using the formula:

$$f_{geometry} = \frac{\pi r^2}{4\pi R^2}$$

8 Using a Geiger counter with a 3 cm² window placed perpendicular to the incoming radiation at 100 cm from a ^{42}K source, a net counting rate of 175 counts per minute is measured. The radionuclide ^{42}K emits a β-particle with $E_{\beta 1,max}$ = 3.5 MeV in 82% of the cases, and a β-particle with $E_{\beta 2,max}$ = 2.0 MeV in 18% of the cases. There is no absorption.

a determine the geometric efficiency $f_{geometry}$

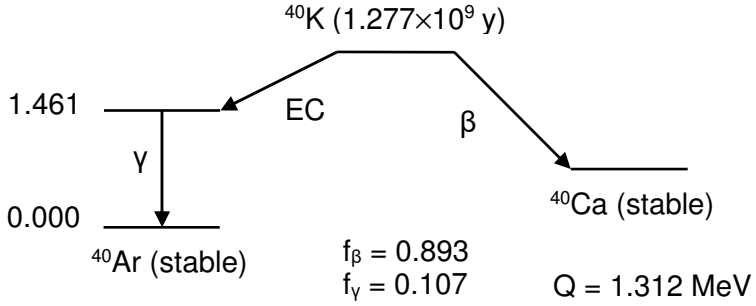
b determine the activity of the source

9 A large uniform surface contamination of 5 Bq cm^{-2} of ^{14}C is measured with a Geiger-Müller counter with a window of 7 cm² and a zero effect of 20 counts per minute. At the same time, a proportional counter is also used, with a sensitive area of 10 cm × 10 cm and a zero effect of 4 counts per second. Suppose the intrinsic detector efficiency is 100% in both cases.

a determine the net counting rate for both instruments used

b determine the minimum detectible surface contamination for each instrument; assume that the measured surface contamination is significant if the gross counting rate is at least three times larger than the background

10 A contamination survey is conducted with a detector with a low background. The background, measured in 65 hours, is 2.30×10^{-2} counts per second. The efficiency for a β-emitter with an end point energy $E_{\beta,max}$ = 1.35 MeV and an emission efficiency of f_β =1 is $f_{geo} \times f_{det}$ = 0.28. The detector is insensitive to γ-radiation.



a determine the number of counts and the standard deviation thereof if only background radiation is detected for 500 seconds

b determine the interval within which the actual zero effect should be, with a reliability of 95%, using the answer obtained in question a

c determine ^{40}K-activity which corresponds to the upper boundary of the interval obtained in question b

Answers

1 a negative charge $3.6\times10^{4}\ \text{min}^{-1} \times 1.6022\times10^{-19}\ \text{C} = 5.76\times10^{-15}\ \text{C min}^{-1}$
b positive charge also $5.76\times10^{-15}\ \text{C min}^{-1}$
c current $5.76\times10^{-15}\ \text{C min}^{-1} = 0.96\times10^{-16}\ \text{C s}^{-1} = 0.96\times10^{-16}\ \text{A}$

2 a energy released $10^{4}\ \text{Bq} \times 5.5\times10^{6}\ \text{eV per Bq s} = 5.5\times10^{10}\ \text{eV s}^{-1}$
number of ions $5.5\times10^{10}\ \text{eV s}^{-1} / 33.7\ \text{eV} = 1.63\times10^{9}\ \text{s}^{-1}$
b no gas amplification $I = 1.63\times10^{9}\ \text{s}^{-1} \times 1.6022\times10^{-19}\ \text{C}$
$= 2.6\times10^{-10}\ \text{C s}^{-1} = 0.26\ \text{nA}$
c 16 times the answer of question b, so $16 \times 0.26\ \text{nA} = 4.2\ \text{nA}$

3 a measured counting rate = $6\times10^{4}\ \text{cpm} / 60\ \text{s min}^{-1} = 1\times10^{3}\ \text{cps}$
$T_W = 1\times10^{3} / (1 - 180\times10^{-6}\ \text{s} \times 1.0\times10^{3}\ \text{s}^{-1})$
$= 1\times10^{3} / (1 - 0.18) = 1\times10^{3} / 0.82 = 1.22\times10^{3}\ \text{cps}$
b $T_W = 1\times10^{3} / (1 - 15\times10^{-6}\ \text{s} \times 1.0\times10^{3}\ \text{s}^{-1})$
$= 1\times10^{3} / (1 - 0.015) = 1\times10^{3} / 0.985 = 1.02\times10^{3}\ \text{cps}$

4 the mass layer thickness is $d\rho = 3.5\ \text{cm} \times 1.66\times10^{-3}\ \text{g cm}^{-3} = 0.0058\ \text{g cm}^{-2}$
a transmission at 8 keV $T = e^{-(\mu/\rho)(d\rho)} = e^{-112\times0.0058} = 0.52$
detector efficiency $f_{det} = 1 - T = 1 - 0.52 = 0.48$
b transmission at 13 keV $T = e^{-(\mu/\rho)(d\rho)} = e^{-27.5\times0.0058} = 0.85$
detector efficiency $f_{det} = 1 - T = 1 - 0.85 = 0.15$

5 a $\Phi(R)$ = (number of photons) / (surface of sphere with radius R)
photons per disintegration 2
flux density $\Phi = 2 \times A$ / (surface of sphere with radius 65 cm)
$= 2 \times A / (4\pi \times 65^2) = 3.77\times10^{-5}\ A$
$= 1400\ \text{cm}^{-2}\ \text{s}^{-1}$
activity $A = 1400 / 3.77\times10^{-5} = 3.7\times10^{7}\ \text{Bq} = 37\ \text{MBq}$

6 a $\Phi(R)$ = (number of photons) / (surface of sphere with radius R)
particles per disintegration 1
flux density $\Phi = 1 \times 37\times10^{6} / (4\pi \times 50^2) = 1.18\times10^{3}\ \text{cm}^{-2}\ \text{s}^{-1}$
b detector window area $1\ \text{cm}^2$
pulse rate $1\ \text{cm}^2 \times 1.18\times10^{3}\ \text{cm}^{-2}\ \text{s}^{-1} = 1.18\times10^{3}$ counts per second

7 a radius of window $r = 40\ \text{mm} / 2 = 20\ \text{mm} = 2\ \text{cm}$
distance source-window $h = 6\ \text{cm}$
opening angle $\tan(\alpha) = 2 / 6 = 0.33 \quad \rightarrow \alpha = 18.43°$
$f_{geo} = 0.5 \times [1 - \cos(18.43°)] = 0.5 \times (1 - 0.949) = 0.0255$
b radius sphere $R^2 = h^2 + r^2 = 6^2 + 2^2 = 40\ \text{cm}^2$
$f_{geo} = (\pi r^2) / (4\pi R^2) = 2^2 / [4 \times 40] = 1 / 40 = 0.0250$

8 a $N = A \times f_{em} \times f_{geo} \times t$
emission efficiency $f_{em} = 82\% + 18\% = 1$
geometry factor f_{geo} = (area of window) / (area of sphere with r = 100 cm)
$= 3\ \text{cm}^2 / [4\pi \times (100\ \text{cm})^2] = 2.39\times10^{-5}$
b number of counts $N = A \times 1 \times 2.39\times10^{-5} \times 60\ \text{s} = 1.43\times10^{-3}\ A = 175$
activity $A = 175 / 1.43\times10^{-3} = 1.22\times10^{5}\ \text{Bq} = 122\ \text{kBq}$

9 $N = A \times f_{em} \times f_{geo} \times t$
emission efficiency $f_{em} = 1$
geometry factor $f_{geo} = 0.5$ (2π-geometry)
a Geiger-Müller counter
activity under detector A = surface contamination × (detector window area)
= 5 Bq cm^{-2} × 7 cm^2 = 35 Bq
time t = 1 min = 60 s
counting rate N = 35 Bq × 1 × 0.5 × 1 min × 60 s min^{-1} = 1050 cpm
proportional counter
activity under detector A = surface contamination × (detector window area)
= 5 Bq cm^{-2} × 100 cm^2 = 500 Bq
time t = 1 s
counting rate N = 500 Bq × 1 × 0.5 = 250 cps
b gross counting rate = 3 × zero effect
so, net counting rate = 2 × zero effect
Geiger-Müller counter
net counting rate $2 \times N_{zero} = 2 \times 20 = 40$ cpm
A_{min} = 5 Bq cm^{-2} × (40 cpm / 1050 cpm) =0.19 Bq cm^{-2}
proportional counter
net counting rate $2 \times N_{zero} = 2 \times 4 = 8$ cps
A_{min} = 5 Bq cm^{-2} × (8 cps / 250 cps) = 0.16 Bq cm^{-2}

10 a zero effect $N_{zero} = 2.30 \times 10^{-2}$ cps × 500 s = 11.5
standard deviation $\sigma_{zero} = \sqrt{11.5} = 3.4$
b confidence interval of 95% corresponds to $2\sigma_{zero} = 2 \times 3.4 = 6.8$
interval $N_{zero} \pm 2\sigma_{zero}$ = [11.5-6.8; 11.5+6.8] = [4.7; 18.3]
c $N = A \times f_{em} \times f_{geo} \times f_{det} \times t$
emission efficiency $f_{em} = 0.893$
detection efficiency $f_{geo} \times f_{det} = 0.28$
time 500 s
number of counts $N = A \times 0.893 \times 0.28 \times 500$ s = 125 A
= 18.3 (upper limit)
maximum activity A_{max} = 18.3 / 125 = 0.15 Bq

12 Shielding of external radiation

1 A pair of safety glasses is made of plexiglass, also called perspex. This material has an average atomic mass of A = 12.4 and density ρ = 1.19 g cm^{-3}. The glasses are 2 mm thick and are used to protect the eye against β-radiation. Determine the transmission of the glasses for β-particles with the following maximum energies:
a 0.5 MeV
b 1.0 MeV
c 2.0 MeV
hint: use the rules of thumb $\rho R_{\beta,max} = 0{,}5\, E_{\beta,max}$ *and* $d_{½} = 0.1\, R_{\beta,max}$

2 A radioactive source contains a nuclide which has only a single γ-transition. With a γ-detector, a net counting rate of 4500 counts per minute (cpm) is measured in a narrow beam of this γ-radiation. If a lead plate with a thickness of 3.0 mm is placed in the beam, the net pulse rate drops to 1200 cpm.
a determine the half-value thickness of lead for the considered γ-radiation

