Accreditation course in radiation protection - Radiation Protection Officer – Dispersible radioactive substances level D (TMS-VRS D)

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Contents

Part I

Quick reference handbook

Chapter 1

Radioactive decay

α **decay**: Occurs when the nucleus is unstable, due to being too big. The parent atom ${}^{A}_{Z}X$ gets split into a daughter atom ${}^{A-4}_{Z-2}Y$ and an alpha particle ${}^{4}_{2}a$.

β^- **decay**: Occurs when the nucleus is unstable, due to having an excess of neutrons. The parent atom ${}^{A}_{Z}X$ gets split into a daughter atom ${}_{Z+1}{}^{A}Y$, a beta particle ${}_{-1}^{0}e^-$, and an anti-neutrino $\overline{v}_e$.

β^+ **decay**: Occurs when the nucleus is unstable, due to having an excess of protons. The parent atom ${}^{A}_{Z}X$ gets split into a daughter atom ${}_{Z-1}{}^{A}Y$, a positron ${}_{+1}^{0}e^+$, and a neutrino v. After a number of interactions, the positron $\beta+$ unites with an electron and converts its entire mass to energy. This annihilation produces 2x 511 keV.

Electron capture: The nucleus absorbs an electron from the electron cloud (usually from shell K -innermost). The parent atom ${}^{A}_{Z}X$ absorbs an electron ${}_{-1}^{0}e^-$, and gets split into a daughter atom ${}_{Z-1}{}^{A}Y$, and a neutrino v.

Gamma decay (γ): Occurs when the atom is excited. The parent atom ${}^{A}_{Z}X\cdot$ gets excited and produces a daughter particle ${}^{A}_{Z}X$ and a gamma ray γ^1. Internal conversion may occur (direct transfer of the energy of the nucleus to an electron).

Chapter 2

Formulas

2.1 Activity determination

$$A(t) = A(0) \cdot (\frac{1}{2})^{\frac{t}{T_{1/2}}}$$

Precise determination with a formula for the half-life using half-life. All time units must be in the same unit.

$$t_{1/2} = \frac{\ln(2)}{\lambda} = \tau \ln(2)$$

Relationship between half-life and decay constant. Tau is the inverse of the decay constant.

$$\frac{dN(t)}{dt} = -\lambda \cdot N(t);\ A(t) = A(0) \cdot e^{-\lambda t}$$

Precise determination with a formula for the half-life using decay constant (λ). All time units must be in the same unit.

2.2 Shielding

$$g \approx 2 \cdot 10^{-4} \cdot Z \cdot E_{\beta,max}$$

Approximation of the energy converted to Bremsstrahlung. Where Z is the atomic number of the shielding material

$$R_{\beta,\ in\ material} = \frac{R_{\beta,\ in\ water} = 0.5E_{\beta,max}}{\rho_{material}}$$

Range of β particle in a specific material. For water and tissue, ρ can be estimated to be 1 g/cm^3. $E_{\beta,max}$ is expressed in MeV.

$$I(d) = I(0) \cdot B \cdot (\frac{1}{2})^{\frac{d}{d_{1/2}}}$$

Shielding of γ radiation using half distance. Buildup factor (P60) may be ignored. All distance units must be in the same unit.

$$I(d) = I(0) \cdot e^{-\mu_{linear} d}; \mu_{mass} = \mu_{linear} \cdot \rho_{material}^{-1}$$

Shielding of γ radiation using linear attenuation coefficient. Above 500keV, $\mu_{mass\ water} \approx \mu_{mass\ concrete}$.

2.3 Dose determination

$$H_T = W_R \cdot D$$

Equivalent dose. W_R is the radiation weighting factor: 1x for β and γ, 20x for α, and 2-20x for N_0. D is the absorbed dose over tissue of organ (Gy).

$$E = \sum (W_T \cdot H_T)$$

Effective dose. W_T is the tissue weighting factor (P64).

$$E(50) = e(50) \cdot A$$

Committed effective dose (Sv). e(50) is the committed effective dose coefficient (Sv·Bq^{-1}).

$$\cdot H * (10) = h(10) \cdot \frac{A}{r}$$

Inverse square law. The activity must be in MBq, the distance in m, and the result in μSv/h

$$X$$

2.4 Measurement

$$rel.error = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

Relative error. N is the number of counted pulses, $\sqrt{N}$ is the counting error

$$\epsilon = \frac{R}{A}$$

Efficiency, where R is the counting rate in units of per second, and A is the activity in Bq (which also has units of rate per second).

2.5 Safety

$$A_{max} = \frac{0.02 \cdot 10^{p+q+r}}{e(50)_{inh}}$$

Maximum permissible activity, expressed in Bq. 0.02 refers to the dose limit for exposed workers, p is the factor for dispersion, q is the parameter for the laboratory level, and r is for the local ventilation. See tables 3.3-3.5 for PQR values.

$$B_{\text{W practice}} = \frac{t_{\text{practice}}}{40} \times \frac{A_{\text{practice}}}{A_{\text{max}}}$$

Load factor of a practice in a laboratory, t in hours, 40 (total number of hours in the laboratory, can be changed), and activity both in the same unit. The sum of all the experiments together is the Load Factor (<1 !!)

Chapter 3

Useful information

Table 3.1: Detectors and their usual applications

	β emitters	Photon radiation
Ionisation detectors		
GM Tube (thin window)	Contamination	Contamination
GM Tube (thick window)	-	Dose rate
Proportional counter (thin window, xenon filled) for low-energy photons	Large area contamination	Large area contamination
Germanium semiconductor	-	Accurate spectrum
Scintillation detectors		
NaI(Tl)	-	Contamination Simple spectrum Dose rate
Andthracene or ZnS	Contamination	Contamination
TLD	Personal dosimeter	Personal dosimeter

Table 3.2: Dose limits

Group	**Effective dose [mSv/y]**	**Equivalent dose [mSv/y]**	
	Total body	Eye lens	Skin & extremities
Category A	20	20	500
Category B **Exposed pupils and students** **Those between 16 and 18**	6	15	150
Category C **"Non-exposed employees"**	1	15	50
Pregnant employees	Maximum 1 mSv equiv to abdomen from announcement to birth.		
Members of the public **Excluding patients**	1	15	50

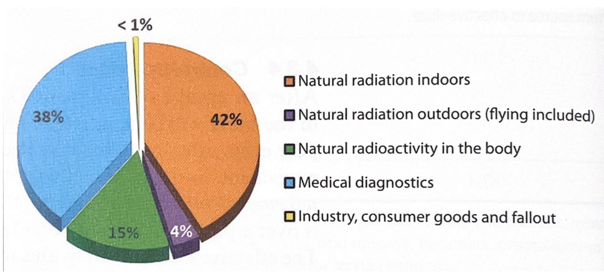

Figure 3.1: Contributions to the dose for a member of the public in the Netherlands

Table 3.3: Dispersion parameter p

p	Phase of material or type of manipulation
-4	Simple work with gases, mixing or grounding of powders, liquid close to boiling point, highly splashing activities
-3	Labelling with volatile compounds, centrifugation, mixing on a vortex, simple work with powder in a closed system, storage of a noble gas in a dispenser, boiling of liquids in a closed system
-2	Simple chemical manipulations, labelling with a non-volatile nucleide
-1	Manipulation in a closed system, pulling up syringes, labelling in closed systems, calibration, labelling of non-dispersible compounds, storage of radioactive waste in a laboratory.

Table 3.4: Laboratory parameter q

q	Laboratory class
0	Outside RNL
1	Class D
2	Class C
3	Class B

Table 3.5: Local ventilation parameter r

r	**Local ventilation**
0	Working outside the fume hood, on a bench
1	Local ventilation, or working in a fume hood that does not comply with the (Dutch-European) standard NEN-EN 14175, but where less than 10% of the material released in the fume hood can reach the workspace.
2	Good fume hood (less than 1% of the material released in the fume hood can reach the workspace), for example a fume hood compliant with NEN-EN 14175 in terms of construction and NPR 4500 in terms of placement, or a class II biosafety cabinet.
3	Closed cabinet: for example, class III cabinet for biological safety or closed Laminar Air Flow Isolator.

Part II

Classes

Chapter 4

Physics 1

4.1 Structure of an atom

An atom of X element has Z number of protons, N number of neutrons [n(0)], and a mass (A) of Z+N. An element can be expressed as ${}^{A}_{Z}X$

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4.2 Radioactive decay

Decay may occur due to:

1. Too many protons
2. Too many neutrons
3. Too many neutrons and protons
4. Energetically excited state

The chart of nucleides expresses in black the stable nuclei and in white the unstable nuclei. Isobars have the same mass (A), and isotopes have the same number of P+ (Z).

4.3 Ionizing radiation

Radiation is energy released as electromagnetic waves or particles.
Ionisation means removing electrons from the electron cloud of the atom.
Ionising radiation can consist of:

1. Particle radiation (with high energy)
   (a) Alpha decay
   (b) Beta decay
   (c) Electron capture
   (d) Positron emission
2. Electromagnetic radiation (with high energy)
   (a) Isomeric transition (gamma emission)

The radiation type that occurs can be seen on the chart of nucleides (see slide 10).

Alpha decay (α)

Occurs when the nucleus is unstable, due to being too big.
The parent atom ${}^{A}_{Z}X$ gets split into a daughter atom ${}^{A-4}_{Z-2}Y$ and an alpha particle ${}^{4}_{2}a$.

Beta decay (β)

Occurs when the nucleus is unstable, due to having an excess of n.
The parent atom ${}^{A}_{Z}X$ gets split into a daughter atom ${}^{A}_{Z+1}Y$, a beta particle ${}^{0}_{-1}e^{-}$, and an anti-neutrino $\overline{v}_{e}$.

