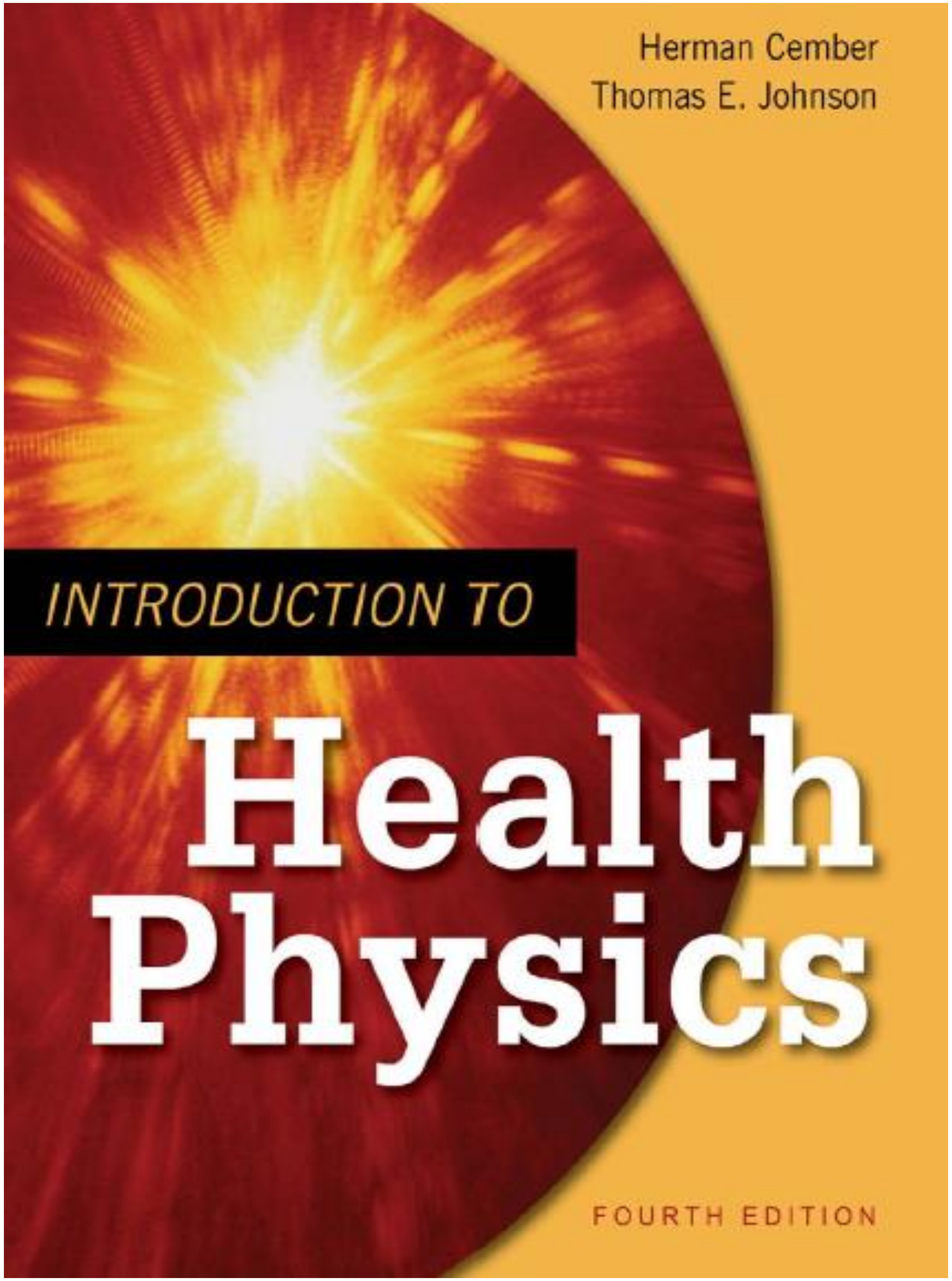
Radiation Protection / Health Physics

Contents:

1. Fundamentals of nuclear and radiation physics
2. Dose quantities and units
3. Detriment of ionizing radiations, regulatory control of sources and activities
4. Measurement of ionizing radiations
5. Natural and artificial radioactivity, radioactive wastes
6. Procedures and practices of radiation protection



References

Downloadable textbook;
Pdf version of the lectures of the previous courses are downloadable from INT website;
Pdf version of the present course will be downloadable before the tests.

Timetable

Lectures: 2x1 contact hours in the academic period
Tests (non-compulsory) 25th March and 20th May; if not taken, exam (=test) is due in the exam period

Radioactivity and ionizing radiations

In the course of radioactive decay the structure of the **atomic nucleus** changes. DECAY = new internal structure is established, the new nucleus is stabilized by emitting particle radiation(s).

Historical milestones:

- Wilhelm Conrad Röntgen (1895-96) identified high energy photon radiation on the wall of cathode ray tube as a consequence of electron acceleration.
- Henri Becquerel (1896) examined uranium and experienced blackening of a photographic paper in total darkness; he identified it as a consequence of invisible radiation.
- Pierre and Marie Curie (1898) chemically separated elements from the decay chain of natural uranium stating that their radiation is not influenced by physical or chemical conditions.
- Ernest Rutherford (1911) examined the ionizing capabilities of particles from nuclear decay and distinguished (at least) two types: α and β radiation; scattering of α particles confirmed that atoms do not fill the space completely, instead, the vast majority of their mass in concentrated in a very small volume, the atomic nucleus.

Structure of atomic nucleus*:*

built up from nucleons (protons and neutrons)

Nuclei are compound particles of10^{-15} m (fm) size.

Number of protons (**Z**):

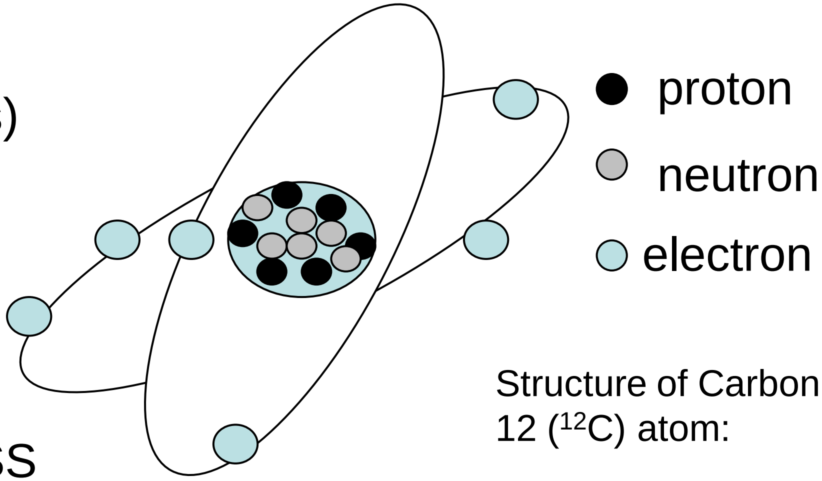
- defines the atomic number of the element, determines the chemical behaviour;
- protons are positively charged, REST MASS of it (m_0) is equivalent with **938.2 MeV** ($E=m_0.c^2$ – Einstein's principle of equivalence).

Number of neutrons (**N**): neutrons are not charged, m_0 = **939.5 MeV.** Unstable in stand-alone state, decays with 10.4 m half-life.

$n \rightarrow p^+ + e^- + E_{kin}$ $E_{kin} = 0.8$ MeV

Mass number: **A = Z + N**

Binding energy = „mass defect" = the „virtual" mass of an atom is always smaller that of the sum of the respective number of nucleons



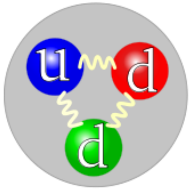
Structure of Carbon-12 (^{12}C) atom:

6 protons

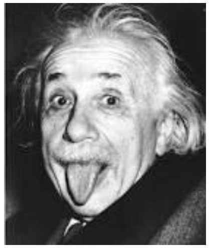
6 neutrons

6 electrons

Nucleons are *hadrons*: they consist of quarks



Proton: u+u+d
Neutron: u+d+d



$$\Delta E = \Delta m \cdot c^2$$

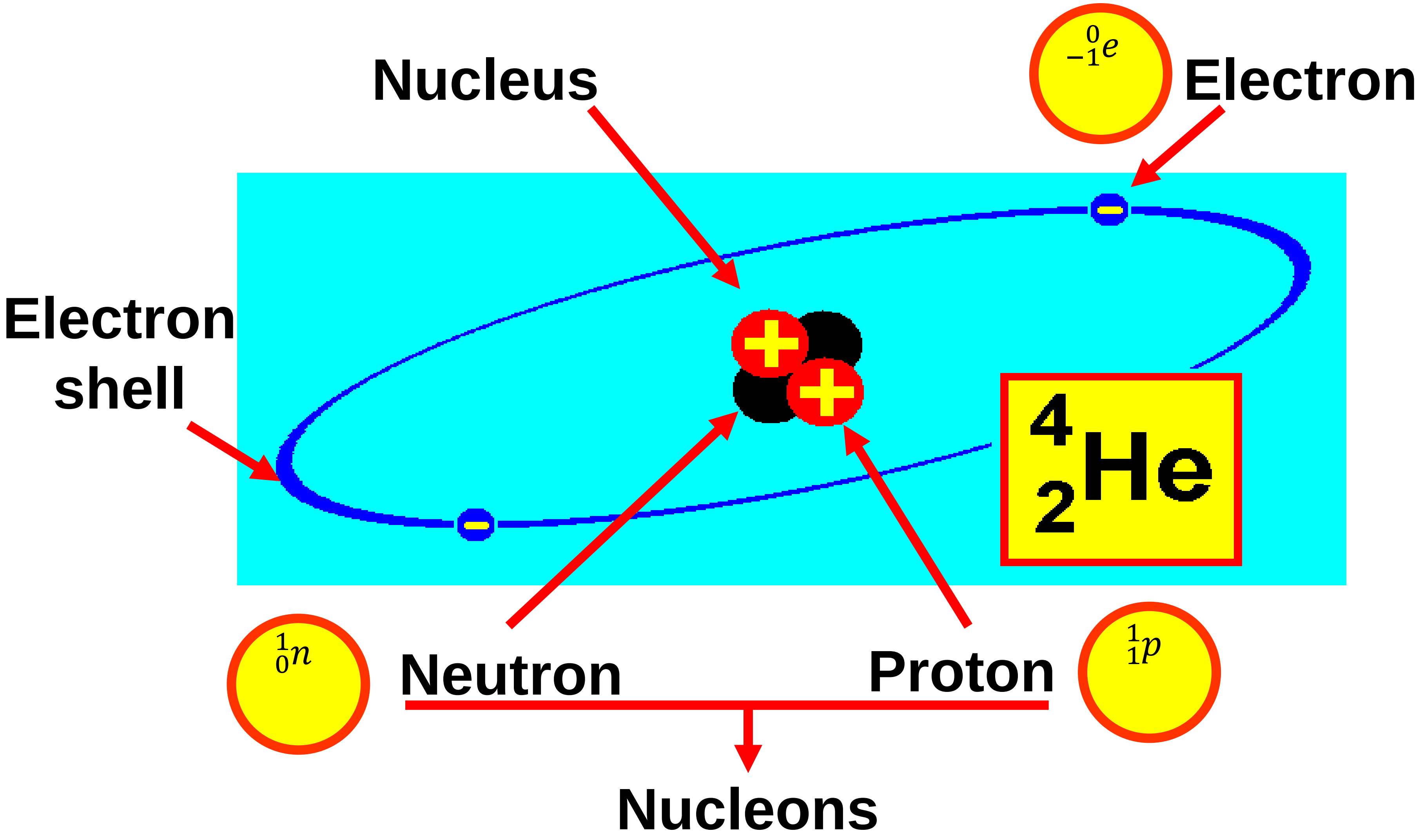
Number of protons (**Z**): = atomic number – defines chemical characteristics
Number of neutrons(**N**):
Mass number: **A = Z + N**

Nuclides = atomic nuclei: **compound particles** having a given number of protons and neutrons.
A nuclide can be **stable** or **unstable** = **radioactive**
Nuclides have different excitation states (energy states). $^{16}_{8}O$
Notation: mass number and sign of element ^{16}O (O = 8 protons)

Protons and neutrons of a nucleus can be odd (o) or even (e) – it has a major influence on stability:

162 e, e
59 e, o
49 o, e stable nuclides exist.
5 o, o

Atomic structure of ^{4}He



Nucleus

$^{0}_{-1}e$ **Electron**

Electron shell

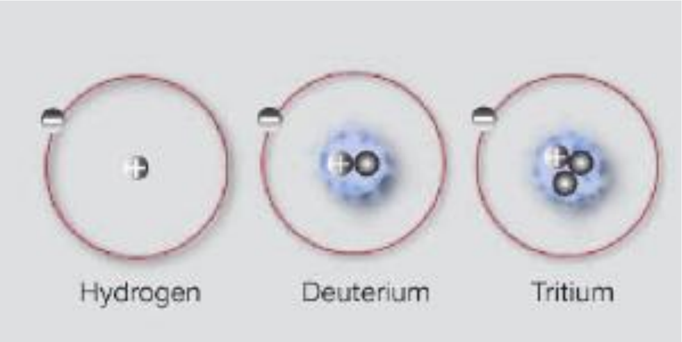
$^{4}_{2}\mathrm{He}$

$^{1}_{0}n$ **Neutron**

Proton $^{1}_{1}p$

Nucleons

AN ELEMENT HAS ONE OR MORE ISOTOPES:



Hydrogen isotopes: hydrogen, deuterium, tritium

Iron has 26 protons, neutrons range from 26 to 35.

Isotopes:

stable (H, D): characterized with isotope abundance

radioactive: characterized with decay mode and probability (half-life)

^{3}H: β^{-}- decay, $T_{1/2}$:12.3 a

Binding forces in nuclei

Nuclear forces are the *strong* and *weak interactions*. They differ from „macroscopic” forces because they are:

a) Attracting, 100 times more intense than electric forces,

b) Independent of charge,

c) Short range, die away beyond 1.4 fm distance,

d) *Saturable* = one particle can interact only with a few other in its vicinity

NUCLEAR MODELS: liquid drop, shell, cluster - collective model (hierarchy of particles inside a nucleus)

http://www.personal.soton.ac.uk/ab1u06/teaching/phys3002/course/05_shell.pdf

Nuclear particles are also affected by „macroscopic” forces (mass attraction, electric and electromagnetic attraction and distraction).

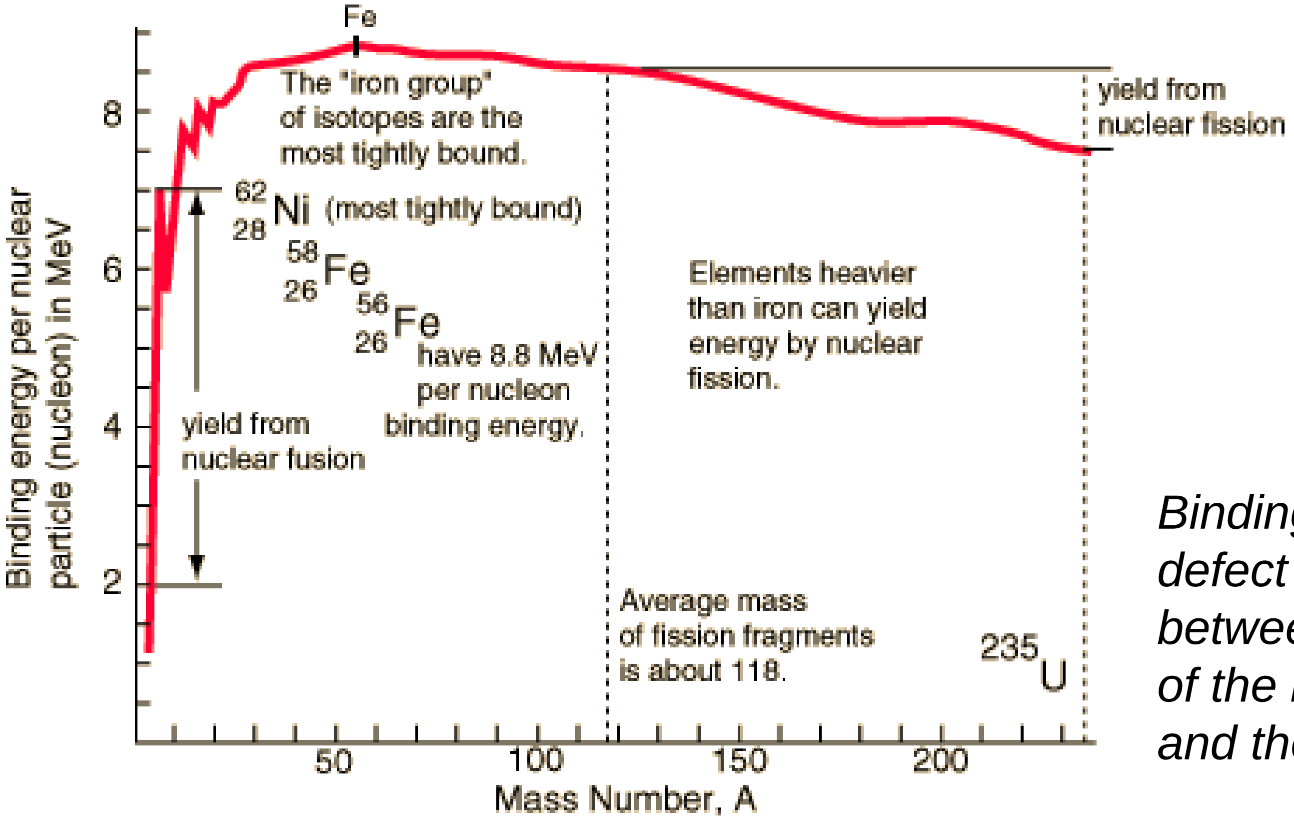
Grouping of elementary particles

- According to spin: fermions (half spin: proton, neutron, electron) and bosons (integer spin: photon)
- According to interactions: particles with ability for strong and weak nuclear interaction (hadrons: consist of **quarks** [baryons, mesons]) or particles with weak interaction only (leptons: electron, muon, neutrino)

Fermions: Pauli-principle: atoms cannot have 2 fermions in the same state

Bosons: „field”-components, mediators of interactions (quarks interact by means of gluons)

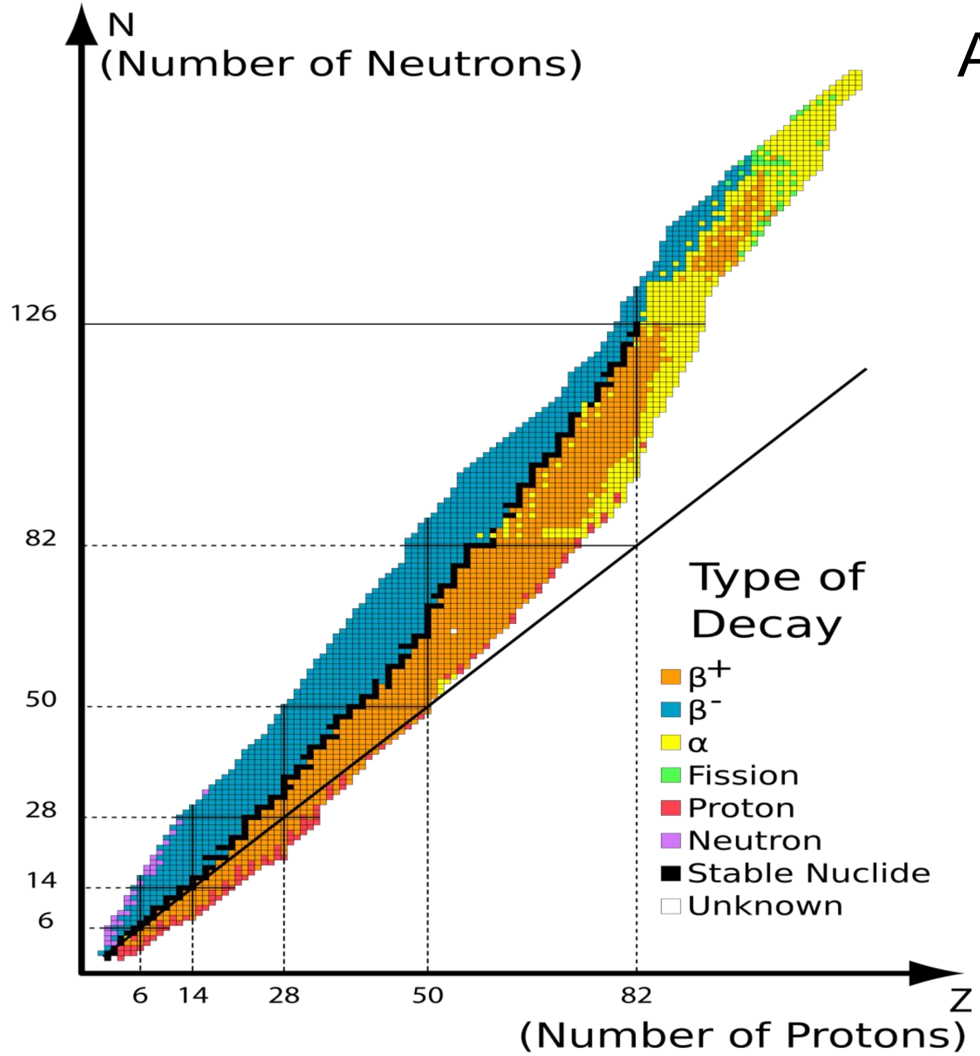
„Stability curve” – binding energy per nucleon



$E_b=(\Delta m).c^2$

Binding energy = mass defect – difference between sum of masses of the individual particles and the real atomic mass

„Belt of stability” of isotopes



As the number of protons increase, more neutrons are required for compensating for the distractive force of the near positive charges

Source of picture: http://chem.libretexts.org/Core/Physical_and_Theoretical_Chemistry/Nuclear_Chemistry/Nuclear_Stability_and_Magic_Numbers

Basic equations of radioactivity

$$dN = -\lambda \cdot N \cdot dt$$

$$A = \left|\frac{dN}{dt}\right| = \lambda N$$

N: number of identical decayable nuclides [piece]
λ: decay constant = probability of decay per time period [1/s]
t: time
A: activity [1/s ; Becquerel; Bq]
$T_{1/2}$: half-life [s]

After integration of this „probabilistic” differential equation we receive:

$$N = N_0 \cdot e^{-\lambda t}$$

$$A = A_0 \cdot e^{-\lambda t}$$

$$T_{1/2} = \frac{\ln 2}{\lambda}$$

Serial decay: parent and descendant nuclides

$$\frac{dN_2}{dt} = -\lambda_2 \cdot N_2 + \lambda_1 \cdot N_1$$

„Secular” equilibrium: if the decay rate (=activity) of the parent is much smaller than that of the descendant the activity of the latter will reach (but cannot exceed) the activity of the former.

$A_2 \approx A_1$

Decay modes

$$\Delta E = \sum_{p} (E_m + E_{kin}) + E_{bs}$$

p: particles emitted in the decay
m: rest (zero kinetic energy) mass
E_{kin}: kinetic energy
E_{bs}: backscatter energy of the „new” nucleus

Decay modes = cessation of a previously generated excited nuclear state ≠ nuclear reaction !

α, β („directly” ionizing radiations)
γ („satellite” decay mode: conclusion (termination) of other decay modes, „fine tuning” of nuclear structure – electromagnetic interaction)
f (fission = spontaneous nuclear fission, dismemberment of nucleus into two parts + emission of neutrons)

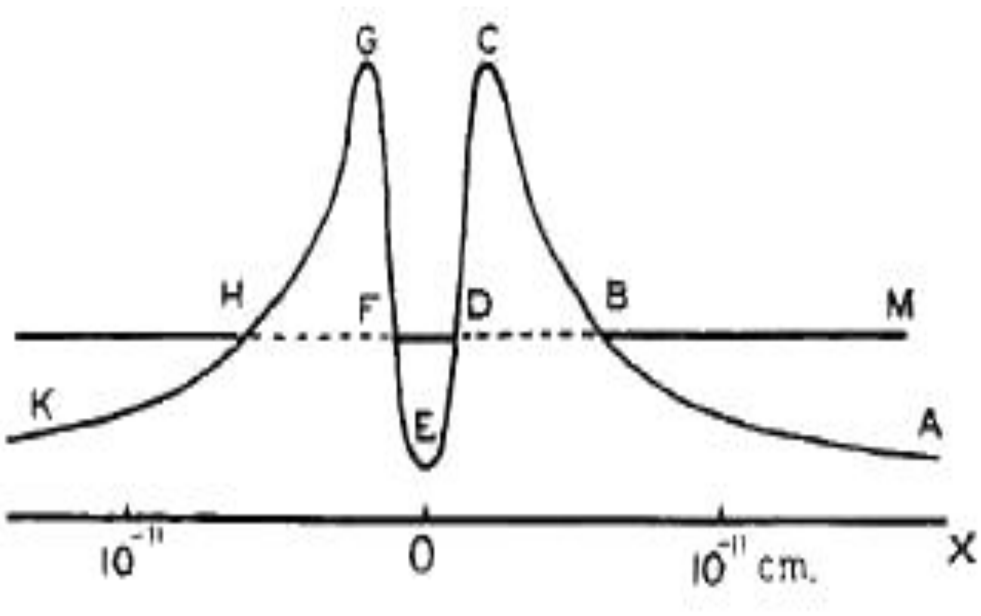
Decay modes – alpha decay

In **α-decay** the initial (parent) nucleus emits a helium nucleus (2p + 2n; 2 positive charges) with 3 -10 MeV kinetic energy. In the descendant nucleus the mass number decreases by 4, protons decrease by 2. It is driven by the strong nuclear interaction.

„Discrete” energy transition: E_{kin} is exclusively characteristic to the given radioisotope but distributed between the α-particle and the backscattered nucleus.

Spectrum: Number of emitted (detected) particles as a function of kinetic (incident) energy.

