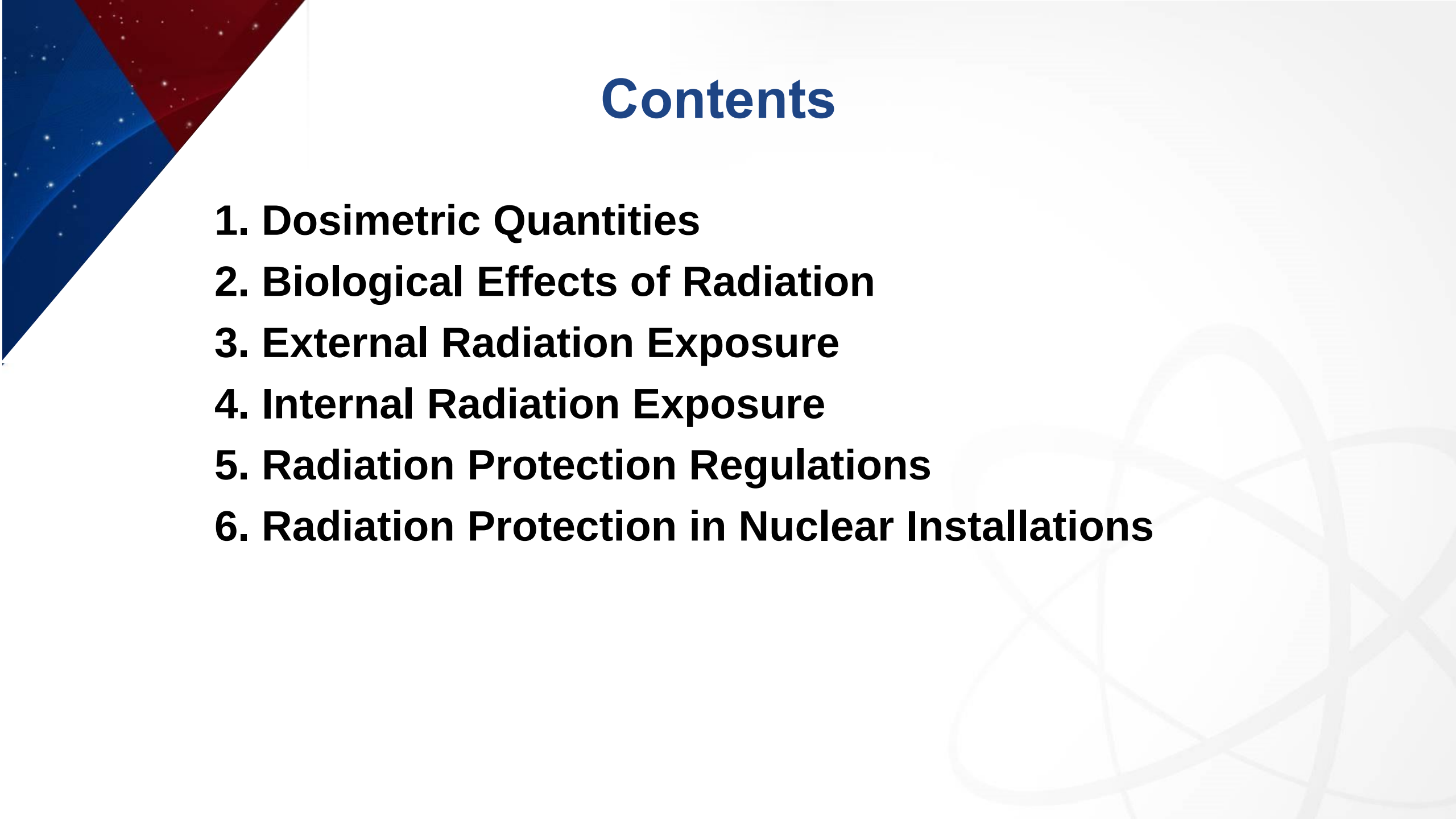


Radiation Protection in Nuclear Facilities

국민에게 신뢰받기





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1. Dosimetric Quantities

Absorbed dose (D)

- **Absorbed dose D** is basic dosimetric quantity - it is defined as energy of radiation deposited in unit mass

- Unit for absorbed dose is **gray (Gy)**: $1 \text{ Gy} = 1 \text{ J/kg}$
- More often smaller units mGy and μGy are used:

$$1 \text{ mGy} = 0.001 \text{ Gy} = 10^{-3} \text{ Gy}$$

$$1 \mu\text{Gy} = 0.000001 \text{ Gy} = 10^{-6} \text{ Gy}$$

- Old unit, often found in literature, is **rad**: $1 \text{ rad} = 0.01 \text{ Gy}$, $1 \text{ Gy} = 100 \text{ rad}$

- **Absorbed dose rate, $\dot{D}$** , tells us how quickly absorbed dose in target increases:

$$\dot{D} = \frac{\Delta D}{\Delta t}$$

- Unit for absorbed dose rate is Gy/h (also mGy/h, $\mu\text{Gy/h}$)

Dose rate for point sources of radiation

- Radiation spreads **isotropically** from point source
- If one photon is emitted per each decay, then the flux of photons at distance **r** from the source with activity **A_c** is:

$$\Phi = \frac{A_c}{4 \pi r^2}$$

- Dose rate in target at distance **r** is proportional to photon flux

$$\dot{D} \propto \Phi \propto \frac{A_c}{r^2}$$

- The absorbed dose rate is directly proportional to the point source activity and inversely proportional to the square of the distance from the source.

Dose rate for point sources of radiation

- The proportionality constant between $\dot{D}$ and Ac/r^2 is called the **Γ constant**:

$$\dot{D} = \Gamma \frac{Ac}{r^2}$$

- **Γ constant could computed for each radionuclide, but in practice we use tables**
 - Γ constants in table are given **for air**.
- **If we want to calculate dose rate in tissue, values should be multiplied with 1.12**

nuclide	half-life	Γ [Gy/h · m ² /Bq]
¹⁶ N	7.1 s	$3.49 \cdot 10^{-13}$
²⁴ Na	15 h	$4.59 \cdot 10^{-13}$
⁵¹ Cr	27.7 days	$5.45 \cdot 10^{-15}$
⁵⁴ Mn	312 days	$1.1 \cdot 10^{-13}$
⁵⁹ Fe	44.5 days	$1.57 \cdot 10^{-13}$
⁵⁸ Co	70.8 days	$1.46 \cdot 10^{-13}$
⁶⁰ Co	5.27 years	$3.25 \cdot 10^{-13}$
⁸⁵ Kr	10.7 years	$4.74 \cdot 10^{-16}$
⁹⁵ Zr	64 days	$1.1 \cdot 10^{-13}$
¹³¹ I	8.04 days	$6.71 \cdot 10^{-14}$
¹³⁴ Cs	2.06 years	$2.37 \cdot 10^{-13}$
¹³⁷ Cs	30 years	$7.56 \cdot 10^{-14}$

Equivalent dose (H)

- Biological damage to live cells, tissues and organs from exposure to ionising radiation depends not only on absorbed dose D , but also on **type of radiation** and, sometimes, also on energy of radiation.
- It has been proven that radiation that have higher **linear energy transfer (LET)** cause more damage than radiation with lower linear transfer.
 - LET is quantity that describes energy transfer to matter per unit length of path
 - For charged particles (alpha particles, beta particles) LET is similar to stopping power
 - Alpha particles, protons, and neutrons have high LET, while beta particles and gamma radiation have low LET

Equivalent dose (H)

- Equivalent dose takes into account absorbed energy (absorbed dose D) and also characteristics of energy transfer to target material:

$$H = w_R \cdot D$$

w_R is radiation weighting factor (between 1 and 20)