Electron capture (E.C. or ϵ)

Occurs when the nucleus is unstable, due to having an excess of p.
The parent atom ${}^{A}_{Z}X$ absorbs an electron ${}^{0}_{-1}e^{-}$, and gets split into a daughter atom ${}^{A}_{Z-1}Y$, and a neutrino v. If the hole is filled by an outer shell electron, X-rays are emmitted. [...]

Positron emission (β^{+})

Occurs when the nucleus is unstable, due to having an excess of p.
The parent atom ${}^{A}_{Z}X$ gets split into a daughter atom ${}^{A}_{Z+1}Y$, a positron ${}^{0}_{+1}e^{+}$, and a neutrino v. After a number of interactions, the positron unites with an electron and converts its entire mass to energy. This annihilation produces 511 keV.

Gamma decay (γ)

Occurs when the atom is excited.
The parent atom ${}^{A}_{Z}X\cdot$ gets excited and produces a daughter particle ${}^{A}_{Z}X$ and a gamma ray γ^1.

4.4 Activity

4.4.1 Unit of activity (A)

The unit of activity is the Becquerel (Bq). 1 Bq = 1 disintegration per second. The specific activity is the activity per mass (Bq/g) The old unit was Curie (Ci), equivalent to $3.710^{10}Bq$

4.4.2 Decay law

Decay is a random process. Activity is proportional to the number of nuclei and the decay constant $\lambda(s^{-1})$:

$$A = -\frac{dN}{dt} = \lambda N$$

The half life is the number of seconds that it takes to decay half of all nuclei present:

$$t_{1/2} = -\frac{ln2}{\lambda} = \frac{0.693}{\lambda}$$

The activity (A_t) on time (t) can be approximated as:

$$A_t = A_0 * e^{-\frac{t}{t_{1/2}}*ln(2)}$$

$$A_t = A_0 * \frac{1}{2}^{-\frac{t}{t_{1/2}}}$$

4.5 Electromagnetic radiation

Electromagnetic radiation is non-material.
The smaller the wavelength, the higher the frequency, and the higher the energy.

$$\lambda = \frac{c}{v}$$

$$E = \frac{hc}{\lambda} = h * v$$

4.5.1 Generation of X-rays

X-rays happen when high energy atoms are slowed down by matter. An atom is bombarded by electrons. When an electron hits another electron, a hole is formed. This is then filled by an electron from the electron shell, which releases energy. Three situations can occur:

1. The electron can hit the nucleus, which produces the maximum energy.
2. The electron can have a close interaction, which produces moderate energy.
3. The electron can have a distant interaction, which prouces low energy.

The X-ray tube produces X-rays. It depends on the electron energy (regulated by the tube voltage), and the anode material (usually tungsten). <1% of energy is converted to X-rays, and the rest is heat. The X-ray tube has a spectrum of emission, called the Spectrum Bremsstrahlung. In an X-ray spectrum there's always peaks. Those are called the characteristic X-rays, and they depend on the material. X-rays can be filtered or unfiltered. This reduces the amount of X-rays in the areas that aren't of interest. The filter affects the X-rays differently depending on the material it's made out of.

4.5.2 Interaction of radiation with matter

Gamma and X-rays can interact with matter in the following ways:

1. Classic scattering (mainly non-ionising radiation)
2. Photo effect
3. Compton effect
4. Pair production

Which method occurs depends on the photon energy and the atomic number (see slide 61)

Classic scattering

Also called elastic, coherent or Rayleigh scattering. Gamma energy remains unchanged, but the direction of the photon may change. It is important at low E_λ

Photo effect

The photon knocks an electron out of its orbit. The electron has binding energy, so the resulting energy is minimal. It goes up to 0.5MeV. The chance is roughly proportional to Z^4, and it produces characteristic X-rays.

Compton effect

The dominant effect at higher energies. Depends on the material. The photon is scattered at weakly bound electrons, transferring partly the energy to the electron. However, it continues and may hit another electron. It can go through the material, with less energy that it came in. The degree of energy transfer depends on the scatter angle. The maximal energy will be at 180ª, and the minimal energy at 0º. With a portable X-ray tube it's better to have it below the bed, as it's shielded, and most of the backscatter will go to the rear.

Pair production

Near the nucleus, the photon can create both an electron and a positron, if it has enough energy. This usually results in an annihilation, usually outside of the atom, creating 2 511keV photons, at 180º from each other. This can only occur at energies of over 1.022MeV (mass of the electron + positron).

Chapter 5

Physics 2

5.1 Interaction of charged particles with matter

Photons do not experience energy loss per distance. However, charged particles do. There is a certain amount of energy loss per cm (LET: Linear Energy Transfer), or Stopping Power. Alpha particles have a high stopping power, as they lose a lot of energy at a short distance.
The range is the maximum distance that charged particles can travel in matter. It depends on the type of charged particle, the energy of the charged particle, and the density of the material. Not every electron has the same speed, as the energy is distributed unequally and randomly between the electron and the neutrino. The mean energy is lower than the 50% of the range.
Rule of thumb (produces an overestimation) for β with E > 0.6 MeV:

$$R(cm) * \rho(\frac{g}{cm}) = 0.5\ E_{\beta,max}(MeV)$$

Soft tissue is very equivalent to water, and thus can be approximated to a density of 1. Air is around 1000 times higher.

5.1.1 Interaction of α particles with matter

Due to the interaction with the electrons of atoms (ionizations and excitations), the energy of an α particle decreases. It disposes of its energy linearly along a straight path. The range/pathway depends on the energy of the radiation and the density of the material
Alpha particles have a high stopping power. They lose a lot of energy at a short distance (small range, thick track). They are unable to pass the epidermis, but they are very dangerous if ingested.

5.1.2 Interaction of protons with matter

Protons behave like α particles, but they can be directed to deposit most of their energy at a specific point (Bragg peak). The Bragg peak can be manipulated with the energy.

5.1.3

5.1.4 Shielding from ionizing radiation

Shielding for particles only needs to be as thick as the maximal range. However, for photons, you the shielding needs to be as thick as deemed reasonably safe.
The γ-photon pathway is much longer than the β-particle, which is longer than the α-particle pathway.

Alpha

For α particles, barely any shielding is necessary.

Beta

For β particles, the rule of thumb can be applied. Shielding materials with a low Z-value cause less Bremsstrahlung. Such materials are Perspex or aluminum (mostly Perspex, as it's see-through, and has an even lower Z-value). Bremsstrahlung causes a loss of energy, which is released as a photon, usually in the X-ray range. β emmitters are usually stored in a perspex container in a lead container. Perspex is often used a a mimic for tissue.

Gamma

For γ and X-rays, the material cannot stop them entirely but rather attenuate them. It depends on the energy of the radiation, and the density of the material (or rather Z value, the highest Z-value attenuates the most). The attenuation can be calculated with:

$$I_d = I_0\ e^{-\mu d}$$

Where d is the thickness of the material and μ is the attenuation coefficient. After $d_{1/2}$, the photon intensity is halved:

$$d_{1/2} = \frac{ln2}{\mu}$$

Transmission is the ratio between the original intensity and the dampened intensity.

$$T = \frac{I_d}{I_0}$$

5.1.5 Inverse square law

Electromagnetic radiation is a Newtonian form of radiation, which means that it decreases in intensity by the square of the distance. This is because the intensity is the number of photons/sm^2, and the surface of a sphere increases with the square of the radius.

5.2 Dose

5.2.1 Definition of dose

An absorbed dose (D) is the absorbed energy per mass of matter. We use the Gray (Gy), equivalent to 1 Joule/kg.

5.2.2 Calculation of a γ dose rate

$$H = \frac{h(10)A}{r^2}$$

Where h(10) is the ambience dose equivalent rate/source constant, H is the dose rate, A is the activity, and r is the distance.
The h(10) is exclusive for nucleides with gamma emission. There's tables that can be used.

5.2.3 Rules of thumb

β radiation

The source of an A MBq source that emits a β particle of E MeV per decay event at 10 cm is

$$H_{skin} = 1000A(\frac{\mu Sv}{h}$$

γ radiation

The source of an A MBq source that emits a γ photon of E MeV per decay event at 30 cm is

$$H = 2A(\frac{\mu Sv}{h}$$

5.2.4 Dose reduction

1. Time $\rightarrow$ Work fast
2. Distance $\rightarrow$ Stay away
3. Shielding $\rightarrow$ Use shielding
4. Activity $\rightarrow$ Use the minimum needed

5.2.5 Buildup factor

The attenuation law assumes a narrow beam. However, that's not correct. Depending on the shielding material, there may be a lot of backscatter, which amplifies the radiation after the shielding. The build-up factor depends on the energy and the material, and it may need additional shielding to compensate. The buildup factor can be considerable, commonly factor 2-4, but even goes higher than 100.

Quantity	Symbol	Unit	Type
Absorbed dose	D	Gray (Gy)	Physical
Equivalent dose	H_T	Sievert (Sv)	Biological (Specific part)
Effective dose	E	Sievert (Sv)	Biological (Whole body)

Type of radiation	W_R
β	1
γ	1
X-ray	1
n	5-20
p	1.1-10
α	20

5.2.6 Dose and biology

Equivalent dose

The seriousness of biological tissue damage is also determined by the way that energy is disposed. It depends on the kind of radiation. α radiation has more ionizations per path length, so it does more damage than β or γ.

$$H_T = D * W_R$$

Where W_R is the radiation weighting factor, and D is the absorbed dose in Gray

Effective dose

It is a quantity used for comparison of risks. The effective dose is the radiation dose needed in homogenous total body irradiation to obtain the same risk.

$$\sum_T H_T \cdot W_T$$

Where H_T is the equivalent dose and W_T is the tissue weighting factor (See Table 5.2 in the book). W_T depends on the rate of division of the cells in each organ.