Decay modes – alpha decay



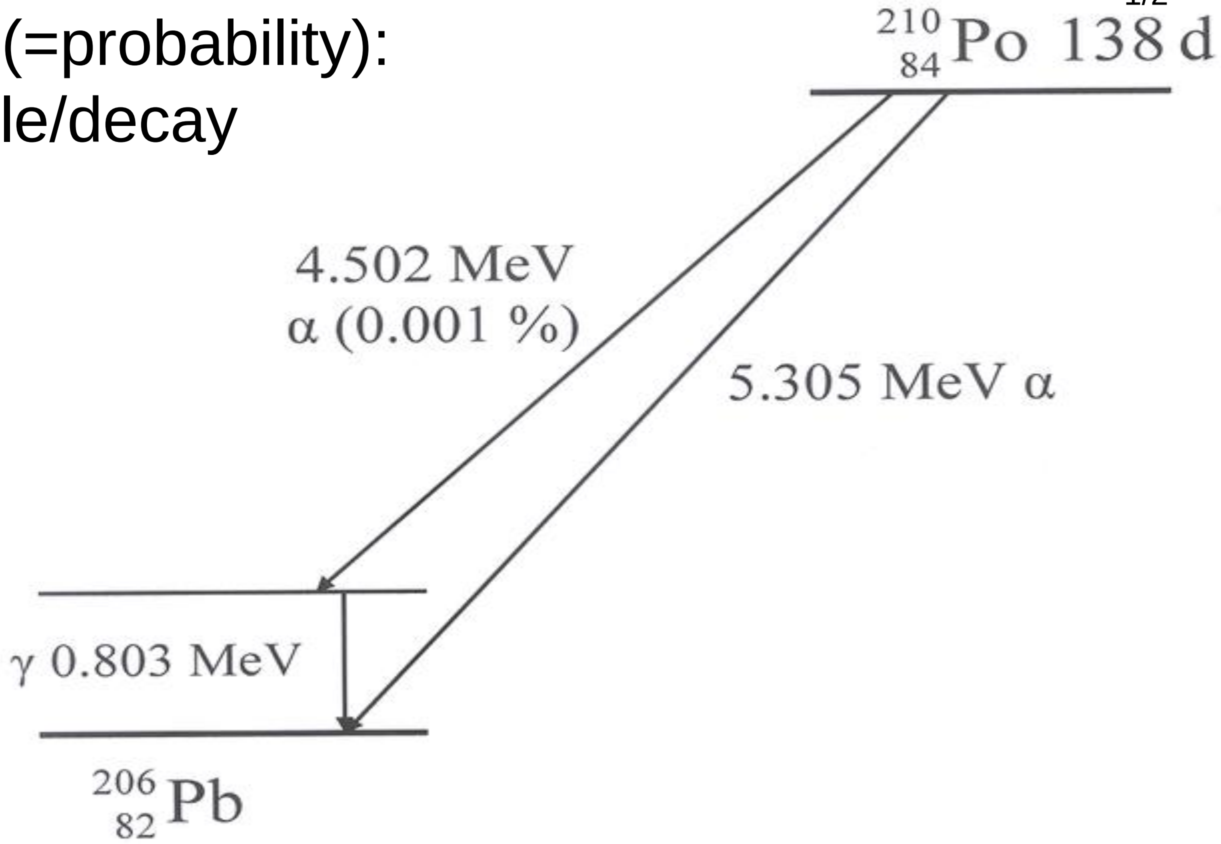
„Tunnel effect": the potential barrier (attractive force that holds back the nuclear particles in the nucleus) can be tunnelled incidentally = in a probabilistic manner.

http://www.nature.com/physics/looking-back/gurney/index.html#f1

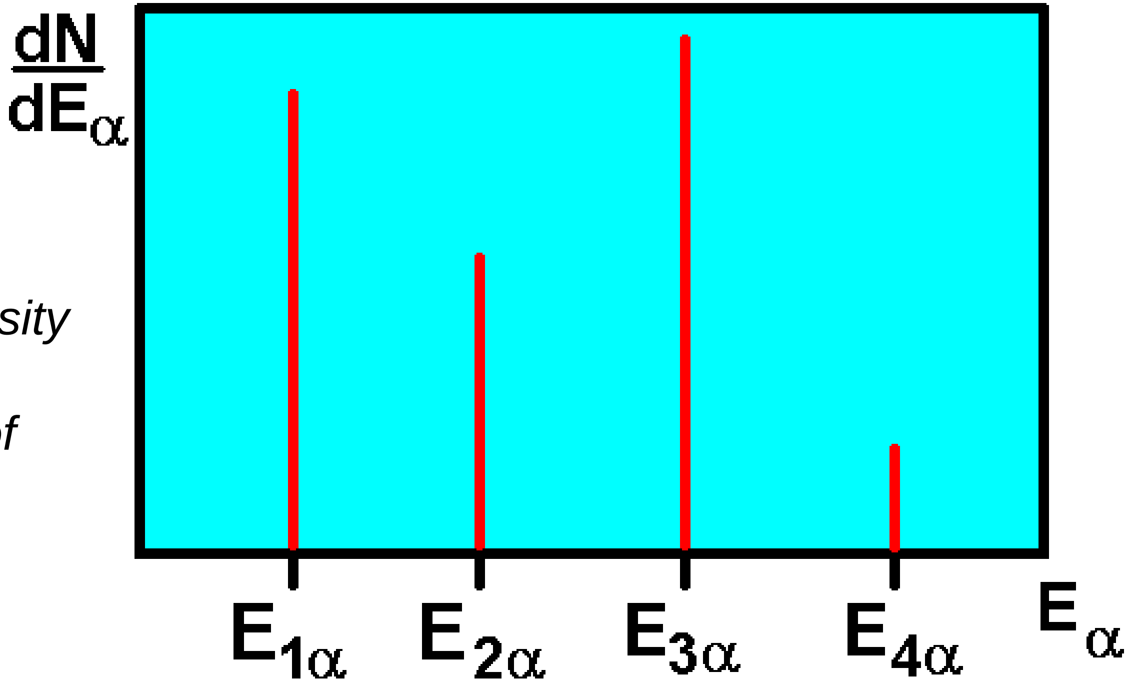
Energy structure of α-decay

Yield (=probability):
particle/decay

$T_{1/2}$=



Alpha radiation: discrete energies

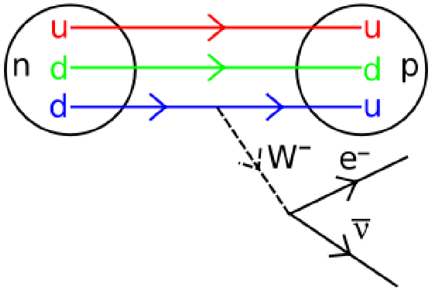


Spectrum: intensity of a radiation versus energy of particles

$$^{A}_{Z}X \xrightarrow{\alpha} {}^{A-4}_{Z-2}Y + {}^{4}_{2}He + Q_\alpha$$

Decay modes – beta decay

Beta decay is a hadronic transformation governed by the weak nuclear interaction. Kinetic energy is stochastically distributed between the electron/positron and the antineutrino/neutrino. Thus the kinetic energy is <u>not discrete</u>.



1) β⁻ : electron and antineutrino are emitted

$n \rightarrow p^+ \,|\, + e^- + \tilde{\nu}$: atomic number increases by 1

2a) β⁺: positron and neutrino are emitted

$$e^+ + e^- = 2f$$

$p^+ \rightarrow n \,|\, + e^+ + \nu$: atomic number decreases by 1

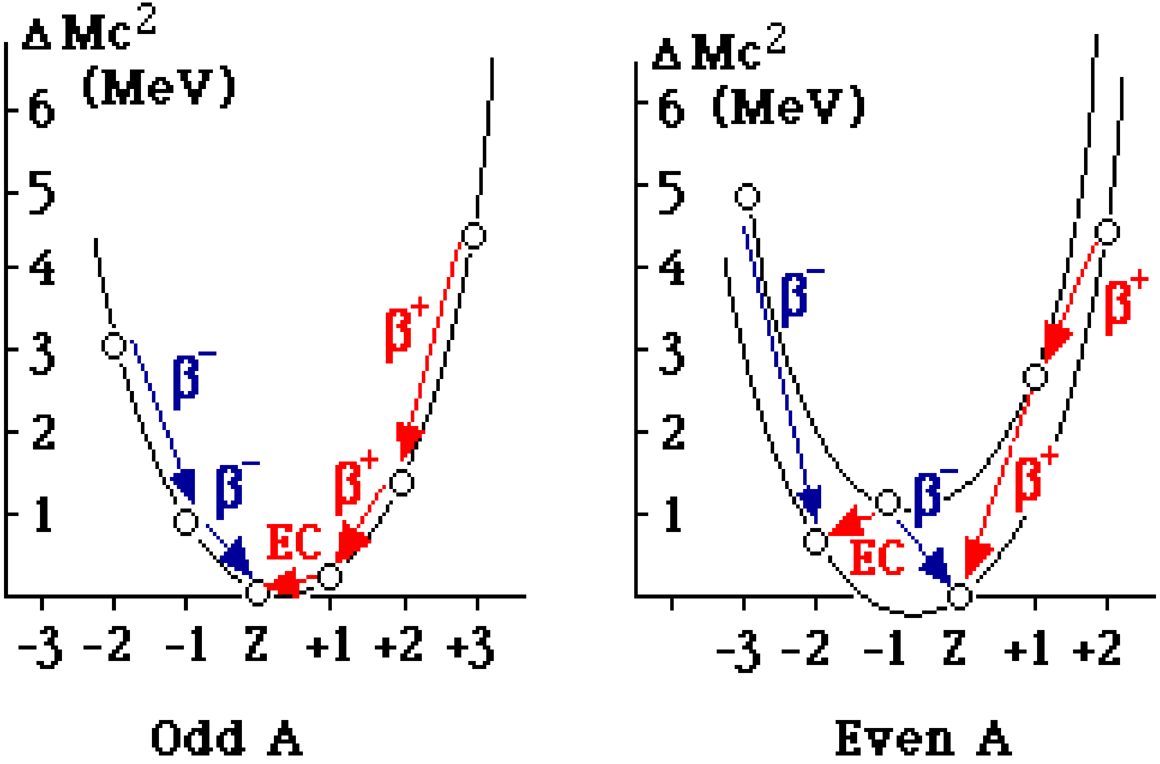
$e^- + e^+$ collision → annihilation = 2 photons of 0.51 MeV are emitted

2b) EC = electron capture - neutrino is emitted

$p^+ + e^- \rightarrow n \,|\, + \nu$: atomic number decreases by 1

The „captured” electron is supplied from an outer shell – satellite characteristic X-ray radiation is generated

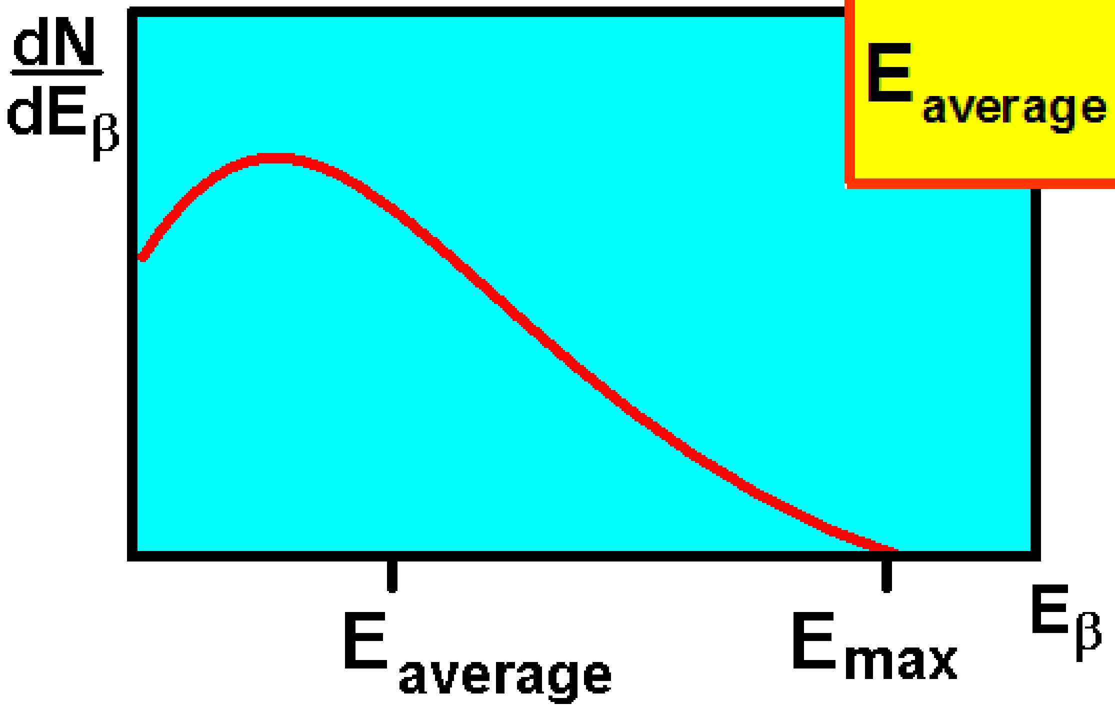
Beta decay series of isobar nuclei



Source of picture: http://physics-database.group.shef.ac.uk/phy303/phy303-4.html

Due to the higher stability of even number of protons and neutrons in a nucleus odd-A isobar series have 1 stable item while even-A series may have more.

Beta radiation: continuous energy distribution = spectrum



$$E_{average} \approx \frac{1}{3} E_{max}$$

$${}^{A}_{Z}X \xrightarrow{\beta^-} {}^{A}_{Z+1}Y + {}^{0}_{-1}e + {}^{0}_{0}\tilde{\nu} + Q_{\beta}$$

Decay modes – gamma transition

Gamma transition: de-excitation of hadronic particles = „rest” energy released by emitting photons following an alpha or beta decay. γ-transition = „fine tuning” of nuclear structure following alpha or beta decay. Nuclear reactions (collision of particles) also can generate prompt gamma photons.

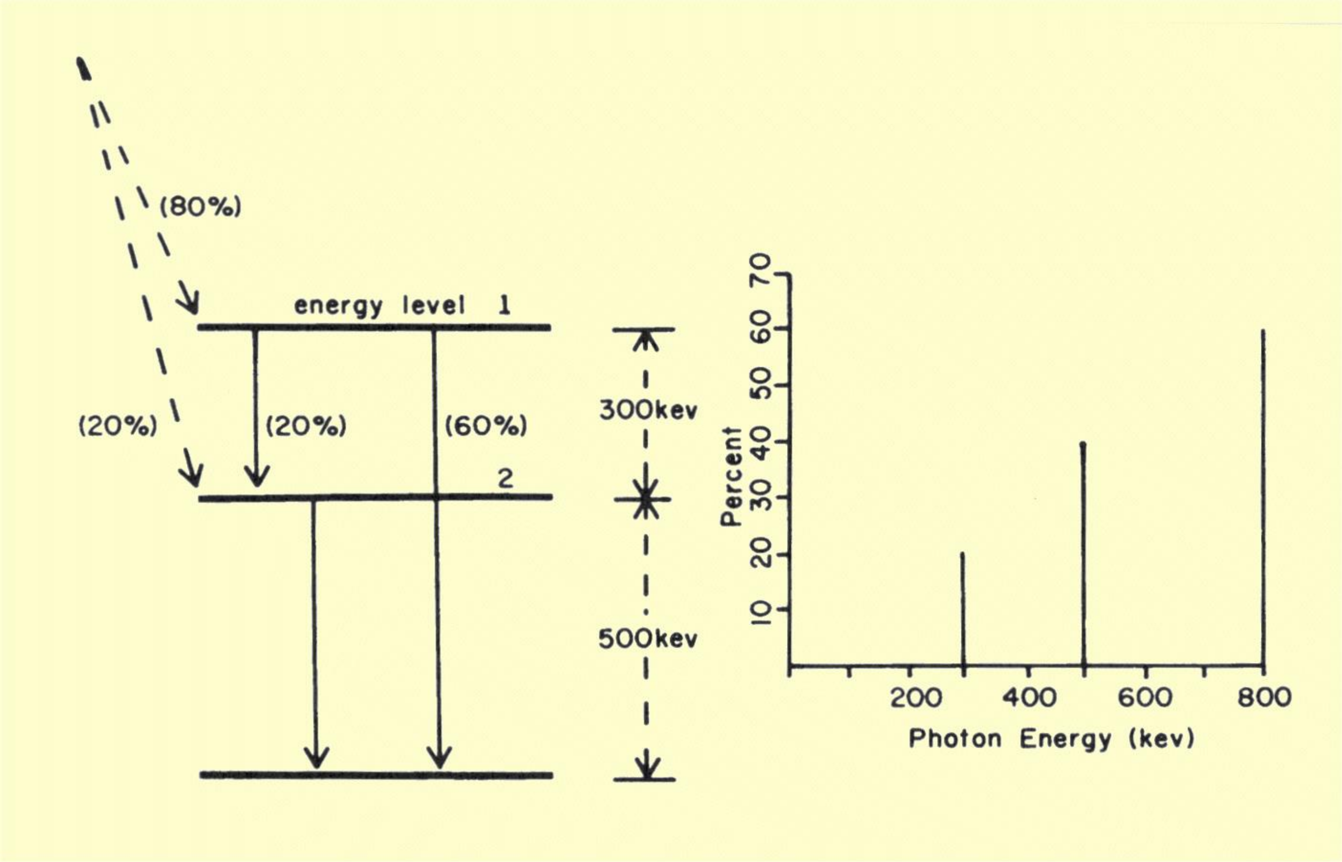
Photon energies are discrete = difference of initial and final energy levels of hadronic particles → characteristic to decaying nuclide → facilitates nuclear identification.

De-excitation of hadronic particles (mostly with large atoms and low „rest” energy Eγ<2-300 keV) can also result in the emission of an electron from an internal spheric (K or L) shell as an alternative to γ-emission. (These electrons have a certain probability to be located „inside” the nucleus.) This is *internal conversion* (IC) that is necessarily followed by the emission of characteristic X-(Röntgen)-photons.

$$E_\gamma \Rightarrow E_{e-,kin} + E_{e-,shell}$$

The energy of the *conversion electron* is discrete – elemental identification of the decay product is possible.

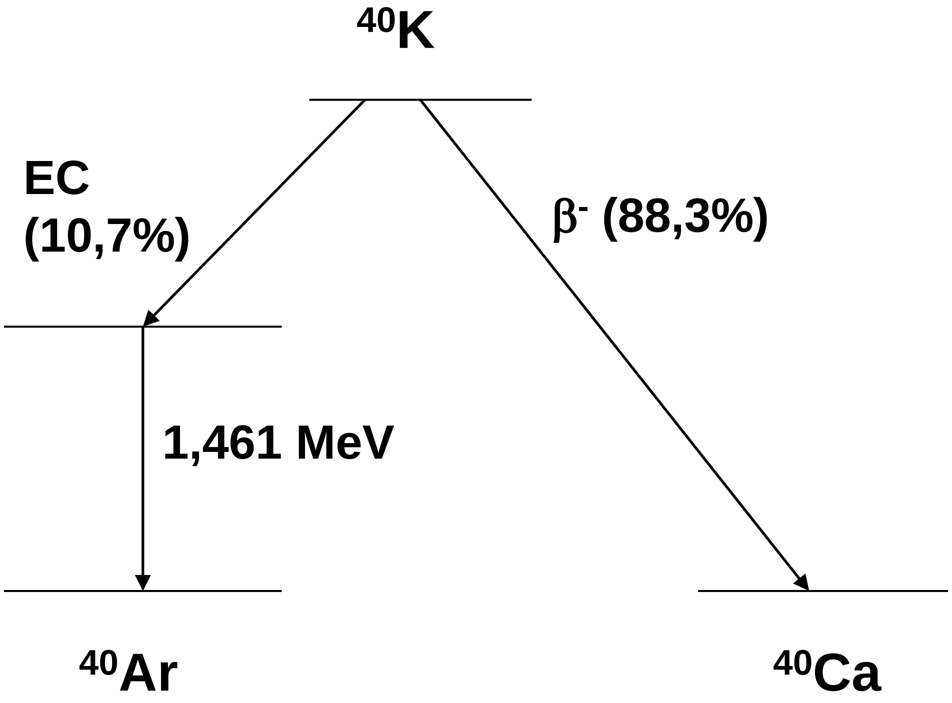
Beta decay and consecutive gamma transition



General structure of gamma transitions following alpha or beta decay

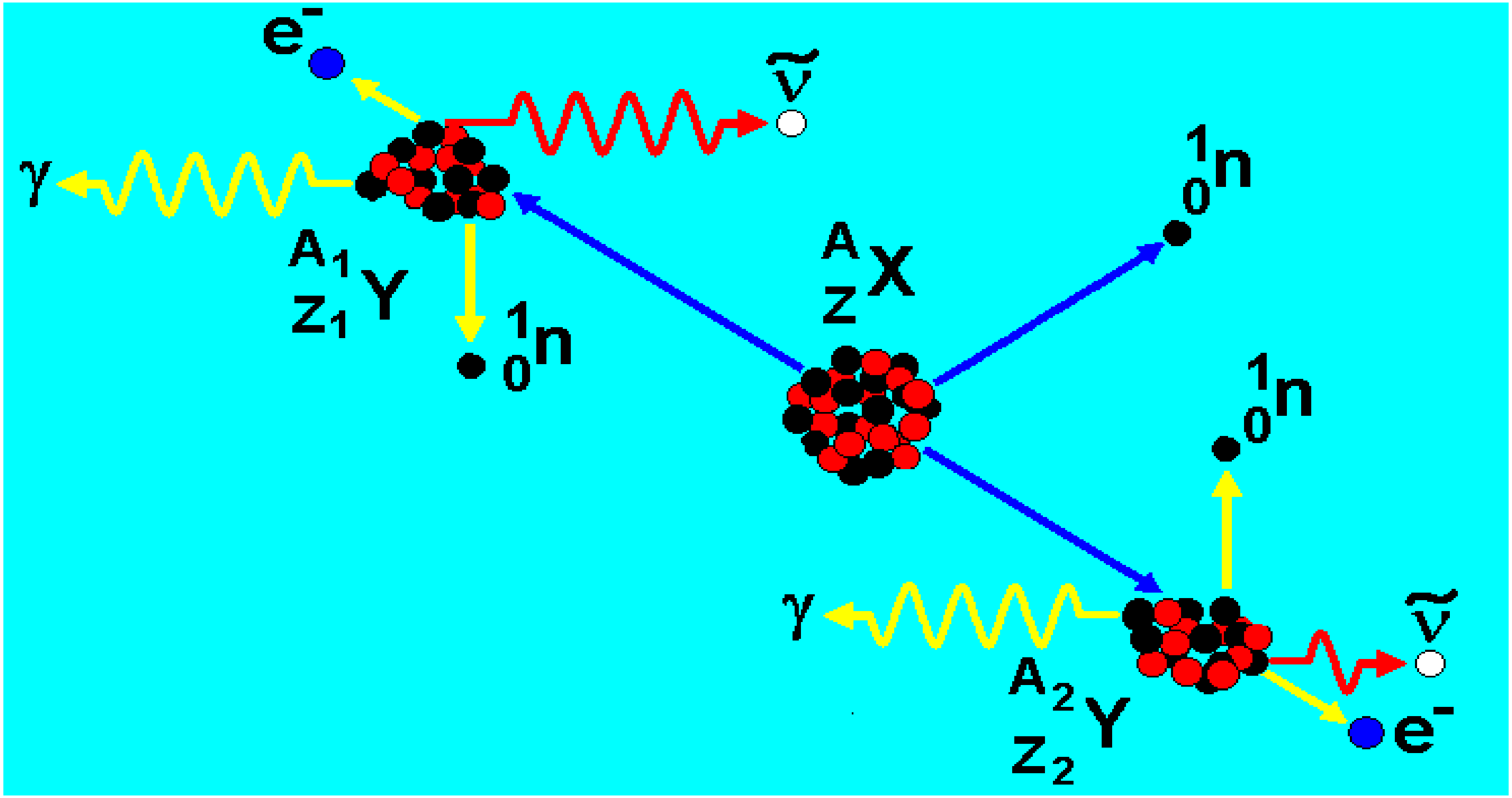
Two types of beta decay and consecutive gamma transition of ^{40}K

Beta minus and beta plus decay of this odd-odd radionuclide are both probable. Electron capture is followed by gamma emission.



Source of picture: http://www.sprawls.org/ppmi2/RADIOTRANS/#Gamma%20Emission

Spontaneous fission



„Superheavy” nuclides may undergo fission resulting in two medium size nuclides which are generally beta-emitters and free neutrons

Calculus: Radioactivity of an adult due to ^{40}K-content of human body

$T_{1/2}$ of ^{40}K = 1.28×10^{9} year,

average body weight (m_e) = 70 kg,

$$A = N \cdot \lambda$$

average (constant) K-content (c_K):

- male 1.7 – 2.7 g/kg,
- female 1.3 – 2.3 g/kg
- average: 0.2 %

$$N = \frac{m_{^{40}K}}{M} \cdot N_A$$

isotope ratio (Θ) = ^{40}K is 0.0118 % of potassium

Activity (A):

4200 Bq

$$m_{^{40}K} = m_{human} \cdot c_K \cdot \Theta$$

f_γ = 0.107 means

455 s^{-1} photon yield

Ionizing radiations - Interactions between radiation and matter

Potential interacting components of matter: electrons, electromagnetic field of atoms and molecules, atomic nucleus.

-Directly ionizing radiations: α, β, γ, X – particles collide with electrons and transfer them kinetic energy large enough to ionize them. Collision with photons is a probablistic process unlike that with α- and β-particles. Energy transferred in a photon-electron collision is further dispersed by the „primary" electron.

-Indirectly ionizing radiation: neutrons cannot directly transfer their kinetic energy to electrons, but they collide with atomic nuclei resulting in formation of radioactive nuclei (=nuclear reactions) and/or emission of ionizing particles (α^{2+}*, γ,* p^{+}*).*

Interactions between radiation and matter

Collision with electrons does not always lead to ionization. Gradual energy transfer in several steps includes excitation of atoms and molecules as well, necessarily resulting the increase of thermal energy.

The quantity of energy loss by ionization depends on the energy required for separating one pair of positive and negative charges in that matter. Typical values: 15 – 40 eV/pair for insulators (gases, ionic crystals etc.) and 2 – 5 eV/pair for semiconductors.