- Unit for equivalent dose is **sievert (Sv)**
 - usually use smaller units mSv and μ Sv
 - Old unit is *rem*: 1 rem = 0.01 Sv, 1 Sv = 100 rem

type of radiation	Energy	radiation weighting factor w_R
alpha (α)	all energies	20
beta (β)	all energies	1
gamma (γ)	all energies	1
neutrons (n)	continuous function of energy	2.5 ~ 20

- **Equivalent dose rate $\dot{H}$** tells us how quickly the equivalent dose to the target increases:

$$\dot{H} = \frac{\Delta H}{\Delta t} = \dot{D} \cdot w_R$$

- Unit for equivalent dose rate is Sv/h (mSv/h, μ Sv/h)

Effective dose (E)

- Biological consequences of human exposure to radiation vary if equivalent dose is received by whole body, or just a part of body
- Not all organs (tissues) are equally sensitive to radiation
- **Effective dose E** expresses the share of whole body effects from exposure of particular organ or tissue:

$$E = w_T \cdot H, \quad w_T \text{ is weighting factor for an organ or tissue (T)}$$

- When several organs (or whole body) are exposed, **total effective dose** equals:

$$E = \sum_T w_T H_T$$

Effective dose (E)

- Unit for effective dose is **sievert (Sv)**
- Concept of effective dose only makes sense for **low doses ($E \ll \text{Sv}$)**
- Organ and tissue weighting factors w_T also apply only for low doses

Organ or tissue weighting
factors (ICRP 103 (2007))

tissue or organ	tissue weighting factor w_T
breast	0.12
bone marrow	0.12
colon	0.12
lung	0.12
remainder	0.12
stomach	0.12
gonads	0.08
bladder	0.04
liver	0.04
oesophagus	0.04
thyroid	0.04
bone surfaces	0.01
brain	0.01
salivary glands	0.01
skin	0.01
TOTAL	1.00

Collective dose (E_c)

- When group of people is exposed to radiation, collective dose is calculated
- Collective dose is sum of effective doses of all group members

$$E_c = \sum_i n_i E_i$$

- where n_i is number group members that have received effective dose E_i
- Unit for collective dose is **man·Sv**

Exposure (X)

- The oldest radiological quantity, not official, but still used somewhere
- It is defined (only) for **X radiation and gamma radiation in air**
- Exposure X is **density of electric charges** of the same sign released in the air:

$$X = \frac{Q}{\Delta m}$$

- Unit for exposure X is As/kg (**in air** !)
- Old unit is *roentgen* (R): $1 \text{ R} = 2,58 \cdot 10^{-4} \text{ As}$

- **Exposure rate $\dot{X}$** tells us what current flows from the air mass Δm

$$\dot{X} = \frac{\Delta X}{\Delta t} = \frac{I}{\Delta m}$$

- Unit for *exposure rate* is A/kg, but use of old unit R/h is more common

2. Biological Effects of Radiation

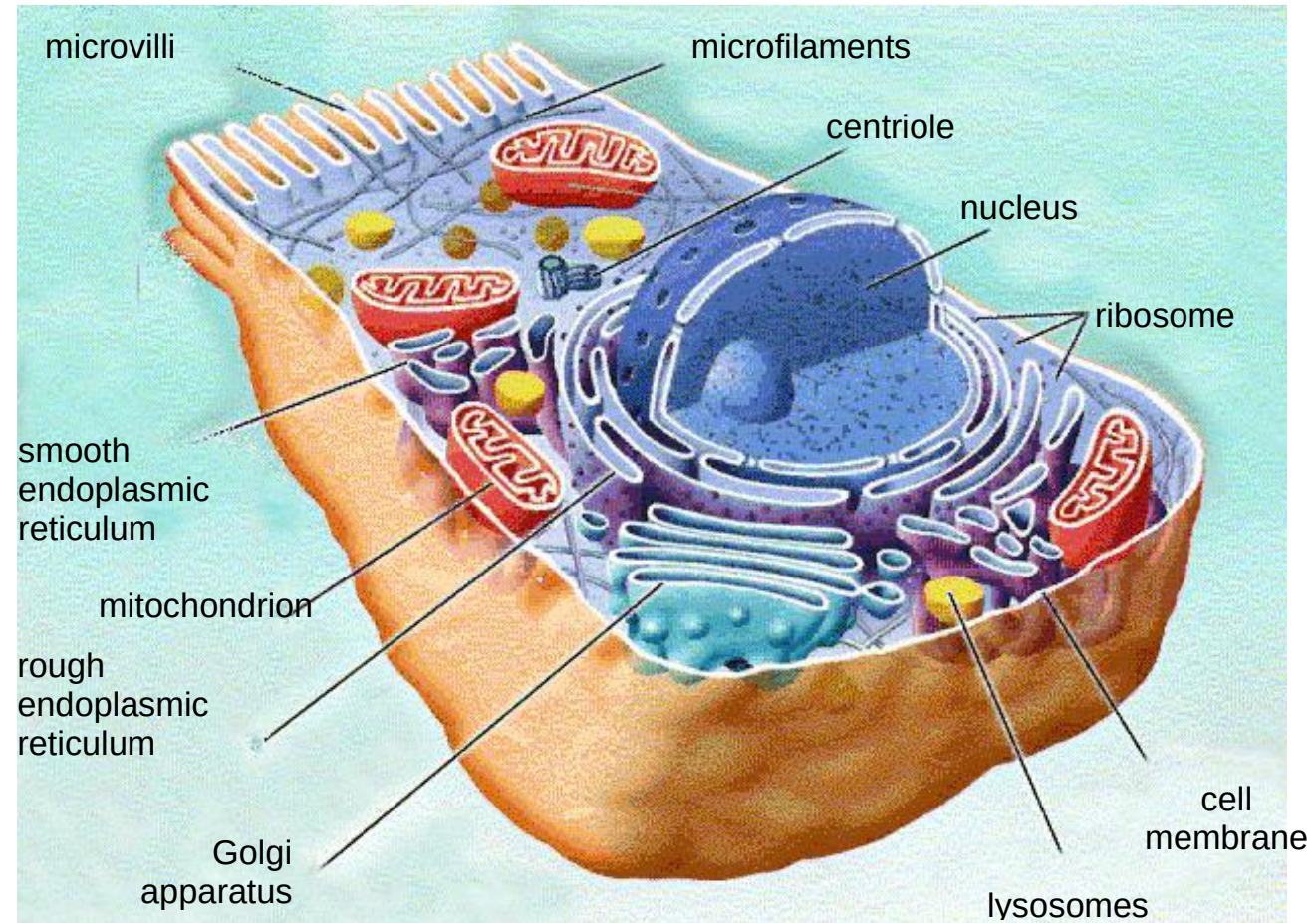


Basic cell biology

- Cells are basic building blocks of living organisms
- Human body consists of around $4 \cdot 10^{13}$ cells
- Cells differ in function and size
- Basic division: *somatic* (bodily) cells and *sex cells* (or gametes, relevant to reproduction)
- Most of the cells are somatic cells, but sex cells are important since they pass hereditary information from one generation to the next
- Cells are composed of ~70-85 % water, ~10-20 % proteins, ~10 % carbohydrates (sugars) and ~2-3 % lipids (fats) and small quantities of inorganic substances.
- Cells are small, but complex.