Dose Conversion Coefficients

To calculate the effective (committed = internal) dose after contamination (ingestion) with radionucleides, the following formula is used:

$$E_{committed} = A * e_{50}$$

E(50) is the effective dose received over 50 years after intake, and it depends on the chemical form, way of intake, and sometimes disease of the patient. The e(50) or DCC or $e_{inh/ing}$ is a coefficient that can be looked up on tables.

To calculate the effective dose after skin contamination, e(50) (Sv/Bq) and DCC_{skin} (mSv/s per kBq/cm^2) are used for contamination, h(10) is used for irradiation (μ Sv/h per MBq/m^2)

Chapter 6

Measuring methods

Principle of operation	Detector material	Detector type
Electrical charge	Gas	Gas-filled
	Solid state	Semiconductor
Luminescence	Solid/liquid state	Scintillation
	Solid state	Thermoluminescence
Chemical reaction	Photographic emulsion	Densitometer
Warmth	Solid/liquid state	Calorimeter
Activation	Solid state	Activation dose meter

The purpose of measuring is to determine the type of radiation, the activity, the energy of the radiation, or the (effective) dose or dose rate.

6.1 Principles of radiation detection

6.2 Ionization/Electric charge

6.2.1 Gas-filled detectors

Gas-filled detectors have a closed tube that contain air or another gas. When radiation enters the tube, ionization occurs. The walls of the detector have a voltage between them, which separates the ions, and this can be measured through the current. The current is proportional to the primary electron-ion pairs, which is proportional to the absorbed amount of energy. However, these detectors have a a recombination region (Applied voltage $<$ Saturation voltage), in which they can work. Above the saturation voltage, there's the saturation region, in which the detector can't detect more because all formed ion pairs can reach the electrodes, and cannot recombinate. They consist of a tube with very thin membranes at the end (protected by a mesh or bars).

Ionization chamber

They produce very small electrical signals. They aren't used in pulse mode to detect indiviual counts, but rather used for radiation intensity. They are most suited to detect radiation with high energy deposition (α or β), or with high energy, but it's not efficient for γ rays. It can be used as a dose calibrator to determine the amount of radioactivity of a known radioisotope.

Proportional counter region

At sufficiently high voltage, the accelerated primary electrons have enough energy to cause ionization themselves and form secondary electron pairs (cascade).
The proportional counter uses the proportional counter region. It produces larger electrical signals than the ionization chamber, so it is used in pulse mode to detect individual counts. The electrical signal is proportional to the amount of deposited energy, so it can be used for energy selective counting. It's most suited to detect radiation with high energy deposition (α and β), and though it can detect γ, it's not as efficient. It can be used as a contamination monitor.

Geiger-Müller region

Similar to the proportional counter region, but even more. This is called the avalanche. At high voltage, emission photons are created, which can interact with gas, creating even more electron-ion pairs. The avalanche is stopped when a large number of 'slow' positive ions reduces the effective voltage, and the electrical charge becomes independent of absorbed energy.
The Geiger-Müller counter uses the Geiger-Müller region. It produces larger electrical signals that can be easily measured with low cost electronics, so they are used in pulse mode. The electrical signal is independent of absorbed energy, so it's not used for energy-selective counting. It's inefficient for γ rays, but it's more sensitive than the ionization chamber and the proportional counters. They are used as survey monitors.

6.2.2 Semiconductors

They work in a similar way to the gas-filled detectors, but they're more efficient for X- and γ-rays, given their higher stopping power. The energy needed to create a single electron-ion pair is much lower than for air, so a larger electrical signal is produced.
Individual counts can be measured with a very high energy resolution, which produces an energy spectrum, which is a 'fingerprint' that is used to identify radio-isotopes.
In order to suppress noise they must be cooled, so they are immovile and very heavy.

6.3 Luminescence

6.3.1 Scintillation

They work through scintillations. This means that a photon is released in the UV or visible-light range when an excited electron returns to its ground state. The produced amount of light is proportional to the amount of energy. But this energy can be very small, so a photomultiplier tube is used by converting scintillation light to pulses of electrical current. The most common cathode is sodium iodide, or not as commonly, another salt. Radiation enters the crystal, and photons are released as a result.
Solid materials can be used, such as NaI or CsI (for γ radiation), or anthracene or stilbene (plastics, used for α and β radiation). Organic liquid materials can also be used to detect α or β radiation (a small amount of sample is put in the liquid), and it's best used for low-energy sources, as it's often the only way to check for contamination (with swipe or smear tests).
Scintillation can also be used to identify materiials, although they have a lower resolution than semiconductors.

6.3.2 Thermoluminescence

It is often used in personal dosimeters. The thermoluminescent detector is made from a material that can emit photons upon heating after exposure to ionizing radiation. Therefore, it 'captures' radiation, and releases it when it's heated.

6.4 Efficiency

No detector is 100% efficient. This is because even if the detector was perfect, you'd only be measuring by one side. The measurement efficiency depends on detector efficiency, geometric efficiency, the source, and the absorption between the source and the detector. The efficiency can be determined by measuring a source with known activity.

$$\epsilon = \frac{R_{net}}{A} = \frac{R_{gross} - R_{background}}{A}$$

Where R<A, R being the count rate, and A being the actual activity.

6.5 Counting statistics

Chapter 7

Biological Effects

7.1 Effects of radiation on cells

Everything in the cell is a possible target. However, the biggest risk is the nucleus, and its DNA. This is because it can create DNA damage, such as base damage, cross-links, single/double strand breaks. In oncology, double strand breaks are needed to treat cancer. 1Gy of LET X-rays produces 1000 single-strand breaks, 40 double-strand breaks and 1000 altered bases.

7.1.1 DNA repair

Cells have a lot of repair mechanisms. Double-stranded breaks can cause many errors due to non-homologous end-joining. NHEJ cuts corners for the sake of speed. Single-strand breaks are easily repaired, in a couple of minutes after irradiation, 80% of breaks are repaired. Double-strand breaks take much longer, taking hours for the same 80% of breaks being repaired.

7.1.2 Stochastic effects

Chance is proportionally related to the dose. There's no threshold, any exposure is any damage. It can cause cancer or congenital defects. There may be a latency period. This is based on the multiple hit theory (multiple 'hits' are needed to cause cancer). The multiple hit theory says that multiple genetic changes are necessary. Oncogenes (such as Ras) are needed to quickly proliferate cells. Tumour supressor genes (such as p53 or RB1) are needed to prevent mutated cells from dividing. DNA-repair genes (such as HNPCC or BRCA) are needed to to repair the DNA. Leukemia is a more immediate form of cancer (around 10-20 years), but most other forms of cancer take at least 15 years.
However, electromagnetic radiation usually only makes around 5-7% of the carcinogenic factors. This also includes the sun's radiation, radon gas from working inside (radon is formed in the same rocks that are used to make buildings). Cancer is a multi-factorial risk, so it's difficult to tell the cause of the cancer. However, risks can be estimated by having large groups of exposed and non-exposed individuals, knowing the exact dose everyone received, and having a big difference with background radiation. One example of research was the one done after Hiroshima and Nagasaki. They had over 85k subjects in the cohort, and it has been running since the atomic bombs. The subjects get questionnaires, medical checkups, etc. yearly. Using the position where everyone was in the city when the bombs hit, the dose was estimated, which ranged from 0.01 to 6 Gy. By this life span study, they found that stomach cancer had an excess risk. There was also an increased chance of lung cancer, due to inhaling fallout. In general, per whole-body 1Gy dose, cancer risk increased by 47%. For those who received over 2 Gy, 56% of cancers were caused by that dose. The age also increases the effect of the cancer. The younger at which you're exposed, the higher the chance of cancer.
The risk of malignancy was set to 5%/Sv for 'civilians', and for workers 4%/Sv. This is because in 'civilians' it's usually because of accidents, with a high dose at once; while in workers it's a lower dose spread through many years, which is more repairable.
Cancer is not the only type of stochastic effect. There's also genetic effects, which are hereditary. This damage is induced before conception, and may skip several generations. It is therefore difficult to study these effects in humans, so we only have animal studies. The studies also only use high doses (>0.5 Gy). A linear dose-effect relation without threshold is assumed. Only the damage in live births is accounted for. One such research was the MegaMouse project (>7000 mice). They looked at 6 types of hair colour and stunted ears. They found that not all the mice were equally sensitive, that repair time before procreation decreased the mutation frequency, and that there was a dose rate effect (high dose rate causes more damage than a low dose rate). From those experiments, there was a risk number of 1%/Sv and a high spontaneous incidence of 10-20% of genetic effects. The individual genetic effects are low.
Radiation during pregnancy is quite risky. The later the fetus is, the lower the risk to it is. During the preimplantation period (0-10 d), cells are pluripotent, so they can replace each other. Any damage results in apoptosis. It's an all-or-nothing effect, if the fetus survives, the child will not have effects. If not, the period will occur normally. During the organogenesis period (3-8 w), congenital malformations may occur. The effects are deterministic, with a threshold dose of 100 mSv. During the fetal period (8-25w) there's a growth delay, which may cause mantal retardation with a threshold dose of 100mSv, and after that a 10-40% chance per Sv, with about 30 IQ points loss per Sv. The childhood malignancy is at 6%/Sv. There's an increased risk of adult malignancy in life (2-3x). The fetal sensitivity is highest during the 1st trimester. With a dose below 100 mSv, the stochastic effects are unlikely, and there's no

harmful tissue reactions. A dose above 500 mSv justifies abortion, as the risks are too high. The law sets an absolute limit from notification until birth of 1 mSv.