3 A narrow beam of mono-energetic γ-radiation is aimed at an absorber consisting of water, lead, or a combination of both materials. The half-value thickness of water is $d_{½,\text{water}}$ = 5.5 cm; that of lead is $d_{½,\text{lood}}$ = 0.08 cm. Determine the transmission if the absorber consists of:
a 1.0 cm water
b 0.2 cm lead
c two 0.1 cm layers of lead with 1 cm water between them

4 To determine the mass attenuation coefficient μ/ρ of aluminum for γ-radiation, a series of measurements is performed with a source which emits γ-radiation with an energy of 800 keV. The measurements are taken on a narrow beam, using a thick lead collimator and a series of flat aluminum absorbers with thicknesses varying between 1 and 128 mm. A Geiger-Müller counter is used as detector. The number of counts per minute (cpm) as a function of the absorber thickness (in mm) is given below:

absorber thickness	0	1	2	4	8	16	32	64	128
counting rate	1805	1720	1725	1680	1530	1404	1020	620	198

The background, measured with a thick lead block as absorber, is 20 counts per minute. The density of aluminum is ρ_{Al} = 2.7 g cm^{-3}.
a plot the transmission against the thickness on single-logarithmic paper
b determine the half-value thickness $d_{½}$ of aluminum for this γ-energy
c determine the mass attenuation coefficient μ/ρ of aluminum for this γ-energy

5 The intensity of the γ-radiation of ^{137}Cs is to be reduced with concrete and lead, respectively, by a factor of 1000. The γ-energy is E_γ = 0.66 MeV. The mass attenuation coefficient of concrete and lead for this γ-energy are $(\mu/\rho)_{concrete}$ = 0.0772 $cm^2\ g^{-1}$ and $(\mu/\rho)_{lead}$ = 0.100 $cm^2\ g^{-1}$, respectively. Furthermore, $\rho_{concrete}$ = 2.35 g cm^{-3} and ρ_{lead} = 11.35 g cm^{-3}.

a determine the required thicknesses using transmission figures
hint: use the transmissions shown in Appendix A10 and A11 of these Exercises

b determine the required thicknesses using the mass attenuation coefficients and the build-up factors
hint: first, determine the necessary value of μd, and then find the corresponding build-up factor B in Appendix A12 of these Exercises; repeat if necessary until the value of B doesn't change anymore

6 An encapsulated ^{252}Cf source is used for a neutron experiment. A proper shielding must be designed for the location where this source is stored. In the decay of ^{252}Cf, α-, β-, γ- and neutron radiation is emitted.

- *the attenuation of γ- and neutron radiation by thesource holder may be neglected*
- *the source may be treated as a point source*
- *contributions from the daughter nuclide may be neglected*
- *^{252}Cf decays for 96,9% by α-emission and for 3,1% by spontaneous fission*
- *the half-life of ^{252}Cf is $T_{½}$ = 2,646 year*
- *the dose conversion factor for the neutrons emitted by ^{252}Cf is $h = 5{,}3\times10^{-10}$ Sv cm^2*
- *the transmission of γ-radiation and neutrons by ^{252}Cf (see Appendix A13 and Appendix A14 of these Exercises); it may be assumed that the graphs can be extrapolated as straight lines*
- *the activity of the ^{252}Cf source is $A_n = 2{,}36\times10^8$ neutrons per second*

a calculate the equivalent dose rate at r = 1 m from the source due to neutrons, if the ^{252}Cf source is shielded with 45 cm polythene

In order to stop the γ-radiation, also a lead shield is applieded. A conservative approach to the shielding effect of polythene on a broad beam of γ-radiation from ^{252}Cf is to assume that the half-width thickness is $d_{½}$ = 17 cm and the build-up factor is B = 2.

b calculate the required thickness of additional lead behind the polythene plate, that is required to reduce the equivalent dose rate due to γ-radiation from ^{252}Cf by a factor of 100 with respect to the unshielded source

The absorbed dose rate at r = 1 m from the source due to γ-radiation, behind 45 cm of polythene is D_γ(0 cm lead) = 10 μGy h^{-1}.

c calculate the equivalent dose rate at r = 1 m from the source due to γ-radiation, behind a shield consisting of 45 cm of polythene plus the lead layer that was calculated in Question b

d calculate the equivalent dose rate at r = 1 m from the source due to both γ-radiation and neutrons, behind a shield consisting of 45 cm of polythene plus the lead layer that was calculated in Question b

Answers

1 thickness glasses d = 2 mm = 0.2 cm

a $R_{\beta,max}$ = 0.5 × 0.5 / 1.19 g cm^{-3} = 0.21 cm
d / $R_{\beta,max}$ = 0.2 cm / 0.21 cm = 1
T = 0, because $d \approx R_{\beta,max}$

b $R_{\beta,max}$ = 0.5 × 1.0 / 1.19 g cm^{-3} = 0.42 cm
$d_{½}$ = 0.1 × 0.42 cm = 0.04 cm
$T = e^{-0.693 \times 0.2/0.04} = e^{-3.5}$ = 0.03

c $R_{\beta,max}$ = 0.5 × 2.0 / 1.19 g cm^{-3} = 0.84 cm
$d_{½}$ = 0.1 × 0.84 cm = 0.08 cm
$T = e^{-0.693 \times 0.2/0.08} = e^{-1.7}$ = 0.2

2 a $T = e^{-\mu d} = e^{-\mu \times 3}$
= 1200 cpm / 4500 cpm = 0.27
μ = -ln(0.27) / 3 mm = 0.44 mm^{-1}
$d_{½}$ = 0.693 / μ = 0.693 / 0.44 mm^{-1} = 1.6 mm lead

3 a T(1.0 cm water) = $2^{-1.0/5.5}$ = 0.88

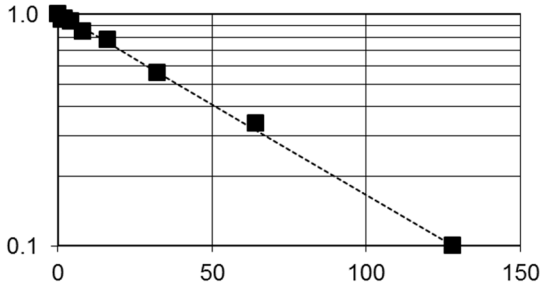
b T(0.2 cm lead) = $2^{-0.2/0.08}$ = 0.18

c T = 0.88 × 0.18 = 0.16

4 a plot transmission $T = N(d) / N(0)$ on single-logarithmic paper

b from graph at d = 50 mm = 5 cm:
T = 0.40
$= e^{-\mu d} = e^{-\mu \times 5}$
μ = -ln(0.40) / 5 cm
= 0.916 / 5 cm = 0.183 cm^{-1}
$d_{½}$ = 0.693 / 0.183 cm^{-1}
= 3.8 cm aluminum

c μ/ρ = 0.183 cm^{-1} / 2.7 g cm^{-3}
= 0.068 cm^2 g^{-1}



5 a from Appendix A10 and A11 of these Exercises, at T = 0.001:

concrete	53 cm
lead	6.5 cm

b $T = B\, e^{-\mu d}$ = 0.001
$\mu_{concrete}$ = 0.0772 cm^2 g^{-1} × 2.35 g cm^{-3} = 0.181 cm^{-1}
μ_{lead} = 0.100 cm^{2}g^{-1} × 11.35 g cm^{-3} = 1.135 cm^{-1}
determine B in each step through linear interpolation to the variables E_γ and μd

concrete	take first B = 1	μd = -ln(0.001 / 1) = 6.91	→ $B \approx$ 13.5
	now take B = 13.5	μd = -ln(0.001 / 13,5) = 9.51	→ $B \approx$ 21.8
	now take B = 21.8	μd = -ln(0.001 / 21,8) = 10.0	→ $B \approx$ 23.4
	now take B = 23.4	μd = -ln(0.001 / 23,4) = 10.1	→ $B \approx$ 23.8
	d = 10.1 / 0.181 cm^{-1} = 56 cm		
lead	take first B = 1	μd = -ln(0,001 / 1) = 6.91	→ $B \approx$ 2.51
	now take B = 2.3	μd = -ln(0,001 / 2.51) = 7.83	→ $B \approx$ 2.68
	now take B = 2.5	μd = -ln(0,001 / 2.68) = 7.89	→ $B \approx$ 2.70
	now take B = 2.5	μd = -ln(0,001 / 2.70) = 7.90	→ $B \approx$ 2.70
	d = 7.90 / 1.135 cm^{-1} = 7.0 cm		

6 a from Appendix A14 of these Exercises, at $d_{polythene}$ = 30 cm

$T = e^{-\mu \times 30} = 0.01$

extrapolating to d = 45 cm gives transmission

$T = e^{-\mu \times 45} = (e^{-\mu \times 30})^{45/30} = 0.01^{1.5} = 0.001$

$H^*_{neutrons} = h_n \times (A_n / 4\pi r^2) \times T$

$= 5.3 \times 10^{-10}$ Sv cm^2 $\times$ [2.36×10^8 s^{-1} / ($4\pi \times 100^2$ cm^2)] $\times$ 0.001

$= 1.0 \times 10^{-9}$ Sv s^{-1} = 3.6×10^{-6} Sv h^{-1} = 3.6 μSv h^{-1}

b $T = T_{polythene} \times T_{lead} = B \times 2^{-45/d1/2} \times T_{lood} = 2 \times 2^{-45/17} \times T_{lead}$ =0.32 T_{lead}

= 0.01

T_{lead} = 0.01 / 0.32 = 0.031

from Appendix A13 of these Exercises, at T_{lead} = 0.031

d_{lead} = 5.5 cm

c H^*_γ(5.5 cm lead) = D_γ(0 cm lead) $\times$ w_R $\times$ T_{lead}

= 10 μGy h^{-1} $\times$ 1 Sv Gy^{-1} $\times$ 0.031 = 0.31 μSv h^{-1}

d from Appendix A14 of these Exercises, at 5.5 cm lead

T_{lead}(for neutrons) = 0.8

$H^*_{neutrons}$(0 cm lead) = 3.6 μSv h^{-1} (see Question a)

$H^*_{neutrons}$(5.5 cm lead) = $H^*_{neutrons}$(0 cm lead) $\times$ T_{lead}(for neutrons)

= 3.6 μSv h^{-1} $\times$ 0.8 = 2.9 μSv h^{-1}

$H^*_{total} = H^*_\gamma$(5.5 cm lead) + $H^*_{neutrons}$(5.5 cm lead)

= 0.31 + 2.9 = 3.2 μSv h^{-1}

14 Laws and regulations

1 The government has set dose limits to prevent stochastic effects. What are the limits that the licensee must comply with:
   a for a non-exposed employee?
   b for an exposed employee?
   c for a member of the public within the location?
   d for a member of the public outside the location?
   e for an unborn child?