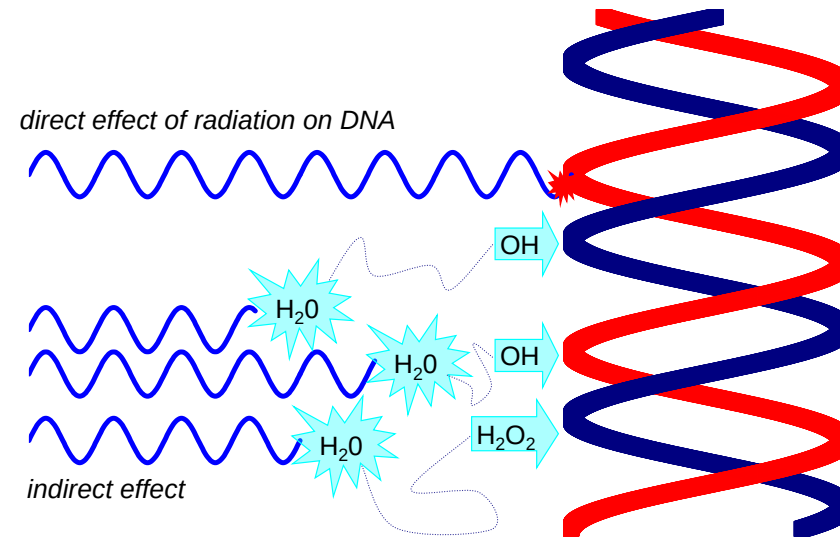
Basic cell biology (cont.)

Somatic cell



Radiation effects on cells

- As result of exposure to ionising radiation in cells some molecular bonds are broken, or some free radicals are formed
- **Direct effect** of ionising radiation: when complex organic molecule splits (or is damaged) due to ionisation
- **Indirect effect** of ionising radiation is consequence of ionisation of water molecules
 - Result is water radiolysis and creation of reactive free radicals (hydroxyl radicals, $\text{OH}^\bullet$,...) and hydrogen peroxide, H_2O_2 .
 - They can travel few nm and damage organic molecules.
- **Damage is essentially chemical process!**



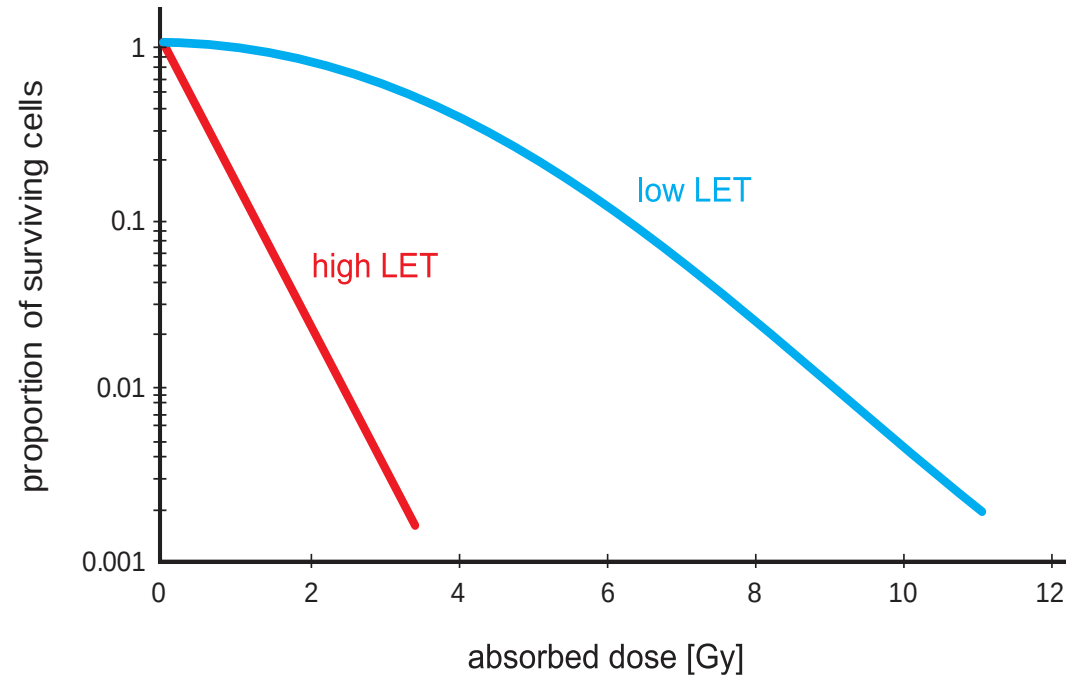


Radiation effects on cells

- **Radiation can damage any part of the cell, but effects depends on which part of the cell is affected**
 - Nucleus and DNA in the nucleus are critical targets
 - Damage to DNA affects the function of the cell as a whole and may be transferred to its progeny by mitosis
- **Many damaged cells continue to function until mitosis, when they die (mitotic death).**
 - Radiation effects are most dramatic in organs with quickly dividing cells (red marrow, large intestine epithelium, skin epithelium, hair follicles).
 - Tissues with rarely dividing cells are less sensitive to radiations.
- **Very sensitive to radiation are embryos, especially in the first months after conception**

Effect of LET

- Experiments with cell colonies have showed that radiation with high LET(alpha or neutron radiation) , causes much greater biological damage to cells than radiation with low LET(beta or gamma radiation)
- Experiments have also suggested, that there is some **repair mechanism** that enables damaged cells to recover if they are exposed to low doses of low-LET radiation



Mutation and cancer

- After damage, some cells keep the ability to divide further.
- The damage (change) in the DNA is passed to next generation. It is called **mutation**.
- But damage to DNA and possible errors in DNA multiplication during mitosis are not only consequence of exposure to ionising radiation.
 - Since radiation damage is basically chemical process, other environmental factors have similar effects.
 - Radiation is just one of the factors, that can cause mutation
- Mutations may also cause pathological changes which are manifested as the abnormal functioning of individual organs or as a greatly increased rate of cell division in a tissue or organ. This pathological change is called **cancer**.



Genetic changes

- **When genetic material in sex cells (in gonads) is damaged, the mutation could be transferred to offspring.**
- **Pathological changes will develop in child, or in the child's child, and not in the organism that was exposed to radiation.**
- **These effects are also called **hereditary effects**.**

Timeline of radiation damage

- Development of radiation damage consists of following phases:
 - **physical phase:** $\sim 10^{-12}$ s: ionization
 - **chemical phase:** $\sim 10^{-6}$ s: formation and diffusion of free radicals
 $\sim 10^{-3}$ s: DNA damage
 - **biological phase:** $\sim$ seconds: DNA repair
 $\sim$ hours: cell death
 $\sim$ days: mutations, cell transformation,
chromosome aberrations
 $\sim$ years: development of cancer, hereditary effects

Radiation effects on humans

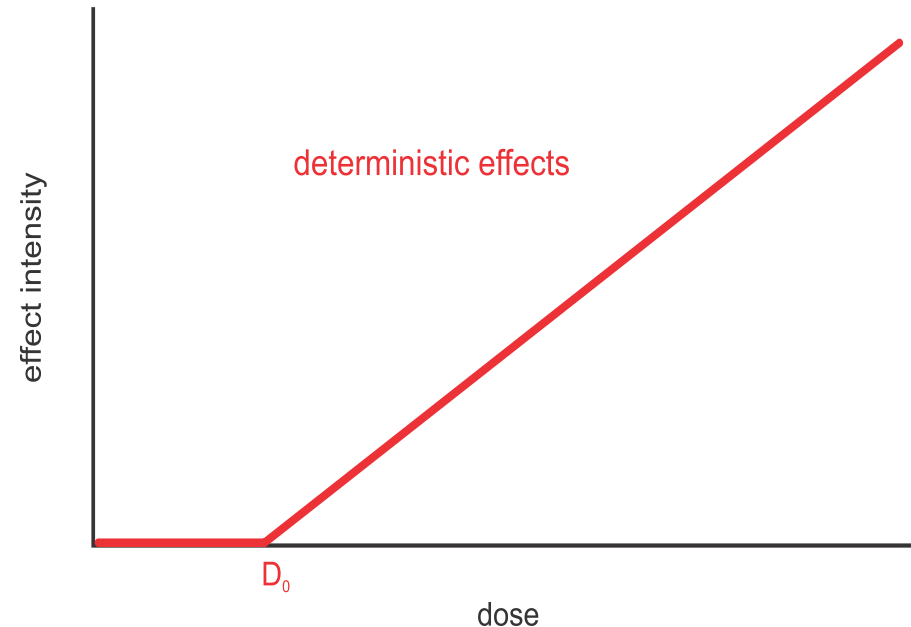
- Radiation effects can be classified in two ways: regarding the type of damaged cells, and regarding the probability that radiation effect will occur.
- Classification regarding the type of cells:
 - **Somatic effects**, that occur on exposed person
 - **Genetic effects**, that occur on exposed person's offspring
- Classification regarding the probability of radiation effect:
 - **Deterministic effects**, that will certainly occur after specific dose
 - **Stochastic effects**, which will occur with certain probability only in a specified percentage of exposed persons