7.1.3 Deterministic effects

Deterministic/harmful tissue reactions depend on the dose. It takes a certain dose (threshold dose) to see effects in a certain amount of people (5% of people see the effect). Below the threshold dose, the effects are unlikely. However, the sensitivity depends on the person, based on how fast their cells repair DNA. It seems like this resistance does not always transmit to the cancer.
With stochastic effects, even with a very low dose, there is a possibility of cancer, even if very small. It is a very cautious approach. That's why the dose given to the general population should be as low as reasonably achievable. The higher the cumulative lifetime dose, the higher the chance of getting effects (cancer or hereditary effects). However, it is a binary effect: you get cancer or you don't, regardless of dose.
DNA damage can cause cell death (resulting in the loss of organ function or sterility - harmful tissue reactions/deterministic effects), mutations (resulting in cancer or hereditary defects - stochastic effects), or repair.
Acute harmful tissue reactions can be seen immediately or delayed. Immediate reactions are mainly cell loss, followed by an inflammatory response. Cell loss can result in anaemia, neutropenia, thrombopenia, epidermolysis, hair loss, ulceration... The following inflammatory response can result in mucositis, cystitis, enteritis, encephalitis, erythema, periostitis, keratitis... Late harmful tissue reactions can include atrophy, damage to blood vessels, chronic inflammatory reactions, fibrosis, sclerosis, necrosis... The effects vary by organ, as they have different sensitivities.
One famous case of carelessness is that of two interventional radiologists, and two nurses in 2 hospitals in Spain. They all developed cataract in both eyes, within two years. They were completely unknowledgeable about radiation protection. They didn't wear enough protection. There was no overhead shielding. They reached 0.45-0.9 Sv/y for several years.

7.1.4 Dose limits

In normal work, no harmful tissue reaction will be seen. There's dose limits which are set well below the damage threshold. The responsability of protection falls on the institution, not the worker. For 'civilians', the limit is 1 mSv/y. For radiation workers, the limit is 20 mSv/y. The damage is first seen at 2000 mSv.

Chapter 8

Risks and Risk Perception

8.1 Ways of radiation exposure

Average yearly dose per person in the Netherlands

1. Medical applications (1-1.2 mSv) - Medical diagnostics (X-ray, CT, PET, SPECT)
2. Radon in housing (0.64-1.37 mSv)
3. Food (0.43 mSv) - Vegetables, meat and fruit have ^{40}K, ^{210}Pb, and ^{210}Po. Fish have ^{137}Cs
4. Building materials (0.34 mSv) - Concrete and sheet rock have ^{226}Ra, ^{232}Th, and ^{40}K.
5. Cosmic radiation (0.22 mSv) - Mostly charged particles (P^+ and e^-)
6. Terrestial radiation (0.03 mSv) - Depends on the soil type (Granite has ^{238}U)
7. Air traffic (increased cosmic radiation) (0.04 mSv)
8. Radiation from atomic bombings (<0.01 mSv)

Total 2.8 mSv per year. Zuid-Limburg has a lot more background radiation than most of the Netherlands, due to higher amount of radon in residential houses. Mountain ranges tend to have higher background radiation. However, as far as science knows, radiation does not seem to have an effect in life expectancy. Belgium has a higher amount of Radon because it's on top of a lot of granite deposits. In Belgium they also do a lot more CT than the rest of the world. In the US, if you can afford it, they give you a lot of CTs.

8.2 Risks and effects of ionizing radiation

Ionizing radiation is harmful for the exposed individual, as well as for the individual's offspring. It causes short and long-term effects. We know it's dangerous because of history (Radium girls, Radithor, X-ray shoe fittings, radioactive toothpaste...). However it does have a few benefits, from medical diagnostics to safety.

8.2.1 Effects

After Hiroshima and Nagasaki, Leukemia peaked around 10 years later, and all-type cancer around 35 years later. There's a dose-effect relation. We work with low amounts of radiation, through a long time of exposure. The Life Span study has drawbacks: it was a high dose rate at a short time of exposure, it was a total body exposure, and it was a specific type of exposure. This makes it difficult to use to calculate risks associated to work. Per Sievert of total body exposure, there's a 4-5% of developing a fatal cancer. Per Sievert of exposure to the gonads, there's a 1% chance at developing severe genetic damage in the offspring.
Hormesis is the beneficial effects due to low levels of radiation (homeopathic). There's no scientific proof (yet). The accepted model is the linear-no threshold model (any radiation is harmful).

8.3 Risk perception

Public perception is quite negative, and it is mostly affected by a few accidents. Radiophobia is an unfounded perceived risk.
MUMC+, UM and Maastro produce a lot of radioactive waste. Risk perception about radiation is much higher than it should be.

Expert	Layman
Based on evidence	Based on emotion
Nuanced decision	Binary decision
Weighing aspects	Binary decision
Relative risk	Specific events
Averaged over the population	Personal consequences
High level of understanding	Low level of understanding

Chapter 9

Legislation

9.1 Formation of legislation

The ICRP makes recommendations. The Euratom turns them into guidelines, which are the basic safety standards. EU guidelines get made from that, which is the obligatory legislation for each member state. Finally, members tweak those rules and set higher standards. This process can take 18 years.

9.2 Radiation protection

The ICRP issues three main principles:

1. Justificate why radiation is used, weighing advantages and disadvantages
2. Limit the risk at chance related effects to acceptable levels
3. Prevent the occurrence of tissue reactions

This translates into

1. Justification
2. ALARA (As Low As Reasonably Achievable)
3. Dose limits

9.3 Dutch Law

Licenses are needed, which are issued by the ANVS. There are three types of licenses in the Netherlands:

1. Single license (1-10 sources or devices), such as industry or dentists.
2. Collection license (>10 sources or devices), such as small medical centers.
3. Complex license (many complex and diverse actions, many sources or devices). UM, MUMC+, Maastro Clinic, Maastro Proton Therapy BV, and Brightlands Incubators Maastricht BV have one complex license.

9.3.1 Complex License Randwyck

A Radiation Protection Unit is obligatory. This unit manages the license, issues internal permits, and acts as a supervisor on behalf of the entrepeneur. The General Coordinating Expert is mandated by the boards of all institutions.
The complex license randwyck is licensed to 5 locations, with a maximum of 115 X-ray devices, 5 linear accelerators, 1 cyclotron, 35 laboratories, 20 GBq of sealed sources... a maximum of 200g of fissionable materials, a maximum of 600 Re_{inh} (Radiotoxicity equivalent, inhaled), storage of solid and liquid (25 kL) radioactive waste.

9.3.2 Inspection

Compliance is enforced by inspections by different departments.

9.3.3 Protection of employees and environment

Classification of employees

- Category A employees - Interventionists (60). Have active monitoring.
- Category B employees - Mainly researchers (400). Have active monitoring.
- Category C employees - Such as transport employees, and some researchers (700). No active monitoring, but have risk exposure.

- Members of the public - Includes employees that aren't exposed at all to radiation.
- Pregnant employees - Dose limit of 1 mSV to the abdoment from the moment of announcing the pregnancy until birth. Regular tasks within the allowed exposure can be continued, though other tasks may be assigned after risk analysis. There are no reduced dose limits when trying to become/get someone pregnant.

Dose limits

See table in slide 15. The eye lens is especially sensitive to radiation, and with a few mSv, cataracts can be developed.
In case of radiological emergencies: out of free will, employees can receive up to per emergency (but it doesn't count towards the yearly limit):

- Employees that act as public safety officers - 100 mSv
- Employees saving important materiaitemizeic interests - 250 mSv
- Employees saving lives - 500 mSv

Dose restrictions

There's the legal obligation to implement dose restrictions. Those are the target value for the maximum dose for an employee. Those must be reaitemizeic, and based on risk analysis. These are lower than de dose limit, which differs for each internal permit, and can be adjusted when necessary. Those aren't hard targets, but rather soft internal goals.

Dosimetry

Monitoring the exposure of individual employees is a legal obligation. Specific dosimetry is needed for specific jobs. There are multiple types of dosimetry devices.

- Photon TLD badge
- Neuron TLD badge
- Photon/Beta TLD badge
- Ring TLD badge
- Electronic Personal Dosimeter (EPD)
- OSL badge (similar to PTLD, but improved)

A personal dosimeter is exchanged every month, results are available 1-3 months later. It must always be worn when working (not needed in the office), worn at chest height, and on top of the lead apron. It shouldn't be taken on airplanes, and the must be handed in on time (and not lost). The risk analysis is leading.

- Category C, no personal dose monitoring needed
- Category B employees wear a personal dose monitor, depending on the type of work. A yearly (and start and end) mandatory routine questionnaire is done. Eye and blood tests are optional.
- Category A employees wear a personal dose monitor, depending on the type of work. A yearly (and start and end) mandatory routine questionnaire, eye and blood tests are done.

Storage facility for dispersible radioactive substances

- Dose rate may not exceed 1 μSv/h at 10cm,
- Fire resistance of at least 60 minimum (fire should not go in)
- Access is restricted to authorized personnel

Classification of work areas/zones

- Supervised zones (1 mSv/y < zone < 6 mSv/y - Categories A, B and C)
- Controlled zones (6 mSv/y < zone < 20 mSv/y - Category A only)

Work areas must be marked with safety signs and symbols. In case of emergency, the risks will be indicated before entering the room. If the dose rate is higher than 10μSv/h an extra sign must be displayed.
Room classification comes with requirements:

- Ventilation
- Equipment, such as a fume hood or detectors
- Finishing of materials (easy to clean)
- Organizational measures
- Changing rooms and specific clothing
- Room pressure must be below ambient pressure
- Fire safety

Maximum permissible activity

There's a maximum permissible activity in radionucleide laboratories. This can be calculated using a mathematical method, based on the risk of inhalation. Check pages 192-193 of the book.
The p factor is the chance at dispersion, which dictates the chance at inhalation/exposure.
The q factor is the lab classification, a parameter assigned to a type of laboratory.
The r factor is the ventilation factor, which depends on where the radioactive substance is being manipulated.
The load factor for working areas must be below 1. If the load factor approaches 1, you must change rooms. In the RNL there's multiple labs with multiple different purposes.