2 The government has set dose limits to prevent tissue reactions. What are the limits for:
   a the eye lens of a non-exposed employee?
   b the eye lens of an exposed employee?
   c the skin and extremities of a non-exposed employee?
   d the skin and extremities of an exposed employee?

3 In a certain area two companies are adjacent to one another. What is the maximum allowable dose on the boundary between the two, if
   a one of the companies has a nuclear energy act license?
   b both companies have a nuclear energy act license?
   c give an argument as to why the actual dose is probably lower
   d give an argument as to why the actual dose may be higher

4 A company can show that the yearly dose caused by external radiation at the boundary remains under the so-called secondary level.
   a how high is the secondary level?
   b is this company therefore exempt from requiring a nuclear energy act license?

5 The value of $e(50)$ is a measure of the radiotoxicity of the radionuclide.
   a is the radiotoxicity of ^{60}Co larger or smaller than that of ^{90}Sr/^{90}Y ?
   b is the radiotoxicity of ^{60}Co larger or smaller than that of ^{125}I ?
   hint: use the following dose conversion coefficients.

^{60}Co	$e(50)_{inh} = 2.9\times10^{-8}$ Sv Bq^{-1}	$e(50)_{ing} = 3.4\times10^{-9}$ Sv Bq^{-1}
$^{90}Sr/^{90}Y$	$e(50)_{inh} = 1.5\times10^{-7}$ Sv Bq^{-1}	$e(50)_{ing} = 2.8\times10^{-8}$ Sv Bq^{-1}
^{125}I	$e(50)_{inh} = 5.3\times10^{-9}$ Sv Bq^{-1}	$e(50)_{ing} = 1.5\times10^{-8}$ Sv Bq^{-1}

6 The decree on basic safety standards radiation protection defines, among others, the concepts "supervised area" and "controlled area".
   a may an exposed employee in category B work in a controlled area?
   b may non-exposed employees work in supervised areas?

7 Certain types of emergency exit lights exist, called beta-lights, which light up due to the fact they contain up to 800 GBq tritium gas. The mass activity of pure tritium is 357 TBq g^{-1}.
a does a nuclear energy act license have to be requested in order to use such lights, when considering the exemption levels for activity and activity concentration in moderate amounts in the decree on basic safety standards radiation protection?
hint: the exemption limits are $A_v = 1{\times}10^9$ Bq and $C_v = 1{\times}10^6$ Bq g^{-1}

8 A certain type of smoke detector contains 36 kBq ^{241}Am. The mass activity of pure ^{241}Am is 127 GBq g^{-1}.
a does such a smoke detector require a license, a registration, or neither, when considering the exemption levels in the decree on basic safety standards radiation protection?
hint: the exemption limits are $A_v = 1{\times}10^4$ Bq and $C_v = 1{\times}10^0$ Bq g^{-1}

9 Gas mantles in old-fashioned gas lights are made of cotton which is impregnated with radioactive thorium nitrate.
a is this application on the list of justified practices in the regulation on basic safety standards radiation protection?
see: https://wetten.overheid.nl/BWBR0040509

10 The Dentistry Education Institute has a number of non-mobile X-ray devices for diagnostic use.
a do such machines require a license, a registration, or a notification?

11 A plastic container is filled with sand contaminated with 37 MBq ^{226}Ra and decay products. The radiation protection expert wants to transport this container as an exempt collo. The container is packaged in a large cardboard box.
a is this method of transportation permitted?
b what is the maximum allowable equivalent dose rate at the surface of the box?
hint: the limit values for ^{226}Ra are $A_1 = 0.3$ TBq and $A_2 = 0.02$ TBq

12 The radiation protection expert wants to transport a bottle which contains 5 ml of a solution of ^{111}InCl in hydrochloric acid. The bottle is encapsulated in a tin can and is then placed in a large cardboard box.
a what is the maximum amount of activity which may be sent in this manner as an exempt collo?
b what is the maximum allowable equivalent dose rate at the surface of the box?
hint: the limit values for ^{111}In are $A_1 = 2$ TBq and $A_2 = 2$ TBq

13 For equipment in medical and veterinary practices, limits are used for the maximum permissible equivalent dose rate as a result of radiation leakage.
a what is the limit in the case of a diagnostic device?
b what is the limit in the case of a therapeutic device?

14 The radiation protection expert swipes a sealed γ-source and determines through a measurement that the swiped activity is 50 Bq.
   a should this source be considered "leaky" ?
   b answer Question a if the source holder was swiped instead of the source itself
   c answer Question a if an α-source is considered

15 In a C-laboratory, an iodine compound labeled with ^{125}I is often made. To do so, the iodine solution is centrifuged under a fume hood. Per experiment, 10 MBq is processed. The experiments last a maximum of 4 hours. The dose conversion coefficient for inhalation is $e(50)_{inh} = 7.3\times10^{-9}$ Sv Bq^{-1}. No other experiments are performed in the C-laboratory.
   a determine the maximum number of experiments which may be performed in the C-laboratory each week
   hint: use the data in Appendix A15 of these Exercises

16 In a B-laboratory, an experiment with a phosphorus compound, labeled with the radionuclide ^{32}P, is performed twice per day under a NEN-approved fume hood. In the experiment, the compound is ground to powder in a ball mill. The $e(50)_{inh}$ of ^{32}P for the considered compound is 2.9×10^{-9} Sv Bq^{-1}. No other experiments are performed in the B-laboratory.
   a determine the maximum amount of activity which can be worked with for each experiment
   b determine the maximum effective committed dose which a laboratory technician may receive in the case he inhales 0.01% of the activity due to sloppy work
   c is the laboratory worker classified as an exposed worker on the basis of answer b and, if so, in which category?
   hint: use the data in Appendix A15 of these Exercises

17 During a contamination check, it is determined that an area of 10 cm × 10 cm on one of the tables in a radionuclide laboratory is contaminated with 1 kBq ^{45}Ca. After the contamination is cleaned as well as possible, there is still 90% of the activity left on the table.
   a is the table contaminated, considering the guidelines given in the directive on radionuclide laboratories?

Answers

1 a 1 mSv
b 20 mSv
c 1 mSv
d 0.1 mSv (per licensee)
e 1 mSv (from the moment the pregnancy is reported)

2 a 15 mSv
b 150 mSv
c 50 mSv
d 500 mSv

3 a 0.1 mSv
b 0.2 mSv
c by applying ALARA, the yearly dose may be kept under the secondary level
d the factor 0.25 when determining the Multifunctional Individual Dose
thus, the effective limit becomes 0.1 mSv / 0.25 = 0.4 mSv

4 a 10 µSv
by applying the factor 0.25 when determining the Multifunctional Individual Dose, the effective limit becomes 10 µSv / 0.25 = 40 µSv
b no, but the company is expected to have done enough towards ALARA

5 a smaller
b larger when inhaled, but smaller when ingested

6 a yes, as long as it is guaranteed that their effective dose is not larger than 6 mSv per year
b yes, as long as it is guaranteed that their effective dose is not larger than 1 mSv per year

7 a yes
because the total activity (800 GBq) and the activity concentration (357 TBq g^{-1}) are both larger than the exemption values (1 GBq and 10^{-6} TBq g^{-1}, respectively)
information: this application falls under consumer products for which different rules apply according to the ANVS-ordonance on basic safety standards radiation protection; see *https://wetten.overheid.nl/BWBR0040581*

8 a requires a license
because the total activity (36 kBq) and the activity concentration (127 GBq g^{-1}) are both larger than the exemption values (10 kBq and 1 Bq g^{-1}, respectively); see further information given in answer b

9 a this application is on the list of not justified practices
for the moment, ionizing smoke detectors already present in homes may still be used; see further information given in answer b

10 a requires a license
because these devices are used for educational purposes

11 a the limit value for ^{226}Ra is $A_1 = 0.3$ TBq
in an exempt collo, a maximum of $10^{-3} \times A_1 = 0.3$ GBq = 300 MBq may be sent; therefore, this method of transportation is permitted
b 5 µSv h^{-1}

12 a the limit value for ^{111}In is $A_1 = 2$ TBq
in a exempt collo a maximum of $10^{-3} \times A_1 = 2$ GBq may be sent
b 5 µSv h^{-1}

13 a 1 mSv h^{-1} at 1 m from the focus
b 10 mSv h^{-1} at 1 m from the focus

14 a the criterion is 185 Bq, so it is not leaky
b the criterion is 18.5 Bq, so it is leaky according to the draft basic directive for sealed sources
note: this part is not included in the regulations
c the criterion is 18.5 Bq, so it is leaky; see note at b

15 a for the described operation $p = -3$, $q = 2$, $r = 2$
radiotoxicity equivalent $Re_{inh} = 1\ Sv / e(50)_{inh} = 1\ Sv / 7.3\times10^{-9}\ Sv\ Bq^{-1}$
$= 1.37\times10^{8}$ Bq
maximum activity $A_{max} = 0.02 \times Re_{inh} \times 10^{p+q+r}$
$= 0.02 \times 1.37\times10^{8}\ Bq \times 10^{-3+2+2}$
$= 2.7\times10^{7}$ Bq = 27 MBq
load factor per experiment B = (4 h / 40 h) × (10 MBq / 27 MBq) = 1 / 27
maximum number of experiments per week = 1 / B = 27

16 a for the described operation $p = -4$, $q = 3$, $r = 2$
radiotoxicity equivalent $Re_{inh} = 1\ Sv / e(50)_{inh} = 1\ Sv / 2.9\times10^{-9}\ Sv\ Bq^{-1}$
$= 3.45\times10^{8}$ Bq
maximum activity $A_{max} = 0.02 \times Re_{inh} \times 10^{p+q+r}$
$= 0.02 \times 3.45\times10^{8}\ Bq \times 10^{-4+3+2}$
$= 6.9\times10^{7}$ Bq
b number of experiments 2 per day × 5 d wk^{-1} × 50 wk y^{-1} = 500 per year
maximum activity A = 500 per year × 6.9×10^{7} Bq = 3.5×10^{10} Bq per year
maximum inhalation $A_{inh} = 0.01\times10^{-2} \times A$
$= 0.01\times10^{-2} \times 3.5\times10^{10} = 3.5\times10^{6}$ Bq
maximum committed dose $E(50) = e(50)_{inh} \times A_{inh}$
$= 2.9\times10^{-9}$ Sv Bq-1 × 3.5×10^{6} Bq
$= 1.0\times10^{-2}$ Sv = 10 mSv
c the exposure is more than 1 mSv
the laboratory worker is therefore an exposed worker
the exposure is more than 6 mSv
the laboratory worker is therefore classified as an exposed worker category-A
note: potential exposures have not been taken into account

17 a the original contamination was 10^{3} Bq / (10 cm × 10 cm) = 10 Bq cm^{-2}
after clean-up, 90% still remains, so 10% has been removed
thus, the removable activity was 0.1 × 10 Bq cm^{-2} = 1 Bq cm^{-2}
the criterion in the directive on radionuclide laboratories is 4 Bq cm^{-2}; so, the table is not contaminated

15 Devices

1 A radiotherapy device is used for a maximum of 10 hours per week.
   a what is the hourly limit in the control room?
   b what would this limit be for an accelerator which is used for 5000 hours per year?