As an alternative to collisions, charge carriers with high velocity (α^{2+}, β^{-}-particles or free „primary” and „secondary” electrons) can interact with the electromagnetic field of atoms and thus emit bremsstrahlung = brake radiation = continuous X radiation while losing their velocity (impulse).

Linear energy transfer ≈ stopping power

Linear Energy Transfer = *LET*

$$L = \frac{dE_{kin}}{dx}$$

$$E_{kin} = \frac{m \cdot v^2}{2}$$

$$E_{kin,ph.} = h \cdot \nu$$

h: Planck constant = 6.63×10^{-34} Js
v: frequency

LET = L = change of kinetic energy of a particle along its pathway through a material

LET depends on
- ☐ *type and actual velocity of the particle*
- ☐ *number and type of collision partners for the particle (material quality and density)*

Primary partners for LET are the electrons of a material

Interactions of alpha radiation with matter

α-particles

LET-value in water: ~ 100 keV/μm
Way of energy impartment: ionization or excitation
Maximum energy transferable in one collision (step) (Q_α):

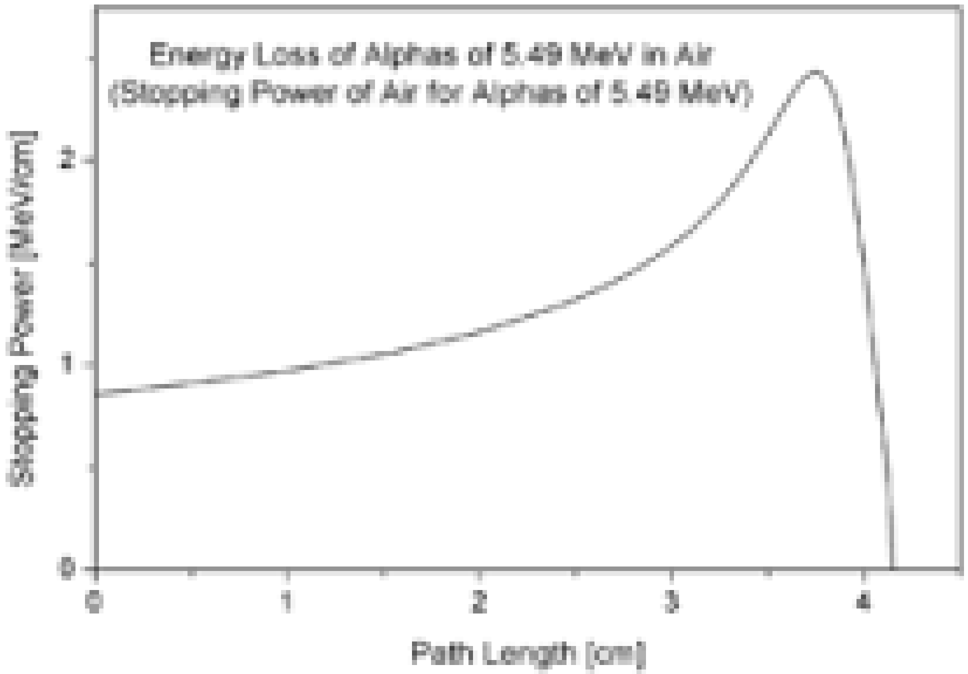
$$Q_\alpha = \frac{4 \cdot m_{e^-} \cdot m_\alpha \cdot E}{(m_{e^-} + m_\alpha)^2}$$

m_{e^-}: mass of electron
m_α: mass of α-particle
E: energy of α-particle before collision

The path of the α-particles is more or less linear due to their big mass compared to that of electrons (collision partners) – the range (R = maximum penetration depth) is small in condensed matter.

R_α (air) 4 – 8 cm
R_α (water) 50 – 100 μm

Interactions of alpha radiation with matter



The differential energy loss (LET) is roughly constant; it increases when the particle „stops" before reaching the range = Bragg-peak

Source: https://www.britannica.com/science/linear-energy-transfer

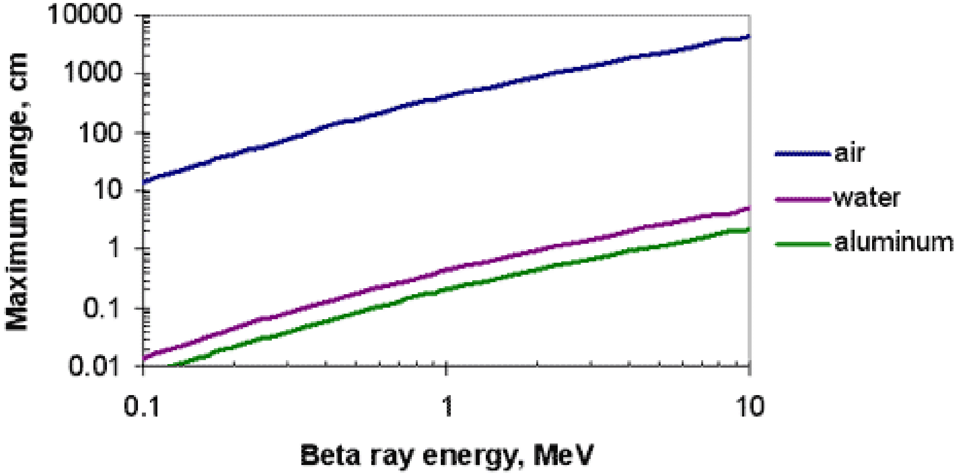
Interactions of beta radiation with matter

β-particles change their direction every time they collide with atomic electrons. Their LET-values are 0.1 – 2 keV/µm in condensed matter. Their range is thus much shorter than their total path length.

Fraction of beta-energy converted to bremsstrahlung radiation increases proportionally with Z of target and E_{max} of the radiation.

The LET vs. range curves are similar to that of alpha radiation.

α and β are considered „weakly penetrating" radiations = short range; thin shielding is sufficient



Source: http://holbert.faculty.asu.edu/eee460/IonizationRange.pdf

R_β *(air) 0.1 – 1 m*
R_β *(water) 1 – 10 mm*

Interaction of gamma- and X-radiation with matter

Energy transfer options of high energy photons to components of materials:

- To electrons: ionization via two competing types of interaction
- To atomic nuclei: absorption – nuclear reactions are possible above >5 MeV threshold only
- To electromagnetic field of atoms – above 1.02 MeV threshold

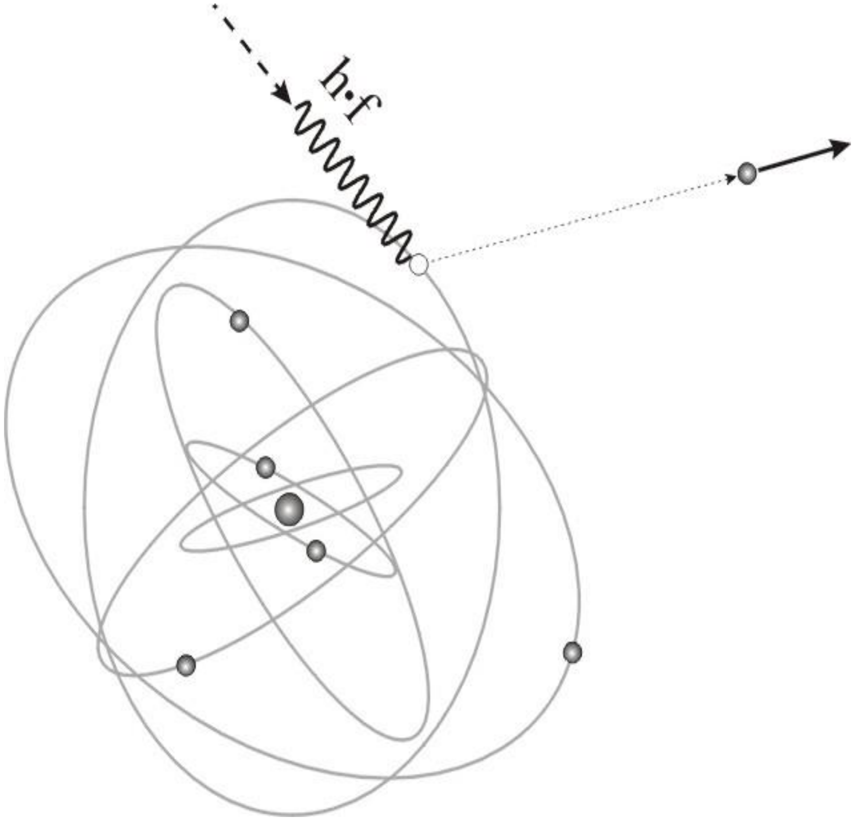
General feature: stochastic (probabilistic) interaction: „wave-type” energy transfer: different from „mechanical” collision of extended particles

Fate of kinetic energy given to electrons freed by the primary collision:

- Causes further ionization;
- Causes excitation;
- Generates secondary photon radiation (continuous X-ray = Bremsstrahlung)

(that is, a secondary electron behaves identically to a β^--particle)

Interactions of gamma photons – total absorption

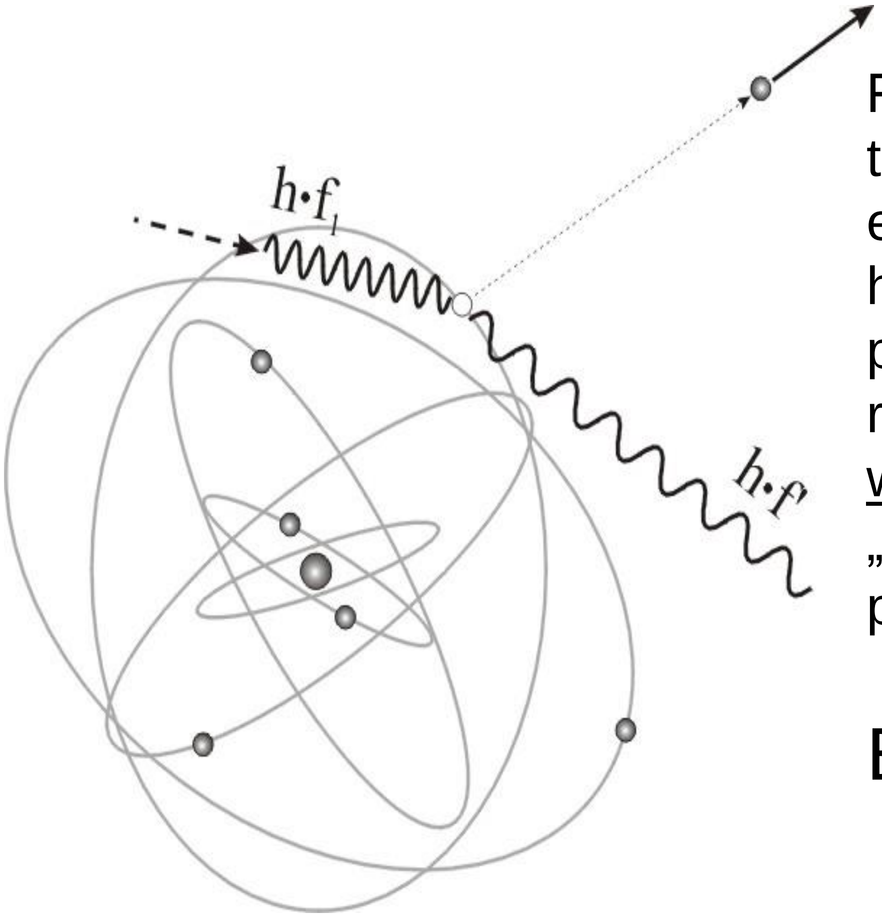


(other name: photoelectric effect)

The total (kinetic) energy of the γ-photon is transferred completely to a dedicated electron (mostly of the K-orbital). As $E_f >> E_{ion}$ the electron is removed from its orbit with a high kinetic energy. Photon ceases to exist.

$$E_f = E_{e,ion} + E_{e,kin}$$

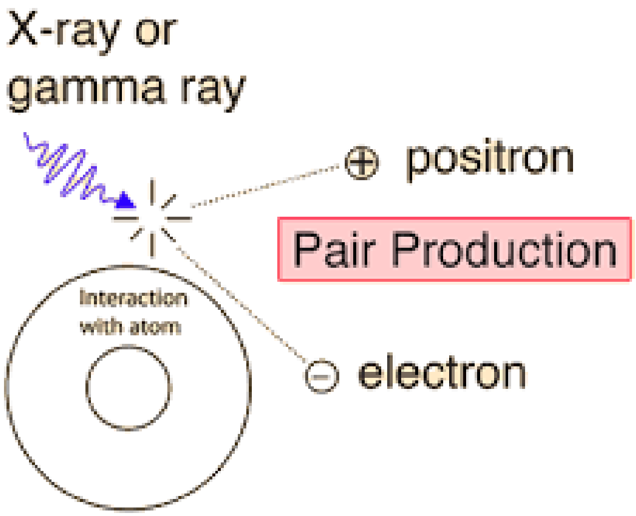
Interactions of gamma photons – Compton-scattering

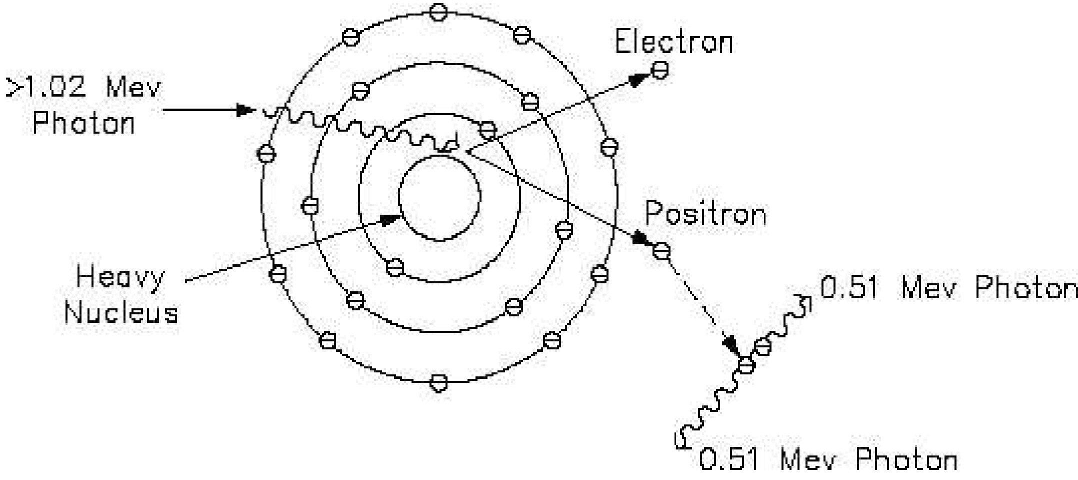


Part of γ-photon energy is transferred to the colliding electron. As $\Delta E_f \gg E_{ion}$ the electron is removed from its orbit with a high kinetic energy. The scattered photon proceeds in a diverted direction with reduced energy. Maximum (but not the whole!) energy transfer occurs by 180° „backscattering" of the generated „new" photon.

$$E_f = E_{f'} + E_{e,ion} + E_{e,kin}$$

Interaction of gamma photons – pair production



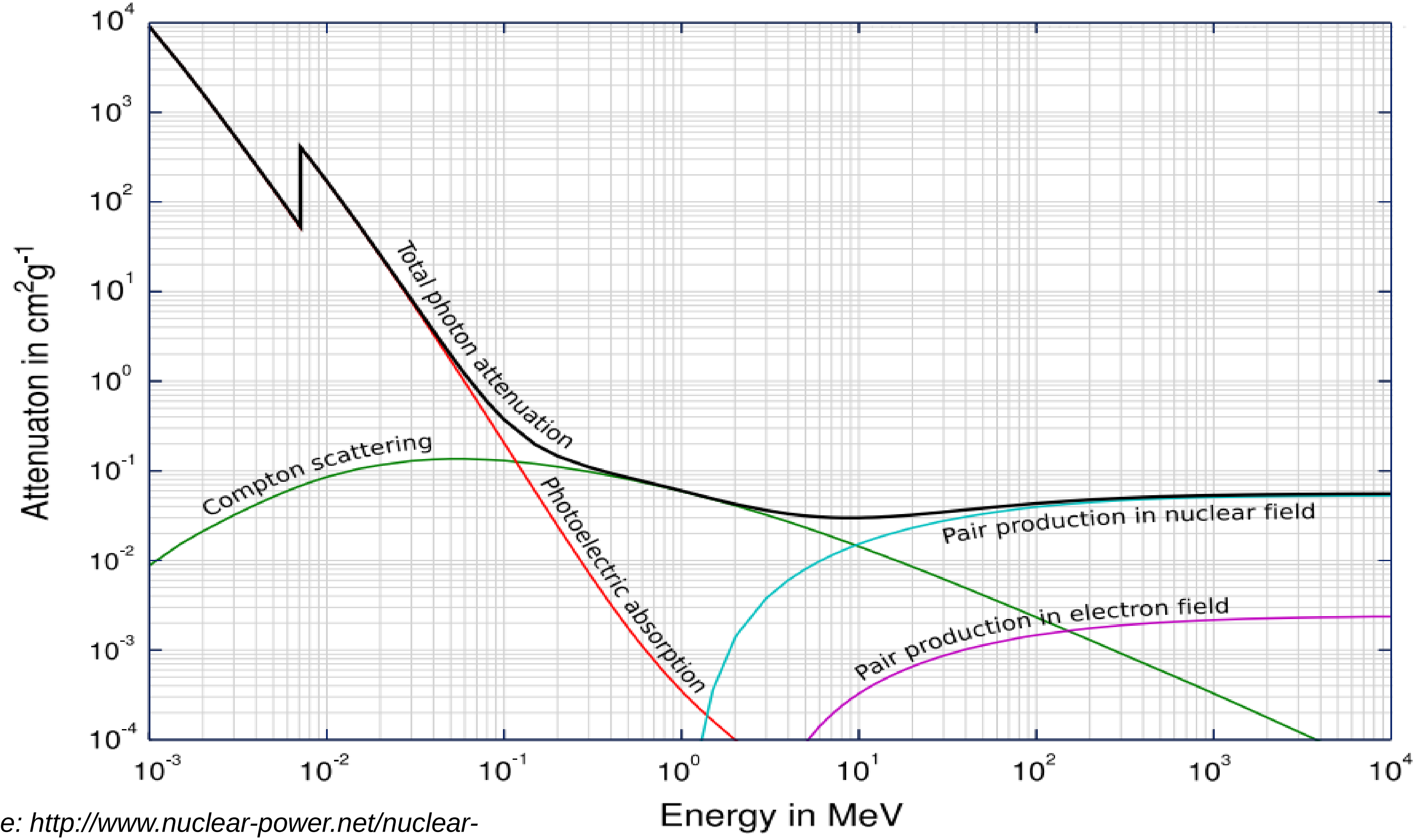


The γ-photon interacts with electromagnetic field of an atom: transfers its complete energy and ceases to exist. Energy of a boson generates two fermions: pair of e^- *and* e^+*.*

$$E_f=E_{e-,m}+E_{e-,kin}+E_{e+,m}+E_{e+,kin}$$

Threshold condition: $E_f > 2\times E_{e,m} = 2\times 511$ *keV (equivalent mass of two electrons)*

Interactions of photons – energy dependence



Source: http://www.nuclear-power.net/nuclear-power/reactor-physics/interaction-radiation-matter/interaction-gamma-radiation-matter/#prettyPhoto/2/

Attenuation of photon radiation

$$\mathbf{dI = -I(x)\,\sigma\,N\,dx}$$

I: intensity [s^{-1}]

σ: interaction probability with 1 „partner” [-]

N: number of „partners” in unit distance [m^{-1}]

$\mu = \sigma . N$ = interaction probability in unit distance [m^{-1}] = linear attenuation coefficient

μ is constant only if
- energy of photons is constant
- the absorbing material is homogeneous both physically and chemically

$$dI = -I \cdot \mu \cdot dx$$

Upon integration: general attenuation equation → next slide

Attenuation of photon radiation

$$I = I_0 \cdot \exp(-\mu x)$$

μ: compound linear attenuation coefficient [m^{-1}] combining the probability of each type of interaction.

The three main types of interaction (= total absorption, Compton scattering and pair production) are combined in „exclusive or” manner.

$\mu = \mu_1 + \mu_2 + \mu_3$

μ/ρ : mass specific attenuation coefficient [$m^2.kg^{-1}$]

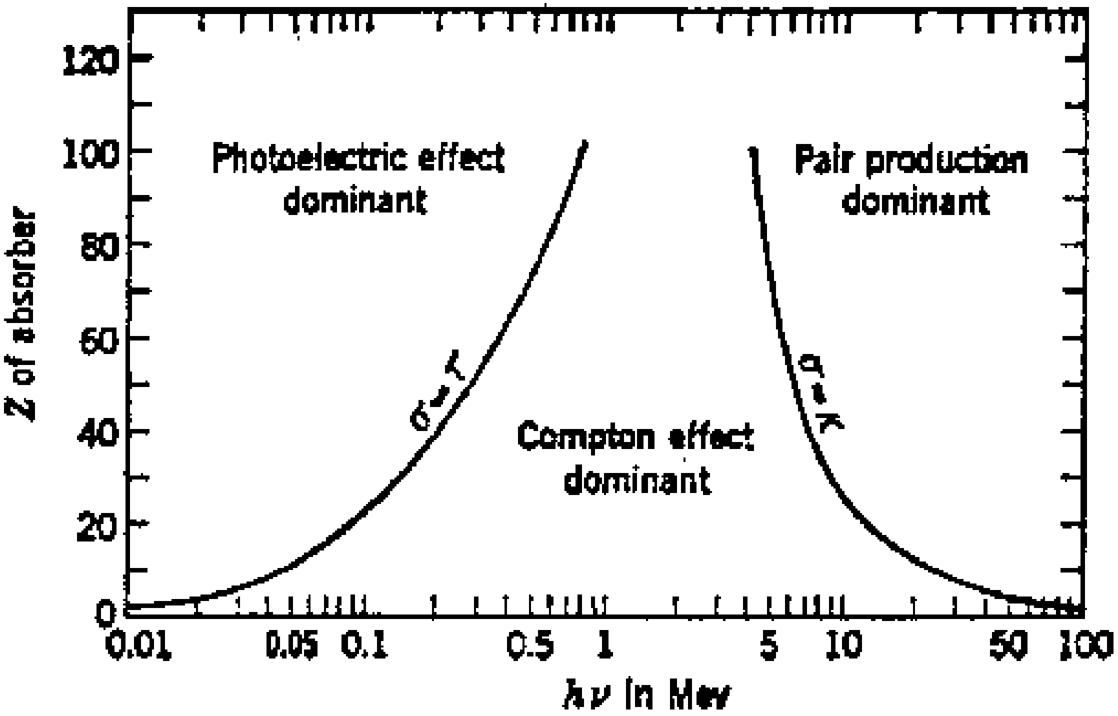
Half value layers (cm)

Matter/ Gamma energy	100 keV	200 keV	500 keV
Air	3555	4359	6189
Water	4.15	5.1	7.15
Carbon	2.07	2.53	3.54
Aluminium	1.59	2.14	3.05
Iron	0.26	0.64	1.06
Copper	0.18	0.53	0.95
Lead	0.012	0.068	0.42

$$X_{1/2} = \frac{\ln 2}{\mu}$$

Interaction of gamma photons – summary

Photoelectric effect = obsolete name of total absorption



Source: http://www.hep.wisc.edu/~prepost/407/gamma/gamma_html.html

Interactions of neutrons with material

$$dI = -I(x)\,\sigma\,N\,dx$$

I: intensity [s^{-1}]
σ: interaction probability in a collision [-]
N: number of „partners” in unit distance [m^{-1}]

Types of collision:
-Elastic or inelastic scattering in collision with protons and neutrons
- Absorption in recipient nuclei = nuclear reaction through transient state
- Spallation = nuclear reaction without „full” excitation
Probabilities depend strongly on
•Neutron energy
• Atomic number (Z) and mass number (A) of target

Dose definition and quantities

$$D = \frac{dE}{dm} \approx \frac{\Delta E}{m}\left[\frac{J}{kg}, Gray, Gy\right]$$

Absorbed dose

Physical (absorbed) dose: total radiative energy absorbed in unit mass, involves only physical interactions.
Characterizes any type of ionizing radiations.
Applicable only for ionizing radiations, but involves not only ionization events (excitation is also involved).
Does not involve energy not imparted to that piece of matter (scattered, secondary radiations).
„Unites” energy inputs to the object (detector, person, etc.) from various sources.

Dose quantities – dose from photon radiations

$$\sigma_A \left[\frac{m^2}{atom}\right]$$

$$\rho_A = \frac{N_A}{V_M}\left[\frac{\frac{atom}{mole}}{\frac{m^3}{mole}}\right]$$

$$\mu = \sigma_A \cdot \rho_A \left[\frac{m^2}{m^3}\right]$$

μ= linear energy transfer coefficient = <u>effective cross-section (surface) for attenuation per unit volume</u>

μ/ρ = „mass specific” absorption/attenuation coefficient = <u>effective cross-section per unit mass</u>

LET = dE/dx
  = linear energy transfer coefficient

σ_A= effective collision cross-section (sensitive surface) for an atom
collision: absorption or inelastic scattering (see energy transfer options before)

μ is the same as deduced for attenuation!

μ/ρ [m^2/kg]

$$\mu = \frac{\left(\frac{dE}{dx}\right)}{E_{inc.}}$$

External gamma dose rate (radiation source is distant from human body)

$$\frac{dD}{dt} = \Phi_E \cdot \frac{\mu}{\rho}$$

$$\Phi_E = \frac{A \cdot f_R \cdot E_R}{4 \cdot r^2 \cdot \pi}$$

Φ_E: surface density of energy intensity = energy flux [J/(m^{2}s)]
dN/dt = A: activity of source [decay/s = Bq]
f_R: particle (photon) yield [photon/decay]
E_R: photon energy [J/photon]

$$\frac{dD}{dt} = k_\gamma \cdot \frac{A}{r^2}$$

Validity: for point γ-source, unattenuated (primary) photon radiation.
Isotropic surface = surface of sphere with radius „r”
r: distance from point source

Reciprocal squared attenuation law – base of dose calculation: **dose coefficient** [(μGy/h)/(GBq/m^2)]
Comprises all material and geometric parameters
„Independently” selectable: A and r

From physical effect to biological effect of radiations

Absorbed dose (physical effect) – ionization and excitation

Chemical consequence: ions generate (by electrochemical reactions) very reactive ions and free radicals (from water and organic molecules)

Biochemical effect: direct ionization and/or free radicals may change the biochemical behaviour of some macromolecules (DNA strand break, damage of membranes etc.)