Transport regulations

All vehicles must comply with the same regulations. For external transport, they must have proper packaging, labelling and shielding. Only certified couriers are allowed to bring it, and they must follow ADR-7. For internal transport, only proper packaging, labelling and shielding is needed, but public roads cannot be crossed, so they are bypassed by using tunnels or bridges. A label is needed depending on the transport index TI and activity. It's based on the dose rate.
Internal transport must have proper packaging, labelling and shielding. The dose rate must be as low as possible. There's set routes through the buildings. There must always be permission from the sender and the receiver. Public roads must not be crossed. A trolley or other transportation device must be used. Elevators are a point of conflict.

Occupational exposure

May be external irradiation or internal contamination (inhalation of gases or aerosols, ingestion, sharps injury or wound contamination -from dispersible sources-). For external irradiation time, distance, and shielding must be considered. **ALARA** must always be applied.
The legal maximum allowed contamination is 0.4 Bq/cm^2 for α-emitters, or 4 Bq/cm^2 for β/γ-emmiters.

Chapter 10

Risk Analysis

10.1 Risk analysis

10.1.1 Why draw up a risk analysis?

A risk analysis is drawn up to identify the riskiest parts of the job. It is mandatory by law. It must be drawn up before working with or employees being exposed to sources of ionizing radiation, prior to performing the actions. The risk analysis includes employees working with sources of ionizing radiation, other employees, visitors, and environment (site boundary). It does not include patients. It is used as an up-to-date quantification of the (possible) exposure.

10.1.2 Who draws up a risk analysis?

It is drawn up by the Radiation Protection Officer (RPO/TMS) of each laboratory. The reasercher supplies all necessary data. It's essential for the Local Internal Permit at our RNL.

10.1.3 What does a risk analysis look like?

The legal framework defines required components, such as regular exposure and potential exposure (Forseeable but Unwanted Events: such as a small spill, subjects not behaving -mouse may bite you, a sheep may vomit or poop-. It's dependent on probability, frequency, and danger). It is required to calculate the exposure for non-exposed employees, the exposure at site boundaries, and the load factor for all actions within a specific laboratory.

Dose limits for employees

See table on slide 7. Must be memorized.

Load factor for rooms

The classification of actions is based on the risk of internal contamination:

- Chance of spreading → Dispersion parameter p
- Type of laboratory → Laboratory parameter q
- Type of ventilation → Ventilation parameter r

See table on slide 9.

$$A_{max} = \frac{0.02 \cdot 10^{p+q+r}}{}$$

10.1.4 Site boundary dose limit

The cumulative dose at the site boundary should be < 40 mSv/y. At Randwyck, there are 4 points where it can be checked. All of the radiation is contained within 3 buildings (UNS50, MUMC+, and Maastro). There are exclaves in Venlo.

10.1.5 Important points

- Be clear in the steps that the researcher needs to take
- Decide which steps are critical (based on exposure)
- Define which employees are helping in some steps
- Think about reducing exposure: can something be changed (time, distance, shielding)?
- Can different equipment be used?
- Can the experiment be performed in an alternative way?
- Always choose the most conservative point.

10.2 Interactive case study: animal research with dispersible radioactive substances

10.2.1 Part 1

What information is missing?

- Is the fume hood formally tested? → Assume fumehood not formally tested.

What information is unnecessary? What information is important?

- 10 mice, 8 scans per mice (twice per week) = Total of 80 scans
- Each mouse gets 5 MBq per scan = Total weekly 100 MBq = Total of the whole study 400 MBq
- Everything takes places in a B-lab.

Part III

Book

Chapter 1

Structure of an atom and decay

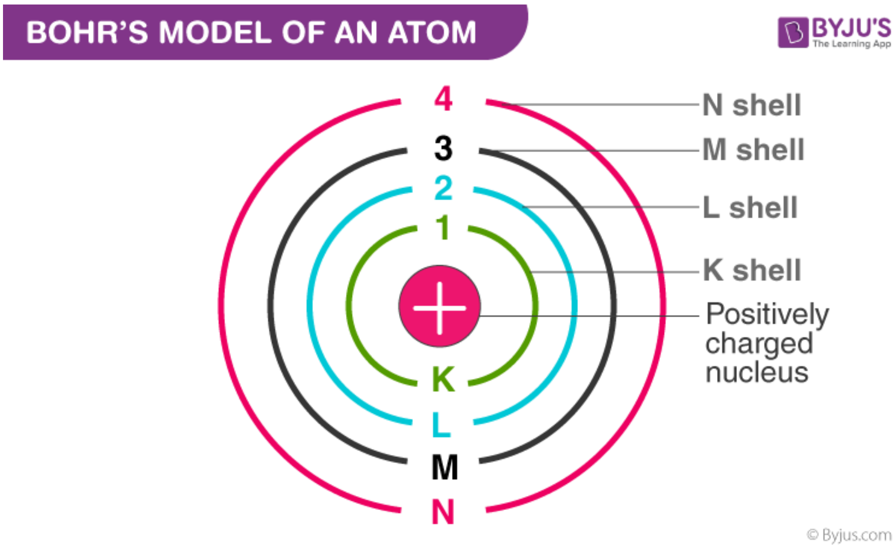

Figure 1.1: Structure of an atom

1.1 Structure of an atom

An atom of X element has Z number of protons, N number of neutrons [n(0)], and a mass (A) of Z+N. An element can be expressed as ${}^{A}_{Z}\mathrm{X}$

.

1.2 Stability of atomic nuclei

1.3 Radionucleides

Some elements only exist as a radionucleide. Some elements exist with a very minute fraction of radioisotopes. There are also many artificial radionucleides.

1.4 Activity and specific activity

The nucleus of an unstable nucleide decays spontaneously to another nucleide (disintegration). Not affected by temperature, pressure, etc. Which nucleus will decay isn't predictable, but on average, it will decay. Activity is the decrease in radioactive nuclei per time.

$$A(t) := \frac{dN(t)}{dt}$$

The activity is expressed in Bq (1 disintegration per second).
Prefixes are used: k (10^3), M (10^6), G (10^9), T ($10^1$2), m (10^-3), μ (10^-6), n (10^-9).

1.5 Electromagnetic radiation

Both a wave and a particle. The energy is expressed in J, or eV. $1\ eV = 1.6 * 10^{-19}\ J$. The binding energy of electrons on the outer shell is ≈ 30 eV. Photons and particles released are expressed in keV or MeV. X-rays are usually between 10 and 100 keV, while γ radiation is usually between 100 and 1000 keV.

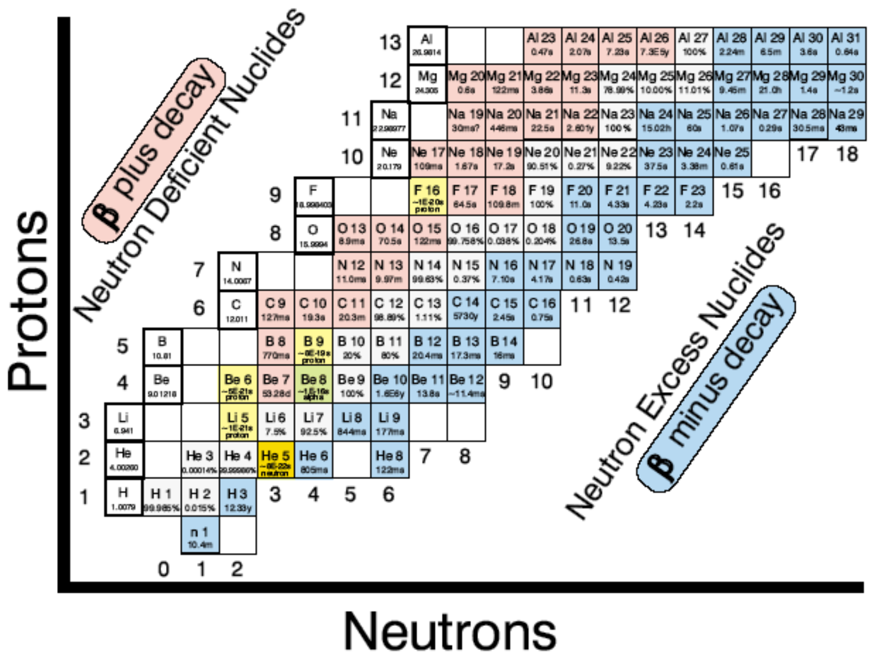

Figure 1.2: Chart of Nucleides

1.6 The radiation and the particles released during decay

1.6.1 α decay

Occurs when the nucleus is unstable, due to being too big. The parent atom ${}^{A}_{Z}X$ gets split into a daughter atom ${}^{A-4}_{Z-2}Y$ and an alpha particle ${}^{4}_{2}a$.

1.6.2 β^{-} decay

Occurs when the nucleus is unstable, due to having an excess of neutrons. The parent atom ${}^{A}_{Z}X$ gets split into a daughter atom ${}_{Z+1}^{A}Y$, a beta particle ${}^{0}_{-1}e^{-}$, and an anti-neutrino $\overline{v}_{e}$.

1.6.3 β^{+} decay

Occurs when the nucleus is unstable, due to having an excess of protons. The parent atom ${}^{A}_{Z}X$ gets split into a daughter atom ${}_{Z+1}^{A}Y$, a positron ${}^{0}_{+1}e^{+}$, and a neutrino v. After a number of interactions, the positron $\beta+$ unites with an electron and converts its entire mass to energy. This annihilation produces 511 keV.