Radiation effects on humans

- **Effects of radiation depends not only on dose, but also how dose was received:**
 - *Acute*: a high dose in a short time interval.
 - *Chronic*: prolonged irradiation with low doses.
 - *Local*: exposure of a particular organ.
 - *Total*: whole body irradiation.
- **Most information about effects of radiation is from acute irradiation with high doses (survivors of Hiroshima and Nagasaki)**
- **More relevant for practical application of radiation protection are data from chronic exposure. Due to the presence of repair mechanisms, we can assume data on radiation effects from acute exposures as **conservative estimation** of data from chronic exposure**

Deterministic effects of radiation

- Deterministic effects are certain to occur after irradiation with high enough dose.
- Deterministic effects **have dose threshold** (minimum dose at which effect occur)
- Severity (or intensity) of effect **increases with dose** above dose threshold
- Deterministic effects manifest **shortly** after irradiation (hours to weeks).



Deterministic effects of radiation

- **Deterministic effects include:**

- *erythema (skin redness),*
- *epilation (hair loss),*
- *reduced number of blood cells (resulting from bone marrow damage),*
- *cataract,*
- *nausea, vomiting, diarrhoea,*
- *damage to children (deformation of organs, mental retardation),*
- *temporary or permanent sterility.*

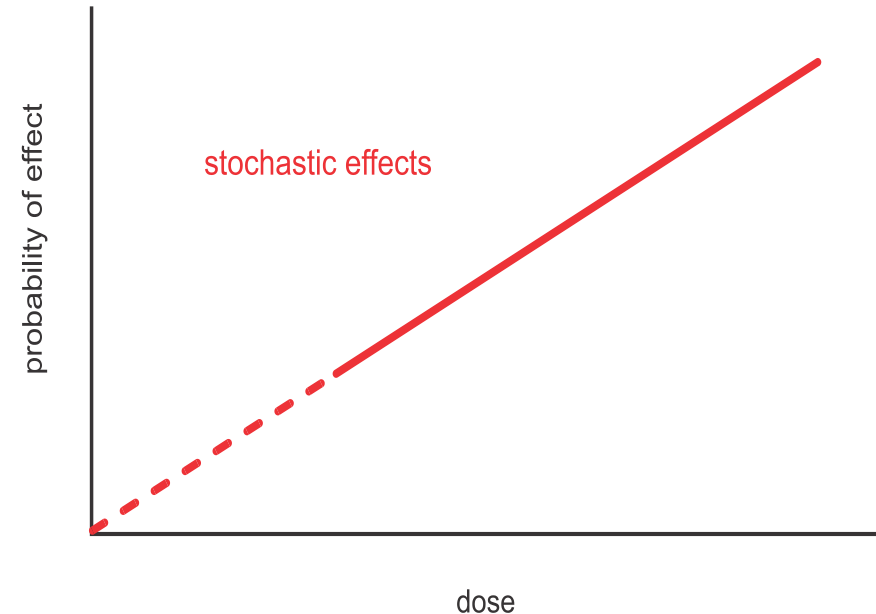
- **Protection against deterministic effects is simple – we keep doses below threshold dose.**

Effects of acute whole-body irradiation.

Dose (Gy)	Probable effect
0 – 0.5	No prominent effects, possible minor changes in blood count.
0.6 – 1.2	Nausea and vomiting occur after the first day in 5-10 % of the cases. No serious incidence of disease.
1.3 – 1.7	The first day is followed by nausea and vomiting, 25 % cases display symptoms of radiation sickness. No fatal cases.
1.8 – 2.2	In 50 % of the cases, nausea and vomiting occurs within the first day. The symptoms of radiation sickness are more prominent. No fatal cases are expected.
2.3 – 3.3	In 100 % of the cases, nausea and vomiting occurs within the first day. Serious signs of radiation sickness appear.
3.4 – 5.0	Median lethal dose, LD _{50/30} – 50 % deaths in 30 days.
> 100	Radiation syndromes. 100 % deaths with a time delay from a few hours to a few months.

Stochastic effects of radiation

- **Stochastic effects** of radiation can only be predicted to occur with a certain probability
 - There is no threshold dose
- Probability of effect occurring **increases** with dose
- Severity of effect is **not related** to dose
- Stochastic effect are **delayed** (they occur years after exposure)
- It is not possible to link radiation exposure with effect unequivocally



Stochastic effects of radiation

- Stochastic effects include
 - *Cancer*
 - *Genetic effect*
- Cancer is second leading cause of deaths.
 - 40% of people contract cancer and almost 20% die from the cancer
- Most of the cancers are caused by various chemicals called carcinogens, most of occur naturally and are present in environment.
- Radiation increases probability that a person will get cancer
 - Data from surviving victims from Hiroshima and Nagasaki show that 87 of 249 lethal leukaemia cases, and 344 of 7578 lethal solid cancer cases were the consequence of irradiation.

Stochastic effects of radiation

- Data from surviving victims from Hiroshima and Nagasaki, and other sources confirm, that probability for developing cancer is proportional to dose received.
 - For low doses, probability is too low to be statistically significant and this relation could not be confirmed.
- As conservative (and safe) approach, proportionality between dose and probability for stochastic effects is considered to be valid also for low doses, without threshold dose. This is *linear no-threshold (LNT) hypothesis*
- Relation between dose and probability for cancer occurrence is **risk coefficient**. According to available data, this coefficient is **5% per Sv**
- **Genetic effects** are only observable in the offspring of irradiated person
- Genetic effects are less probable than cancer and so far have not been observed in descendants of irradiated persons.

3. External Radiation Exposure

Types of radiation exposure

- **Types of exposure:**

- **External exposure**: when the source is located outside body
- **Internal exposure**: when source is inside human body

- **When source is outside body:**

- **Alpha radiation** is harmless, since it is stopped with dead outer layer of skin
- **Beta radiation** is harmful in certain cases (vicinity of unshielded source/contamination, contamination of skin, direct eye irradiation)
- **Gamma radiation** is present in most cases (and situations) in nuclear objects and can not be avoided, Therefore protection must be well understood
- Except in some special cases, operating reactor is only source of **neutrons**. Protection relies mostly on built-in shields and knowledge of survey results and local rules.