Biological effect: modified biochemical structures may change the outcome of biological „events” = changes in metabolic and genetic processes.

Biological effects of ionizing radiations

Classification of biological effects/responses:

Somatic: occurs to the affected person

Genetic: occurs to the descendants of the affected person

Deterministic: Severity of biological effect depends on dose, effect is apparent only if a threshold is exceeded.

Stochastic: Probability of occurrence of the biological effect depends on dose, no apparent threshold exists.

Biological effects of ionizing radiations

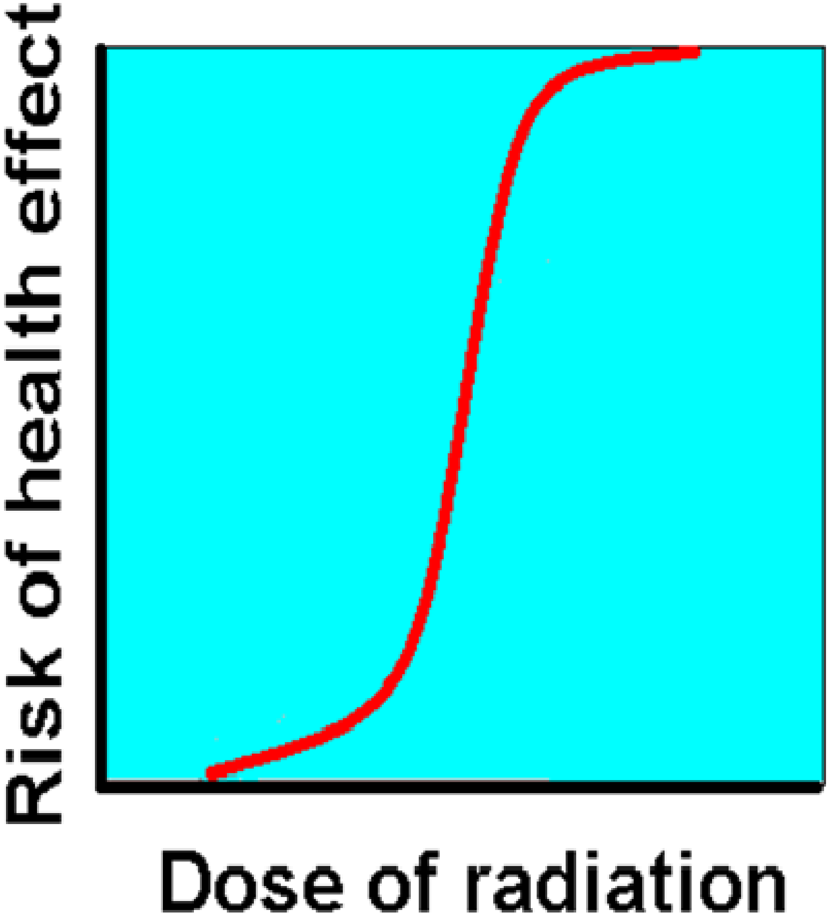
- *Stochastic effect: the cell survives the collision but the DNA structure is changed so the next generation cell (following mitosis = cell replication) will be different from the parent.*

- *Deterministic effect: the cell does not survive the collision – it is „deadly damaged” by the energy transferred from collision with radiation.*

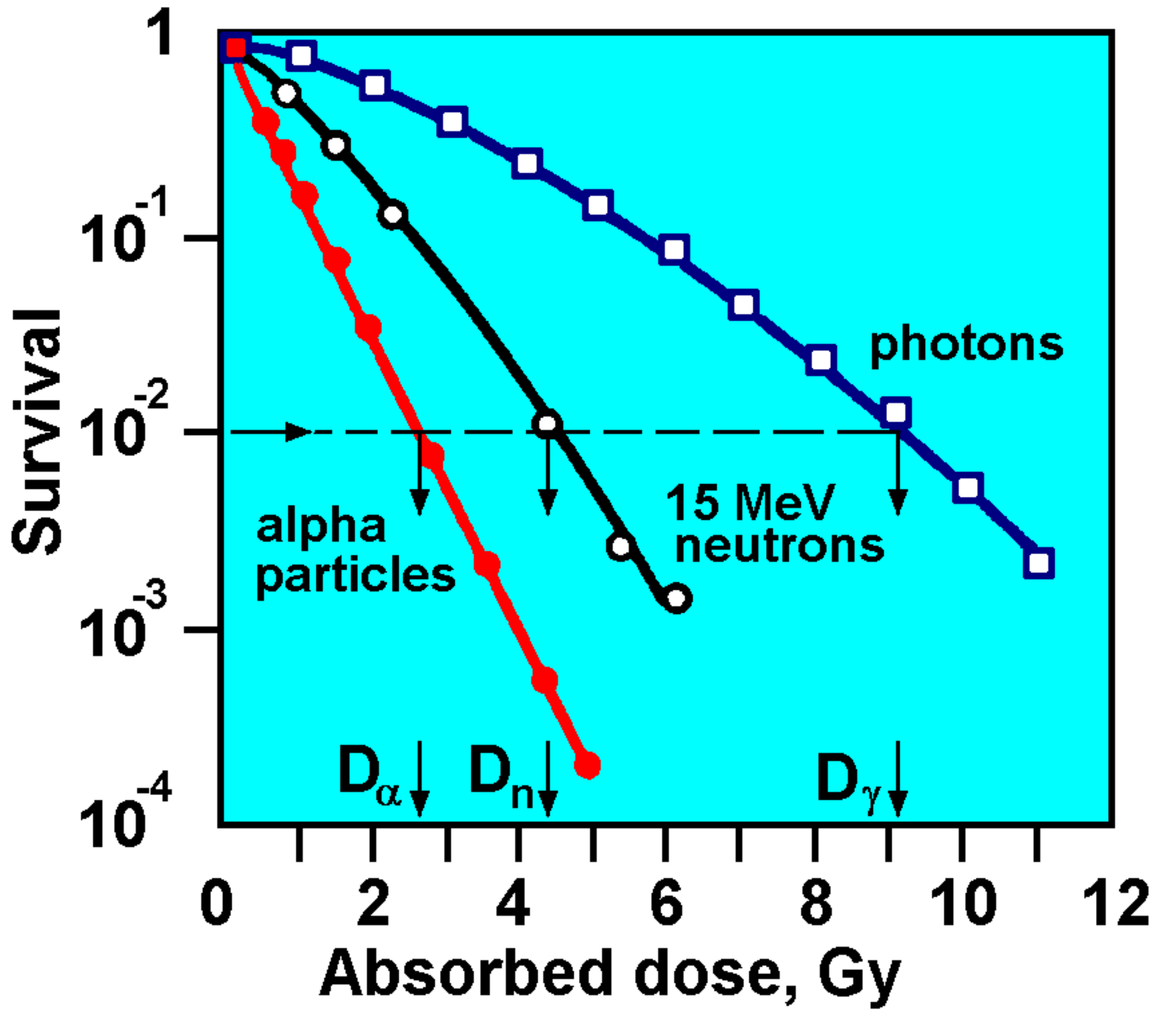
Deterministic effects

Deterministic effects

- occur only if a threshold is exceeded (threshold for most sensitive tissues: 0.3 – 0.4 Gy, foetus: 0.1 Gy)
- so many cells are damaged that devastation (necrosis, „burning”) of tissue takes place
- acute/immediate effect
- life-threatening effects on these tissues: central nerve system, gastrointestinal system, haematopoietic system



Role of radiation quality in deterministic effects



RBE = relative biological effectiveness

$$D_\alpha < D_n < D_\gamma$$

$$RBE_\alpha = \frac{D_\gamma}{D_\alpha}$$

$$RBE_n = \frac{D_\gamma}{D_n}$$

$$RBE_\alpha > RBE_n$$

Doses causing deterministic effects

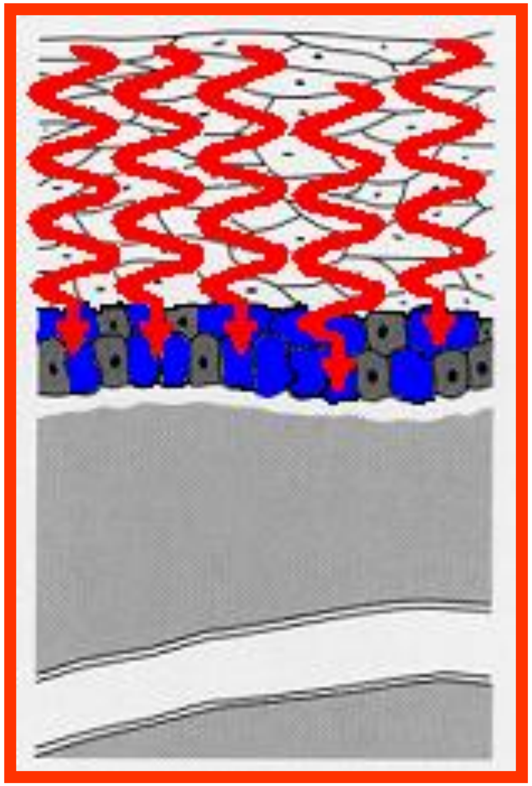
ND = D . RBE(R) [Gray]

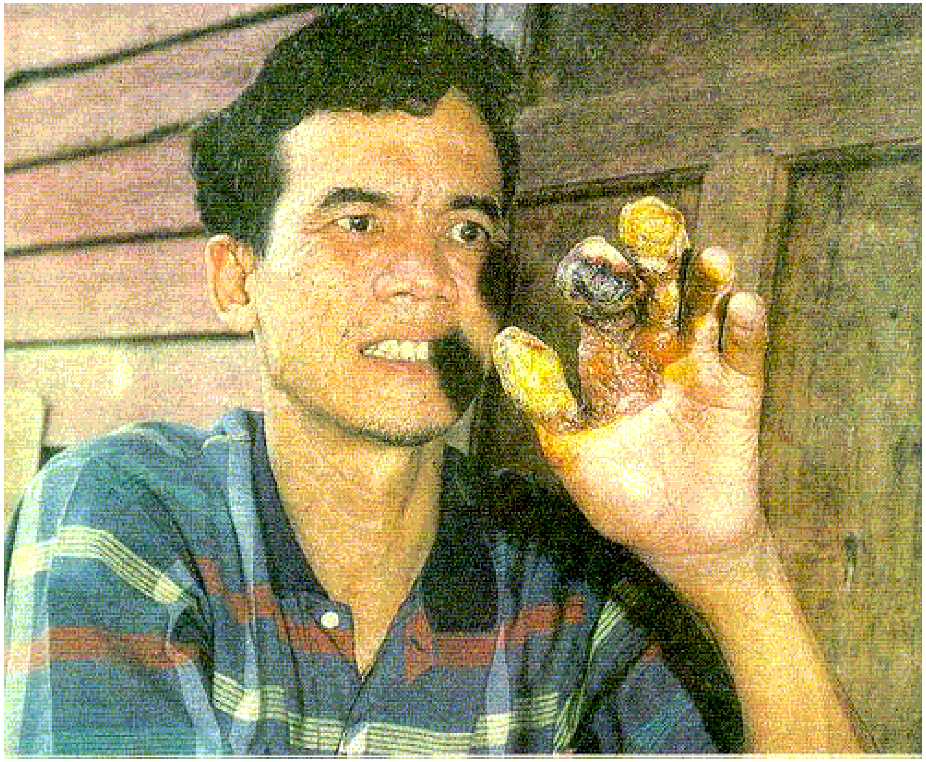
ND: necrotic dose = absorbed dose causing necrosis (devastation)

RBE: relative biological effectiveness = (capability for necrosis) – different according to radiation type, tissue type and circumstance of exposition!!

R: radiation type

Deterministic health effects





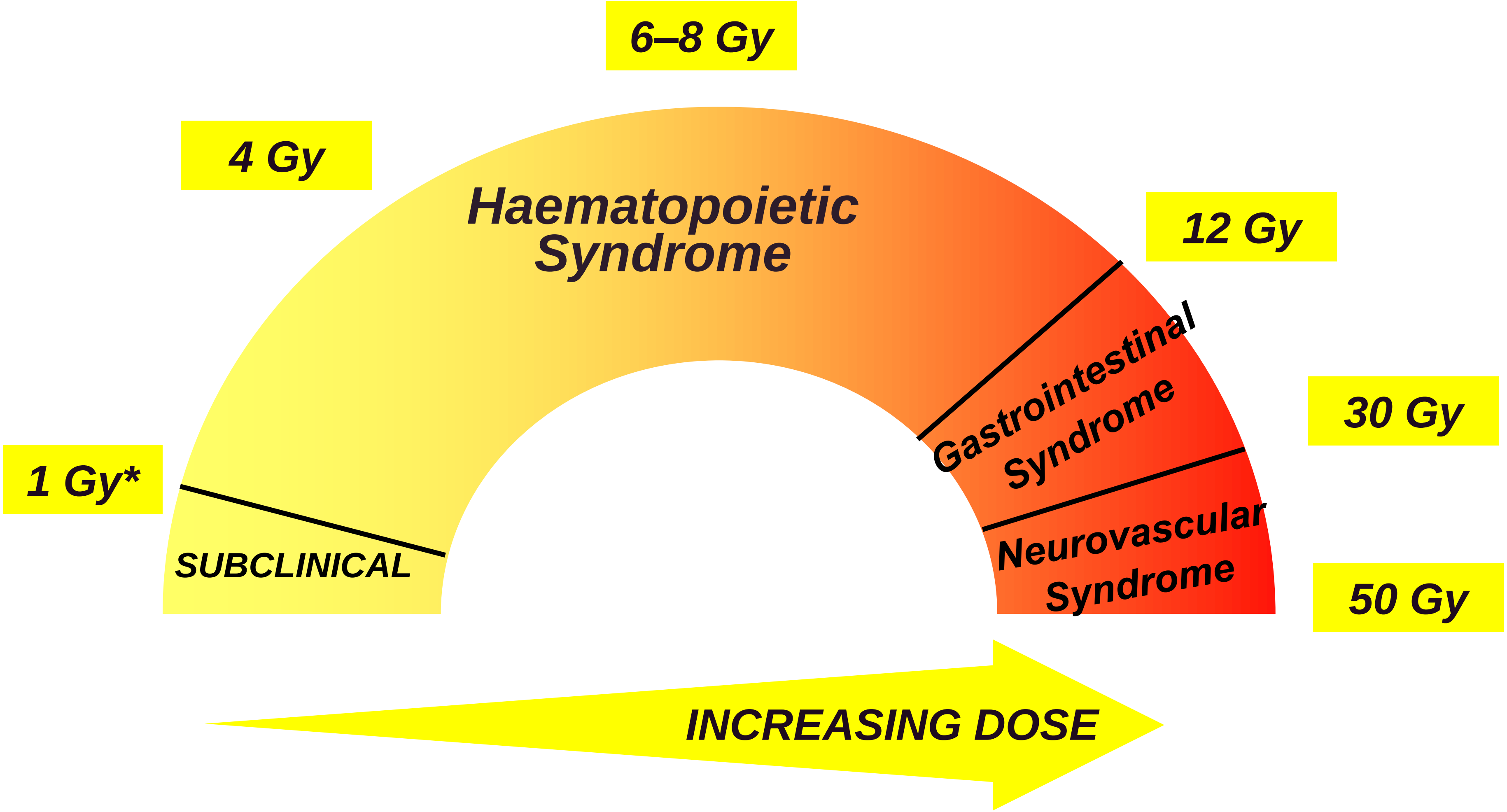
Massive cell death

Clinical effect reflected loss of tissue function and structure

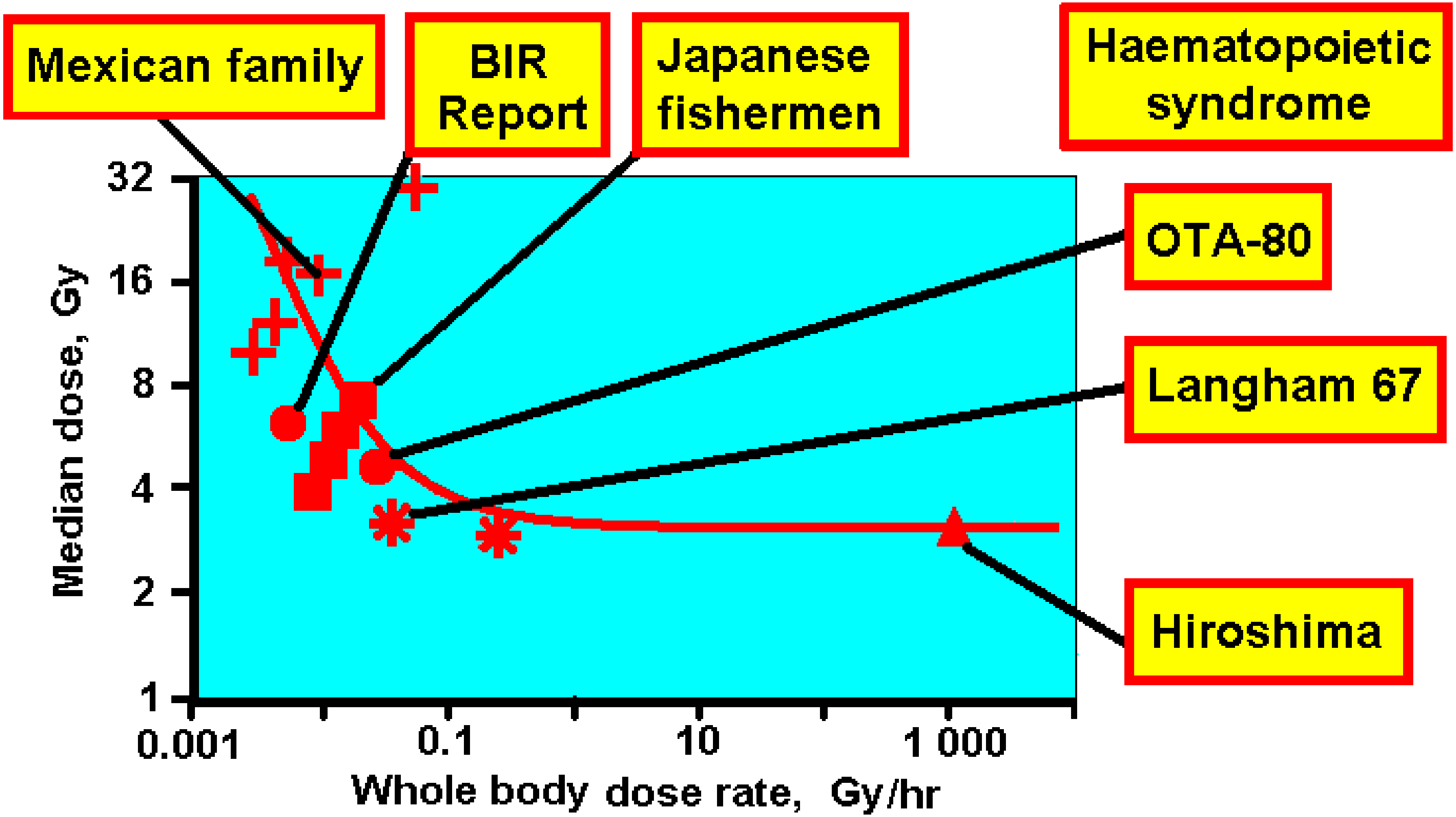
Deterministic health effects

Necrosis on skin as a consequence of intensive high-energy beta radiation

Severity of deterministic effects



Dose rate in relation to the extent of deterministic effect



„Japanese fishermen” case

On 1 March 1954 the US army detonated a nuclear bomb codenamed "Bravo" on the island of Bikini. A Japanese tuna fishing boat, the Lucky Dragon, was caught in the path of Bravo's fallout. The crew members suffered from radiation sickness, and one of them died of liver and blood damage on 23 September.

„Mexican family” case

In March 1962 a 10-year-old Mexican boy discovered a 200 GBq source of ^{60}Co in a field, although no one recognized it as such at the time. It presumably had been in a shielded container; how it was removed from the container is not known. The boy carried the source in his pocket for several days. Then it was placed in a cabinet that held kitchen utensils, where it remained until recovered 112 days later. Over a period of seven months four people died. All had hematopoietic depression syndrome, but the diagnosis was not made until the third victim was dying. The father had mild anaemia and darkening of the fingernails, but no serious difficulty, presumably because he was away at work most of the time. Estimated radiation doses were 20 – 50 Gy for the victims and 10 Gy for the surviving father.

Acute Radiation Syndrome (ARS) in Chernobyl NPP staff and first responders

Degree of ARS	Range of RBE weighted whole body dose [Gy]	Number of patients	Number of deaths
Mild (I)	0.8-2.1	41	-
Moderate (II)	2.2-4.1	50	1
Severe (III)	4.2-6.4	22	7
Very severe (IV)	6.5-16	21	20
Total	0.8-16	134	28*

** 28 died in 1986 from a combination of high external doses of γ-exposure and skin burns due to β-emitters*

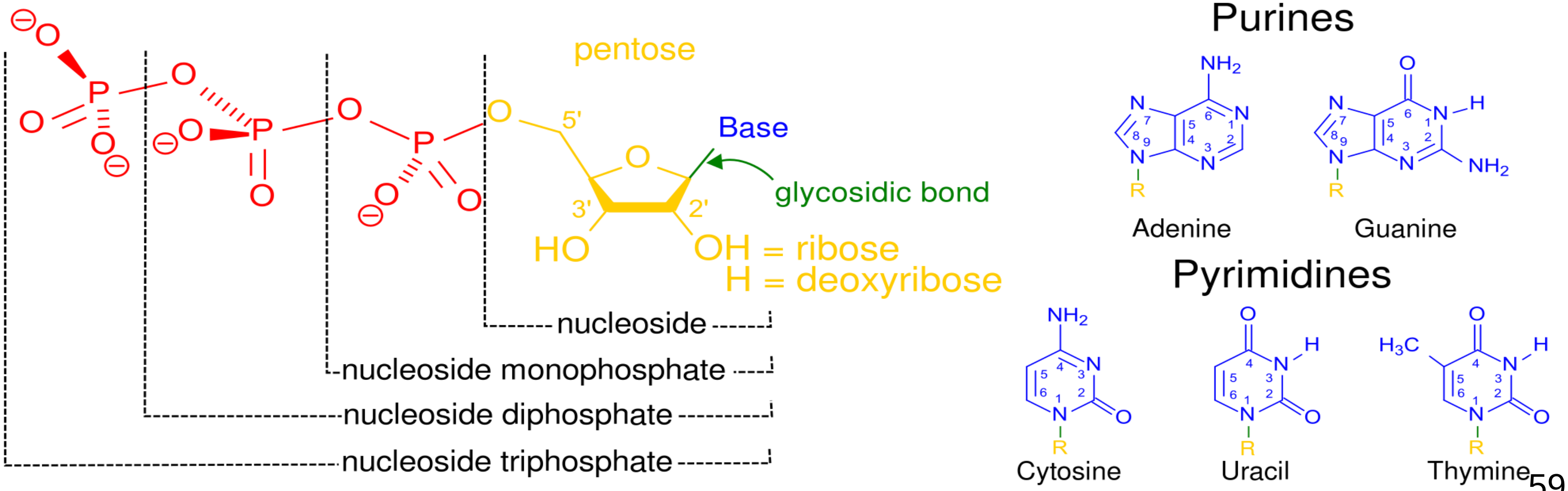
Stochastic effects of ionizing radiations

„Primary target”: DNA-content of cell nucleus

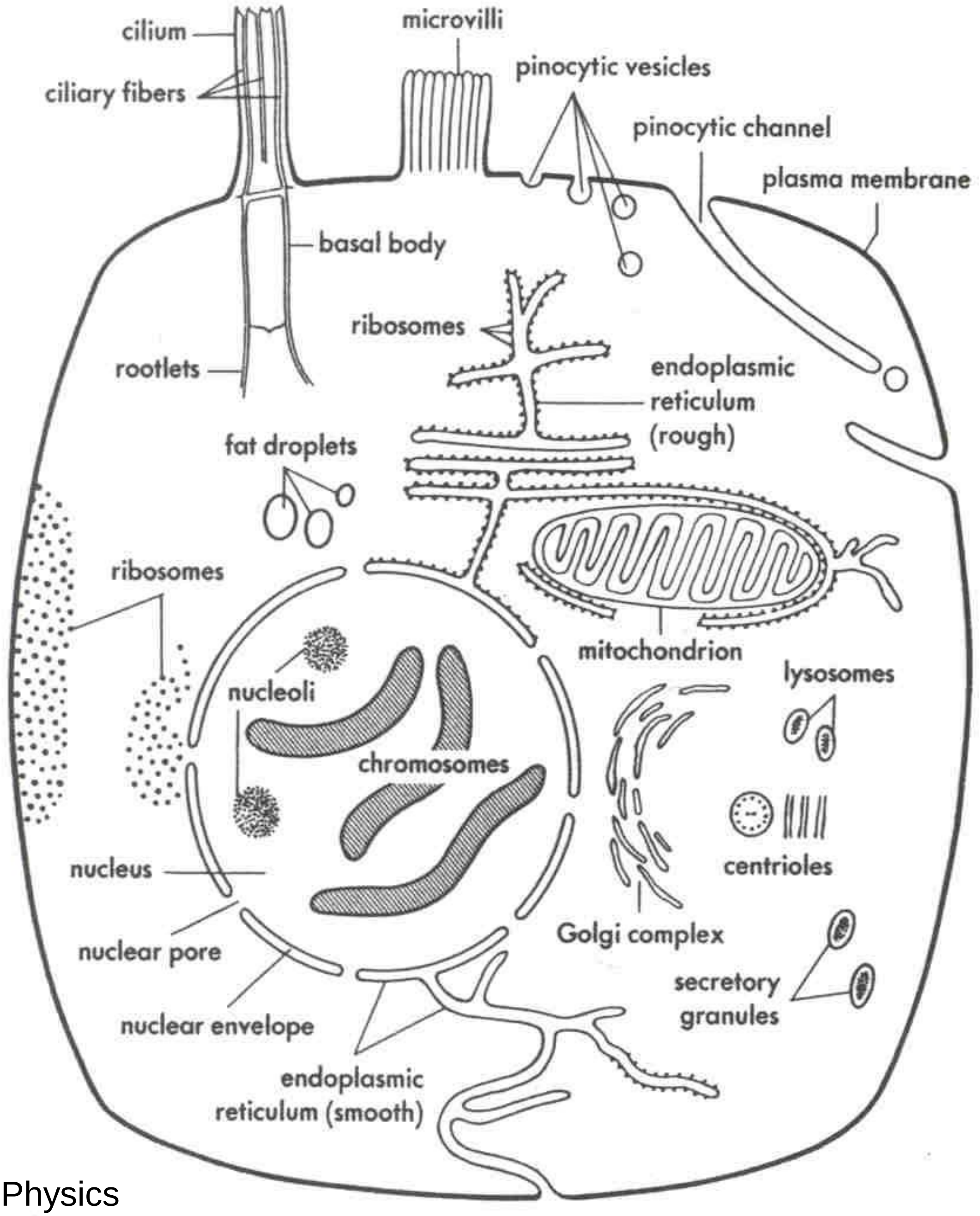
DNA: macromolecule with a double spiral shape constructed from sugar- and phosphate groups accompanied by organic bases (A,D,C,T,U). Chain link: nucleotide. The spirals are connected by hydrogen bonds between the bases.