1.6.4 Electron capture

The nucleus absorbs an electron from the electron cloud (usually from shell K -innermost). The parent atom ${}^{A}_{Z}X$ absorbs an electron ${}^{0}_{-1}e^{-}$, and gets split into a daughter atom ${}_{Z-1}^{A}Y$, and a neutrino v.

1.6.5 Gamma decay (γ)

Occurs when the atom is excited. The parent atom ${}^{A}_{Z}X\cdot$ gets excited and produces a daughter particle ${}^{A}_{Z}X$ and a gamma ray γ^1. Internal conversion may occur (direct transfer of the energy of the nucleus to an electron).

1.6.6 Internal conversion (IC)

Instead of γ decay, internal conversion can occur. This is the the direct transfer of energy of the nucleus to an electron. The electron (conversion electron) is ejected from orbit with large energy, and can be detected as a β^- particle, but with a sharply defined energy (unlike β^-, who share with neutrinos). Otherwise, can be considered a β^- particle. This leaves a gap in the electron cloud, becoming unstable

1.6.7 Follow-up processes: characteristic X-rays and Auger electrons

After the nucleus transfers energy to an electron or captures an electron, a vacancy is formed, filled by an electron a shell further away from the nucleus. The difference in binding energy causes the emission of characteristic X-ray spectrum (there's one emission per electron that descends = as many as electron shells there are). Due to this, other electrons may be ejected, known as Auger electrons.

1.7 Parent-daughter relations

After decay, the daughter nucleide may also be unstable. If the half-life is shorter, it's called "ingrowth of activity" (total activity grows). This must be taken into account.

1.8 The time sequence in the decay processes

An instable nucleide may have more than one decay process. Decay schemes explain graphically the decay. Parent level (top level), daughter level (bottom level), disintegration energy between them (Q). Increase in Z-value = right arrow; decrease in Z-value or EC = left arrow.

Chapter 2

Definitions and overview of applications

2.1 Definitions

Radiation sources: entities that may cause exposure, including radioactive, X-ray, and accelerators. Some States call them **Sources**.

Radioactive substances: any substance that contains one or more radionuclide in the activity or activity concentration of which cannot be disregarded from a safety point of view.

Radioactive sources: radiation source incorporating radioactive material for the purpose of utilising its radioactivity. Include sealed and dispersible sources.

Sealed sources: the radioactive material is PERMANENTLY sealed in a capsule or incorporated in a solid form to prevent under normal use the dispersion of radiation.

HASS/HAS-bron: High Activity Sealed Source/Bron. Have additional regulations.

Open/dispersible/unsealed sources. there's a chance of dispersion.

X-ray equipment: equipment that can emit ionising radiation but doesn't contain any radioactive source, fissile material, or ore. When the equipment is off, no radiation is produced.

Fissile material: substances containing some percentage of uranium, plutonium, thorium, or other designated elements.

Ore: contain at least 10% uranium or 3% thorium, used for their fission or fertile properties. They are more regulated. Some substances, such as uranyl acetate (electron microscope stain) is considered a fissile material. Other States may use other definitions

Sources of natural radiation: may originate in the Earth or Space. Also known as NORM (Naturally Occurring Radioactive Material). Fewer regulations apply, unless used for their radioactive properties.

Artificial sources: sources with man-made radioactive substances.

2.2 Overview of applications

About 7500 licenses are granted in the Netherlands.
Academic hospitals (8 licenses) have the most extensive licenses, concerning X-ray equipment, some sealed sources, and most of the open sources in the Netherlands.
HASS are used in 4 companies that carry out non-destructive testing.
Less strong sealed sources are used in measurement and control technology.
Open sources are mostly used in radionuclide laboratories of universities or research institutions.
X-ray equipment is used in over 250 academic and non-academic hospitals and outpatient clinics, 4700 dental practices and 2400 veterinary practices.

Chapter 3

Interaction of radiation with matter and shielding of radiation

3.1 Interaction of β radiation

β radiation has a spectrum between 0 and $E_{\beta,max}$. β particles have an energy between 0 and $E_{\beta,max}$. They can be absorbed by 4 types of interactions.

3.1.1 Elastic collisions

It can collide with an electron that is strongly bound to the nucleus, without ejecting it from the orbit. The β particle will bounce, without any energy transfer or loss, but a change in direction. This causes the particle to follow a winding path.

3.1.2 Inelastic collisions

In an inelastic collision, an electron is shot away from the electron shell, creating an ion. A β particle has about 500x fewer ionisations per volume. Therefore, the energy is lower, but the range is higher.

3.1.3 Bremsstrahlung

When a moving electrically charged particle enters an EM field, its trajectory is deflected. This causes some energy loss, braking radiation. The higher energy of the particle and the stronger the field (Z-number), the higher this effect is. It is approximately:

$$g \approx 2 \cdot 10^4 \cdot Z \cdot E_{\beta,max}$$

Perspex blocks well, and causes low Bremsstrahlung.

3.1.4 Čerenkov radiation

For a β particle with energy >250keV, the speed approaches the speed of light. In water, a high energy particle may travel faster than light, emitting energy in the form of photons in the blue to violet region. The light may be visible to the naked eye. This does not slow the particles much.

3.1.5 Annihilation (β^+)

Occurs when a β^+ particle collides with an electron at the end of its path. They both get converted to 2 photons of 511keV each.

3.2 Interaction processes of X-rays and γ radiation

See section 3.5 of book.

3.3 Shielding of β radiation

The range of β radiation can be calculated with

$$R_{\beta,\ in\ material} = \frac{R_{\beta,\ in\ water} = 0.5E_{\beta,max}}{\rho_{material}}$$

For water and tissue, ρ can be estimated to be 1 g/cm³. $E_{\beta,max}$ is expressed in MeV.

3.4 Shielding of a narrow beam of X-rays and of γ radiation

We are ignoring scattering/buildup.

$$I(d) = I(0) \cdot B \cdot (\frac{1}{2})^{\frac{d}{d_{1/2}}}$$

Buildup factor (P60) may often be ignored. All distance units must be in the same unit. The buildup factor increases with increasing half-thicknesses. With lead, it won't exceed 5 if <14 half-thicknesses are applied. For ther materials, it can reach >20.

$$I(d) = I(0) \cdot e^{-\mu_{linear} d}; \mu_{mass} = \mu_{linear} \cdot \rho_{material}^{-1}$$

Above 500keV, $\mu_{mass\ water} \approx \mu_{mass\ concrete}$.

Chapter 4

Quantities and units in radiation protection

4.1 Quantities and units describing the risk

4.1.1 Absorbed dose

The absorbed dose (D) is the energy absorbed per unit mass. The unit is the Gray (Gy), which equals 1 J/kg. 1 Gy $\approx$ 100 Röntgen. The absorbed dose rate is Gy/h.

4.1.2 Equivalent dose

The equivalent dose depends on the type of radiation.

$$H_T = W_R \cdot D$$

Where H_T is the absorbed dose for tissue and organ, W_R is the radiation weighting factor (1 for β and γ, 20 for α particles, and 2-20 for neutrons. Its unit is the same as for absorbed dose, but is called Sievert (Sv).

4.1.3 Effective dose

An equivalent dose for the whole body correlates with a higher risk than an equivalent dose in a part of the body. This is what the Effective Dose is for. It gives an approximation of the total body dose. The equivalent dose for each tissue is multiplied by a W_T tissue weighting factor.

$$E = \sum W_T \cdot H_T = \sum W_T \cdot W_R \cdot D$$

4.1.4 Committed dose

After an intake of radioactive substances in the body, tissues will be irradiated. The equivalent dose caused by this is calculated with the committed equivalent dose $H_T(50)$ (50 = summation period of 50 years for adults).

$$E(50) = e(50) \cdot A$$

Where e(50) is the committed dose coefficient. These coefficients vary, and depend on the rate of excretion, physical decay, and uptake paths. Some substances can enter the body in different ways, so there's different e(50) for inhalation, ingestion and inoculation.

4.2 Quantities and units in measurements

Measurements are often not fully accurate, and approximations are taken.

4.2.1 H*(10) and H*(0.07)

A phantom is an object that mimics the human body, in this case, a sphere of diameter 30cm. A measurement of the equivalent dose is done at a depth of 10 mm in the phantom, which is a good estimate of the effective dose of a human standing in a parallel incident radiation field. The H*(10) is based on this, and it's called the ambient dose equivalent (Sv). Below 100 keV, this causes an overestimation of E. For photons under 50 keV, this can lead to up to 5x overestimation. It's only a good measure for whole-body irradiation. If only part of the body is irradiated, it is a good measure for the equivalent dose to that part of the body. However, it's only aq good measure if the body is irradiated from front to back. If the irradiation is back to front, it causes a 30% overestimation. It is not a good equivalent for the skin dose, for which H*(0.07) is used.

Chapter 5

Radiation detection

5.1 Detector material

Depending on the material of the detector, different types of radiation can be measured.

5.2 Ionisation detectors

5.2.1 Gas-filled

The ionisation chamber

In the ionisation chamber, the applied voltage between cathode and anode is low, but large enough to prevent recombination of the electron-ion pair. If they recombine into a neutral molecule, no current pulse will be formed. If electron-ion pairs, they can be detected as an electric pulse. It's rarely used, as it is tricky to process the data. It may be used when the dose rate is very high.

The proportional counter

Using a higher voltage causes a stronger electric field, in which the electrons are accelerated to such high energies that they cause new ionizations. As a consequence, the signal will be increased proportionally. The thin window allows for detection of α and β particles. To boost X-ray and low-energy γ radiation, a high-Z-value gas is used.

GM tube

The GM tube uses a higher voltage, and regardless of the energy, each incident particle will cause an avalanche of electron-ion pairs. It's useful for small-surface contaminations. It's mostly a qualitative (boolean) measurement.