2 A person is 1 m away from a patient who is irradiated by an X-ray device, and as a result of this the person receives an effective dose of 10 μSv due to scattered radiation.
   a what would the effective dose be if this person had taken four steps back of 0.5 meter each?
   b what would the effective dose have been if the person had been 0.5 m closer?

3 An X-ray device requiring a license is located in a room which is adjacent to a public road. Without a protective concrete wall, the absorbed dose on the street would be 1 Gy per week. The density of concrete is $\rho = 2.35$ g cm^{-3} and the mass attenuation coefficient is $\mu/\rho = 0.041$ cm^2 g^{-1}. The build-up-factor is $B = 10$.
   a determine the minimum wall thickness on the street side of the room

4 In industry, an X-ray device with a tube voltage of 400 kV is used to irradiate material with an absorbed dose of 100 Gy. The material is at 50 cm from the focus. A maximum of 1 irradiation is performed per day. In-line with the radiation beam, at 5 m from the focus, is an office space. The radiation room and the office are separated by a concrete wall.
   a determine the illumination per irradiation (in mA min)
   b determine the minimum required thickness of the wall
   hint: neglect the absorption in the irradiated material and use the date in Appendix A16 of these Exercises

Answers

1 a maximum number of hours $10\ \text{h wk}^{-1} \times 50\ \text{wk y}^{-1} = 500\ \text{h y}^{-1}$
yearly limit $1\ \text{mSv y}^{-1}$
hourly limit $1\ \text{mSv y}^{-1} / 500\ \text{h y}^{-1} = 0.002\ \text{mSv h}^{-1} = 2\ \mu\text{Sv h}^{-1}$
b a person will not be exposed for more than 2000 hours per year while working, even if the accelerator is used for 5000 hours per year
hourly limit $1\ \text{mSv y}^{-1} / 2000\ \text{h y}^{-1} = 0.0005\ \text{mSv h}^{-1} = 0.5\ \mu\text{Sv h}^{-1}$

2 a old distance $r_1 = 1\ \text{m}$
new distance $r_2 = r_1 + 4 \times 0.5\ \text{m} = 3\ \text{m}$
effective dose $E = 10\ \mu\text{Sv} \times (r_1 / r_2)^2 = 10\ \mu\text{Sv} / 9 = 1.1\ \mu\text{Sv}$
b old distance $r_1 = 1\ \text{m}$
new distance $r_2 = r_1 - 1 \times 0.5\ \text{m} = 0.5\ \text{m}$
effective dose $E = 10\ \mu\text{Sv} \times (r_1 / r_2)^2 = 10\ \mu\text{Sv} \times 4 = 40\ \mu\text{Sv}$

3 a yearly dose without shielding $H^*(0) = 1\ \text{Gy wk}^{-1} \times 50\ \text{wk y}^{-1} \times 1\ \text{Sv Gy}^{-1} = 50\ \text{Sv y}^{-1}$
yearly limit $H^*(d) = 100\ \mu\text{Sv y}^{-1} = 1\times10^{-4}\ \text{Sv y}^{-1}$
required transmission $T(d) = H^*(d) / H^*(0)$
$= 1\times10^{-4}\ \text{Sv y}^{-1} / 50\ \text{Sv y}^{-1} = 2.0\times10^{-6}$
$= \text{Be}^{-(\mu/\rho)(d\rho)} = 10 \times \text{e}^{-0.041\times d\times 2.35} = 100\ \text{e}^{-0.096\times d}$
thickness of wall $0.096 \times d = -\ln(2\times10^{-6} / 10) = 15.4$
$d = 15.4 / 0.096 = 160\ \text{cm concrete}$

4 a from Appendix A16 of these Exercises, at 400 kV
$\text{d}D(1\ \text{m})/\text{d}t = 23.5\ \text{mGy per mA min at 1 m from focus}$
at 50 cm from focus $\text{d}D(50\ \text{cm})/\text{d}t = 23.5\ (\text{mGy}) \times (0.5\ \text{m} / 1\ \text{m})^2$
$= 94\ \text{mGy per mA min}$
absorbed dose $100\ \text{Gy} = 1\times10^5\ \text{mGy}$
illumination $1\times10^5\ \text{mGy} / 94\ \text{mGy per mA min} = 1064\ \text{mA min}$
b at 5 m from focus $\text{d}D(5\ \text{m})/\text{d}t = \text{d}D(50\ \text{cm})/\text{d}t \times (0.5\ \text{m} / 5\ \text{m})^2$
$= 1\times10^5\ (\text{mGy}) / 100$
$= 1000\ \text{mGy per irradiation}$
number of irradiations $1\ \text{per day} \times 5\ \text{d wk}^{-1} \times 50\ \text{wk y}^{-1} = 250\ \text{per year}$
yearly dose without shielding $H^*(0) = 250 \times 1000\ \text{mGy} \times 1\ \text{Sv Gy}^{-1} = 2.5\times10^5\ \text{mSv}$
yearly limit $H^*(d) = 1\ \text{mSv}$
required transmission $T(d) = H^*(0) / H^*(d)$
$= 1\ \text{mSv} / 2.5\times10^5\ \text{mSv} = 4\times10^{-6}$
from Appendix A16 of these Exercises, at 400 kV
$D = 23.5\ \text{mGy per mA min} \times T(d)$
$= 23.5\ \text{mGy per mA min} \times 4\times10^{-6}$
$= 9.4\times10^{-5}\ \text{mGy per mA min}$
required thickness $d = 58\ \text{cm concrete}$

16 Sealed sources

1 Out of habit, an employee grabs a small 0.4 MBq source of ^{60}Co with his fingers. If he were to use a long pair of tweezers, the action would take twice as long. Suppose the average distance between source and fingers is 5 mm when not using the tweezers, and is 5 cm when using tweezers.

a with what factor can the dose on the fingers be reduced by using the tweezers?

b give another reason to handle sealed sources with tweezers

2 Due to a leaking ^{90}Sr/^{90}Y source, 50 MBq is spilled on the workbench. The radionuclides ^{90}Sr and ^{90}Y only emit β-radiation with a maximum energy of 0.55 MeV and 2.29 MeV, respectively.

a determine the equivalent dose rate at 10 cm from the contaminated area using the rule of thumb

b determine the effective committed dose if 1% of this activity were to be ingested
hint: use the following data

source constant for β-radiation	$d_\beta = 9\ \mu Gy\ h^{-1}\ MBq^{-1}\ m^2$
source constant for γ-radiation (E_γ in MeV)	$d_\gamma = E_\gamma / 7$ *in* $\mu Gy\ h^{-1}\ MBq^{-1}\ m^2$
dose conversion coefficient for ^{90}Sr/^{90}Y	$e(50)_{ing} = 31\ mSv\ MBq^{-1}$

3 Two sources, one ^{60}Co and one ^{90}Sr/^{90}Y, each contain 1 MBq of activity. The radionuclide ^{60}Co emits two γ-photons with energies of 1.17 MeV and 1.33 Mev, respectively. The radionuclides ^{90}Sr and ^{90}Y are pure β-emitters.

a determine the ambient dose equivalent rate dH^*/dt at 50 cm from the ^{60}Co source

b determine the equivalent dose rate dH_β/dt at 50 cm from the ^{90}Sr/^{90}Y-bron using the rule of thumb

c determine the ratio of the values dH^*/dt and dH_β/dt determined under a and b

d does the same ratio exist for the effective doses?