Genetic information (composition of proteins of a cell) is coded by DNA structure in the chromosomes.

Gene: piece of DNA chain coding a protein or a cellular feature; group of genes = genom.



Components of a human cell



Components of a human cell nucleus

Membrane – cover/boundary

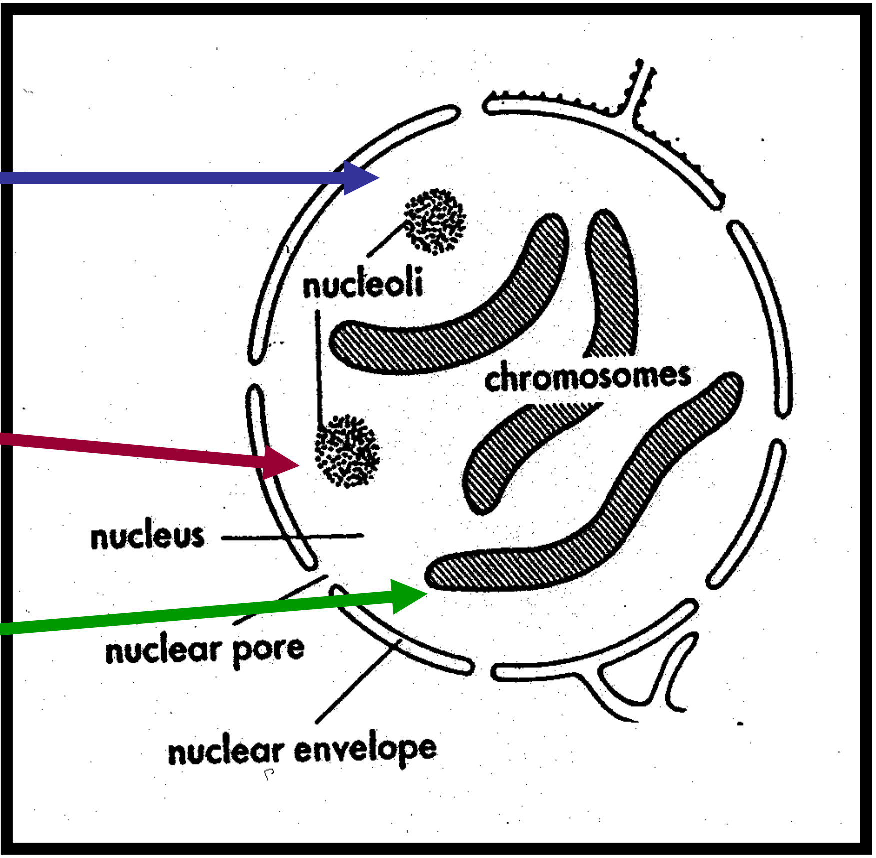
- Semipermeable

- Separates nuclear liquid from cytoplasm

Nucleolus – contains RNA

- Synthesis of proteins (albumin) and DNA

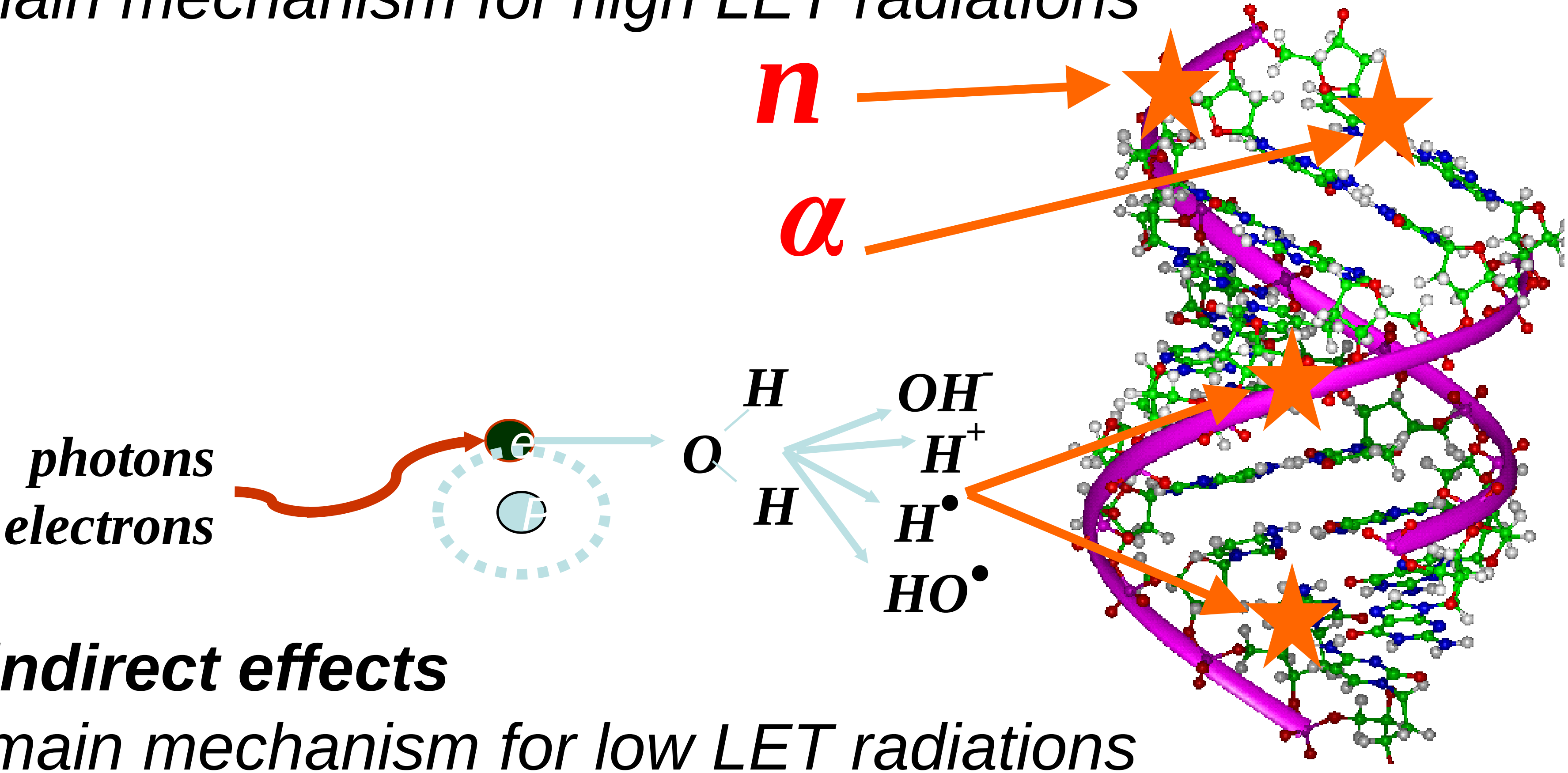
DNA – macromolecule containing the genetic code of tissue-building cells



Radiation effects on DNA

direct interaction

main mechanism for high LET radiations



n

α

photons
electrons

e

e

O

H

H

OH^-

H^+

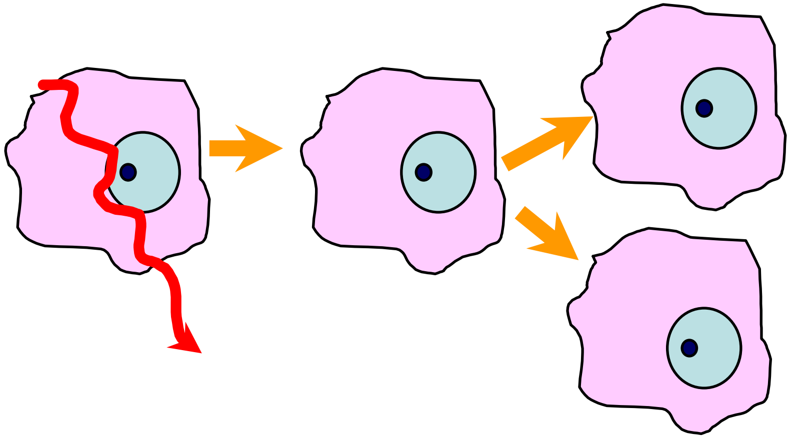
$H^\bullet$

$HO^\bullet$

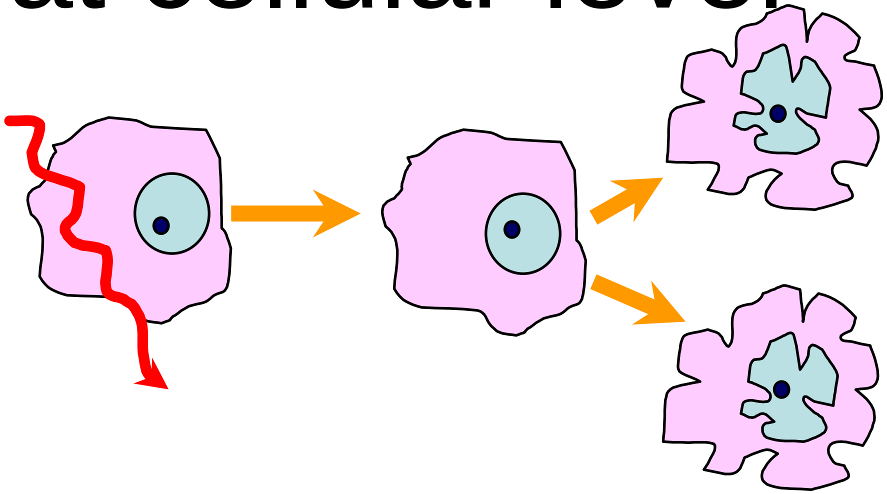
indirect effects

main mechanism for low LET radiations

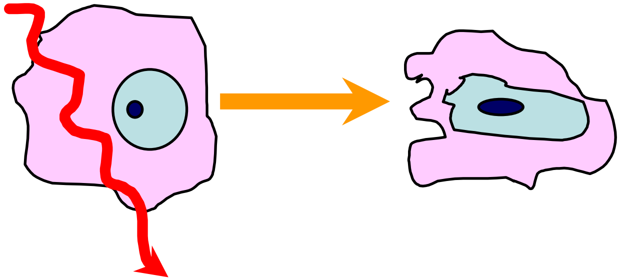
Radiation effect at cellular level



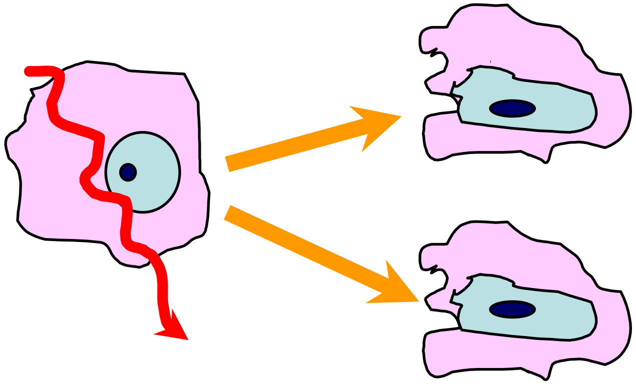
Normal repair of damage



No repair or faulty repair

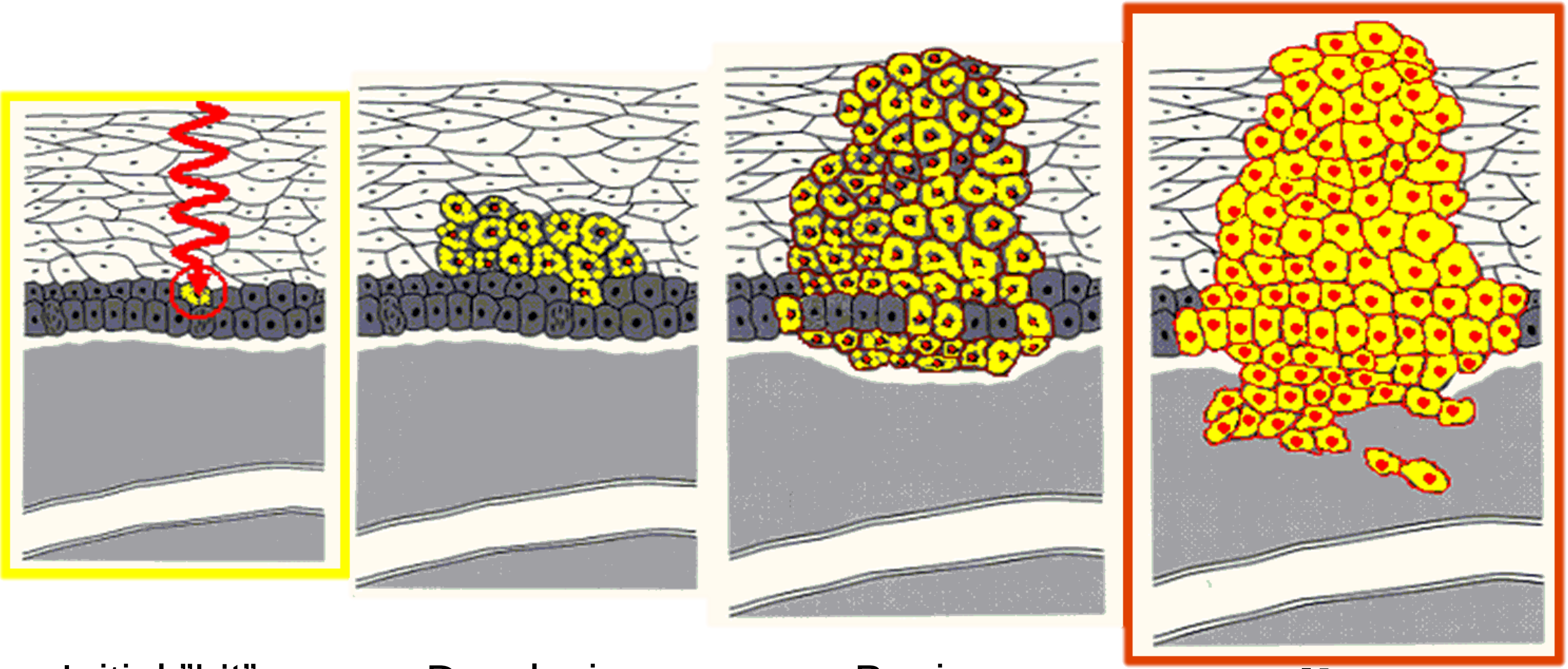


Cell dies from damage



Daughter cells die

Development of stochastic harm



Initial ”hit”

Dysplasia

Benign tumour

Malignant tumour

Years after irradiation

Stochastic and deterministic effect of ionizing radiations

Human cells: stem cells or tissue specific cells

Cellular life cycle (eukaryotic):

mitosis → interphase → mitosis or apoptosis

Damage of cellular elements:

- Immediate devastation: necrosis
- Programmed death (inviability): apoptosis
- DNA-chain defects (strand break): survival → mutation

DNA breaks: correction by „repair” enzymes

Equivalent dose – measure of stochastic biological effect of ionizing radiations

$$H = D \cdot w_R \quad [\text{Sievert}, \text{Sv}]$$

w_R radiation weight factor – function of LET
$w_{R,\alpha} = 20$
$w_{R,\gamma} = 1$
$w_{R,\beta} = 1$
$w_{R,n} = 2{,}5 \div 20$ depending on neutron energy

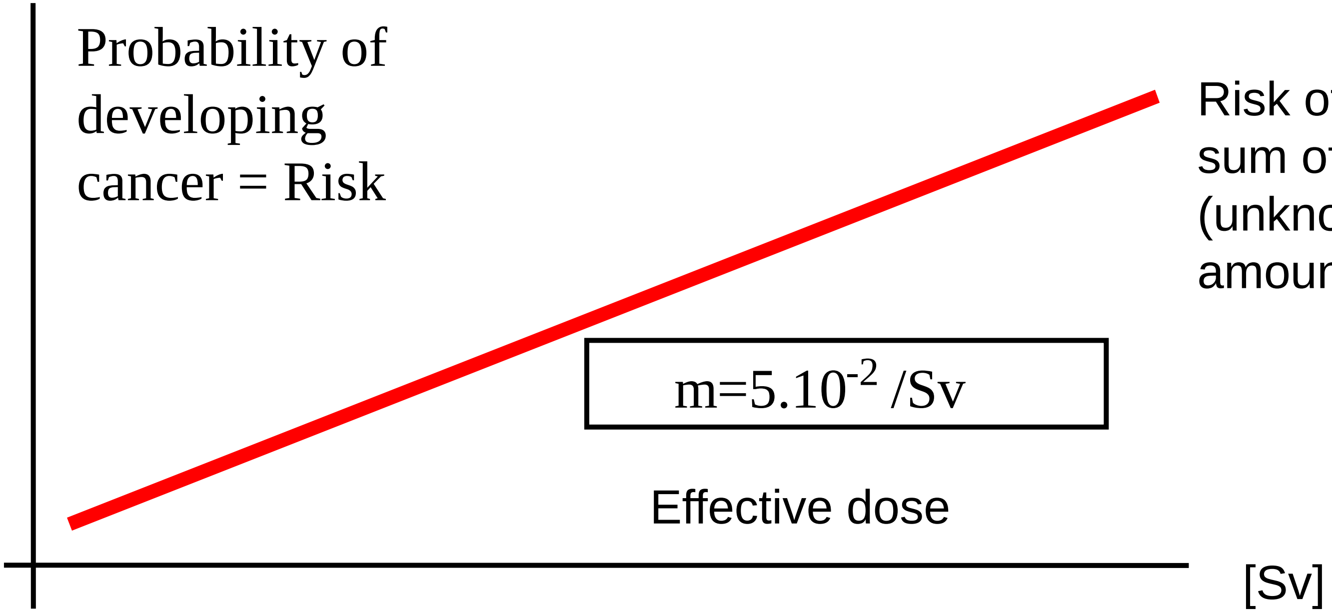
Detriment of absorbed dose depends on energy transferred to a cell-size volume of living material (microdose).

„Anthropomorphous” dose quantity and unit: radiation weight factors are different for other living organisms (animals, plants).

Equivalent dose characterizes ONLY the stochastic effect!!!

Detriment of ionizing radiations – stochastic effect:

- no dose threshold (carcinogenesis of low doses is not confirmed)
- cellular mutation (chance for repair until mitosis/meiosis)
- dose/risk function is linear (?)



Risk of an individual is the sum of the risks of the tissues (unknown owing to small amount of certified data)

Dependence was calculated from the epidemiological statistics of the survivors of Hiroshima and Nagasaki bombings.

ICRP 103 – Table 1. Risk per Sv

Detriment-adjusted nominal risk coefficients for stochastic effects after exposure at low dose rate

Exposed population	Cancer		Heritable effects		Total	
	ICRP103	ICRP60	ICRP103	ICRP60	ICRP103	ICRP60
Whole	5.5	6.0	0.2	1.3	5.7	7.3
Adult	4.1	4.8	0.1	0.8	4.2	5.6

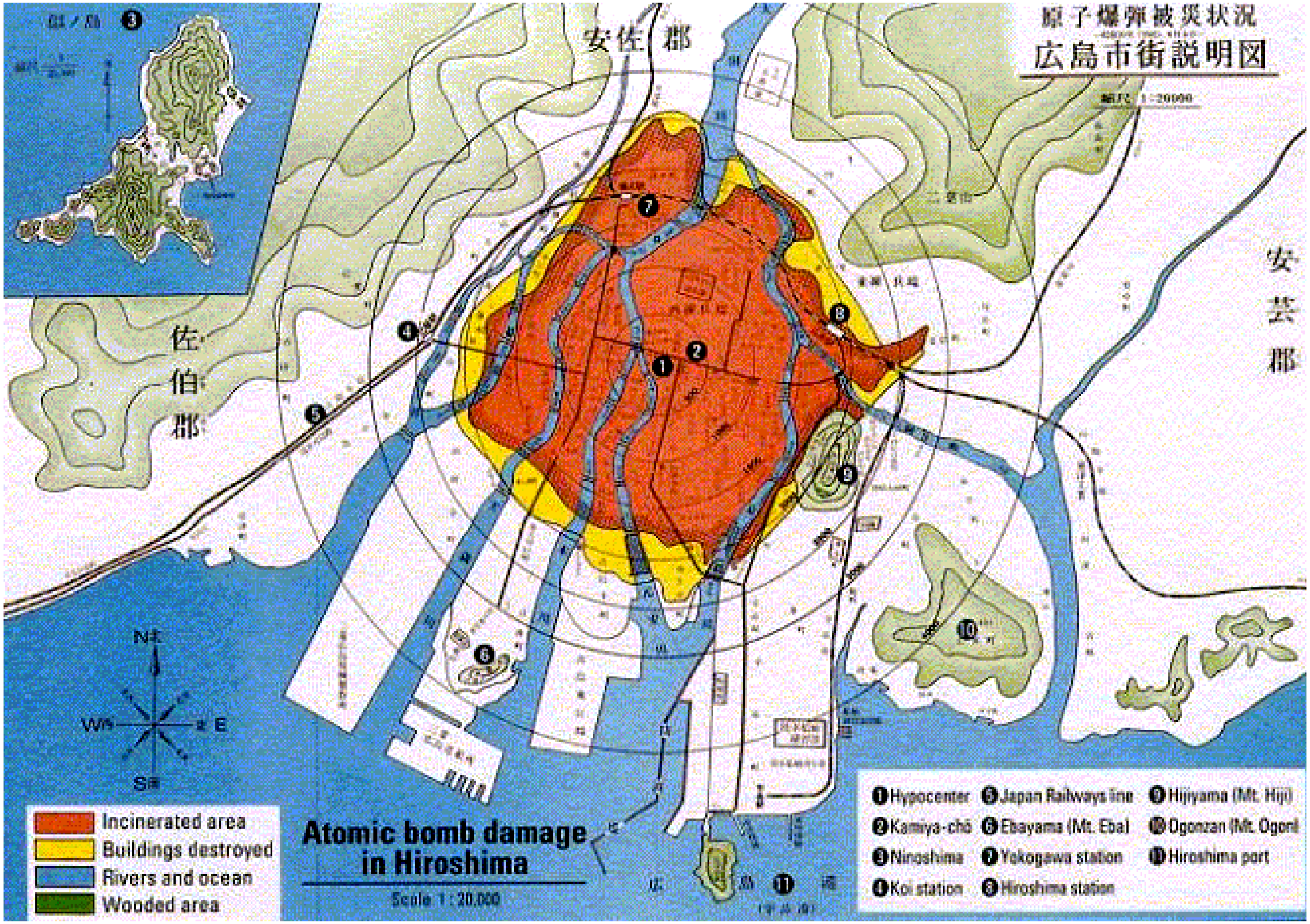
“It is therefore the recommendation of the Commission that the approximated overall risk coefficient of **5% Sv^{-1}** on which current international radiation safety standards are based continues to be appropriate and should be retained for the purposes of radiological protection”

© HPA

The nuclear bombing events (Japan, 1945)

1. *About **200 000** people died in Hiroshima and Nagasaki in 2-4 month after bombing. Almost 50% of them died in the first day.*
2. *A survey on A-bomb exposure as part of Japan’s 1950 national census revealed that about **284 000** people had been exposed to the bombs and survived.*
3. *Life Span Study (**LSS**) cohort with the total number of about **120 000** was organized in 1958:*
   - *all of the heavily exposed A-bomb survivors;*
   - *a selected population of the less exposed and non-exposed residents of both cities matched by age and sex with the first group*

The nuclear bombing survivors



Life Span Study mortality (1950-2002)