Time, distance, shielding

- External exposure to radiation may be reduced (and controlled) by three parameters:
 - *Time*
 - *Distance*
 - *Shielding*
- What we try to reduce is **dose**, which is **product of dose rate and time** of exposure.
- **Distance** and/or **shielding** can reduce dose rate
- Although each of these parameters can reduce dose, they are not always considered independently (especially when high doses are expected)

Time

- **The less time is spent in a field of radiation, the smaller is the dose received.**
- **For time shortening, proper preparation and practice prior to actual work is essential**
 - Time of exposure is the shortest and chances of mistake are minimal
- **Examples of good practice:**
 - *precise planning and organisation of the work*
 - *meetings before the work is started (planning and coordination),*
 - *training on a mock-up,*
 - *tools preparation in a clean environment,*
 - *optimizing protective clothing,*
 - *delaying the beginning of work (for decay of short-lived nuclides)*

Distance

- The radiation **dose rate falls with increasing distance**: for point sources with the **square of the distance**, and for line sources **proportionally with distance**.
- **Distance may be used by:**
 - *using tongs, pincers, tweezers and other adapted tools,*
 - *using telescopic measuring instruments (teletectors),*
 - *remote reading of instruments,*
 - *remote control of tools,*
 - *using remote communication,*
 - *indicating hot spots and radiation levels,*
 - *removing sources of radiation,*
 - *repairing portable parts in a hot machine shop.*

Shielding

- It is **the most reliable method of dose rate (dose) reduction**
- In practice, it depends on possibilities
- Effect on collective dose should be also considered (setting up shielding also requires exposure of workers)
- Shielding consists of:
 - *portable lead mats or screens,*
 - *lead bricks,*
 - *water (primary system, secondary side of steam generators),*
 - *existing concrete walls, etc.*
- Preparation of effective shielding requires involvement of expert

Shielding from gamma radiation

- With shielding, intensity of monoenergetic gamma radiation falls exponentially:

$$j = j_0 2^{-\frac{d}{d_{1/2}}}, \text{ here } d_{1/2} \text{ is half-value layer.}$$

- Similar equation could be written with using tenth-value layer $d_{1/10}$.
- Dose rate is proportional to photon flux j and j_0 and equation could be used to calculate for dose rate with shielding ($\propto j$) from dose rate without shielding ($\propto j_0$)

Shielding from gamma radiation

- In realistic calculations scattered radiation, which increases dose rate behind shielding, must be taken into account
- Therefore for practical purposes we use slightly higher (i.e. conservative) values of **half-value layer and tenth-value layer**

substance	$d_{1/10}$ [cm]
water	60
concrete	25
steel	10
lead	5.6

Conservative values of tenth-value layers for various substances for radiation from spent fuel elements

- This approach gives only rough estimate and **must be always verified with measurements**
- **Real design and evaluation of shielding should be left to experts!**

Shielding from beta radiation

- There are two contributions to exposure when dealing with beta radiation:
 - beta radiation itself, and
 - **bremsstrahlung** produced by stopping electrons in matter.
- Beta radiation can be stopped by using a shield with thickness larger than beta radiation range
- **Bremsstrahlung production** is reduced by using shield with **low atomic number, Z** .
- The most effective beta radiation shielding consists of two layers
 - inner shield from material with low Z stops beta particles, while outer shield from high Z material absorbs bremsstrahlung.

Shielding from neutron radiation

- **Neutron radiation is highly penetrating**
- **Shielding is more complicated than gamma shielding:**
 - Neutron cross sections vary quite unsystematically from element to element, and
 - Interactions include complicated processes and resonances depending on the energy of the neutrons
 - Absorption cross section for fast neutrons is normally small, and higher for thermal neutrons.
 - We also try to avoid radiative neutron capture, which releases high energy gamma rays
- **Good neutron shielding consist of the following components:**
 - a material which slows down fast neutrons (by elastic scattering on light nuclei), e.g. hydrogen in water, paraffin or concrete,
 - a material which absorbs slow neutrons, e.g. boron, cadmium,
 - a material which absorbs secondary gamma rays, i.e. heavy elements, e.g. steel or special concretes containing heavy elements.

4. Internal Radiation Exposure

The pathways of radionuclides into the body

- Internal exposure is consequence of the presence of radionuclides in the body. Radionuclides that have entered the body, and are not result of natural radioactivity in food and air, are considered to be *internal contamination*.
- Radionuclides can enter body:
 - with food and drink (**ingestion**),
 - by breathing (**inhalation**),
 - through the skin,
 - through open wounds.

} (**absorption**)
- The greatest danger from internal contamination comes from alpha radiation, less dangerous is beta radiation and even less gamma radiation.



The pathways of radionuclides into the body

- **After intake, total activity of radionuclides diminishes over time due to radioactive decay and biological elimination from the body.**
- **If presence of radionuclides in environment (workplace) can not be prevented or avoided, work in that area should be subjected to special measures.**
- **Measures usually also include use of special personal protective equipment**
 - protective clothing and respiratory protection equipment.
- **Internal exposure can not be directly measured**
 - doses could only calculated or estimated.

Effective half-life

- **Behaviour of radionuclides in body is defined only by their chemical properties**
 - body is not aware of radioactive properties of particular nuclide.
- **Radioactive isotopes of particular element behave like nonradioactive isotopes of same or similar elements normally present in our body.**
 - Some elements ‘prefer’ particular *target organs* (e.g. iodine builds up in thyroid gland, calcium in bones), while other disperse evenly through the body
- **Alpha radiation from radionuclides is absorbed in immediate vicinity of decayed nuclei (i.e. in target organ), while beta radiation is mostly absorbed in target organ.**
- **Gamma radiation irradiates more organs, or even manage to ‘escape’ body.**

Effective half-life

- Activity of particular radionuclide in the body diminishes in time due to radioactive decay and to removal of radionuclide from the body (elimination)
- Due to removal, concentration (activity) of radionuclide falls as: $\propto 2^{-\frac{t}{t_{1/2b}}}$
where $t_{1/2b}$ is **biological half-life** and is determined experimentally

- If we combine well known expression for radioactive decay and removal, we can write equation for time dependence of activity in the body:

$$Ac = Ac_0 \cdot e^{-\frac{t}{t_{1/2}}} \cdot e^{-\frac{t}{t_{1/2b}}} = Ac_0 \cdot e^{-\left(\frac{1}{t_{1/2}} + \frac{1}{t_{1/2b}}\right)t} = Ac_0 \cdot e^{-\frac{t}{t_{1/2E}}}$$

where $t_{1/2}$ is **normal (physical) half-life**.

- Instead of normal half life, the time dependence of activity is defined by **effective half-life** $t_{1/2E}$:

$$\frac{1}{t_{1/2E}} = \frac{1}{t_{1/2}} + \frac{1}{t_{1/2b}} = \frac{t_{1/2} \cdot t_{1/2b}}{t_{1/2} + t_{1/2b}}$$

radionuclide	organ	$t_{1/2b}$
^3H (in water)	whole body	12 days
^{60}Co	whole body	10 days
^{90}Sr	whole body	36 years
	bones	49 years
^{131}I	whole body	138 days
	thyroid	138 days
^{137}Cs	whole body	70 days
	bones	140 days

Committed effective dose

- **Calculating equivalent dose for organs and effective dose for person is very complicated**
 - Need to estimate time dependence of activity, but dose also depend on other factors.
 - Exposure of organs and body will take place as long as radionuclide is in the body.
- **For radionuclides with short effective half-life exposure will last days or weeks (e.g. ^{131}I), for those with long effective half-life decades (e.g. ^{90}Sr , or ^{239}Pu).**
- **As a rule, doses are calculated for 50 years after intake for adults, and 70 years after intake for children. The dose received in this period is called committed effective dose.**
- **Committed effective dose is calculated and added to external effective dose in the year of intake!**

Dose coefficients

- Committed effective dose have been calculated for all radionuclide (for inhalation and ingestion)
- Committed effective dose per Bq is called *dose coefficient $h(g)$*