Answers

1 a the dose is proportional to time and inversely proportional to the square of the distance; thus, the reduction factor is $2 \times (0.5 \text{ cm} / 5 \text{ cm})^2 = 0.02$

b prevention of internal and external contamination

2 a the β-energies are so large that absorption in air is negligible
the radionuclides ^{90}Sr and ^{90}Y each emit 1 β-particle, which makes a total of 2 β-particles
$dH_\beta/dt = 2 \times (50 \text{ MBq} / 1 \text{ MBq}) \times (100 \text{ cm} / 10 \text{ cm})^2 \times 9 \text{ μGy h}^{-1} \times 1 \text{ Sv Gy}^{-1}$
$= 9 \times 10^4 \text{ μSv h}^{-1} = 90 \text{ mSv h}^{-1}$

b ingested activity $A_{ing} = 50 \text{ MBq} \times 10^{-2} = 0.50 \text{ MBq}$
effective committed dose $E(50) = e(50)_{ing} \times A_{ing}$
$= 31 \text{ mSv MBq}^{-1} \times 0.50 \text{ MBq} = 15.5 \text{ mSv}$

3 a the total γ-energy is 1.17 + 1.33 = 2.50 MeV
the source constant is $d_\gamma = 2.50 / 7 = 0.36 \text{ μGy h}^{-1} \text{ MBq}^{-1} \text{ m}^2$
$dH_\gamma/dt = 0.36 \text{ μGy h}^{-1} \text{ MBq}^{-1} \text{ m}^2 \times 1 \text{ Sv Gy}^{-1} \times 1 \text{ MBq} / (0.5 \text{ m})^2 = 1.4 \text{ μSv h}^{-1}$

b the radionuclides ^{90}Sr and ^{90}Y each emit 1 β-particle, which makes a total of 2 β-particles
$dH_\beta/dt = 2 \times 9 \text{ μGy h}^{-1} \text{ MBq}^{-1} \text{ m}^2 \times 1 \text{ Sv Gy}^{-1} \times 1 \text{ MBq} / (0.5 \text{ m})^2 = 72 \text{ μSv h}^{-1}$

c $dH_\beta/dt \; / \; dH_\gamma/dt = 72 \text{ μSv h}^{-1} / 1.4 \text{ μSv h}^{-1} = 51$

d the β-particles have a short range and are stopped by small amounts of matter, which makes the local equivalent dose high
the effective dose is much smaller, as the skin (tissue weighting factor $w_T = 0.01$) and the outer tissue layer are practically the only organs to be irradiated
$dE_\beta/dt \; / \; dE_\gamma/dt = (w_T \times dH_\beta/dt) / (dH_\gamma/dt) = 0.01 \times 51 \approx 0.5$

17 Open sources

1 An exposed employee inhales 0.26 MBq ^{131}I in the form of iodine vapor.
   a determine the effective committed dose
   b determine the equivalent dose of the thyroid; assume that this is the only organ to contribute to the effective committed dose
   hint: the dose conversion coefficient of ^{131}I is $e(50)_{inh} = 2.0 \times 10^{-8}$ Sv Bq^{-1} and the tissue weighting factor of the thyroid is $w_{thyroid} = 0.04$

2 A barrel contains 40 l of watery, ^{14}C-containing waste. The activity concentration is 1 kBq per ml.
   a can the contents be discharged into the sewer?
   b if not, can the waste be diluted with water to such a point that it may be discharged into the sewer?
   c if not, can the barrel be stored for such a time that the contents may be discharged in the sewer?
   hint: the dose conversion coefficient of ^{14}C is $e(50)_{ing} = 5.8 \times 10^{-10}$ Sv Bq^{-1}; the secondary level for discharge in water is $w_{SN} = 100\ Re_{ing}$; as the half life $T_{½} > 250$ years, the correction factor becomes $R_w = 100$

Answers

1 a inhalation $A_{inh} = 0.26$ MBq $= 0.26\times10^{6}$ Bq

effective committed dose $E(50) = e(50)_{inh} \times A_{inh}$

$= 2.0\times10^{-8}$ Sv Bq^{-1} $\times$ 0.26×10^{6} Bq

$= 0.0052$ Sv $= 5.2$ mSv

b equivalent tissue dose $H_{thyroid} = E(50) / w_{thyroid}$

$= 5.2$ mSv / $0.04 = 130$ mSv

2 a radiotoxicity unit $1\ Re_{ing} = 1\ Sv / e(50)_{ing}$

$= 1\ Sv / 5.8\times10^{-10}$ Sv Bq^{-1} $= 1.7\times10^{9}$ Bq

discharge limit $w_{SN} / R_w = 100\ Re_{ing} / 100 = 1\ Re_{ing} = 1.7\times10^{9}$ Bq

total activity $A = 40$ l $\times\ 10^{3}$ ml l^{-1} $\times\ 10^{3}$ Bq ml^{-1} $= 4\times10^{7}$ Bq

this is less than the corrected discharge limit, so the barrel may be discharged into the sewer

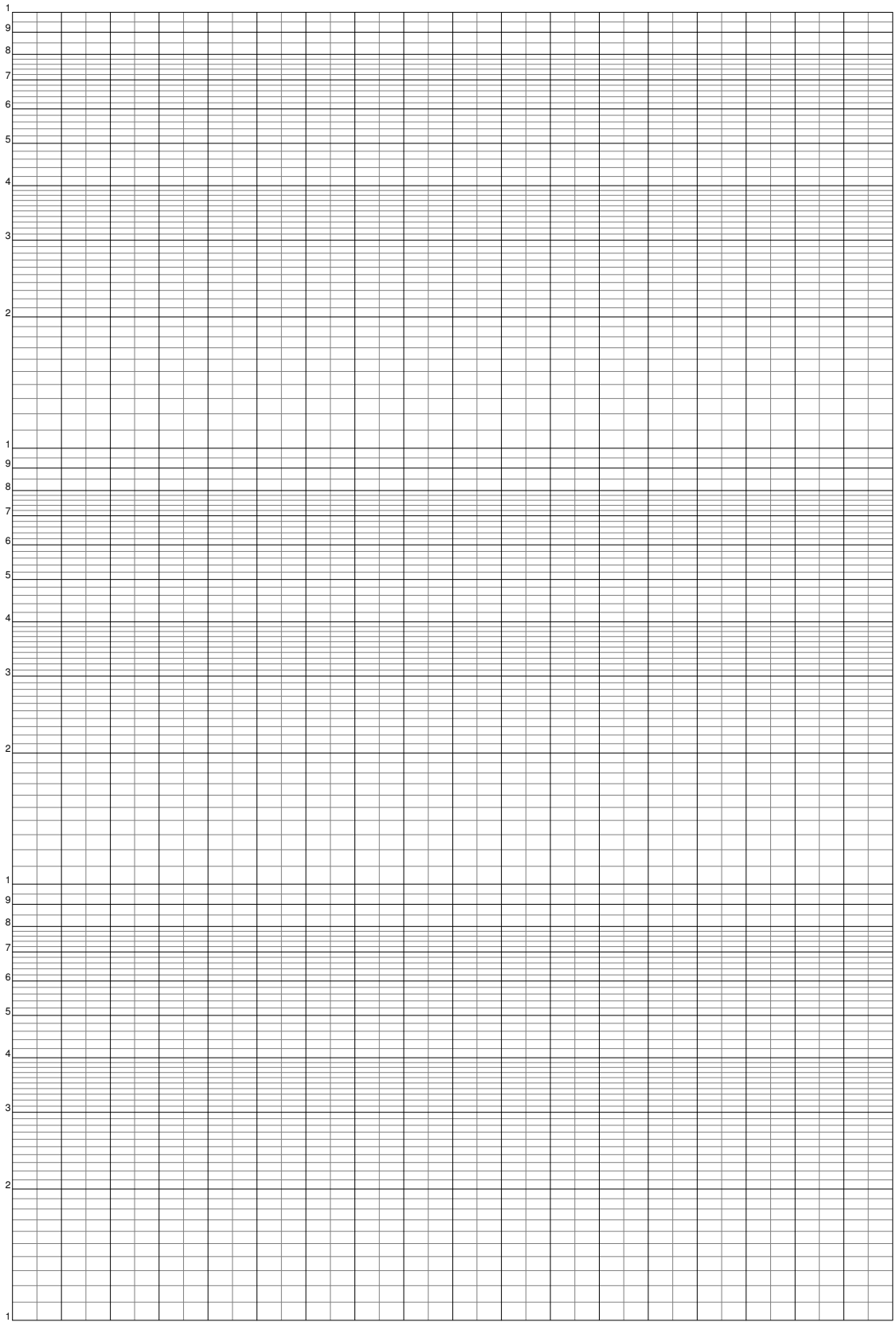
b diluting the contents does not reduce the total activity, and therefore is not a solution

c waste may be kept for a maximum of 2 years in storage

as $T_{½} > 250$ years >> 2 years, storage is also not a solution

note: if either the total activity per annum or the activity concentration is less than the exemption level, the activity may be handed over to a third party, irrespective the fact whether this party is licensed or not; the third party is not bound to any regulations and may subsequently discharge the activity into the sewer; this shows that different regulations may be at odds with one another