5.2.2 Solid-state semiconductor detectors

These are very expensive to use, as they require tons of active cooling. However, they give a very detailed spectrum of energies released.

5.3 Scintillation detectors

5.3.1 Solid state scintillation detectors

Most notable is ThermoLuminescence Detectors (TLDs), used in personal dosimeter badges. The radiation is "stored" as electrons, and can be released with heat.

5.3.2 Liquid scintillation

Liquid scintillation is an organic solvent with an organic scintillator. The sample being dissolved in here helps it detect even extremely low energy samples.

5.4 Application of radiation detection in radiation protection

5.4.1 Identification of a source

Sometimes, the nuclide is unknown. When there's a limited number of possibilities, different shielding materials can be used to compare activity after half-thicknesses with theoretical values. The energy can be measured, or solid state detectors can be used to get a spectrum.

5.4.2 Determination of the activity

Activity can be estimated by holding the source in front of a contamination monitor. For more precise applications, various detectors can be used.

5.4.3 Determination of the dose rate

Dose rate from β and γ particles can be measured with a dosimeter.

5.4.4 Measurement of active contamination

Contamination monitors are used to determine whether radioactivity is present. These contamination monitors are much more sensitive than dosimeters. For small areas, simple GM tubes are used for β, while NaI crystals are used for γ. For α, ZnS scintillation detectors are used, though a swipe test and liquid scintillation count is more effective.
Proportional counters can be used for large surface contaminations. A Hand Feet Clothes monitor is used at the exit of the laboratory, to check whether there is contamination.

Chapter 6

Biological effects and risks of radiation

6.1 Effects at the molecular and cellular level

The DNA is the most important target for ionising radiation. The DNA can be ionised and damaged (See Chapter 3). DNA can be damaged through a single-strand, double-strand break, base or cluster (damage to closely spaced places, causing debris) damage.
Ionising radiation can also damage DNA and tissue through radical formation. Radicals can be formed in water: H and OH. Indirect DNA damage accounts for 2/3 of the damage, while direct damage only accounts for 1/3.
The cell can repair single-strand damage quite well, but double-strand break reparation often causes even more damage.
α radiation causes many ionisations close to each other, so double-strand breaks are common. It has the most harmful effect (x20).

6.2 Effects in humans

It can either be on the individual or on the offspring. On the individual:

6.2.1 Stochastic/probabilitstic effects

LNT. Random in nature, always has some probability of ocurring. They have no threshold dose, but the probability increases with increasing dose.
Example: cancer

6.2.2 Harmful tissue reaction/deterministic/non-stochastic effects

Takes place when enough cells in an organ have been killed. The dose needed to create an observable effect is the threshold dose. After exceeding the threshold, the severity of the effect increases with an increase of dose.
Example: erythrema.

6.3 Harmful tissue reactions

The severity of the effect increases with the dose. If the loss of functionality is not too serious, the recovery process will ensure the organ returns to normal (though it may take a long time and leave scar). If a dose is received over a longer period of time, more in-between recovery will take place and the long-lasting damage will be lower. It may appear immediately or after a latency period. Threshold doses are normally specified for conditions where the dose is received in a short period, with almost no recovery.
Threshold doses and latency periods can be seen in Table 6.1.

For a radiation worker in a diagnostic or research laboratory, the threshold cannot be exceeded, even in an incident, as the activity is too low. In medical applications, there may be damage if carelessness is present, and any threshold dose can be exceeded after an incident. For patients, the risk is greater, especially in radiotherapy. In industrial radiography, any threshold can be exceeded after an accident.

6.4 Stochastic effects

Data has been obtained through epidemiological studies such as: Hiroshima and Nagasaki, medical irradiation, radiation workers, Chernobyl and Fukushima, etc. Approximations* can be derived from that (*however, those approximations only apply to a select population: those healthy enough to survive the high radiation dose). This may underestimate the risk to the random group of all healthy and non-healthy people together; or it could be overestimated, and low doses can't be harmful because we're already used to them.
For the determination of risk, a LNT model (linear, no-threshold) is used. It means that a low additional dose also increases the risk of cancer a bit. There is plenty of debate in this topic.
The latency period is the period befor the cancer (late effect) becomes manifest. After the latent period,

a risk follows. The latency period depends on the cancer type. Leikemia has a short latency period of 2 years, and a maximum risk of 20; lethal tumors have a latency period of 5-10 years, and risk of at least 30 years. CVD has a latent period of 40 years.
It's estimated that the risk of lethal cancer for β and γ radiation, at low dose and low dose rate is 5.5%/sV. The risk of lethal cancer in women is 20% higher, due to breast and thyroid cancer. Children are also more susceptible, as they have a longer life expectancy. Their risk is 2-3 times the normal public. For workers, the risk coefficient is lower, at 4.1%/sV. This is because there's no children and usually it's healthier. However, not everyone is equally sensitive to radiation.
The probability of a non-lethal cancer is at around the same order of magnitude as the probability of lethal cancer.

6.5 Effects on offspring

Radiation acts as a mutagenic. The dose that the germ cells receive is called the gonad dose. The doubling dose (estimate from animal data) is the absorbed dose to the gonads that is required to produce as many hereditable mutations as those arising spontaneously in a generation (2x the mutations). No statistically significant effect, but estimated at around 1Gy at a low dose rate.

6.6 Effects on the unborn child

It depends on when the radiation exposure happens.
During the preimplantation period (first 10 days), upwards of 1 Gy will almost always lead to the death of the embryo. If they survive, it's unlikely they'll have mutations, as the cells can still differentiate.
During the organ formation period (10-40 days), failure or damage to cells can lead to organ malformations. The threshold is set to 100 mGy.
During the fetal development (the rest), the sensitivity lowers, but growth disorders and functional defects may happen. The threshold is set to 100 mGy.
The brain is separate. Irradiation during week 8 and week 25 leads to a decrease in IQ of 25-30 pts/Gy. In weeks 16 to 25, it's 1/4th.
It may be LNT, but it's effectively considered as deterministic.

6.7 Comparison with other risks

The risk of death can be compared to the risk of laboral deaths. The risk of radiation is much lower than the normal risk. With the legal limits, it is less risky than working with carcinogenic chemicals. The risk is much lower and can be managed.

Chapter 7

Regulations and ethics

7.1 Terminology

Exposed worker/Radiation worker Employee exposed to >1mSv/y.

Practices Everything that may increase one's exposure. Including storage.

RPO/TMS Technically competent in a specific branch of radiation protection. 9 groups: medical applications, dentistry, veterinary X-ray, nuclear fuel cycle, dispersible radiation substances, NORM, accelerators, industrial radiography, mesurement and control applications. See Annex 5.2 of Rbs for training requirements. Every company that works with ionising radiation must employ an RPO, RPO does not have to be recorded in a national register.

RPE Gives advice about radiation protection and is recognised by the State as an expert. They also have supervisory tasks.

Radiation expert RPOs and RPEs

Undertaking The person (or company) under whose responsibility a practice is carried out or a measure is taken.

Exposure situations Planned exposure situations, radiological emergency situations (immediate action), existing exposure situations.

Radiation incident An unintended event or situation or unintended spread of activity, in which there is or is danger of exposure to ionising radiation by public of >0.1 mSv, discharge to or into the soil, sewer, surface water or air above a specific level, or an exposure to ionising radiation of workers exceeding 2 mSv. This must be reported.

Anticipated and non-anticipated unintended event Whether it's in the radiation risk inventory and evaluation

Reporting obligations Radiation incidents + non-anticipated unintended events + anticipated unintended events if dose is higher than predicted.

7.2 The system of radiation protection

Justification The application must be justified, and no alternative non-ionising methods must exist. Pros and cons must be evaluated as individual and society (present and future). Annex 2.1 of Rbs includes justified examples. RPO and radiation worker won't notice justification, as license has also been granted.

ALARA/optimisation As Low As Reasonably Achievable. Even if the dose is already low, it should be lowered if possible. It concerns everyone, present and future. Dose constraints contain ALARA (not LIMITS, these are guidances). An undertaking must establish dose constraints below the limits, unless practice results in extremely low exposure. Dose constraing of 10 μSv as an annual dose for the public, 100x lower than the limit. ALARA is applied as a source-oriented strategy: examine whether a less risky source is possible, containing the source, shielding the source, increasing the distance between the source and the individual, and as a last step, personal measures. Reasonable = 1€ to save 10 μSv (QALY).

Dose limitation The limits are there to avoid too high a dose for an individual. They should not be used as a guide for a maximum permissible dose, they CANNOT be exceeded, and act as a safety net. See table in QRH for dose limits. The annual limit for Cat. A is almost never exceeded in the Netherlands. Dose limits do not apply to patients, or to an existing exposure situation, or to a radiological emergency, which are then reference levels. For existing exposure situations the limit is between 1 and 20 mSv/y. For emergencies, it is between 20 and 500 mSv, depending on the severity, the possibilities for taking protecive measures, and the role in the emergency response. In an emergency, anything over

100 mSv requires informed consent.

