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Operational radiation protection

Exercises & Solutions

EPFL, RPRA – 2018/2019

CHUV

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1. Annual dose

Estimate the annual dose for a person working 10 h per week at 1 m from an unshielded Cesium-137 source with an activity of 500 kBq.

Radionuclide	Half-life	Type of decay/ radiation	Assessment quantities					Clearance limit	Licensing limit	Guidance values		Unstable daughter nuclide
			e_{inh} Sv/Bq	e_{ing} Sv/Bq	h_{10} (mSv/h)/ GBq at 1 m distance	$h_{0,07}$ (mSv/h)/ GBq at 10 cm distance	$h_{c,0,07}$ (mSv/h)/ (kBq/cm^2)	LL Bq/g	LA Bq	CA Bq/m^3	CS Bq/ cm^2	
1	2	3	4	5	6	7	8	9	10	11	12	13
Cs-125	45 min	ec, β+ / ph	2.30E-11	3.50E-11	0.114	500	0.7	1.E+01 [1]	2.00E+08	4.00E+05	10	→ Xe-125
Cs-127	6.25 h	ec, β+ / ph	4.00E-11	2.40E-11	0.079	100	0.2	1.E+02	1.00E+08	2.00E+05	30	→ Xe-127
Cs-129	32.06 h	ec, β+ / ph	8.10E-11	6.00E-11	0.063	30	<0.1	1.E+01	6.00E+07	1.00E+05	1000	
Cs-130	29.21 min	ec, β+, β− / ph	1.50E-11	2.80E-11	0.087	500	0.8	1.E+02 [1]	3.00E+08	6.00E+05	10	
Cs-131	9.689 d	ec / ph	4.50E-11	5.80E-11	0.016	2	<0.1	1.E+03 [1]	1.00E+08	2.00E+05	1000	
Cs-132	6.479 d	ec, β+, β− / ph	3.80E-10	5.00E-10	0.119	50	0.1	1.E+01	1.00E+07	2.00E+04	100	
Cs-134	2.0648 a	β−, ec / ph	9.60E-09	1.90E-08	0.236	1000	1.1	1.E-01	5.00E+05	9.00E+02	3	
Cs-134m	2.903 h	it / ph	2.60E-11	2.00E-11	0.009	1000	1.5	1.E+03	2.00E+08	3.00E+05	3	→ Cs-134 [6]
Cs-135	2.3 E6 a	β−	9.90E-10	2.00E-09	0.000	600	0.7	1.E+02	5.00E+06	8.00E+03	10	
Cs-135m	53 min	it / ph	2.40E-11	1.90E-11	0.239	70	0.2	1.E+01 [1]	2.00E+08	3.00E+05	30	→ Cs-135
Cs-136	13.16 d	β− / ph	1.90E-09	3.00E-09	0.327	1000	1.5	1.E+00	3.00E+06	4.00E+03	3	
Cs-137 / Ba-137m	30.1671 a	β−, it / ph	6.70E-09	1.30E-08	0.092	2000	1.5	1.E-01 [2]	7.00E+05	1.00E+03	3	
Cs-138	33.41 min	β− / ph	4.60E-11	9.20E-11	0.445	1000	1.8	1.E+01 [1]	1.00E+08	2.00E+05	3	

1. Annual dose

Estimate the annual dose for a person working 10 h per week at 1 m from an unshielded Cesium-137 source with an activity of 500 kBq.

Solution:

- We assume 48 working weeks per year
- The equivalent dose is given by:

$$H^*(10) = A \cdot h_{10} \cdot \frac{1}{r^2} \cdot T \cdot t$$

$$= 0.5\ \text{MBq} \cdot 0.092 \frac{\mu\text{Sv/h}}{\text{MBq}} \cdot 1 \cdot \frac{10\ \text{h/w} \cdot 48\ \text{w}}{1^2}$$

$$= 22\ \mu\text{Sv}$$

2. Working time

You are working with a source of F-18, 200 MBq, at a distance of 10 cm. How long can you work with this source without exceeding a dose limit of 100 µSv ?