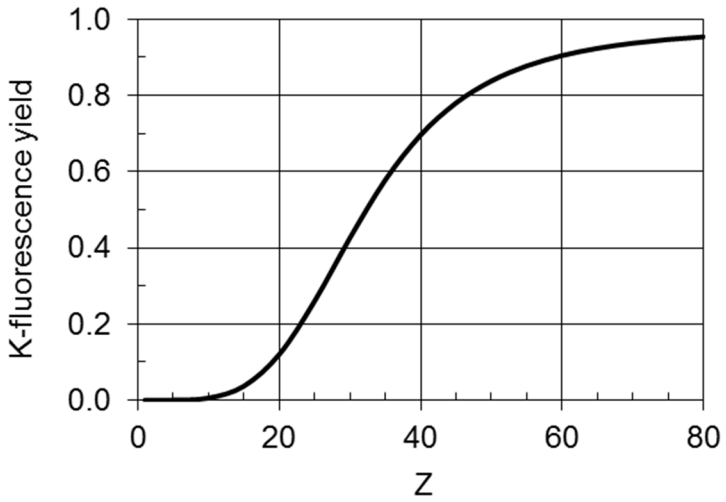
Appendix



A1. Single-logarithmic graphing paper

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

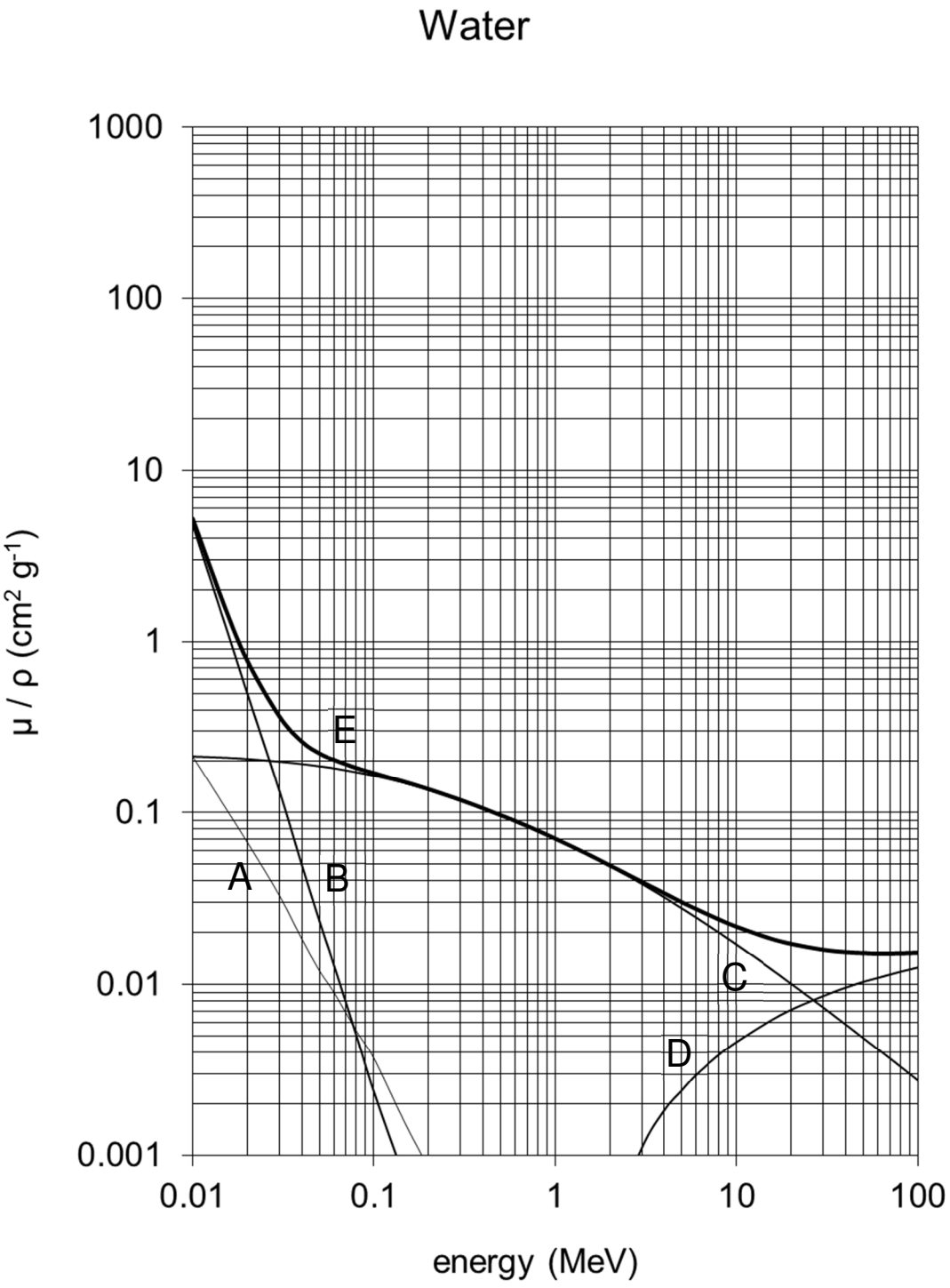
A2. One-tailed probability P(k) for a normal distribution



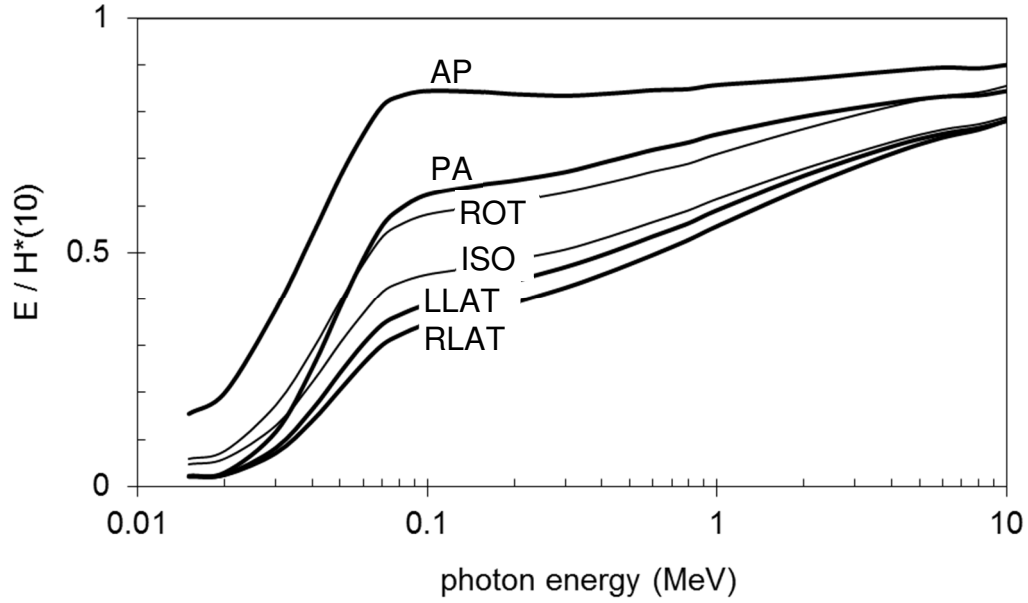
A3. K-fluorescence yield

material	μ/ρ *(cm² g⁻¹)*	μ_{tr}/ρ *(cm² g⁻¹)*	μ_{en}/ρ *(cm² g⁻¹)*
water	0.0966	0.0330	0.0330
wuscle	0.0958	0.0328	0.0328
bone	0.0926	0.0317	0.0317
air	0.0868	0.0296	0.0296
lead	0.0886	0.0503	0.0481

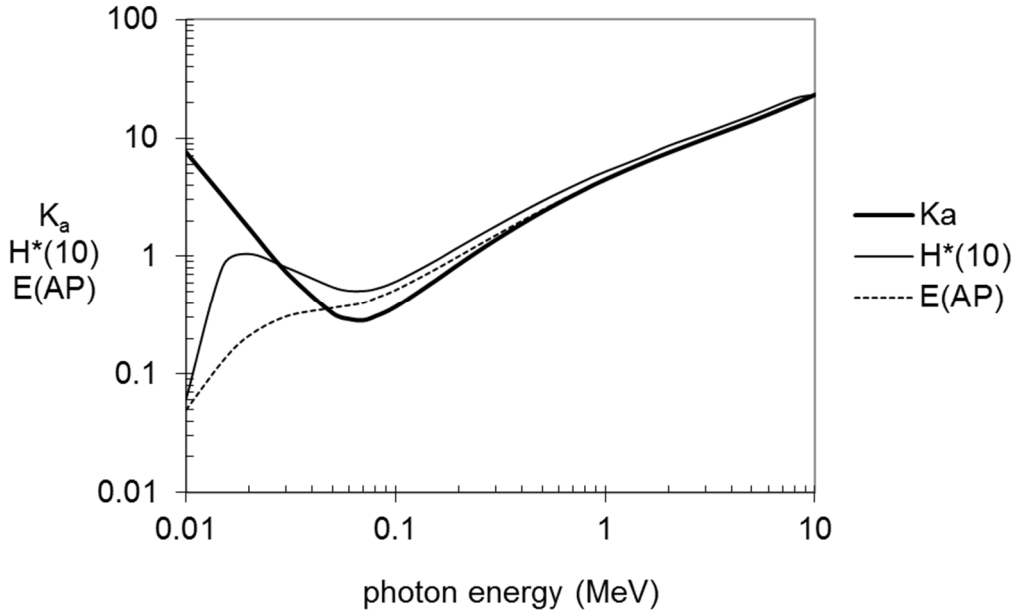
A4. Coefficients for mass attenuation, energy transfer, and energy absorption, for several materials and a photon energy of 0.5 MeV



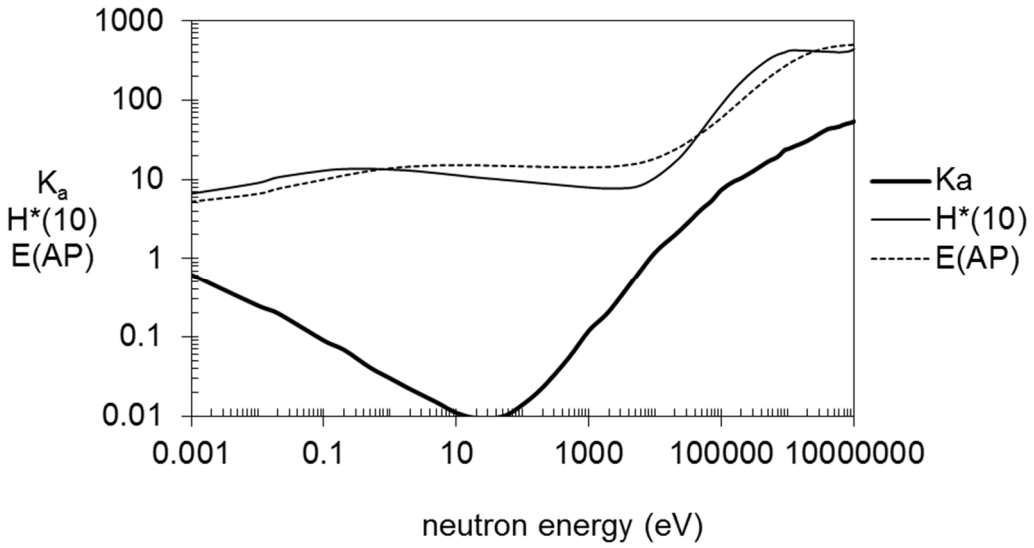
A5. Mass attenuation coefficients of lead
(A) Rayleigh-scattering, (B) photo-electric effect, (C) Compton-effect, (D) pair forming, and (E) the total mass attenuation coefficient μ/ρ