7.3 Regulations at the workplace

Before a new practice is carried out, a risk inventory and evaluation (Risk Assessment) must be carried out. Radiation risks during normal operations are considered, but also anticipated unintended effects (fire, loss of source, etc). The RPO will draft a concept, and the RPE will ratify it. The RA must be adapted when there's new developments, and at most must be revised every 5 years. Instruction must be given, including of all local protocols, as well as emergency protocols. Women need extra information.
Category A workers must receive a yearly medical visit by a registered medical radiation specialist, also before and after the employment, as well as yearly thereafter.
Category A and Category B workers must have a TLD badge or personal dosimeter. Category C **MUST? NOT HAVE IT**.
A controlled area is where it's possible to get $>$ 6mSv/y effective dose. A supervised area it's between 1 adn 6 mSv/y effective dose. If a dose rate of $>$ 10 μSv/h can occur, a special sign must be placed stating so. Class B laboratory and workplace with an accelerator are controlled. Classs C and workplace with X-ray devices is supervised. Category B workers can work in controlled areas in specific circumstances.
The storage facility must be fire resistant for >60 mins. The dose rate outside must be <1 μSv/h. The storage facility must be easy to decontaminate and a ventilation rate of 3x/h if dispersible sources are used.
TLD badges for Class A and B employees have their data recorded in NDRIS (National Dose Registration and Information System). This data must be kept until the age of 75 of the employee, OR AT LEAST 30 years after the termination of the work, whichever is longer. The badge is worn on the collar, mid-torso or waist with the label facing out; on top of an apron if it's worn. If the worker always wears an apron, the TLD company must take this into account, and a correction factor of 0.2 will apply only if the lead aprons are adequate, in the medical profession, and the voltage of X-ray apparatus is <125 kV.
Any information relevant for radiation protection must be kept in the Nuclear Energy Act File.

7.4 Regulations regarding security

The security category of a source is determined by the A (activity)/D-value. For an A/D <1, no special security measures are needed, but it's necessary to prevent loss, robbery, or dispersion.

7.5 Transport regulations

Any transport should be done by an ADR-certified carrier. The transport must be notified 3 weeks in advance to the ANVS; unless done by an ADR, in which case it's a yearly notification and no 3-week notice is needed; unless for fissile material, where a license is needed.

Packages (collo/colli). For an exempted package, the total activity and activity concentration are so low, no labelling is needed. The TI level must be specified, it's 0.1x (μSv) the radiation level 1m away from the collo. A safety label is needed:

1. I - White. Radiation level on collo surface <5 μSv/h.
2. II - Yellow. Radiation level on collo surface <500 μSv/h, >5 μSv/h, must not exceed 10 μSv/h at 1m.
3. III - Yellow. Radiation level on collo surface <2000 μSv/h (limit MAY be exceeded in some conditions), >500 μSv/h, must not exceed 100 μSv/h at 1m, but higher than 10 μSv/h at 1m.

Chapter 8

Dosimetry in practice

8.1 External irradiation by a radioactive source emitting γ radiation

The 10 H(10) refers to the depth in mm in a phantom (tissue equivalent)

8.1.1 Time

The duration of the exposure determines the ambient dose equivalent:

$$H^*(10) = \dot{H}^*(10) \cdot t$$

8.1.2 Distance

Radiation follows the inverse square law

$$\dot{H}^*(10)(10) = h(10) \cdot \frac{A}{r^2}$$

8.1.3 Shielding

For γ radiation, it applies that

$$I(d) = I(0) \cdot B \cdot (\frac{1}{2})^{\frac{d}{d_{1/2}}}$$

Therefore

$$\dot{H^*}(10)_{shielding} = \dot{H}^*(10)(10)_{raw} \cdot B \cdot (\frac{1}{2})^{\frac{d}{d_{1/2}}}$$

8.1.4 Full formula for the ambient dose equivalent rate

$$\dot{H}^*(10)_{\text{(at distance r, with shielding d)}} = h(10) \cdot \frac{A}{r^2} \cdot B \cdot \left(\frac{1}{2}\right)^{\frac{d}{d_{1/2}}} \tag{8.1}$$

8.1.5 Rule of thumb for γ radiation

$$\dot{H}^*(10) = 2A \approx \dot{E}$$

With A in MBq and $\dot{H}^*(10)$ in μSv/h. For $\dot{E}$, this is at a distance of 30cm from the source, without shielding.

8.2 Skin irradiation

8.2.1 Rule of thumb for external radiation of the skin by β (+ and -) radiation

$$\dot{H}^*(0.07) = 1000 \cdot A$$

This formula is for a source 10 cm away from the skin without shielding.
Where the 0.07 represents a depth of 0.07 mm in a phantom, representing the top layer of skin. The annihilation photons (β^+) have a negligible contribution.

8.2.2 Rule of thumb for external contamination of the skin by β (+ and -) radiation

$$\dot{H}^*(0.07) = 2000 \cdot A$$

With A units of kBq/cm^2.

Chapter 9

Safety measures for open sources

9.1 Introduction

All information in this section is for the RW (Radiation Worker). The RPO must monitor that these measures are taken. Radiation risks might concur as a result of conventional hazards, called anticipated unintended events. There are also non-radiation risks. Both types of risks are included in the Radiation Risk Assessment, and the General Risk Assessment.

9.2 Elaboration on the legal framework

Applications of open sources must be justified. ALARA must be applied. No dose constraints are set by the authorities (but may be set by the company), but the limits still apply.
There is no specific law aimed at open sources, general radiation laws apply.
A licence is almost always required when working with open sources, exemption levels don't matter, but clearance levels do.
A RA must be available before work starts, and new workers must be informed about radiation safety measures. For unusual applications, a separate RA and an internal authorisation are required.
Before the work:

- Verify that there is a license or internal authorization
- Check the maximum permitted activity with the pqr formula
- Make sure you are sufficiently informed about your work, risks, and mitigation measures
- Check which category of employee you are
- Consider reporting a pregnancy (NOT MANDATORY)
- Arrange your personal dosimeter
- Plan your work in accordance with source-oriented strategy
- Check thee facilities of your work (especially radiation detectors and fume hoods)
- Make sure you have enough time for your planned work
- If needed, practice "cold" at first

9.3 Reducing activity

The activity applied sometimes is high in order to obtain a quick and accurate result, but sometimes it's not needed. Counting overnight with less activity may be an option, or less accuracy. This is safer and cheaper. After preparing a work solution, the stock solution must be immediately returned to storage.

9.4 Containment

Measures must be taken to prevent dispersion as much as possible outside the containment. The activity should remain within the splash tray, and inside the RNL
An adequate splash tray must be available, and everything must be in place prior to the work. The liquid waste bottle or vessel should be in a sufficiently large drip tray.
Aerosol formation should be avoided. Vacuum pumps' oil should be checked if the cold trap is full or not large enough. Using dirty vials in Liquid Scintillation Counters may give wrong results. Centrifuges may be a source of contamination, as they're not always properly cleaned after leakages (warn RPO). Pipettes should be kept clean, for example by wrapping the bottom in parafilm or using filter tips. Stof in fridges or freezers should be well-closed, and parafilm should NEVER be used.
Doors must always be closed, as there's a negative pressure in each room. Opening doors must happen the least amount possible. The lab coat should not be worn outside the laboratory. Nothing with radioactive contact must be taken out of the laboratory without consulting the RPO. Special packaging must be used during transport. Radioactive warning signs must be employed, and radiation must be checked.

9.5 Removal of airborne contamination

Class B and C laboratories must have at least one properly functioning fume-hood, and the lab must also be properly ventilated (>8x/h)

9.5.1 Fume hood

The fume hood is the most used local exhaust ventilation. The air has a directional flow into the fume hood so when used correctly no air will leave the fume hood. It should not be overfilled, and the equipment should be placed as far back as possible (15-20cm to the front at least). Suction gaps should not be blocked. The window should be almost-closed as much as possible. No violent movements should be done, and distance should be kept from fume hoods in use. No agressive substances should be allowed to evaporate.

9.5.2 Biosafety cabinet

Basically, an upgraded fume hood. The air is always biologically clean. Usually it provides better protection than a normal fume hood.

9.5.3 Glove box

The most effective local exhaust ventilation. The space inside the box is completely closed off, and all interaction is done with gloves. There's negative pressure inside. They are rare, and it is tedious to work with them. They usually have an alarm button which can be operated with the knee.

9.5.4 Inadequate systems

Laminar flow cabinets are prohibited, as they have positive pressure inside, allowing radiation to escape towards the worker. Extractor hoods and point extractions don't work, other than with warm air.

9.6 Individual protection

Safety glasses with closed sides should be used if splashing may occur. Disposable, well-fitting gloves should be used, and they shouldn't be used when handling utensils. They should be regularly tested for contamination and replaced regularly, especially when working with VOCs, as they may affect the integrity. Gloves should not be used outside radiation areas. There may be allergy to gloves.
As much as possible, the single-glove method should be used.

9.7 Contamination check and decontamination

A regular contamination and external exposure check should be performed. If a contamination is present, the extent should be determined and labelled. Then, all material needed for contamination must be rounded up, sometimes a spill kit exists. The contaminated area should be wiped from outside to inside with damp tissues with or without detergent, but not foaming agents.
Radiation may be removed up to 4 Bq/cm^2 for β and γ emitters, and 0.4 Bq/cm^2 for α, measured over 5 cm^2. Decontamination is usually continued until radiation can no longer be detected above background on the most sensitive apparatus (ALARA). If this isn't possible, RPO must be alerted.
If the spill is too big, it must be contained immediately, and colleagues alerted. The contaminated area must be marked, and covered with foil to prevent evaporation. The RPO must be alerted, who will supervise the decontamination.
When a person is contaminated or exposed, the RPO must be alerted immediately. A contaminated person must stay in place, not contaminating others. After arrival, the RPO will supervise the decontamination.

9.8 Topics

9.8.1 Radionucleide laboratories

Laboratories with open sources are classified as B, C, or D, increasing in strictness if the hazard is higher. The categories depend on the place where the laboratory is situated, the maximum amount of radioactivity, the construction, the layout, the processing of radioactive waste, and the level of expertise of the RPO.
C laboratories are the most common. All walls, floors, and bench surfaces are smooth, seamless, and easy to decontaminate. At least 1 fume hood must be present; air must be refreshed >8x/h, and there must be suitable monitors. Similar requirements exist for D laboratories, but B laboratories have much more stringent requirements.
To calculate the maximum permissible activity, the A_{max} formula is used.