Radionuclide	Half-life	Type of decay/ radiation	Assessment quantities e_{inh} Sv/Bq	e_{ing} Sv/Bq	h_{10} (mSv/h)/ GBq at 1 m distance	$h_{0,07}$ (mSv/h)/ GBq at 10 cm distance	$h_{c,0,07}$ (mSv/h)/ (kBq/cm²)	Clearance limit LL Bq/g	Licensing limit LA Bq	Guidance values CA Bq/m³	CS Bq/ cm²	Unstable daughter nuclide
1	2	3	4	5	6	7	8	9	10	11	12	13
C-14	5.70 E3 a	β^-	5.80 E-10	5.80 E-10	<0.001	200	0.3	1.E+00	9.00E+06	1.00 E+04	30	
C-14 monoxide			8.00 E-13						6.00E+09	1.00 E+07		
C-14 dioxide			6.50 E-12						8.00E+08	1.00 E+06		
N-13	9.965 min	ec, β^+ / ph			0.160	1000	1.7	1.E+02 [1]	7.00E+07	7.00 E+04 [3]	3	
O-15	122.24 s	ec, β^+ / ph			0.161	1000	1.7	1.E+02 [1]	7.00E+07	7.00 E+04 [3]	3	
F-18	109.77 min	ec, β^+ / ph	9.30 E-11	4.90 E-11	0.160	2000	1.7	1.E+01 [1]	7.00E+07	7.00 E+04 [3]	3	
Na-22	2.6019 a	ec, β^+ / ph	2.00 E-09	3.20 E-09	0.330	2000	1.6	1.E-01	3.00E+06	4.00 E+03	3	
Na-24	14.9590 h	β^- / ph	5.30 E-10	4.30 E-10	0.506	1000	1.9	1.E+00	9.00E+06	2.00 E+04	3	
Mg-28 / Al-28	20.915 h	β^- / ph	1.70 E-09	2.20 E-09	0.529	2000	3.1	1.E+01 [2]	3.00E+06	5.00 E+03	3	

2. Working time

You are working with a source of F-18, 200 MBq, at a distance of 10 cm. How long can you work with this source without exceeding a dose limit of 100 µSv ?

Solution:

- The equivalent dose is given by: $H^*(10) = A \cdot h_{10} \cdot \frac{1}{r^2} \cdot T \cdot t$
- We limit the dose to: $H^*(10) = 100\ \mu Sv$
- We solve for the duration t: $t = \frac{H^*(10) \cdot r^2}{A \cdot h_{10}}$

$$= \frac{100\ \mu Sv \cdot 0.1^2}{200\ MBq \cdot 0.160 \frac{\mu Sv/h}{MBq}}$$

$$= 0.03\ h \approx 110\ s$$

3. Manipulating sources with tweezers

1) Calculate, for the surface dose H(0.07), the benefit linked to using tweezers (handle length of 20 cm) to hold a flask of Technetium-99m.

2) If the operation using the tweezers lasts 1 minute, calculate the duration of the manipulation without tweezers if we want to maintain the same dose.

			Assessment quantities					Clearance limit	Licensing limit	Guidance values		
Radionuclide	Half-life	Type of decay/ radiation	e_{inh} Sv/Bq	e_{ing} Sv/Bq	h_{10} (mSv/h)/ GBq at 1 m distance	$h_{0,07}$ (mSv/h)/ GBq at 10 cm distance	$h_{c,0,07}$ (mSv/h)/ (kBq/cm^2)	LL Bq/g	LA Bq	CA Bq/m^3	CS Bq/ cm^2	Unstable daughter nuclide
1	2	3	4	5	6	7	8	9	10	11	12	13
Tc-97	2.6 E6 a	ec / ph	1.60E-10	8.30E-11	0.017	4	<0.1	1.E+01	3.00E+07	5.00E+04	1000	
Tc-97m	90.1 d	it / ph	2.70E-09	6.60E-10	0.014	30	0.7	1.E+02	2.00E+06	3.00E+03	10	→ Tc-97
Tc-98	4.2 E6 a	β⁻ / ph	6.10E-09	2.30E-09	0.215	2000	1.5	1.E-01	8.00E+05	1.00E+03	3	
Tc-99	2.111 E5 a	β⁻	3.20E-09	7.80E-10	<0.001	1000	1.1	1.E+00	2.00E+06	3.00E+03	3	
Tc-99m	6.015 h	it, β⁻/ ph	2.90E-11	2.20E-11	0.022	300	0.2	1.E+02 [1]	2.00E+08	3.00E+05	30	→ Tc-99
Tc-101	14.2 min	β⁻ / ph	2.10E-11	1.90E-11	0.055	1000	1.6	1.E+02 [1]	2.00E+08	4.00E+05	3	
Tc-104	18.3 min	β⁻ / ph	4.80E-11	8.10E-11	1.219	1000	1.8	1.E+01 [1]	1.00E+08	2.00E+05	3	

3. Manipulating sources with tweezers

1) *Calculate, for the surface dose H(0.07), the benefit linked to using tweezers (handle length of 20 cm) to hold a flask of Technetium-99m.*
2) *If the operation using the tweezers lasts 1 minute, calculate the duration of the manipulation without tweezers if we want to maintain the same dose.*