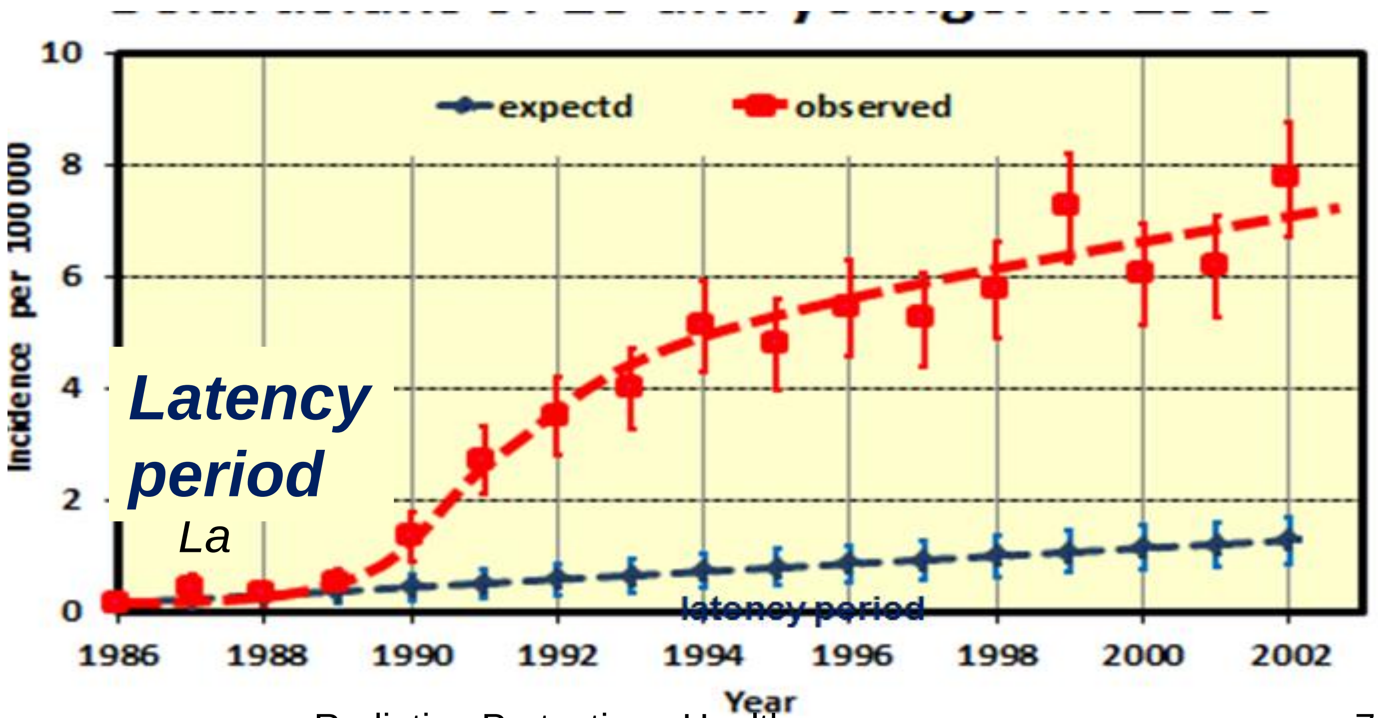
Diseases	Deaths			Attributable fraction
	observed	expected	excess	
Solid cancer	**6 718**	**6 205**	**513**	**8.3%**
Leukemia	**317**	**219**	**98**	**44.7%**

86 611 *people with evaluated dose*
38 509 *with Colon dose < 5 mSv (mean = 0.2 mSv)*
37 401 *with Red marrow dose < 5 mSv*

Thyroid cancer – stochastic effect of ^{131}I incorporation

Consequences of Chernobyl release

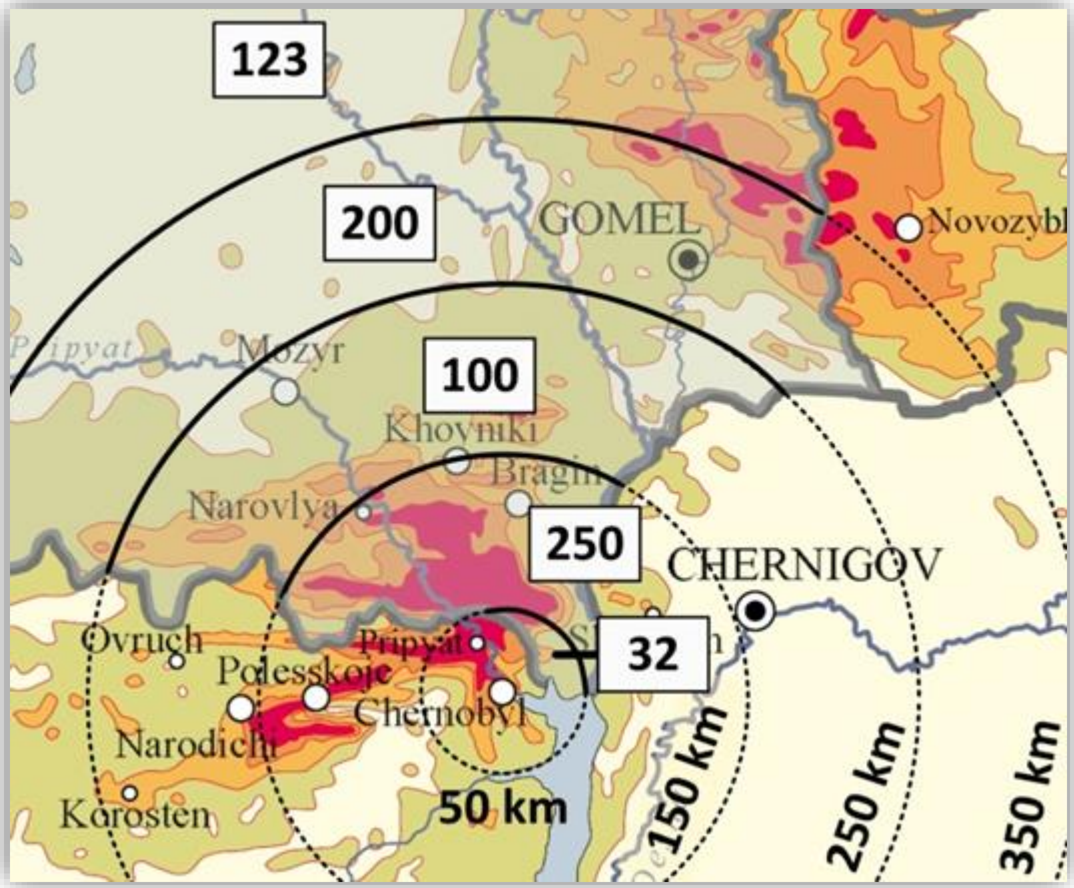
- An increase in thyroid cancers was easily observed due to low background
- No increase in others cancers seen in public



Latency period

La

Thyroid cancer cases versus distance from damaged reactor



Excess thyroid cancers by 1998 – does not show inverse dependence with distance from NPP

Explanation: iodine uptake was due to milk consumption, not inhalation – it should have been avoided

Normal cancer incidence rates

Cancers per 100 000 deaths			
Canada		**Belarus**	
Number	**Rate**	**Number**	**Rate**
All cancers			
31 500	32%	19 000	19%
Thyroid (0–19 year olds)			
330	0.3%	120	0.1%

Much easier to see excess thyroid cancers due to the low background level

Detectable increase - radiation carcinogenesis

Organ	Dose at which excess incidence may be seen	Number of people needed to be studied to see excess
Whole body: external exposure (all cancers)	**E>100 mSv (effective dose)**	**>100 000**
Thyroid: intake of ^{131}I	**$H_{thyroid}$ > 50 mSv (equivalent dose)**	**> 10 000**

Internal dose: radioactivity is incorporated (inhaled, ingested)
External dose: ionizing radiation penetrates the human body

$$E = H_E = \sum_T H_T w_T [Sv]$$

Effective dose

w_T tissue weight factor

$$\sum_T w_T = 1$$

New tissue weight factors (recommended in 2007 in ICRP#103):

gonads

w_T=0.08 (genetic effects – not confirmed)

Somatic effects

most vulnerable

w_T=0.12 lungs, stomach, colon, red bone marrow, breast, remainder

vulnerable

w_T=0.04 liver, kidney, thyroid, bladder, oesophagus

less vulnerable

w_T=0.01 skin, bone surface, salivary gland, brain

Standard measurable dose quantitites

- Dose and dose rate meters are capable of measuring absorbed dose only
- Real biological dose is different at every part of the body even in a homogeneous radiation field
- Personal dose equivalent $H_P(d)$ – absorbed dose measured at depth *d* (mm) in human body
- Ambient dose equivalent $H^*(d)$ – absorbed dose measured at depth *d* (mm) in ICRU sphere of standard composition (76% O, 11% C, 10% H, 3% N)
- Strongly penetrating radiation d = 10 mm
- Weakly penetrating radiation d = 0.07 mm

Problems of stochastic dose-risk dependence

Accepted model for health physics regulations: LNT (linear – no threshold)

Question marks:

- Clear distinction is a must between „sample group” and „control group” – but how?
- Hormesis: low doses create „immunity”?
- Supralinearity: no necrosis at low doses: better chance of survival for mutant cells?
- Nonlinearity: at higher doses the reproduction rate of necrotised cells increases – higher survival rate for mutated cells?
- Tissue weight factors reflect vulnerability - primary tumour or metastasis?
- How long can doses be integrated?
- Bystander effects?

Further dose quantities

Committed dose (H_C): effective dose of incorporated radioactive material that is not excreted from the body in 1 year

$$H_C = \int_0^T \frac{dH_E}{dt} dt$$

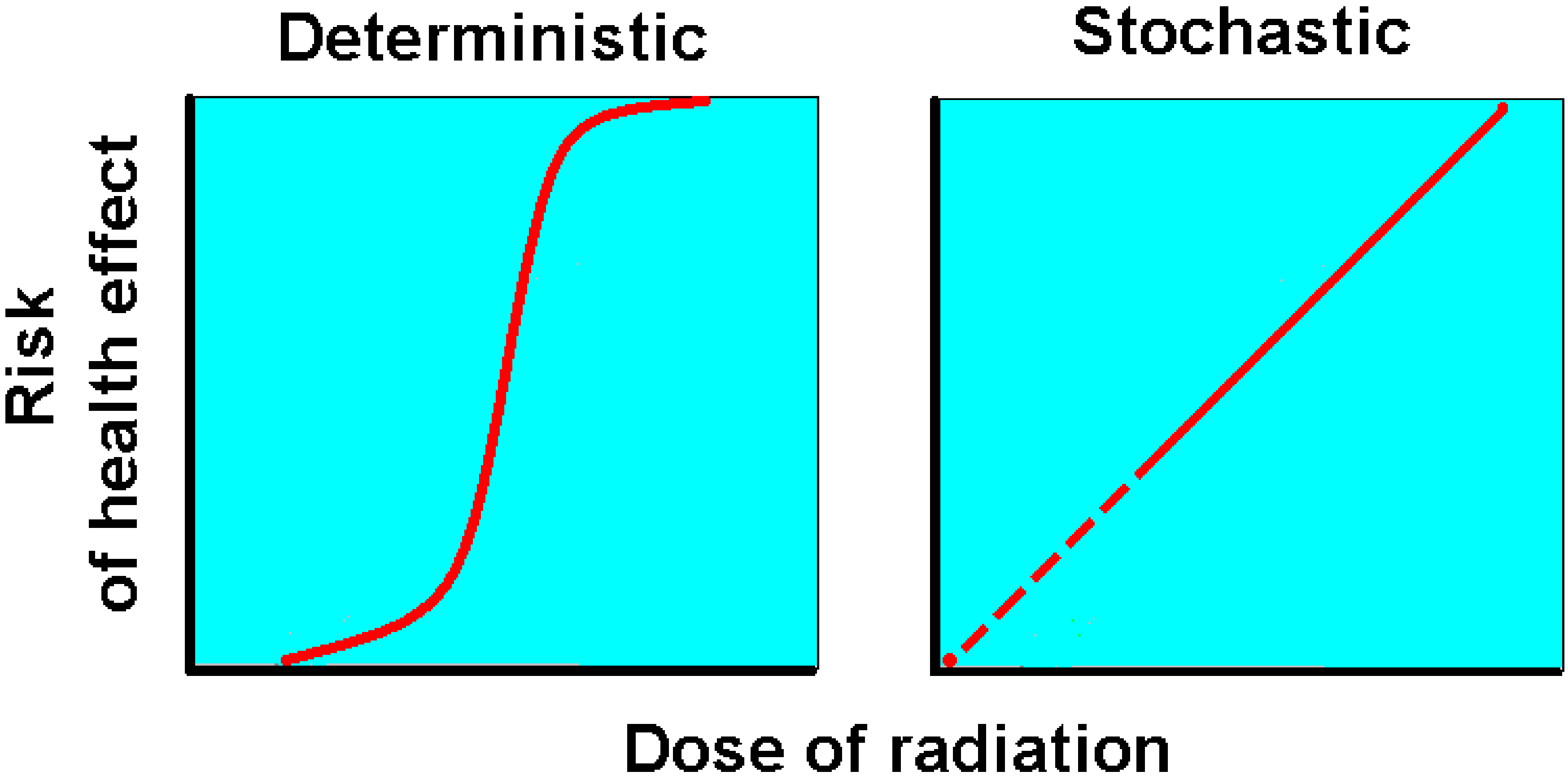
Collective dose: Sum of committed effective doses of members of the public originating from a dedicated radiation source.

$$C = \sum_i H_{E,i} . n_i$$

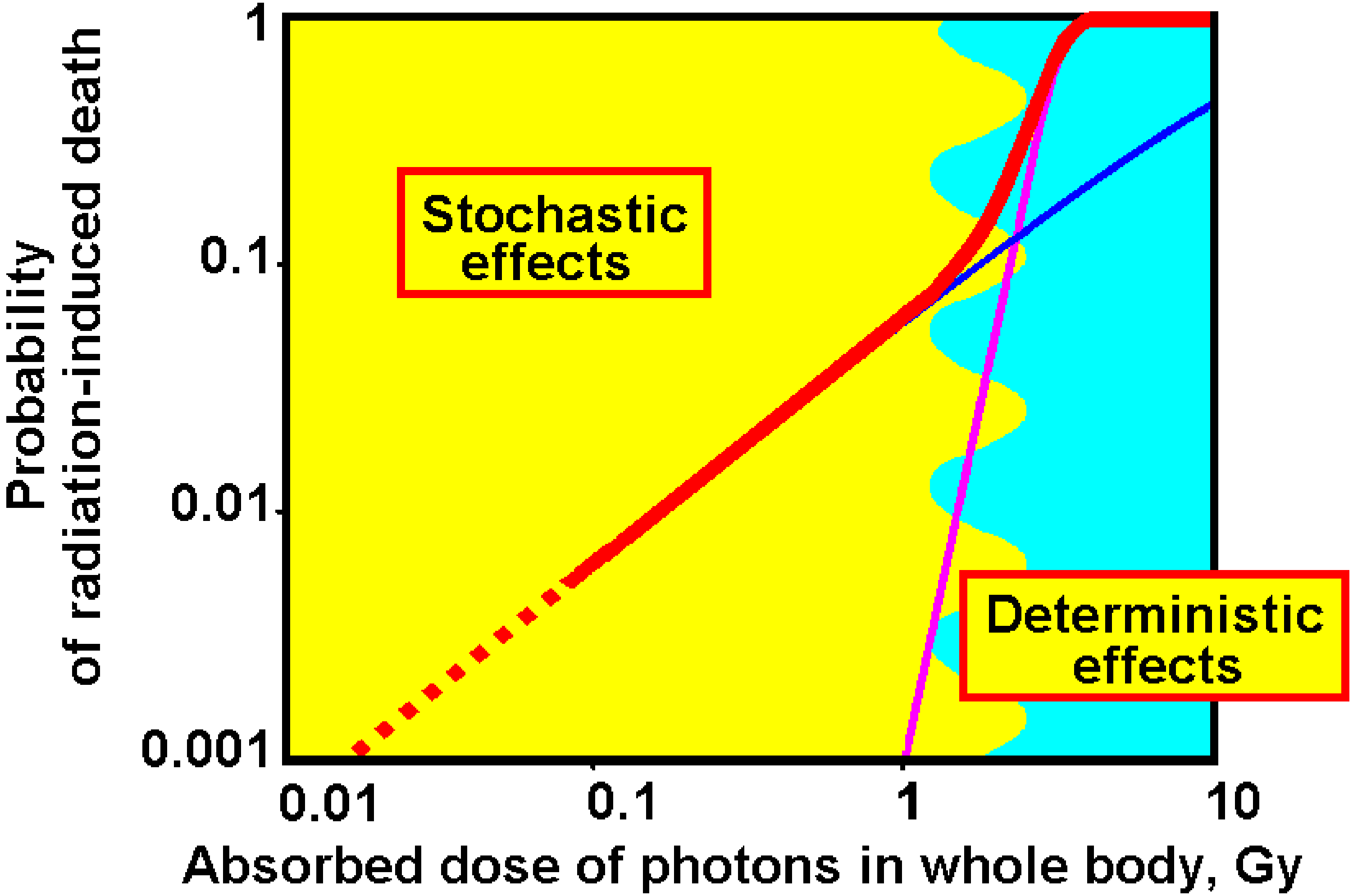
[man.Sv]

Recommended to be applied only for comparing sources of emission!

Effects of ionizing radiation - summary



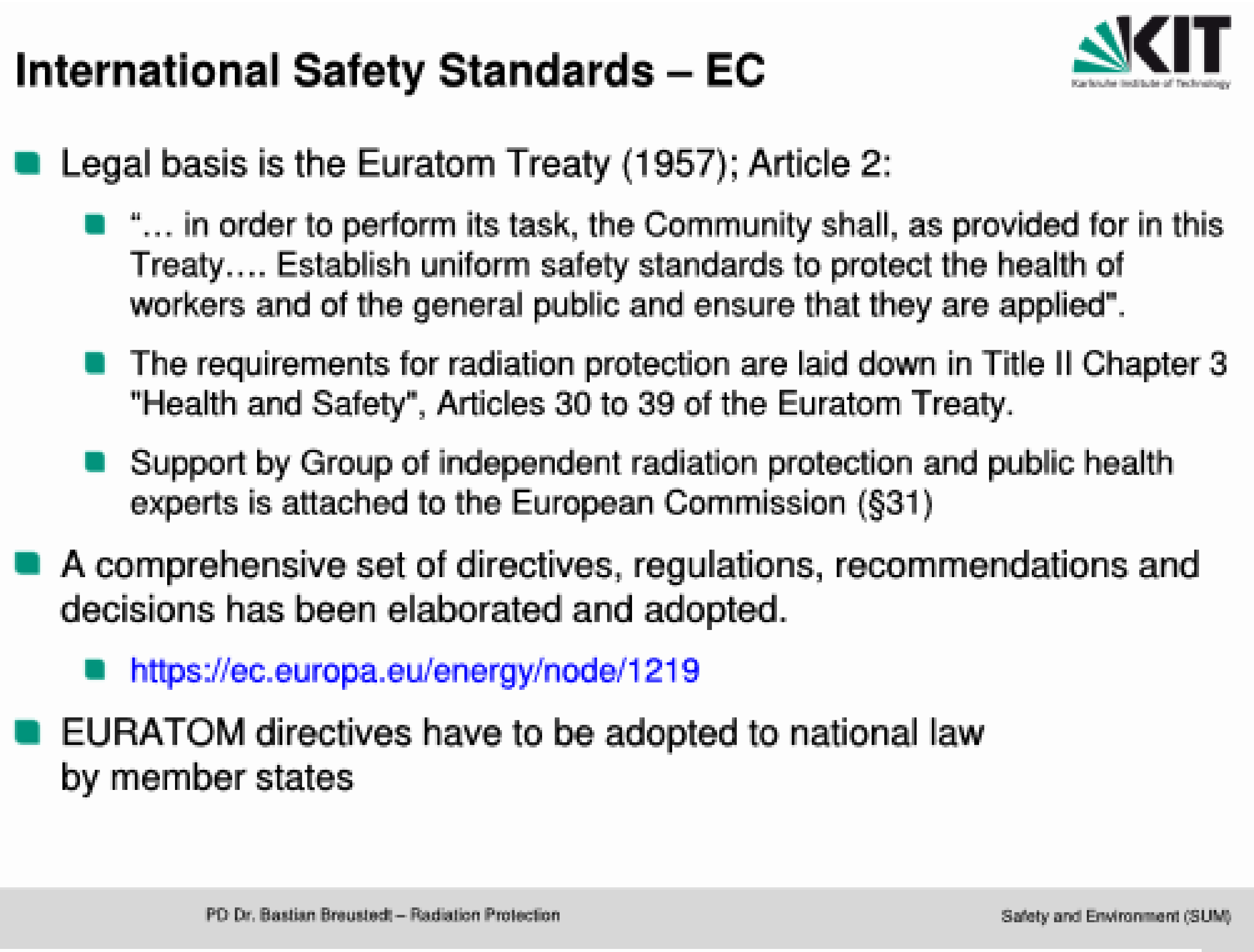
Radiation health effects - summary



Radiation Protection – How?

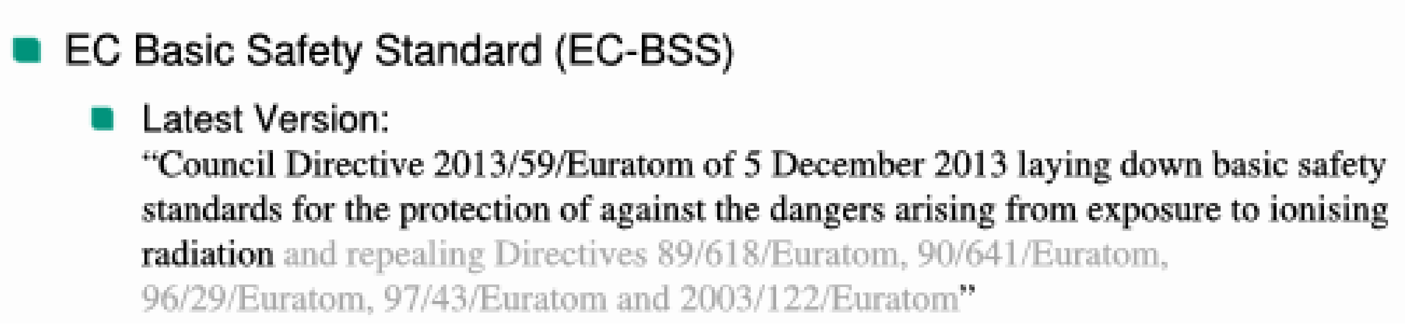
- From Science via Recommendations and Regulations to Compliance

Image Source: https://en.wikipedia.org/wiki/International_Commission_on_Radiological_Protection, 17.06.2015 (modified)



International Safety Standards – EC

- Legal basis is the Euratom Treaty (1957); Article 2:
  - "… in order to perform its task, the Community shall, as provided for in this Treaty…. Establish uniform safety standards to protect the health of workers and of the general public and ensure that they are applied".
  - The requirements for radiation protection are laid down in Title II Chapter 3 "Health and Safety", Articles 30 to 39 of the Euratom Treaty.
  - Support by Group of independent radiation protection and public health experts is attached to the European Commission (§31)
- A comprehensive set of directives, regulations, recommendations and decisions has been elaborated and adopted.
  - https://ec.europa.eu/energy/node/1219
- EURATOM directives have to be adopted to national law by member states



- EC Basic Safety Standard (EC-BSS)
  - Latest Version:
    "Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for the protection of against the dangers arising from exposure to ionising radiation and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom"

Radiation protection regulations

International recommendation and guidance:

ICRP #60 (1991), IAEA Safety Series #115 (1996) „IBSS”, 96/29 EU Directive – these are based on LSS statistics between 1950 - 1988

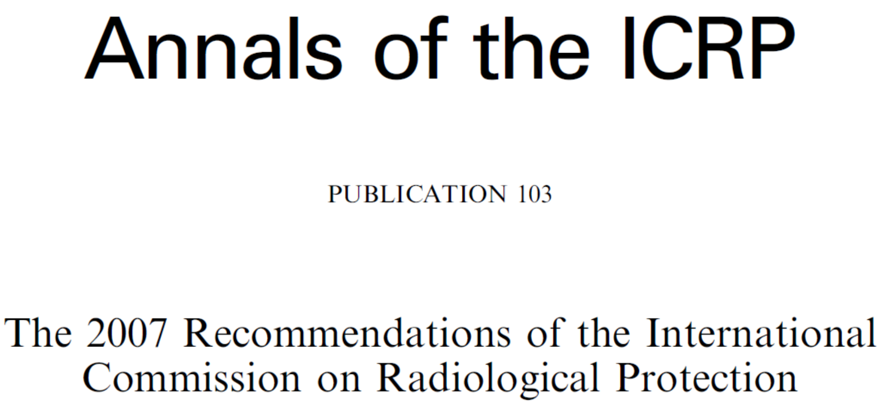
ICRP #103 (2007), IAEA General Safety Requirements GSR Part 3 (2014) „new IBSS”, 2013/59/EURATOM directive

Hungarian regulations: from January 2016 the basis is the „new IBSS”

- Personal protection: controlled by Hungarian Atomic Energy Authority (HAEA)
- Environmental protection: controlled by HAEA and environmental protection departments
- Nuclear operations and safety: Hungarian Atomic Energy Authority – Nuclear Safety Ordinance in 10 volumes

Germany: Die Strahlenschutzverordnung ist die deutsche Verordnung innerhalb des Atomrechts. Rechtsgrundlage ist §54 Atomgesetz. Die „StrlSchV” stammt aus dem Jahr 1976 und wurde seitdem mehrfach novelliert, zuletzt 2011.