A6. Ratio of E and H(10) for different geometries, as a function of E_γ*



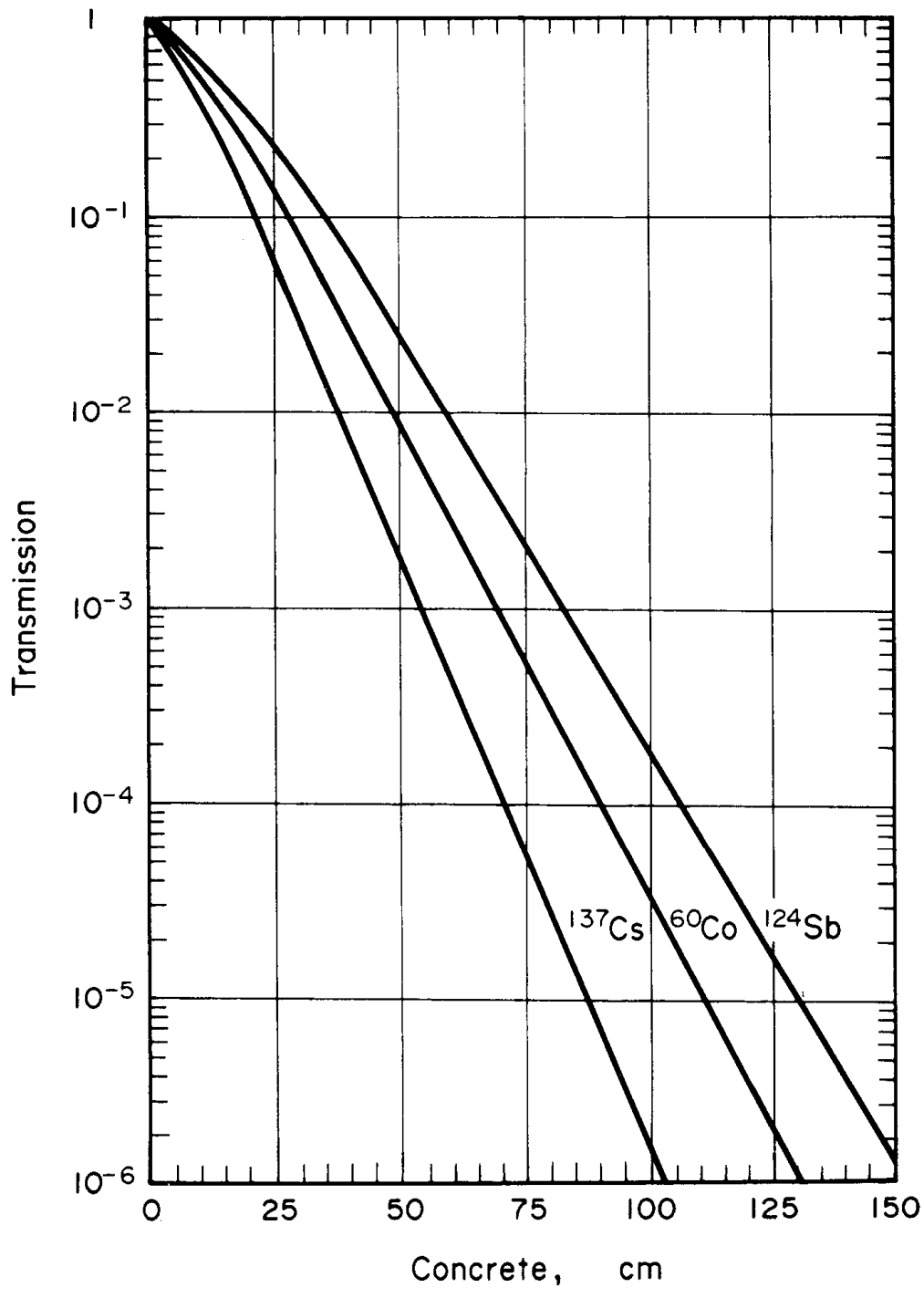
A7. K_a, H(10) and E(AP) per unit of Φ, as a function of E_γ (K_a in pGy cm², and H*(10) and E(AP) in pSv cm²)*



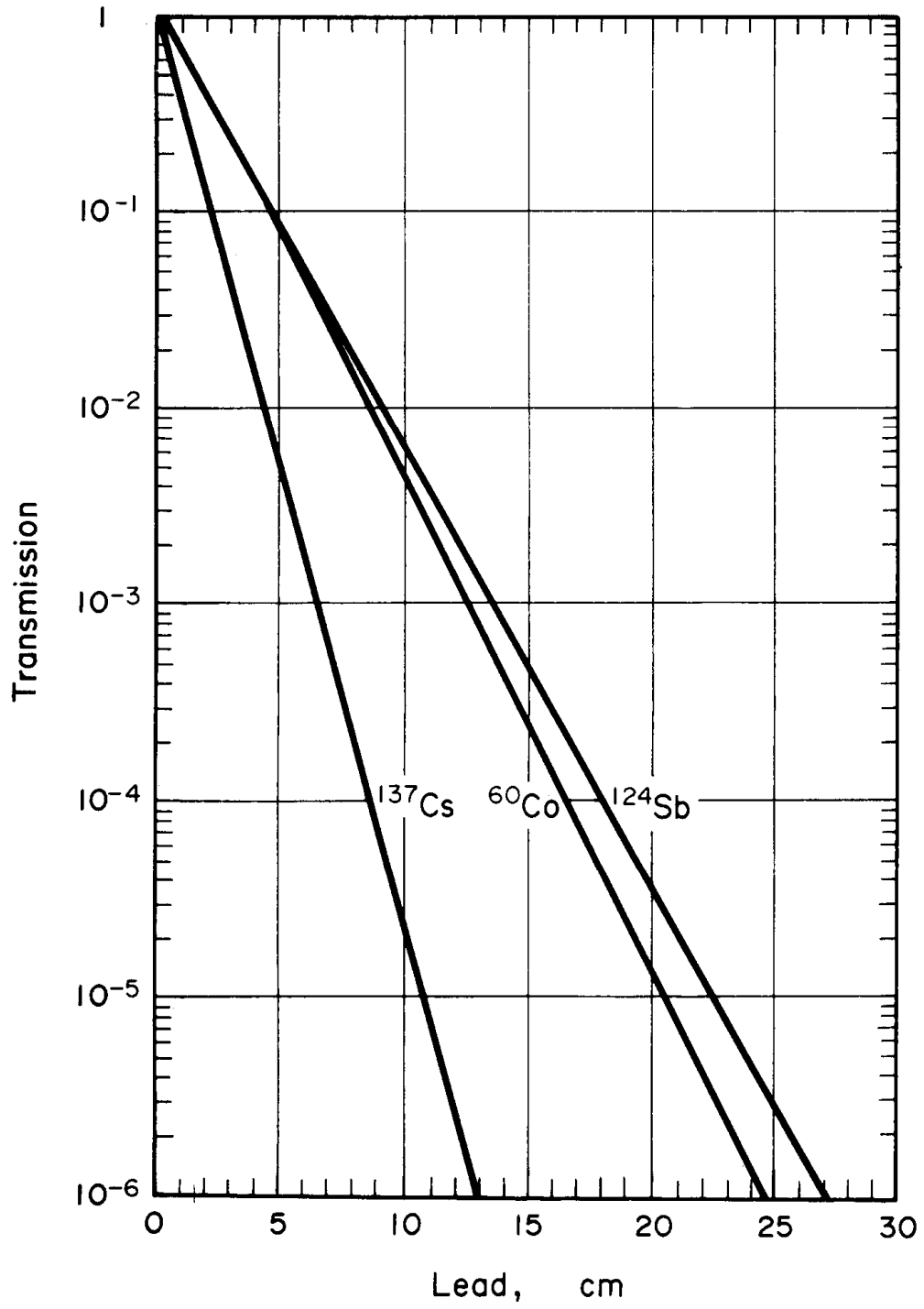
A8. K_a, H(10) and E(AP) per unit of Φ as a function of the $E_{neutron}$ (K_a in pGy cm², H*(10) and E(AP) in pSv cm²)*

AMAD (μm)	*ET_1*	*ET_2*	*BB*	*bb*	*AI*	*total*
0.0006	0.45	0.44	0.06	0.04	0.00	0.99
0.001	0.40	0.40	0.08	0.10	0.00	0.99
0.002	0.30	0.32	0.08	0.22	0.04	0.96
0.005	0.16	0.18	0.05	0.26	0.27	0.92
0.01	0.09	0.10	0.03	0.19	0.47	0.88
0.02	0.05	0.06	0.02	0.13	0.49	0.74
0.05	0.03	0.03	0.01	0.07	0.31	0.46
0.1	0.03	0.03	0.01	0.05	0.21	0.33
0.2	0.06	0.06	0.01	0.03	0.15	0.30
0.5	0.09	0.11	0.01	0.02	0.12	0.35
0.7	0.12	0.15	0.01	0.02	0.11	0.42
1	0.17	0.21	0.01	0.02	0.11	0.51
2	0.25	0.32	0.02	0.01	0.09	0.70
3	0.30	0.37	0.02	0.01	0.08	0.78
5	0.34	0.40	0.02	0.01	0.05	0.82
7	0.35	0.40	0.01	0.01	0.04	0.81
10	0.35	0.38	0.01	0.00	0.02	0.77
15	0.34	0.36	0.01	0.00	0.01	0.71
20	0.32	0.33	0.01	0.00	0.01	0.67

A9. Lung deposition fractions for an adult male (nose breather)



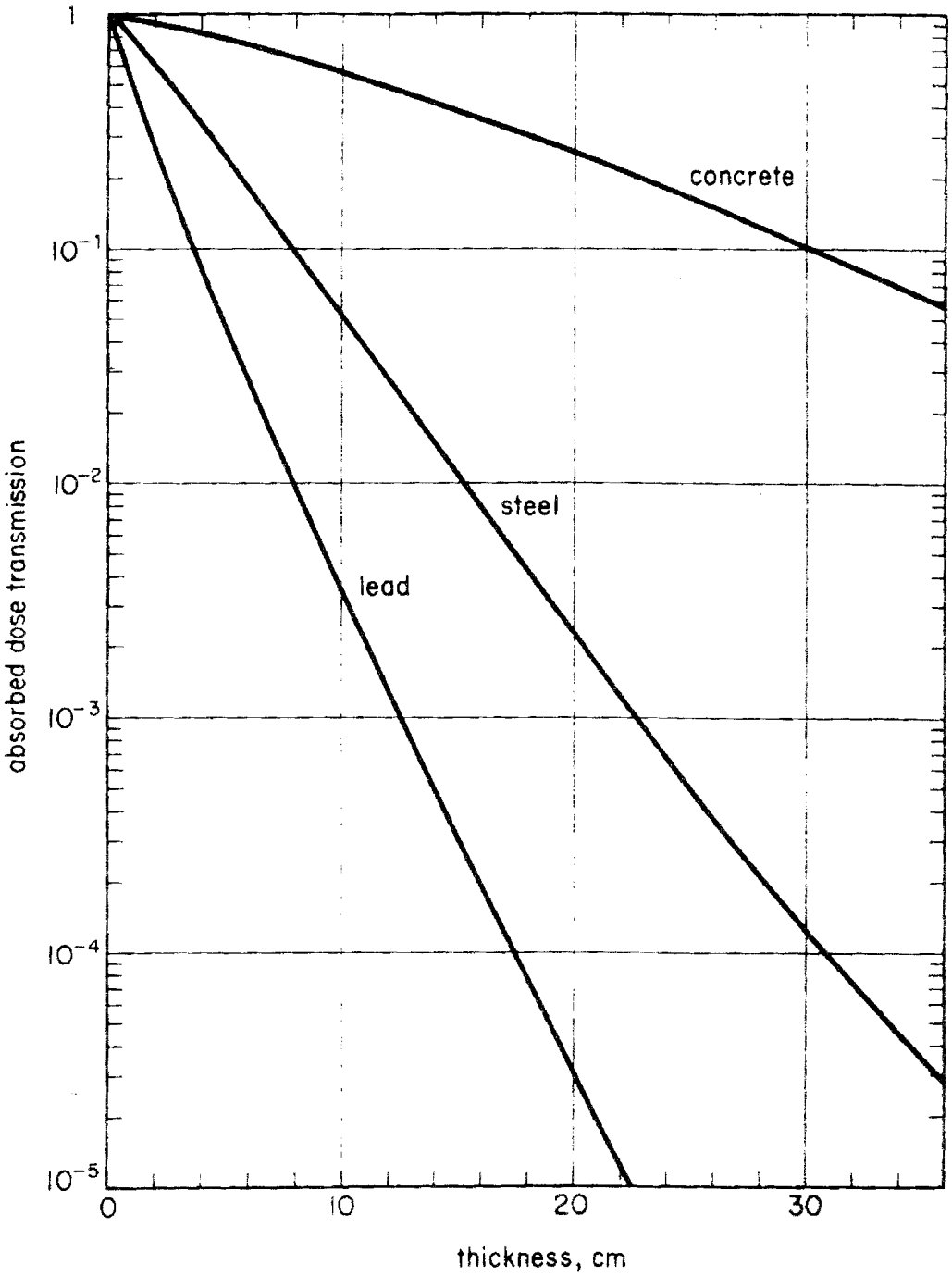
A10. Transmission of broad-beam γ-radiation through concrete