Solution:

1. The dose ratio w/ vs. w/o tweezers is: $\frac{H_1'(0.07)}{H_2'(0.07)} = \left(\frac{r_2}{r_1}\right)^2$

   Not knowing the distance between source and fingers when manipulating without tweezers, we assume the thickness of the gloves, i.e. 1 mm:

$$\frac{H_1'(0.07)}{H_2'(0.07)} = \left(\frac{20\ \text{cm}}{0.1\ \text{cm}}\right)^2 = 40'000$$

2. To maintain the same dose, the manipulation must not last longer than:

$$t_1 = t_2 \bigg/ \frac{H_1'(0.07)}{H_2'(0.07)} = 1\ \text{min}/40'000 = 1.5\ \text{ms}$$

4. The choice of the source

For a 2-year science project you will need to irradiate thin layer samples with gamma rays.

Which source of Cobalt would you chose taking into account the duration of the project and radiation protection aspects?

			Assessment quantities					Clearance limit	Licensing limit	Guidance values		
Radionuclide	Half-life	Type of decay/ radiation	e_{inh} Sv/Bq	e_{ing} Sv/Bq	h_{10} (mSv/h)/ GBq at 1 m distance	$h_{0,07}$ (mSv/h)/ GBq at 10 cm distance	$h_{c,0,07}$ (mSv/h)/ (kBq/cm^2)	**LL** Bq/g	**LA** Bq	**CA** Bq/m^3	**CS** Bq/ cm^2	Unstable daughter nuclide
1	2	3	4	5	6	7	8	9	10	11	12	13
Co-55	17.53 h	ec, β^+ / ph	8.30E-10	1.10E-09	0.302	1000	1.4	1.E+01	6.00E+06	1.00E+04	3	→ Fe-55
Co-56	77.23 d	ec, β^+ / ph	4.90E-09	2.50E-09	0.485	300	0.6	1.E-01	1.00E+06	2.00E+03	10	
Co-57	271.74 d	ec / ph	6.00E-10	2.10E-10	0.021	100	0.1	1.E+00	8.00E+06	1.00E+04	100	
Co-58	70.86 d	ec, β^+ / ph	1.70E-09	7.40E-10	0.147	300	0.3	1.E+00	3.00E+06	5.00E+03	30	
Co-58m	9.04 h	it / ph	1.70E-11	2.40E-11	<0.001	10	<0.1	1.E+04	3.00E+08	5.00E+05	1000	→ Co-58 [6]
Co-60	5.2713 a	β^- / ph	1.70E-08	3.40E-09	0.366	1000	1.1	1.E-01	3.00E+05	5.00E+02	3	

4. The choice of the source

For a 2-year science project you will need to irradiate thin layer samples with gamma rays.

Which source of Cobalt would you chose taking into account the duration of the project and radiation protection aspects?

Solution:

1. From a practical point of view, we need an isotope of Cobalt with a sufficiently long physical half-life to span the duration of the experiment. For this purpose, one would envisage Co-57 ($T_{1/2}$ = 271 d) or Co-60 ($T_{1/2}$ = 5.27 y).

2. From a radiation protection point of view, we will chose the isotope of Cobalt that produces the less dose / dose-rate possible:

$$\frac{h_{10}^{Co-60}}{h_{10}^{Co-57}} = 17.4$$

→ Co-57 is the best choice for the requirements of the experiment

5. Shielding of sources

1. Compare at equal transmission (1%) the thickness of lead to shield a source of Cobalt-60 (E_γ = 1.25 MeV) and Iridium-192 (E_γ < 0.5 MeV).

2. In order to reduce the dose rate of an Iodine-131 source by a factor of 10’000, the source must be shielded with approximately :
   - 0.6 cm of lead
   - 6 cm of lead
   - 6 cm of concrete
   - 60 cm of concrete

5. Shielding or sources

1. *Compare at equal transmission (1%) the thickness of lead to shield a source of Cobalt-60 (E_γ = 1.25 MeV) and Iridium-192 (E_γ < 0.5 MeV).*
2. *In order to reduce the dose rate of an Iodine-131 source by a factor of 10’000, the source must be shielded with approximately :*
   - *0.6 cm of lead*
   - *6 cm of lead*
   - *6 cm of concrete*
   - *60 cm of concrete*

Solution:

1. We need 4 cm of lead for the source of Cobalt-60 and 1 cm of lead for Iridium-192.
2. To achieve an attenuation of 10’000 for Iodine-131, we need 60 cm of concrete (or 7-8 cm of lead).