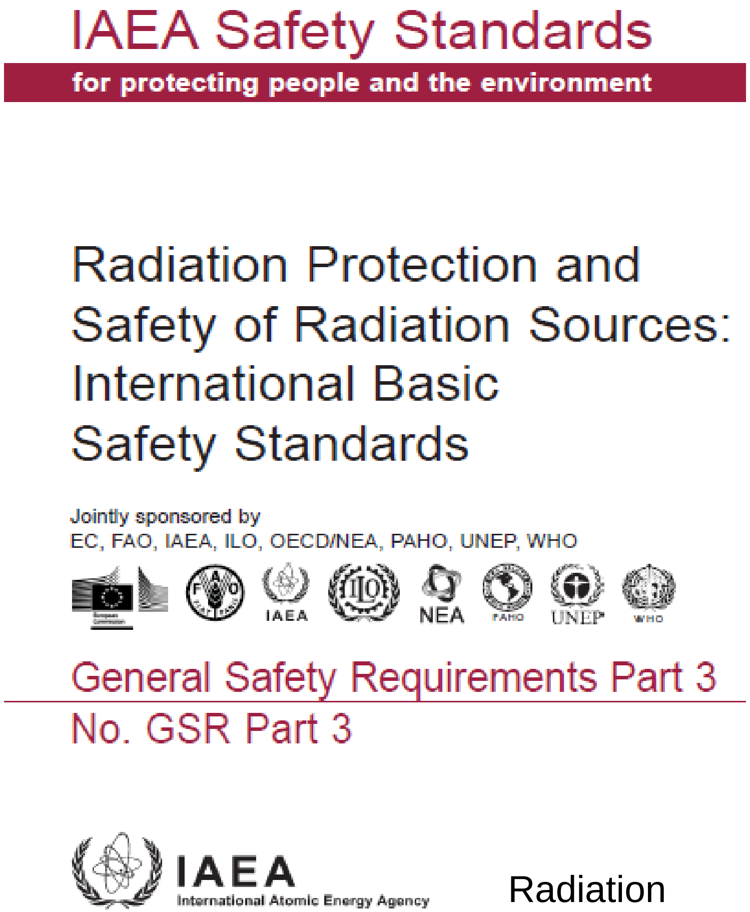
From international recommendations to national regulations



Annals of the ICRP

PUBLICATION 103

The 2007 Recommendations of the International Commission on Radiological Protection



IAEA Safety Standards

for protecting people and the environment

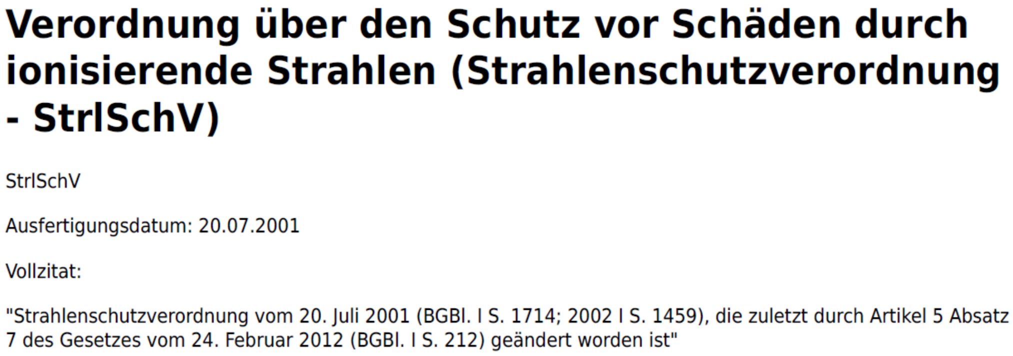
Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards

Jointly sponsored by
EC, FAO, IAEA, ILO, OECD/NEA, PAHO, UNEP, WHO

General Safety Requirements Part 3

No. GSR Part 3

IAEA
International Atomic Energy Agency



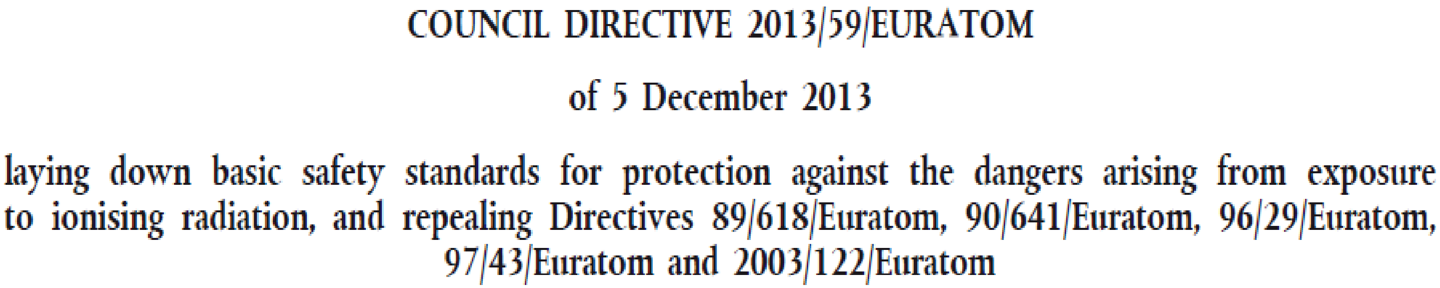
Verordnung über den Schutz vor Schäden durch ionisierende Strahlen (Strahlenschutzverordnung - StrlSchV)

StrlSchV

Ausfertigungsdatum: 20.07.2001

Vollzitat:

"Strahlenschutzverordnung vom 20. Juli 2001 (BGBl. I S. 1714; 2002 I S. 1459), die zuletzt durch Artikel 5 Absatz 7 des Gesetzes vom 24. Februar 2012 (BGBl. I S. 212) geändert worden ist"



COUNCIL DIRECTIVE 2013/59/EURATOM

of 5 December 2013

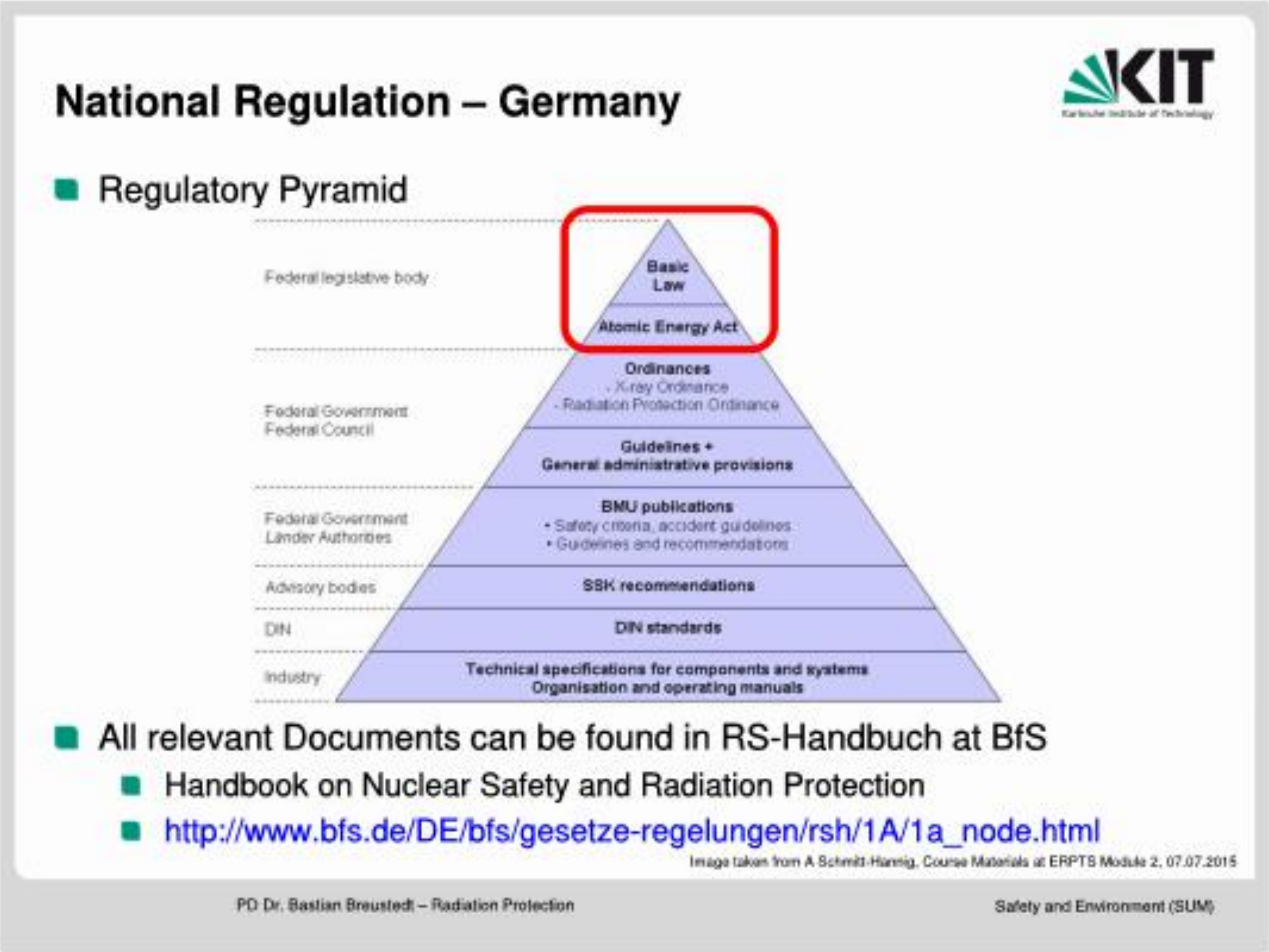
laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom

National Regulation – Germany

- Federal Republic of Germany – RP Legislation/Organisation
  - Basic (Constitutional) Law of the Federal Republic of Germany
  - Atomic Energy Act
  - Responsible Federal Ministry (in2015): BMUB
    - Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit
    - Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety
  - Responsible Federal Office (in 2015): BfS
    - Bundesamt für Strahlenschutz / Federal Office for Radiation Protection
    - BfS is an organisationally independent, scientific-technical, higher federal authority in the portfolio of BMUB Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB).
  - Advisory Bodies
    - Strahlenschutzkommission (SSK)
    - Reaktorsicherheitskommission (RSK)
    - Kerntechnischer Ausschuss (KTA)

PD Dr. Bastian Breustedt – Radiation Protection

Safety and Environment (SUM)



National Regulation – Germany

- Regulatory Pyramid

Federal legislative body	Basic Law
	Atomic Energy Act
Federal Government Federal Council	Ordinances - X-ray Ordinance - Radiation Protection Ordinance
	Guidelines + General administrative provisions
Federal Government Länder Authorities	BMU publications • Safety criteria, accident guidelines • Guidelines and recommendations
Advisory bodies	SSK recommendations
DIN	DIN standards
Industry	Technical specifications for components and systems Organisation and operating manuals

- All relevant Documents can be found in RS-Handbuch at BfS
  - Handbook on Nuclear Safety and Radiation Protection
  - http://www.bfs.de/DE/bfs/gesetze-regelungen/rsh/1A/1a_node.html

Image taken from A Schmitt-Hannig, Course Materials at ERPTS Module 2, 07.07.2015

PD Dr. Bastian Breustedt – Radiation Protection

Safety and Environment (SUM)

National Regulation – Germany

- <u>Radiation Protection Ordinance:</u> **Ordinance on the Protection against Damage and Injuries Caused by Ionizing Radiation (StrlSchV)**
  - of 20 July 2001, last amendment of 11 December 2014

- <u>X-Ray Ordinance:</u> **Verordnung über den Schutz vor Schäden durch Röntgenstrahlung (Röntgenverordnung – RöV)**
  - vom 8. Januar 1987 (BGBl. I 1987, Nr. 3, S. 114), Neufassung vom 30. April 2003 (BGBl. I 2003, Nr. 17, S. 604), zuletzt geändert durch Artikel 6 der Verordnung vom 11. Dezember 2014 (BGBl. I 2014, Nr. 58, S. 2010)
  - No English translation available

- Both Documents will be merged during adaption of new EC-BSS

- Other Relevant Ordinances: See RS-Handbuch

Contents of radiation protection regulations

Basic principles – first stated in 1976

- Justification: application of a radiation source must have a positive benefit = cause more good than harm
- Optimization: application of a radiation source must have a maximum benefit = planning basis - ALARA (As Low As Reasonably Achievable) for magnitude of incurred dose and number of exposed persons
- Individual limitation – limits for immission and emission for individual persons are set that shall not be exceeded.

Other general statements of recent ICRP guidance:

❑ Exposures of high doses causing severe deterministic effects shall be *averted.*

❑ Only doses from „applications” can be limited, purely natural phenomena leading to elevated doses are *excluded* from regulatory aspects.

Exposure situations and exposed persons

- ICRP 103 (2007), EU BSS (Basic Safety Standards – 2013) and IAEA General Safety Requirements (GSR) Part 3 (2014):

  Planned, emergency and existing exposure situations;

  Occupational, public and medical exposures;
- EU BSS (42): Introduction of reference levels in emergency and existing exposure situations allows for the protection of individuals as well as consideration of other societal criteria in the same way as dose limits and dose constraints for planned exposure situations.

Dose limitations for planned exposures

DL – dose limits given as effective or equivalent dose → limiting individual *immission* (from all possible sources):

effective (committed) dose; sum of external and internal doses

occupational	**20 mSv/year** (special permit: average of 5 consecutive years, annual maximum: 50 mSv)
general public	**1 mSv/year**

additional DLs for lens of the eye, skin and extremities

DC – dose constraint → limiting *emission* (given in the operational licence of facilities): effective dose of a fictitious representative person (<u>most affected person</u>; member of the critical population group) originating from a given facility generally DCs range from 0.3 to 0.03 mSv/year → basis of maximum permissible emission level for individual radionuclides

Test #1
18-03-2022

$$DC << DL$$

$$DL \neq \sum_s DC_s$$

s: emission source

DCs cannot be summed as they pertain to different locations

Doses - measured and/or calculated

External dose

- Measured by dose meters and dose rate meters
- Calculation (doses from gamma sources with known activity)
- k_γ dose coefficients: determined for point and extended sources aand different detector materials

Internal dose cannot be directly measured

- Determined by: whole body counting, radioanalysis of blood and excreta, radioanalysis of intakes (air, water, foodstuff)
- dose conversion coefficient [Sv/Bq] – consequence of intake = committed effective dose from intake of 1 Bq activity (different for inhalation and ingestion, significantly depends on age and residence time of „carrier" substances in human body)
- Acute (instantaneous) and chronic (continuous) intake are to be calculated differently

Release limits derived from dose constraints

- ☐ „Negligible dose” ≤ 10 - 30 μSv/year – not declared directly, belongs to negligible risk (≤10^{-6}) → basis of EXEMPTION and CLEARANCE from regulatory control
- ☐ Maximum permissible emission levels = release limits for planned situations (normal operations and „regular operational occurrences”) are given in [Bq/year] unit.
- ☐ Separate data sets for airborne and liquid releases
- ☐ Relation between maximum intakes and dose constraint:

$$DC \leq \sum_{i} A_{i,max} \cdot e(g)_i$$

A_{max}: Maximum intake from radionuclide *i,* e(g): dose conversion coefficient (committed effective dose consequence of unit intake)

Release limits derived from dose constraints

$A_{i,max} << A_{i,out}$ and $A_{i,max} = f(A_{i,out})$

Activity reaching the most affected person (A_{max}) = maximum intake is much less than the released (A_{out}) value. Maximum permissible A_{out} = release limit.

Release limits (RL) [Bq/year] of facilities are approved by the regulatory body. They are combined in a joint Release Limit Criterion (RLC)

$$RLC = \sum_i \frac{A_{i,out}}{RL_i} < 1$$

Release limits (airborne and liquid) are related to the *dose constraint* of the facility by means of **DISPERSION MODELS** consisting of parts for emission, migration and exposure. Dispersion models should be validated by comparing their results to realistic emission events.

Environmental reference levels for existing exposure situations

- Dose consequence of environmental contamination (via internal exposure) ≤ reference level. Acceptable: maximum activity concentration c_L [Bq/kg]
- Definition:

$$c_{m,i} = \frac{RL}{\Gamma \cdot Q_m \cdot e(g)_i}$$

m: major foodstuff

(water, milk etc.)

Q: consumption [kg/year]

i: radionuclides

Γ: safety factor ≥1 (max. 5)

$e(g)_i$: dose conversion factor [Sv/Bq]

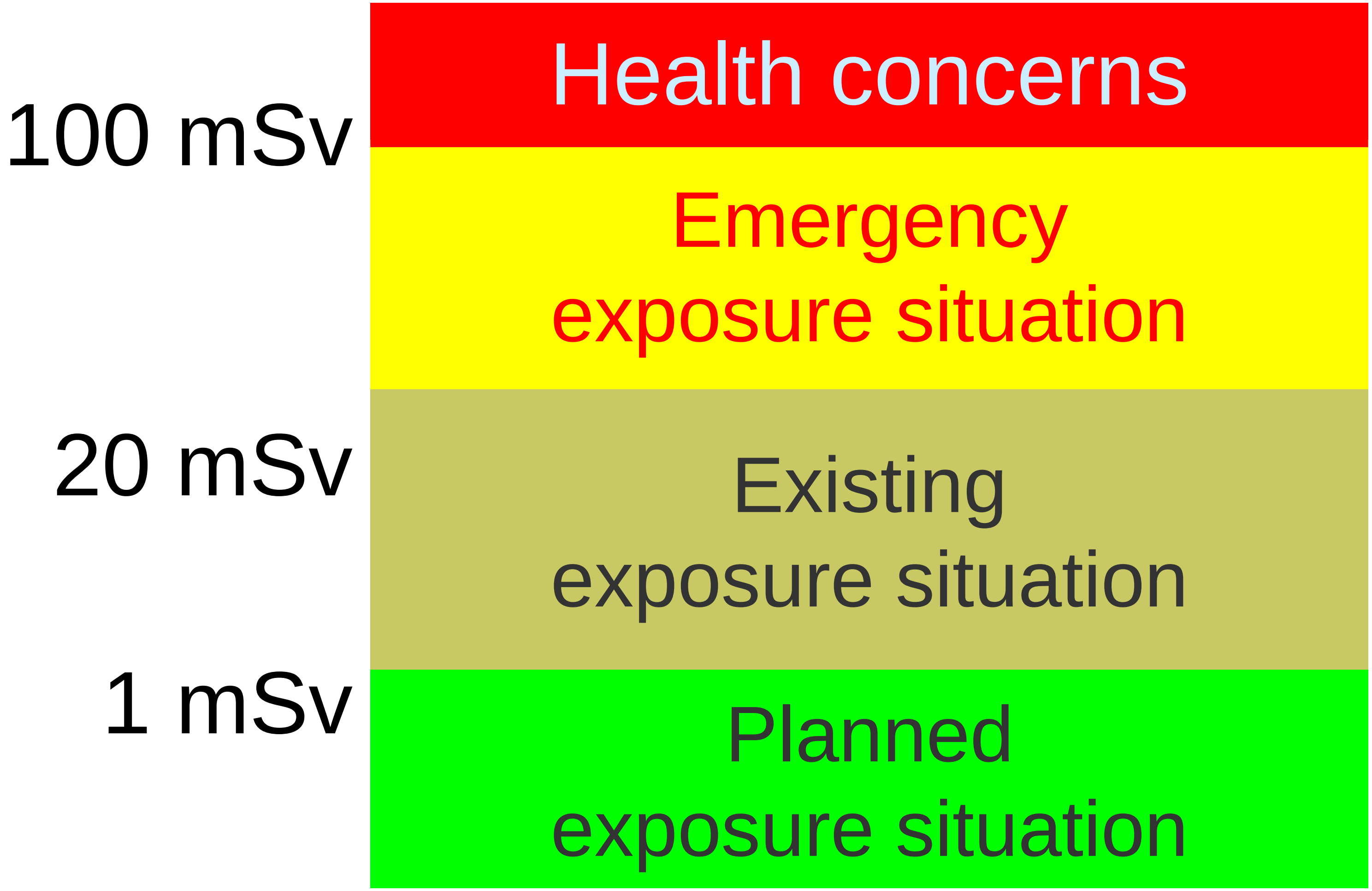
RL: reference level (different from DL)

Guidance levels for emergency workers (EW)

Intervention	$H_P(10)$
Life saving	< 500 mSv(*) Hungary: 250 mSv
Preventing severe deterministic effects Preventing development of severe accidents	< 500 mSv
Preventing high collective dose	< 100 mSv

(*) This level can be exceeded if the success of the action is more important than the risk of the EW, the EW acts on a voluntary basis and is aware of the risks.

Reference levels and dose limits for the general public (residual dose)



Health concerns

100 mSv

Emergency exposure situation

20 mSv

Existing exposure situation

1 mSv

Planned exposure situation

Further health physics regulations

Exemption: A material does not fall in the scope of health physics regulations on the basis of an *a priori* decision if

a) the total activity **or**

b) the mass specific activity concentration

is less than the exemption level given in legislation.

Exemption level [Bq] and [Bq/g] – any application of the material cannot lead to a dose consequence exceeding the negligible dose (= **10 – 30 µSv/year**) under any circumstances (**scenario)**

Further health physics regulations

Clearance level

Activity concentrations [Bq/kg] or [Bq/m^2] defined by the authority below which the previously controlled materials can be released (cleared) from control. Conditional clearance: clearance is connected to certain **scenarios** of further use or disposal.

Previously controlled (= dose consequences were limited by instructions) radioactive materials and wastes are cleared according to radioactive decay and/or successful purification so their dose consequence will be negligible (= **10 – 30 µSv/year**)

Exemption versus clearance

- Similarity: relation to negligible dose (≤10 – 30 μSv/year) and the associated risk (≤10^{-6})
- Difference: exposure scenarios, units (exemption: Bq or Bq/g, clearance: Bq/g, in some EU countries: Bq/m^2 as well)
- New nomenclature: exemption levels = specific exemption levels (SEL); clearance levels = general exemption levels (GEL)
- Values in [Bq/g]: SEL > GEL with 1-3 orders of magnitude

Measurement of external dose

Dose measurements: evaluation after the exposure – *personal dosimetry*

- Film badge: chemical change (blackening: silver bromide decomposition)
- TLD: (thermoluminescence – radiation damage of crystals turns to light emission upon heating) – official dose meter in most European countries
- „Active” dose meters: gas-filled detectors, semiconductor detectors, bubble detectors – „operational” = additional dose meters in workplaces

Dose rate meters: immediate evaluation – *area dosimetry*

- Gas-filled detectors
- Organic scintillation detector
- Semiconductor (Si) detector with energy dependence compensation

Requirements:

- „Energy independence”: the response (=sum of generated signals) must not depend on the distribution of the individual energy pulses
- Proportionality between response signal intensity and dose rate
- Fading = 0 – the dose must not „disappear” between exposition and evaluation

Principle of operation of tissue equivalent dose meters

If the detector and a person are in the same distance from a radiation source both „objects” are exposed to the same radiation field (energy flux).

$$\frac{D_x}{D_m} = \frac{\Phi_{E,x}}{\Phi_{E,m}} \cdot \frac{\left(\frac{\mu}{\rho}\right)_x}{\left(\frac{\mu}{\rho}\right)_m} = f_m$$

The energy dependence of the compound absorption coefficient must be similar to the material of the detector and the human tissue
- „tissue equivalent” detector
- „energy independence” of detector response: f_m should be **constant** for a wide energy range

The energy dependence of response can be mitigated by „energy filters”

Measuring external dose

Dose dependence of response of film badge

Official dosimeter in Hungary before 2013; then: TLD

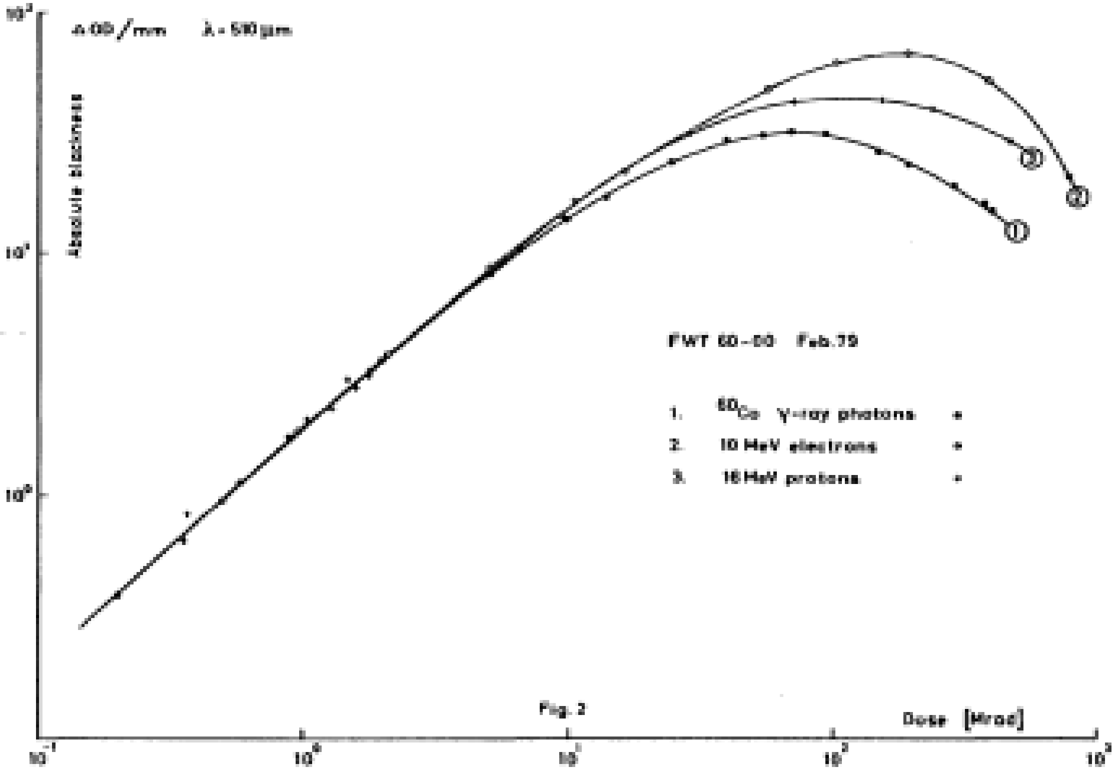


Fig. 2

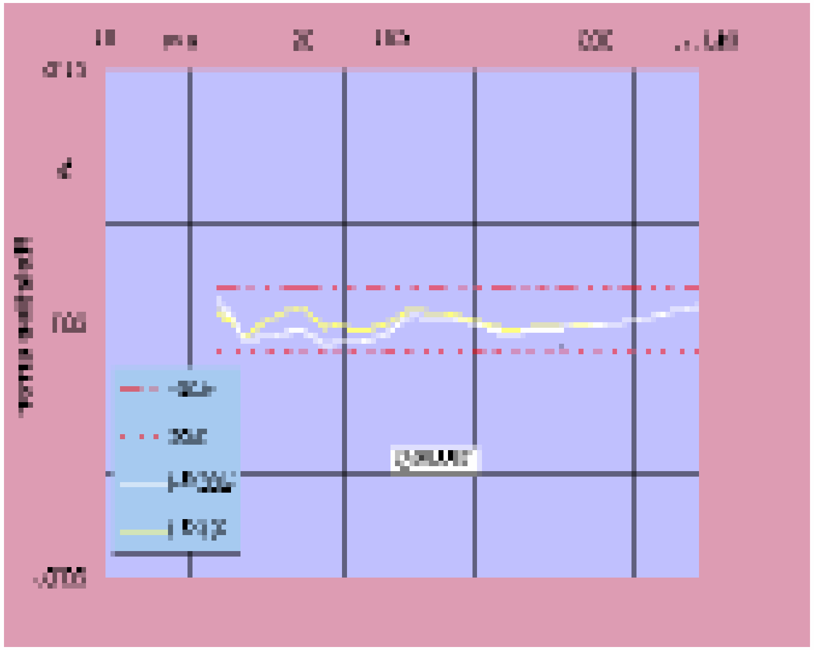
Measurement of external dose

TLD detector and reader „Butterfly”