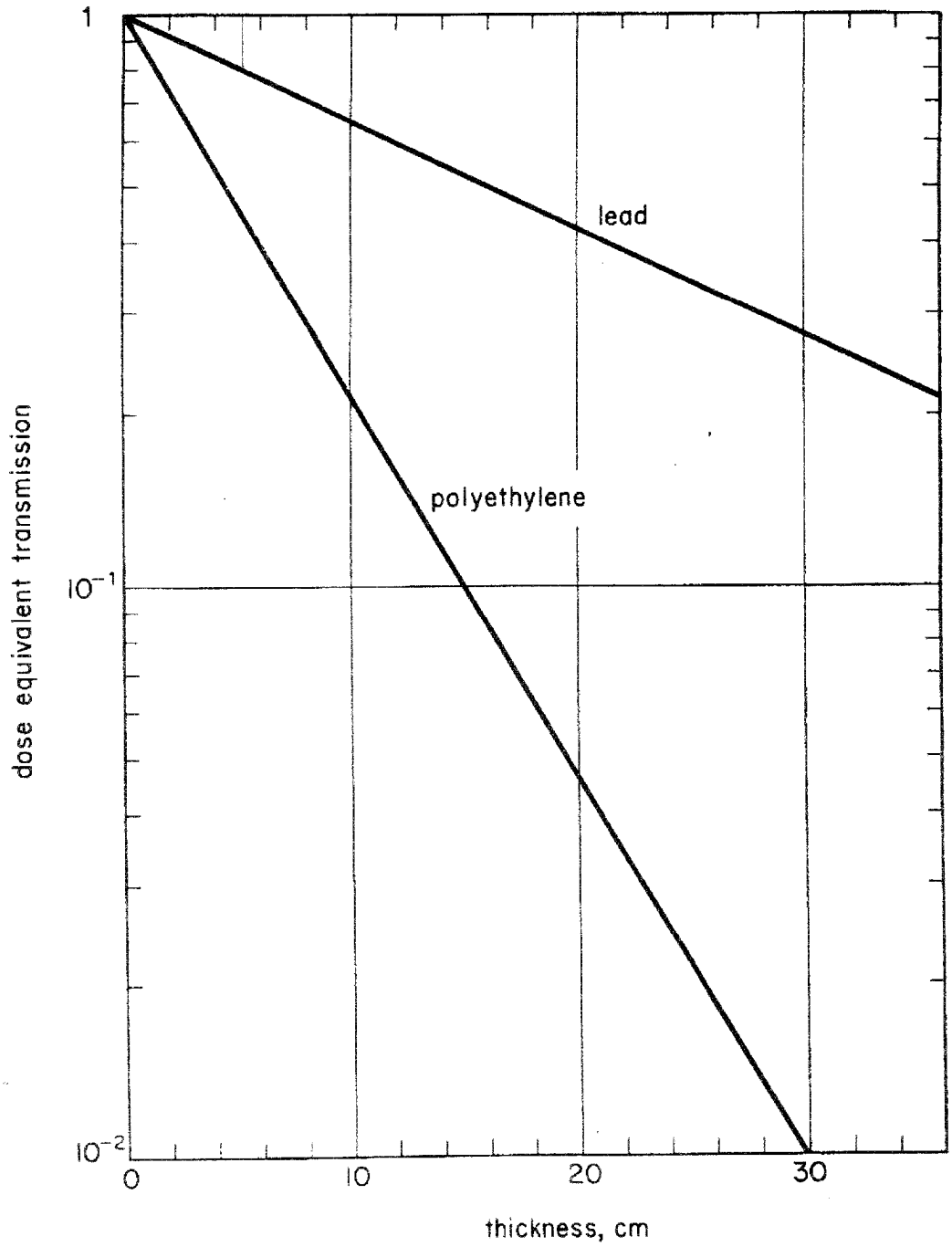
A11. Transmission of broad-beam γ-radiation through lead

material	*E*				*μd*			
	(MeV)	*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	3.91	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

A12. Build-up factors for water, concrete, iron and lead as a function of the thickness and the photon energy



A13. Transmission of broad beam γ-radiation of ^{252}Cf through concrete, steel and lead



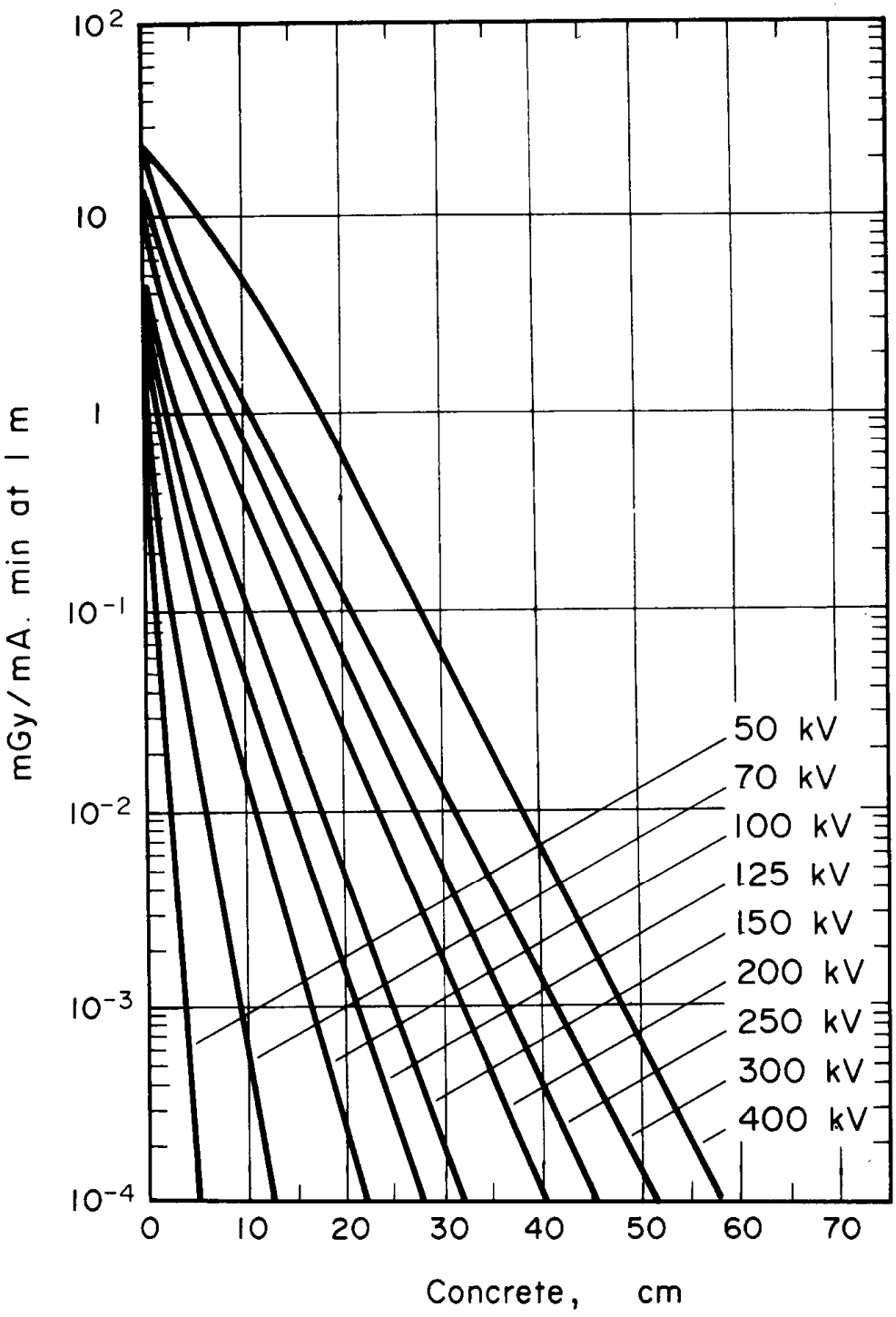
A14. Transmission of broad beam neutron radiation of ^{252}Cf through polyethylene (= polythene) and lead

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

q	*area*
0	area outside of laboratory management
1	D-laboratory ancillary space in a D-laboratory
2	C-laboratory
3	B-laboratory

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

A15. The p-, q- and r-values according to the directive on radionuclide laboratories



A16. Transmission of broad-beam X-radiation through concrete (50-300 kV: half-sine wave, anode from 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 from gold and filter of 3 mm copper; the intensity at 0 cm lead 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)