6. Shielding for a public area

Calculate the thickness of a concrete wall for an irradiation room (area: 25 m^2), where a source of Cesium-137 with an activity of 20 GBq is used for 10 h per week. The adjoining area is occupied by non professionally exposed workers, i.e. public individuals (dose limit: 0.02 mSv per week).

6. Shielding for a public area

Calculate the thickness of a concrete wall for an irradiation room (area: 25 m^2), where a source of Cesium-137 with an activity of 20 GBq is used for 10 h per week. The adjoining area is occupied by non professionally exposed workers, i.e. public individuals (dose limit: 0.02 mSv per week).

Solution:

We assume a quadratic room with 5 m length. The irradiator is placed in the middle of the room, i.e. r = 2.5 m :

$$H^*(10) = h_{10}^{Cs-137} \frac{A \cdot t}{r^2} = 2.9 \text{ mSv/week}$$

$$\tau = \frac{0.02 \text{ mSv/week}}{2.9 \text{ mSv/week}} = \frac{1}{145}$$

$$\Rightarrow \quad \sim 40 \text{ cm of concrete}$$

7. Measurement of external exposure

True or False

When working with γ emitters :

- The Automess can be used to monitor the ambient dose rate.
- The active individual dosemeter can be used to know instantaneously the dose received while working.
- The passive and active individual dosemeter have the same utility.

7. Measurement of external exposure

True or False

When working with γ emitters :

- *The Automess can be used to monitor the ambient dose rate.*
  → true
- *The active individual dosemeter can be used to know instantaneously the dose received while working.*
  → true
- *The passive and active individual dosemeter have the same utility.*
  → false: They both measure Hp(10), but usually only the passive dosemeter measures Hp(0.07). Only the passive dosemeter is accepted by the authorities.

8. Surface contamination

Calculate the waiting time so that a surface contamination of 200 Bq/cm^2 of Iodine-125 decays below the legal limit of surface contamination for uncontrolled areas.

Radionuclide	Half-life	Type of decay/ radiation	Assessment quantities					Clearance limit	Licensing limit	Guidance values		Unstable daughter nuclide
			e_{inh} Sv/Bq	e_{ing} Sv/Bq	h_{10} (mSv/h)/ GBq at 1 m distance	$h_{0,07}$ (mSv/h)/ GBq at 10 cm distance	$h_{c,0,07}$ (mSv/h)/ (kBq/cm^2)	LL Bq/g	LA Bq	CA Bq/m^3	CS Bq/ cm^2	
1	2	3	4	5	6	7	8	9	10	11	12	13
I-120	81.6 min	ec, β^+ / ph	1.90E-10	3.40E-10	1.155	800	1.5	1.E+01 [1]	3.00E+07	4.00E+04	3	
I-120m	53 min	ec, β^+ / ph	1.40E-10	2.10E-10	1.108	800	1.7	1.E+01 [1]	4.00E+07	6.00E+04	3	
I-121	2.12 h	ec, β^+ / ph	3.90E-11	8.20E-11	0.077	400	0.4	1.E+02 [1]	1.00E+08	2.00E+05	10	→ Te-121
I-123	13.27 h	ec / ph	1.10E-10	2.10E-10	0.043	400	0.3	1.E+02	5.00E+07	8.00E+04	30	→ Te-123
I-124	4.1760 d	ec, β^+ / ph	6.30E-09	1.30E-08	0.170	300	0.5	1.E+01	8.00E+05	1.00E+03	10	
I-125	59.400 d	ec / ph	7.30E-09	1.50E-08	0.033	4	<0.1	1.E+02	7.00E+05	1.00E+03	10	
I-126	12.93 d	ec, β^+, β^- / ph	1.40E-08	2.90E-08	0.078	700	0.7	1.E+01	4.00E+05	6.00E+02	10	
I-128	24.99 min	β^-, ec, β^+ / ph	2.20E-11	4.60E-11	0.016	1000	1.5	1.E+02 [1]	2.00E+08	4.00E+05	3	
I-129	1.57 E7 a	β^- / ph	5.10E-08	1.10E-07	0.016	100	0.3	1.E-02	1.00E+05	2.00E+02	3	→ Xe-129
I-130	12.36 h	β^- / ph	9.60E-10	2.00E-09	0.325	1000	1.6	1.E+01	5.00E+06	9.00E+03	3	
I-131	8.02070 d	β^- / ph	1.10E-08	2.20E-08	0.062	1000	1.4	1.E+01	5.00E+05	8.00E+02	3	→ Xe-131m
I-132	2.295 h	β^- / ph	2.00E-10	2.90E-10	0.338	1000	1.7	1.E+01 [1]	3.00E+07	4.00E+04	3	
I-132m	1.387 h	it, β^- / ph	1.10E-10	2.20E-10	0.055	300	1	1.E+02	5.00E+07	8.00E+04	10	→ I-132 [6]
I-133	20.8 h	β^- / ph	2.10E-09	4.30E-09	0.093	1000	1.6	1.E+01	2.00E+06	4.00E+03	3	→ Xe-133, Xe-133m
I-134	52.5 min	β^- / ph	7.90E-11	1.10E-10	0.385	1000	1.8	1.E+01 [1]	6.00E+07	1.00E+05	3	
I-135	6.57 h	β^- / ph	4.60E-10	9.30E-10	0.223	1000	1.6	1.E+01 [2]	1.00E+07	2.00E+04	3	→ Xe-135, Xe-135m