Dose coefficients $h(g)$ for
inhalation and ingestion

Radionuclide	Half-life	$h(g)$ [Sv/Bq]	
		inhalation	ingestion
^3H	12.3 years	$1.8 \cdot 10^{-11}$	$1.8 \cdot 10^{-11}$
^{51}Cr	27.7 days	$3.6 \cdot 10^{-11}$	$3.8 \cdot 10^{-11}$
^{54}Mn	312 days	$1.5 \cdot 10^{-9}$	$7.1 \cdot 10^{-10}$
^{59}Fe	44.5 days	$3.5 \cdot 10^{-9}$	$1.8 \cdot 10^{-9}$
^{58}Co	70.8 days	$2.0 \cdot 10^{-9}$	$7.4 \cdot 10^{-10}$
^{60}Co	5.27 years	$2.9 \cdot 10^{-8}$	$3.4 \cdot 10^{-9}$
^{90}Sr	29.1 years	$1.5 \cdot 10^{-7}$	$2.8 \cdot 10^{-8}$
^{131}I	8.04 days	$7.6 \cdot 10^{-9}$	$2.2 \cdot 10^{-8}$
^{137}Cs	30 years	$4.8 \cdot 10^{-9}$	$1.3 \cdot 10^{-8}$
^{239}Pu	24100 years	$4.7 \cdot 10^{-5}$	$2.5 \cdot 10^{-7}$

Annual limit of intake (ALI)

- Legislation lays down **dose limits E_m** , which may be received by workers and members of the public per year.
- If we use these limits and dose coefficients, we can calculate activity (intake), that would result in committed effective dose equal to annuals effective dose limit E_m . This activity is called **annual limit of intake, ALI**.

$$ALI = \frac{E_m}{h(g)}$$

Derived air concentration (DAC)

- Annual limit of intake, ALI, could be used to calculate that concentration of radionuclide in air that we breath during work, which will cause committed effective dose equal to annual effective dose limit.
 - For occupationally exposed workers, 2000 working hours per year and 1.2 m³/h breathing rate is considered.

- **Derived air concentration(DAC) is:**
$$DAC = \frac{ALI}{V_a}$$

V_a is volume of air breathed per year ($V_a = 1.2 \text{ m}^3/\text{h} \cdot 2000 \text{ h} = 2400 \text{ m}^3$)

- DAC in air were calculated for all radionuclides.
- DAC could be calculated also for members of public (for inhalation and drinking water)

Radionuclide	DAC [Bq/m ³]
³ H (HTO)	460 000
⁶⁰ Co	290
⁹⁰ Sr	56
¹³¹ I	1100
¹³⁷ Cs	1700
²³⁹ Pu	0.18

Derived air concentration for inhalation for occupationally exposed workers

Protection against internal contamination

- Since possibility to prevent or limit internal exposure after intake is limited, protection against internal exposure reduces to prevention (or control) of intake of radionuclides.
- This prevention is implemented using principles of *defence in depth*:
 - **Restriction of open sources of radiation:**
 - Use of sources should be restricted to a reasonably small number of designated areas.
 - **Control of areas containing sources of radiation:**
 - Areas where work takes place should be suitably designed and equipped.
 - Controlled area should be designated when necessary with physical control of access, suitable personal protective equipment at the entrance and personal monitoring control at the exit.



Protection against internal contamination

- **Preventing internal contamination by ingestion and absorption:**

- While working in radiation controlled areas it is prohibited to eat, drink, smoke and work with open cuts or wounds.

- **Worker protection:**

- Workers are required to use personal protective equipment to prevent skin contamination (**protective clothing**) and – in cases of increased air contamination – to restrict the intake of radioactive material by inhalation (**respiratory protective equipment**).



Protective clothing and equipment

- **Protective clothing prevents contamination of body surface (skin and hair)**
- **It should be put on when entering controlled area and taken off when leaving.**
- **Used clothing (when leaving controlled area) should be considered contaminated**
- **Clothing (and other personal protective equipment) should be properly designed to enable taking off without transfer of contamination to workers body**
- **Workers should be trained to use clothing in correct way**
- **Due to other industrial hazards in controlled area of nuclear objects, other (additional) protective equipment may be required.**

Basic protective equipment in nuclear power plant

- This equipment is used always and should be provided on entrance to controlled area:
 - a hard hat, underwear, cotton overalls, cotton gloves, protective shoes,
 - a set of personal dosimeters (a daily – electronic and a monthly – TLD/OSL dosimeter).
- In areas where increased surface or air contamination is probable or confirmed, one or several pieces of **additional protective equipment** are also used according to the level of contamination
 - additional rubber gloves, shoe covers, Tyvek coveralls,
 - special protective clothing, a respirator,
 - a half mask, a mask, an air-supplied mask



A worker wearing basic protective equipment (example).



A worker in Tyvek coveralls with a respirator.

Respiratory protective equipment

- A typical **protection factor requirement** for breathing equipment is that the concentration of activity in inhaled air is **less than 0.1 DAC**
- Examples of respiratory protection equipment



Filter half mask



Protective clothing (suit)
with an air line



Self-contained breathing
apparatus

5. Radiation Protection Regulations

The aim of radiation protection

- There are great **benefits** from use of X-radiation, radionuclides and nuclear fuel in medicine, industry, research and electricity generation.
- Use of X-radiation, radionuclides and nuclear fuel also implies exposure of people to radiation, and associated risk.
- **The fundamental principle of radiation protection is to assess the risks and benefits brought by the use of radiation. Exposure is justified only when the benefit derived from using a source is greater than risk associated with exposure.**
- Decision on justification is not simple – it could be only answered by society as a whole.
- Radiation protection provides standards of protection for use of sources that is considered safe, considering other risks encountered in society.

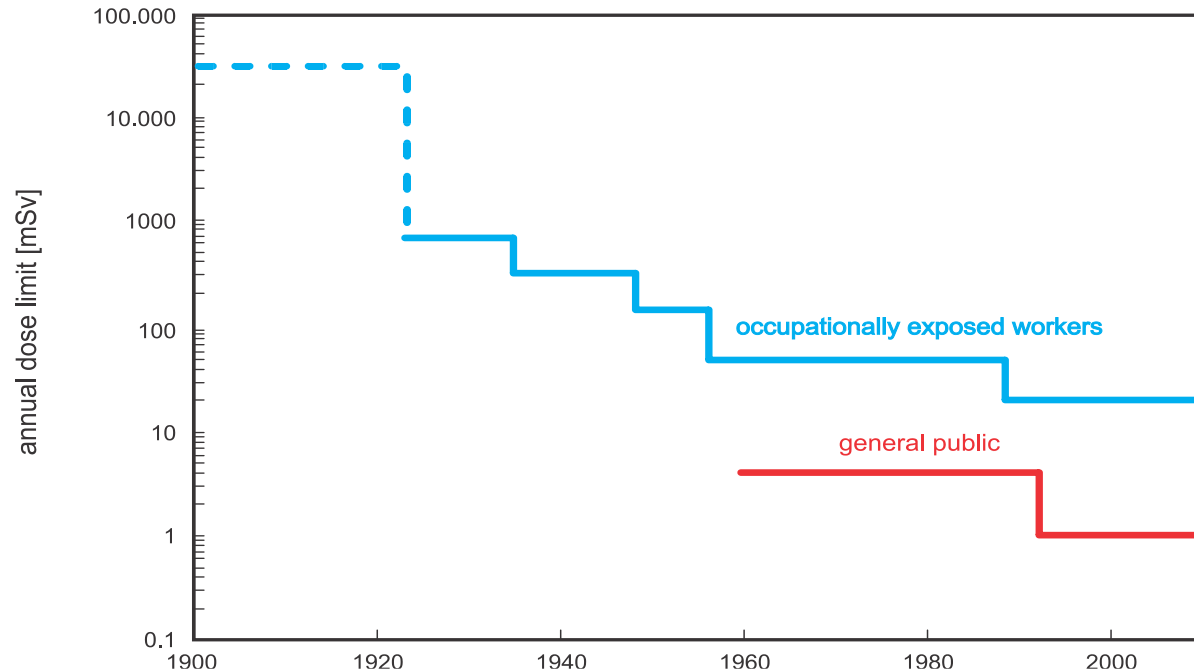


International recommendations and standards

- **More international bodies and organisations study effects of radiation and issues recommendations on radiation protection**
- **Non-governmental organisations:**
 - **ICRP** (International Commission on Radiological Protection) issue recommendations on radiation protection
 - **ICRU** (International Commission on Radiation Units & Measurements) provides international standards for radiation units and measurements
- **International organisations:**
 - **UNSCEAR** (United Nations Scientific Committee on the Effects of Atomic Radiation) mostly deals with epidemiological studies of radiation effects
 - **IAEA** (International Atomic Energy Agency) issues safety standards which are aligned with ICRP recommendations and indirectly binding on member states

ICRP recommendations

- ICRP issues recommendations on radiation protection since 1928
- Based on available data, ICRP has been providing recommendation regarding dose limits for occupationally exposed workers and members of public.