8. Surface contamination

Calculate the waiting time so that a surface contamination of 200 Bq/cm² of Iodine-125 decays below the legal limit of surface contamination for uncontrolled areas.

Solution:

The legal limit of surface contamination for uncontrolled areas is 1x CS, i.e. 10 Bq/cm² for Iodine-125. The surface activity needs to decay by a factor of 20.

With $\frac{A_s(t)}{A_s(0)} = e^{-\frac{\log(2)\cdot t}{T_{1/2}}}$

We obtain: $t = \log\left(\frac{A_s(0)}{A_s(t)}\right) \cdot \frac{T_{1/2}}{\log(2)} = \frac{\log(20)}{\log(2)} \cdot T_{1/2}$

$$= 4.32 \cdot T_{1/2} = 256.7 \text{ d}$$

9. Working sector

1. Which type of working area is required to handle 10 MBq of an open radioactive source of Sr-90 ?
2. Which type of working area is required to handle 300 MBq of an open radioactive source of P-32 ?
3. True or false :

   Type B working sector :

   - The exit must be equipped with a hand and foot monitor.
   - All structures (doors and walls) must be shielded.
   - Is only used for handling sealed sources.

			Assessment quantities					Clearance limit	Licensing limit	Guidance values		
Radionuclide	Half-life	Type of decay/ radiation	e_{inh} Sv/Bq	e_{ing} Sv/Bq	h_{10} (mSv/h)/ GBq at 1 m distance	$h_{0,07}$ (mSv/h)/ GBq at 10 cm distance	$h_{c,0,07}$ (mSv/h)/ (kBq/cm^2)	LL Bq/g	LA Bq	CA Bq/m^3	CS Bq/ cm^2	Unstable daughter nuclide
1	2	3	4	5	6	7	8	9	10	11	12	13
P-30	2.498 min	ec, β^+ / ph			0.371	900	1.7				3	
P-32	14.263 d	β^-	2.90E-09	2.40E-09	<0.001	1000	1.6	1.E+03	2.00E+06	3.00E+03	3	
P-33	25.34 d	β^-	1.30E-09	2.40E-10	<0.001	700	0.8	1.E+03	4.00E+06	6.00E+03	10	
Sr-90	28.79 a	β^-	7.70E-08	2.80E-08	<0.001	1000	1.4	1.E+00 [2]	6.00E+04	1.00E+02	3	→ Y-90 [6]
Sr-91	9.63 h	β^- / ph	5.70E-10	7.60E-10	0.117	1000	1.6	1.E+01 [2]	9.00E+06	1.00E+04	3	→ Y-91m, Y-91
Sr-92	2.66 h	β^- / ph	3.40E-10	4.90E-10	0.194	1000	1.4	1.E+01 [1]	1.00E+07	2.00E+04	3	→ Y-92 [6]

9. Working sector

1. *Which type of working area is required to handle 10 MBq of an open radioactive source of Sr-90 ?*

$$\frac{10\ \text{MBq}}{\text{LA}(\text{Sr-90})} = \frac{10\ \text{MBq}}{60\ \text{kBq}} = 167 \quad \Rightarrow \text{Type B working sector}$$

1. *Which type of working area is required to handle 150 MBq of an open radioactive source of P-32 ?*

$$\frac{300\ \text{MBq}}{\text{LA}(\text{P-32})} = \frac{150\ \text{MBq}}{2\ \text{MBq}} = 75 \quad \Rightarrow \text{Type C working sector}$$

2. *True or false :*

   Type B working sector :

   - *The exit must be equipped with a hand and foot monitor.* → true
   - *All structures (doors and walls) must be shielded.* → false
   - *Is only used for handling sealed sources.* → false