ICRP recommendations

- Data from Hiroshima and Nagasaki survivors confirm that the probability of developing radiation-induced cancer is proportional to the dose received.
- Since there is no firm evidence that sufficiently low doses are harmless, ICRP adopted conservative *hypothesis of the linear dependence of the probability of stochastic effects with no threshold* (the linear no-threshold model – LNT).
- ICRP system of radiation protection is based on **three principles**:
 - justification,
 - optimization,
 - dose limits;



ICRP recommendations

- **Justification** requires that sources of radiation be used only for those activities which bring more benefit than harm due to exposure to radiation.
- **Optimization** requires that all exposures shall be kept as low as reasonably achievable (ALARA), economic and social factors being taken into account.
- **Dose limits** are values of the effective dose or equivalent dose that should not be exceeded

IAEA Safety standards

- IAEA Safety standards are based on ICRP recommendations and findings of UNSCEAR.
 - In preparation other international organisations and member states are also involved.
- Last publication of Basic Safety Standards (BSS):
 - *Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, General Safety Requirements Part 3, No. GSR Part 3, 2014.*
- BSS lay down requirements for establishing governmental, legal and regulatory frameworks for safety, specify basic obligations and administrative requirements for practices, dose limits and relevant radiation protection, management, technical and safety verification requirements.



IAEA Safety standards

- **BSS also lay down detailed requirements for occupational exposure, public exposure, emergency exposure situations (including interventions), and also specify other exposures (potential, medical) to ionizing radiation.**
- **BSS also identify the protection of the environment as an issue necessitating assessment and the necessity of designing and implementing security and radiation safety measures in an integrated manner so that they do not conflict with each other.**
- **Other publications of the IAEA safety standards series give more detailed guidance on how the BSS requirements should be met in particular situations.**

IAEA Safety standards

- BSS distinguish between **three types of exposure**:
 - **Planned exposure** situation
 - situation of exposure that arises from the planned operation of a source or from a planned activity that results in an exposure from a source.
 - **Emergency exposure** situation
 - situation of exposure that arises as a result of an accident, a malicious act, or any other unexpected event, and requires prompt action in order to avoid or to reduce adverse consequences.
 - **Existing exposure** situation
 - situation of exposure which already exists when a decision on the need for control has to be taken.
 - include situations of exposure to natural background radiation, of exposure due to residual radioactive material that derives from past practices, or that remains after an emergency exposure situation.
- For each of these exposure situations requirements applicable to occupational exposures and for public exposures are stated.
- **Requirements for medical exposures** are stated **only for planned exposure situations**.

IAEA Safety standards

- **Dose limits** for planned exposure situations were established based on the ICRP 103(2007) recommendations

Table 6. Recommended dose limits in planned exposure situations ^a .		
Type of limit	Occupational	Public
Effective dose	20 mSv per year, averaged over defined periods of 5 years ^e	1 mSv in a year ^f
Annual equivalent dose in:		
Lens of the eye ^b	150 mSv	15 mSv
Skin ^{c,d}	500 mSv	50 mSv
Hands and feet	500 mSv	—

- For occupational exposure of workers over the age of 18 years:
 - **An equivalent dose to the lens : 20 mSv per year averaged over 5 consecutive years** (100 mSv in 5 years) and of 50 mSv in any single year;
 - Additional restrictions for a female worker who has notified pregnancy or is breast-feeding.
- For occupational exposure of apprentices or students of 16 to 18 years of age
 - An effective dose of 6 mSv in a year;
 - An equivalent dose to the lens of the eye of 20 mSv in a year;
 - An equivalent dose to the extremities (hands and feet) or the skin of 150 mSv in a year.



IAEA Safety standards

- For **emergency situations**, the Safety Standards :
 - specify **generic criteria for acute doses** for which protective actions and other response actions are expected to be undertaken under every circumstance to avoid or to minimize severe deterministic effects, and also
 - sets **guidance levels for restricting the exposure** of emergency workers

IAEA Safety standards

- **BSS states a number of requirements for government, regulatory bodies, registrants (registered users) and licensees, employers and workers.**
- **Employers, registrants and licensees shall:**
 - be responsible for the protection of workers against occupational exposure,
 - ensure that protection and safety is optimized and that the dose limits for occupational exposure are not exceeded,
 - establish and maintain organizational, procedural and technical arrangements for the designation of controlled and supervised areas, for local rules and for monitoring of the workplace,
 - establish, maintain and keep under review a programme for workplace monitoring under the supervision of a radiation protection officer or qualified expert,
 - be responsible for making arrangements for the assessment and recording of occupational exposure and for workers' health surveillance,
 - provide workers with adequate information, instruction and training for protection and safety,
 - not offer benefits as substitutes for measures for protection and safety,
 - make special arrangements for female workers, as necessary, for protection of the embryo or foetus and of breast-fed infants,
 - make special arrangements for the protection and safety of persons under 18 years of age who are undergoing training.



IAEA Safety standards

- BSS also provides criteria for **exemption** of practices and sources and criteria for **clearance** of sources.
- A general requirement related to all aspects of radiation protection and safety is the requirement for a **graded approach**:
 - the application of the Standards shall be commensurate with the characteristics of the practice or the source within a practice, and with the magnitude and likelihood of exposures.

6. Radiation Protection in Nuclear Installations

Aspects of RP in the nuclear fuel cycle

- Nuclear fuel cycle contains broad range of nuclear installations that employ a variety of technologies to process uranium, plutonium and thorium.
- At each stage of nuclear fuel cycle, variety of radionuclides are released in environment as liquids, gases or solid effluents.
- During normal operation, releases are low and doses to public must be estimated by models (annual doses are generally less than 1 μ Sv)

Annual effective doses
in the nuclear industry

Stage of nuclear fuel cycle	Dose (mSv)
Uranium mining	4.5
Uranium milling	3.3
Enrichment	0.1
Fuel fabrication	1.0
Nuclear reactors	1.4
Reprocessing	1.5

Important radionuclides for RP – fuel cycle

- Different radionuclides are of prime concern in particular stages of nuclear fuel cycle.
- At the front end, (**uranium/thorium mining and milling**) only the natural radionuclides from the uranium (or thorium) decay series present radiation risk. The purified form of uranium concentrate is ‘yellowcake’ (U_3O_8).
- In next stage (**conversion to UF_6 , enrichment, fuel fabrication**) risk is substantially lower (there is no uranium progeny) except for MOX fuel fabrication.
 - For MOX fuel fabrication the main risk is from hot particles containing actinides (uranium or plutonium) that may be inhaled.

Important radionuclides for RP – fuel cycle

- In **power and research reactors;**

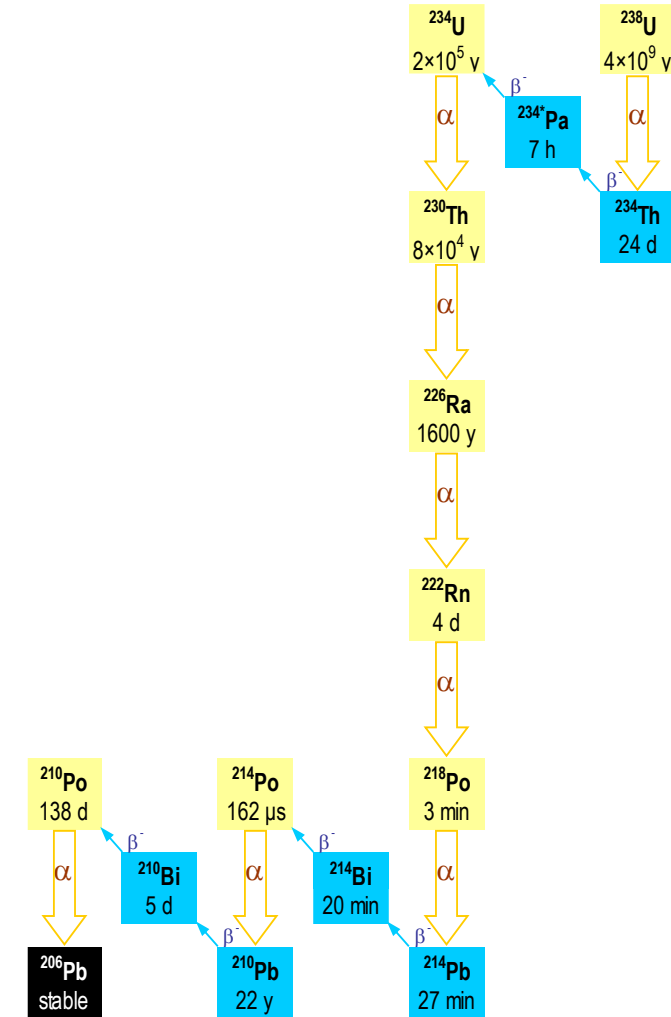
- During reactor operation, reactor core is the main source of neutrons and gamma radiation.
- Fission products from fuel are highly radioactive, also activated construction materials and activated corrosion products.
- Radiation protection issues are in principle similar in NPPs and research reactors.

- In the back end of nuclear fuel cycle (**reprocessing and/or waste management, storage and disposal**);

- all types of radionuclides (fission products, activation products, actinides) are important for radiation protection.
- For reprocessing or waste disposal, usually only long lived radionuclides are of importance.

Important radionuclides for RP – natural radionuclides

- The most important among **natural radionuclides** is uranium and its daughter products (progeny).
- In uranium ore and soil, daughter products tend to be in equilibrium.
 - Exception is ^{222}Rn , which is noble gas and can escape (exhale) from soil.
- ^{222}Rn and its short-lived daughter products (up to ^{210}Pb) are present in the air (they are attached to dust particles) and are inhaled.
- **Polonium isotopes** are **alpha emitters** and produce substantial dose to respiratory system.



Important radionuclides for RP – natural radionuclides

- **^{222}Rn and its progeny** are the largest contributors to exposure from natural sources (they contribute 1.2 mSv of 2.4 mSv per year, world average)
- In uranium mines and milling facilities, the concentration of radon is substantially higher than the average natural background,
 - special measures need to be taken to protect the workers and the population in the neighbourhood of these facilities

Radon and its short-lived progeny

Nuclide	$t_{1/2}$	E_{α} [MeV]	$E_{\beta,\text{max}}$ [MeV]
^{222}Rn	3.8 d	5.5	-
^{218}Po	3.1 min	6.0	-
^{214}Pb	27 min	-	1.0
^{214}Bi	20 min		3.2
^{214}Po	164 μs	7.7	-

Important radionuclides for RP – fission products

- **Fission products** are produced in the fuel and have by far the greatest activity of all radionuclides in NPP.
- During power reactor operation (or immediately after shutdown) total activity of a single fuel element is higher than 10^{18} Bq, a month after shutdown it is around 10^{17} Bq and after 10 years in the spent fuel pit it is around 10^{16} Bq.
- Most of the fission products are chemically bound in uranium dioxide.
- Fuel pellet is **the first barrier** to prevent the spreading of radioactive materials.

Major fission products

Nuclide	$t_{1/2}$	E_{γ} [MeV]	$E_{\beta, \max}$ [MeV]
^{85m}Kr	4.48 h	0.151	
^{133}Xe	5.25 d	0.081	
^{135}Xe	9.10 h	0.250	
^{131}I	8.02 d	0.364; 0.637	
^{137}Cs	30.2 y	0.662	
$^{90}\text{Sr}/^{90}\text{Y}$	28.6 y	-	2.3
^3H	12.3 y	-	0.02

Important radionuclides for RP – fission products

- Noble gases (**Kr and Xe** isotopes; practically entirely), volatile elements (**I, Cs, Sr, tritium**; the bulk of the inventory), and partly the isotopes of **Ba, Ce** and **Ru/Rh** escape from pellet and build up into in the gap (space between pellet and fuel cladding). The cladding is therefore **second barrier**.
- Power reactor core contains 20,000 to 50,000 fuel rods and just in few, if any, have cladding failure during service life.
- Some fission products (**tritium and the noble gases** in particular) are able to diffuse through the cladding.
 - a fraction of the fission products passes into the reactor coolant.
- The highest activity of all fission products has **^{133}Xe** .

Important radionuclides for RP – activation and corrosion products

- Fission neutrons **activate** materials in the core and core surrounding:
 - the coolant and construction materials.
- Corrosion and erosion products from primary system and brought by reactor coolant are also activated in the core.

Major activation and corrosion products

Nuclide	$t_{1/2}$	formation	E_γ [MeV]
^{16}N	7.1 s	$^{16}\text{O} (n, p) ^{16}\text{N}$	6.13; 7.12
^{41}Ar	1.83 h	$^{40}\text{Ar} (n, \gamma) ^{41}\text{Ar}$	1.29
^{51}Cr	27.7 d	$^{50}\text{Cr} (n, \gamma) ^{51}\text{Cr}$	0.32
^{54}Mn	312 d	$^{54}\text{Fe} (n, p) ^{54}\text{Mn}$	0.835
^{58}Co	70.8 d	$^{58}\text{Ni} (n, p) ^{58}\text{Co}$	0.811
^{59}Fe	44.5 d	$^{58}\text{Fe} (n, \gamma) ^{59}\text{Fe}$	1.099; 1.292
^{60}Co	5.27 y	$^{59}\text{Co} (n, \gamma) ^{60}\text{Co}$	1.332; 1.173

Important radionuclides for RP – activation and corrosion products

- During normal operations the activation and corrosion radionuclides are spread by the coolant through the primary circuit. Part of these radionuclides eventually binds to the inner walls of primary system and cause **contamination of primary system**.
- Fission products are also released to coolant, but contained within primary system.
- Pressure boundary of primary system is **the third barrier** to the dispersal of radioactive material.
- One of the activation products is also ^{16}N . It is formed by fast neutron reaction on oxygen.
- ^{16}N emits highly penetrating gamma radiation and is **the most important source of radiation in the coolant during reactor operation**.
- Argon is present in the air (1%) and is activated (^{41}Ar) in hollow spaces adjacent to the reactor vessel. In pool type research reactors ^{41}Ar accounts for the largest part of activity released from the reactor site.

Important radionuclides for RP – hot particles

- **During the maintenance of different components, tiny particles could be released into primary system.**
 - These particles are activated when passing reactor core.
- **Similar thing can happen when foreign object enter the system and is carried with coolant causing damage to primary system walls and components.**
 - Result are microscopically small particles which are activate in core.
- **These small, mobile and highly radioactive particles are called **hot particles**.**
 - Hot particles can produce high local doses if they attach to skin, or if they are inhaled.

All materials in this presentation are based on IAEA safety standards and training materials developed by the IAEA.

THANK YOU