TL materials:
For photon radiation only:
CaF_2, $CaSO_4$, LiF, Al_2O_3
For neutrons and photons:
^{6}LiF + ^{7}LiF

Measurement of external dose

Electronic personal dosimeter (EPD) with semiconductor detector (gamma and neutron)



Energy independence of EPD signals

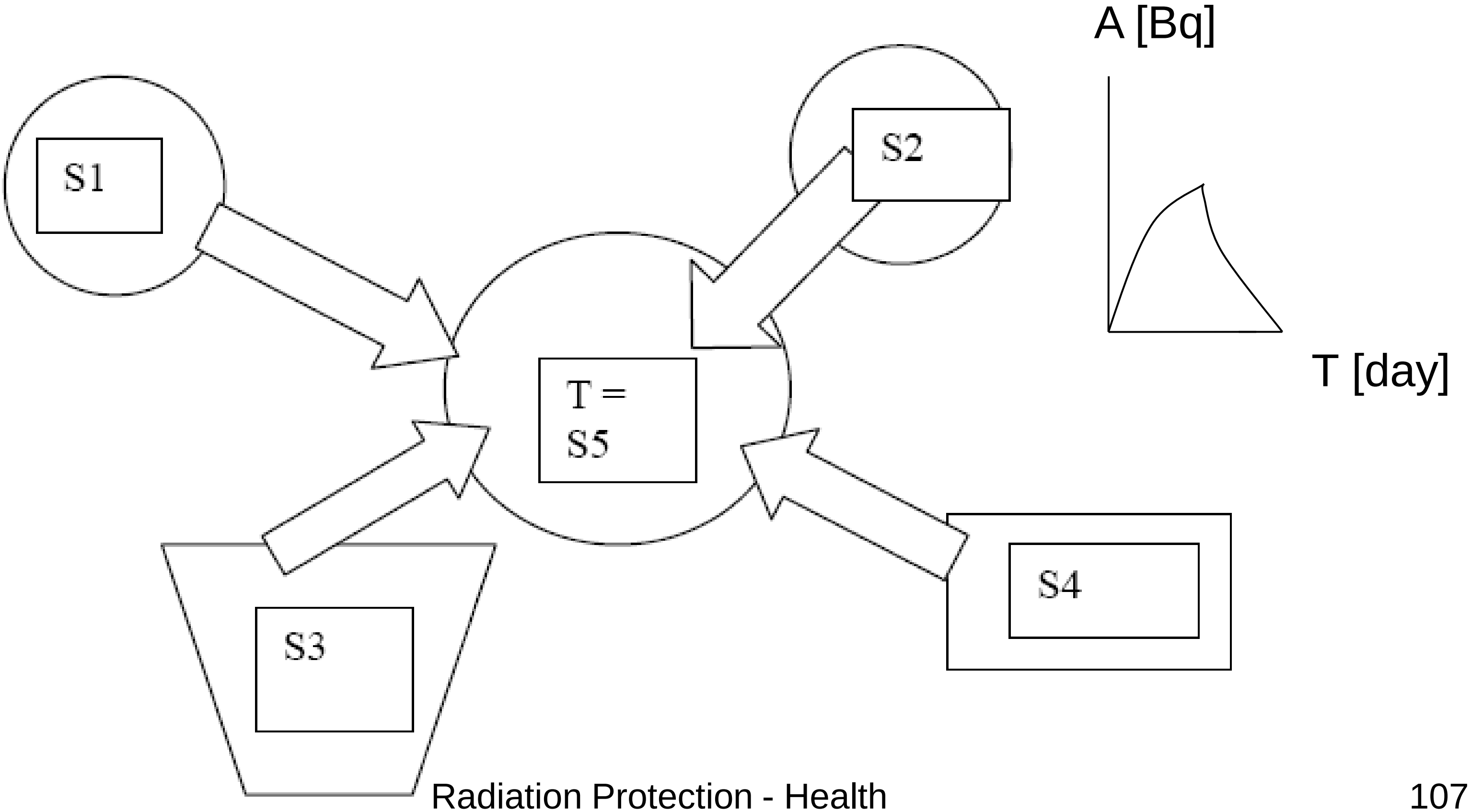
Measurement of external dose

FH-40-G dose rate meter

Bubble detector for neutron dose measurement

Internal dose

Dose is summed from the equivalent doses of tissues caused by the ionizing radiation (R) from source (S) tissues containing radioactive species imparting energy in target (T) tissues (S=T is possible)



Internal dose from incorporated radioactivity

Dose of target tissue T is caused by radiation R of the contaminant present in source tissues S (S=T is possible)

$$H_T = \left[\sum_S u_S \cdot \sum_R w_R \cdot E_R \cdot f_R \cdot Q_R(S \to T) \right] \cdot \frac{1}{m_T}$$

H_T equivalent dose in tissue T from a given radionuclide
u_S: number of <u>decays</u> occurring in tissue S [-]
$w_{R:}$ radiation weight factor [Sv/Gy]
E_R: radiation energy [keV/particle]
f_R: particle abundance (yield) [particle/decay]
m_T: mass of target tissue [kg]
Q: <u>absorbed quotient</u> of radiation R coming from source S into target T
(0 ≤ Q ≤ 1)

Calculation of external and internal dose

External dose: calculated if the quality and activity of the source is known and the distance of the source is given. (Absorption in air and other materials is neglected.)

$$\dot{D}_0 = k_\gamma \cdot \frac{A}{r^2}$$

k_γ = dose coefficient

Related to
- radionuclide
- absorbing material

Internal dose: elements of source-target model is determined and dose conversion factor is calculated.

e(g) [Sv/Bq] – Committed effective dose from the incorporation of unit activity (H_E/A_{BE}) – depending on type of radiation, residence time, way of intake, age

$$H_C = e(g) \cdot A_{in}$$

e(g) = dose conversion factor

Intake must be determined by radioanalysis.

Example: calculation of external dose

External dose: How long can a technician work with a ^{60}Co source of 0,5 GBq from a distance of 10 cm if his work-specific dose constraint was set to10 μSv?

($k\gamma$=305 [(μSv/h)/(GBq/m^2)])

Answer: 2.4 seconds – if it is possible…

Example: calculation of internal dose

Internal dose: How much will the annual dose of a person be from the natural ^{40}K content of the body? It is assumed that potassium is uniformly distributed in the body.

Body weight 70 kg;
K-content 0.2 %, ^{40}K-ratio in potassium: 0.0117 %, ^{40}K half-life 1.277×10^{9} a;
Decay forms of ^{40}K: beta probability 89 %, EC + gamma probability 11%
E_γ = 1461 keV, average beta energy 510 keV, X-ray-energy 3 keV

absorption quotient for gamma radiation in the body: 37 %,
absorption quotient for beta- and X-ray radiations in the body: 100 %;

$1\ \text{eV} = 1{,}6.10^{-19}$ J
Avogadro's number $N_A=6\times10^{23}$ atom/mole

Example: calculation of internal dose

Results:

- Activity of the person: 4240 Bq
- Decays per year: 1.34×10^{11} pieces
- Beta dose per 1 decay: 1.04×10^{-15} J
- Gamma dose per 1 decay: 1.36×10^{-16} J
- X-ray dose per 1 decay: 7.54×10^{-19} J
- Total dose per year: 160 µSv

Natural radioactivity

Components:

- Cosmic radiation
  - *primary solar and galactic radiation*: mostly protons, much less α-particles, other small atoms, fragments – they reach the upper atmosphere
  - *scattered*: Bremsstrahlung (reaching ground level), muons and neutrons;
- Cosmogenic radionuclides (from nuclear reactions between primary cosmic radiation and atmospheric atoms)
- Primordial radionuclides: residues of ancient supernova explosions occurred before the formation of „our” solar system

Cosmic rays cause external, radionuclides cause external and internal dose.

Natural radioactivity

- **Cosmic radiation:** *primary*: solar, galactic, extragalactic (solar: „solar wind” – cyclic) >95 % protons

  scattered: muons (decay to electrons and photons in collisions), neutrons; cosmic photon dose rate at ground level is 30 – 40 nSv/h, neutrons are hardly detectable (decay - $T_{1/2}$=615 s).

- **Cosmogenic radionuclides:**

  from reactions of cosmic particles with N and O:

  ^{3}H ($T_{1/2}$=12.3 a, weak β^{-}-emitter),

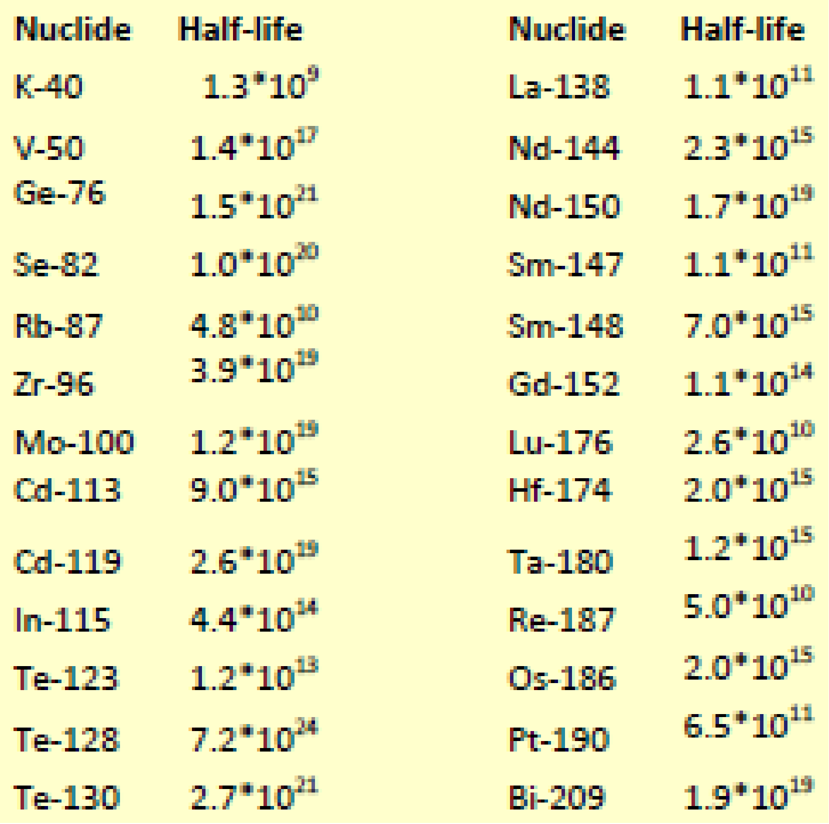
  ^{7}Be ($T_{1/2}$=53.3 day, EC and γ-emitter)

  ^{14}C ($T_{1/2}$=5730 a, weak β^{-}-emitter)

  from reactions with Ar:

  ^{22}Na, ^{36}Cl

Natural radioactivity – primordial radionuclides



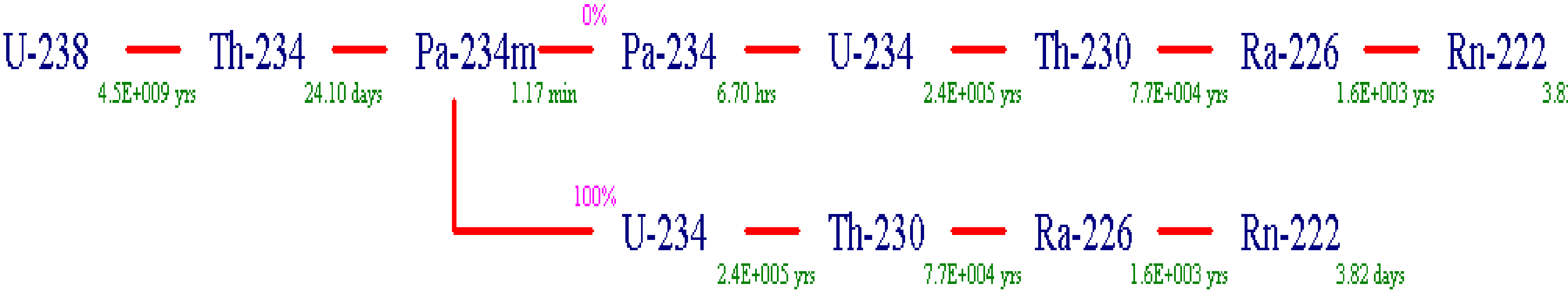
Nuclide	Half-life	Nuclide	Half-life
K-40	$1.3*10^{9}$	La-138	$1.1*10^{11}$
V-50	$1.4*10^{17}$	Nd-144	$2.3*10^{15}$
Ge-76	$1.5*10^{21}$	Nd-150	$1.7*10^{19}$
Se-82	$1.0*10^{20}$	Sm-147	$1.1*10^{11}$
Rb-87	$4.8*10^{10}$	Sm-148	$7.0*10^{15}$
Zr-96	$3.9*10^{19}$	Gd-152	$1.1*10^{14}$
Mo-100	$1.2*10^{19}$	Lu-176	$2.6*10^{10}$
Cd-113	$9.0*10^{15}$	Hf-174	$2.0*10^{15}$
Cd-119	$2.6*10^{19}$	Ta-180	$1.2*10^{15}$
In-115	$4.4*10^{14}$	Re-187	$5.0*10^{10}$
Te-123	$1.2*10^{13}$	Os-186	$2.0*10^{15}$
Te-128	$7.2*10^{24}$	Pt-190	$6.5*10^{11}$
Te-130	$2.7*10^{21}$	Bi-209	$1.9*10^{19}$

This list does not contain the three natural decay chains (^{238}U, ^{232}Th and ^{235}U)

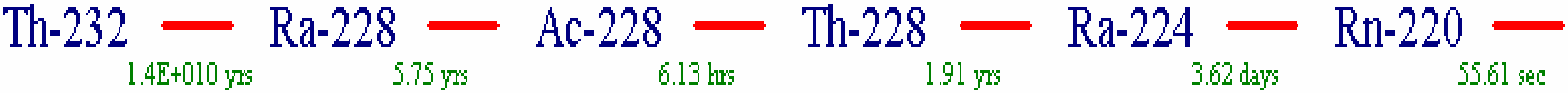
Natural radioactivity

Element	Primordial radionuclide
Potassium	^{40}K (0.01%) $T_{1/2} = 1.28 \times 10^{9}$ a
Thorium	^{232}Th (100%) [4n] $T_{1/2} = 1.4 \times 10^{10}$ a
Uranium	^{234}U (0.00548%) $T_{1/2} = 2.44 \times 10^{5}$ a
	^{235}U (0.714%) [4n+3] $T_{1/2} = 7.04 \times 10^{8}$ a
	^{238}U (99.28%) [4n+2] $T_{1/2} = 4.47 \times 10^{9}$ a

Natural decay series to radon



Radon



Thoron

Radon (^{222}Rn) descendants

$^{222}\mathbf{Rn}$	$T_{1/2}$= 3.82 d	α (5.5 MeV)

$^{218}\mathbf{Po}$	$T_{1/2}$= 3.05 m	α (6.00 MeV)
$^{214}\mathbf{Pb}$	$T_{1/2}$= 26.8 m	β^- (185 keV – 1.02 MeV) γ (295 keV, 352 keV + other weak lines)
$^{214}\mathbf{Bi}$	$T_{1/2}$= 19.9 m	β^- (526 keV – 1.26 MeV) γ (76 keV….2.45 MeV 14 intensive gamma lines)
$^{214}\mathbf{Po}$	$T_{1/2}$= 0.164 ms	α (7.69 MeV)

Radionuclides causing lung dose

$^{210}\mathbf{Pb}$	$T_{1/2}$= 22 a	β^-, γ (low energy)
$^{210}\mathbf{Bi}$	$T_{1/2}$= 5 d	β^- (300 keV…1.16 MeV)
$^{210}\mathbf{Po}$	$T_{1/2}$= 138 d	α (5.3 MeV)

End: ^{206}Pb - stable

Internal dose from descendants of ^{222}Rn and ^{220}Rn

- Radon and thoron nuclides decay in atmosphere;
- Descendant = metal ions adhere onto dust and vapour particles floating in air;
- Inhaled particle precipitates/sticks onto cells in respiratory tract (inhomogeneous distribution);
- Alpha and other decays occur generally before clearance (removal of particles by lymph and mucus).
- General condition of respiratory tract (e.g. chronic irritation by smoking) influences fixation and removal.

Radon levels

^{222}Rn ($T_{1/2}$= 3.8 d)

short-lived, α- and β^--emitting descendants:

^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po

Internal dose from them: **1.0 – 2.0 mSv/a** on average

^{222}Rn-progeny concentration (EEC – equilibrium equivalent concentration, less than or equal to c_{Rn}):

outdoors 1 – 10 Bq.m^{-3}

indoors 5 – 100 Bq.m^{-3} (intervention required
intervention: above 200 – 1000 Bq.m^{-3} – different values in different EU countries)

high radon level: cellar, mine, cave, slag

low radon level: above water bodies

uranium mine: 10^5 – 10^6 Bq.m^{-3}

in clean, wet air: EEC << c_{Rn}

EURATOM - Guidance for radon levels (Defined in 2013/59/EURATOM Directive)

- Recent epidemiological findings from residential studies demonstrate a statistically significant increase of lung cancer risk from prolonged exposure to indoor radon at levels of the order of 100 Bq m^{-3}.
- National action plans are needed for managing long-term risks from radon exposure. They also provide a means to consider other factors including tobacco smoking. It is scientifically established that most lung cancers attributable to radon can be avoided by cessation of smoking.

Other primordial decay series

^{232}Th: $T_{1/2}$= 14.1×10^9 a (7-10 ppm near ground surface)
decay series: 4n (α and β^- decays)
progeny: ^{220}Rn „thoron" and others
^{220}Rn ($T_{1/2}$= 55.6 s) – small amount is released into the atmosphere, dose consequence 0.1 mSv/a

^{235}U: $T_{1/2}$= 0.71×10^9 a (0.7 % of natural uranium)
decay series: 4n+3
most important raw material of nuclear power:
induced fission upon collision with „thermal" neutrons
progeny: ^{219}Rn „actinon" ($T_{1/2}$= 4 s) and others

^{220}Rn („Thoron”) descendants

^{220}Rn	**$T_{1/2}$= 55.6 s**	α (6.3 MeV)
^{216}Po	**$T_{1/2}$= 0.15 s**	α (6.77 MeV)
^{212}Pb	**$T_{1/2}$= 10.6 h**	β^- (100 keV) γ (87 keV – 300 keV)
^{212}Bi	**$T_{1/2}$= 61 m**	γ (70 keV – 1.8 MeV) β^- 64% (2.25 MeV) α 36% (6.06 MeV)
^{212}Po	**$T_{1/2}$= 0.3 μs**	α (8.78 MeV)
^{208}Tl	**$T_{1/2}$= 3.1 m**	β^- (200….700 keV) γ (84 keV…2.6 MeV)

End: **^{208}Pb** - stable

Sum of doses from natural origin

European average **2 - 3 mSv/a**

- Internal dose 65 – 70 % (radon and thoron progeny, ^{40}K, ^{14}C etc.)
- External dose 30 – 35 % (cosmic radiation, γ-radiation of primordial radionuclides from soil and building materials)

Dose from medical services: average 1.2 mSv/a (Hungary, 2018, increasing)

Radioactivity from artificial origin – wastes/operational releases

- Wastes from nuclear reactors
    - fission products (e.g. ^{131}I, ^{137}Cs)
    - activation products from nuclear fuel (e.g. ^{239}Pu)
    - activation products of structural materials (e.g. ^{60}Co)
- Wastes from military sources (nuclear bombings, test explosions,
- Industrial sources turned to waste
- Medical waste (from diagnostics and therapy)
- „TENORM”: technologically enhanced naturally occurring radioactive materials

Classification of RW

IAEA GSG-1 and GSR-3 recommends:

„moderate ” amount: exemption levels [EL] should be used for waste classification as reference level RL

„bulk” amount (>1 t): clearance levels [CL] should be used for waste classification as reference level

S: safety index $S = \sum_i \frac{c_i}{RL_i}$

<u>Release (emission) limits (REL)</u>: radioactivity that – if emitted – would cause a dose corresponding to the dose constraint [Bq/y] – applicable only for operational waste

Common feature for EL, CL, REL: values to be determined at the location of emission, <u>not</u> in the environment.

Classification of RW in Hungary (in compliance with IAEA and EU guidance)

Government decree on all issues of radiation protection: 487/2015. It defines exemption and clearance levels according to IAEA GSR Part 3 and 2013/59/EURATOM. Clearance is related to 10 - 30 μSv/year dose consequence.

$$WI = \sum_i \frac{c_i}{RAC_i}$$

WI waste index (=HI hazard index, =S safety index)
RAC: Reference activity concentration [Bq/g] – small quantity: exemption levels, big quantity (>1 t): clearance levels
c: activity concentration [Bq/g]
i: radioisotopes in a waste stream

Very low level waste (VLLW)	**$1 < WI < 50$, $T_{1/2} \leq 30$ *a***
Low level waste (LLW)	**$1 < WI < 1000$**
Intermediate level waste (ILW)	**$10^3 < WI < 10^6$**
High level waste (HLW)	**$WI > 10^6$,**
	***heat generation*> 2 kW/m^3**

Major sources of RW in Hungary

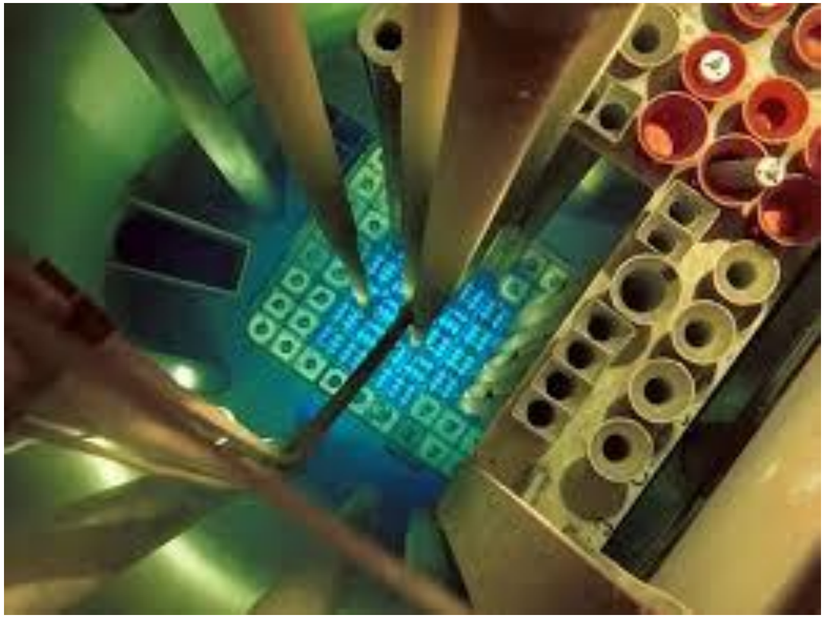
Primary nuclear facilities in Hungary:

- NPP Paks (4 operating units of 500 MWe)
- ISFSF (interim spent fuel storage facility Paks)
- 2 research reactors -BRR (Centre for Energy Research)
  -TR (BUTE INT)
- National Radioactive Waste Repository Bátaapáti (NRWR) – waste from NPP Paks
- Radioactive Waste Processing and Storage Facility Püspökszilágy (RWPSF) – waste from anywhere else
- Level „A” radioisotope laboratory of Isotope Institute Co. Ltd.

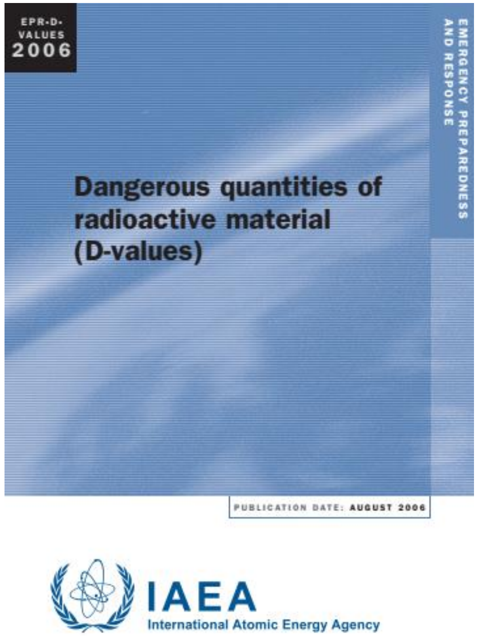
NPP Paks (by the Danube – 4 units 500 MW_e each)

Budapest Research Reactor (10 MW_{th})

Training reactor of Budapest Technical University (BME) – 100 kW_{th}



Level „A” isotope laboratory of Isotope Institute Co. Ltd.



EPR-D-VALUES 2006

EMERGENCY PREPAREDNESS AND RESPONSE

Dangerous quantities of radioactive material (D-values)

PUBLICATION DATE: AUGUST 2006

IAEA
International Atomic Energy Agency

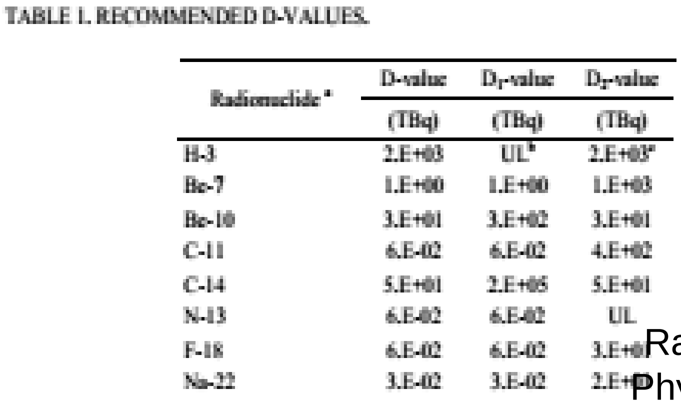
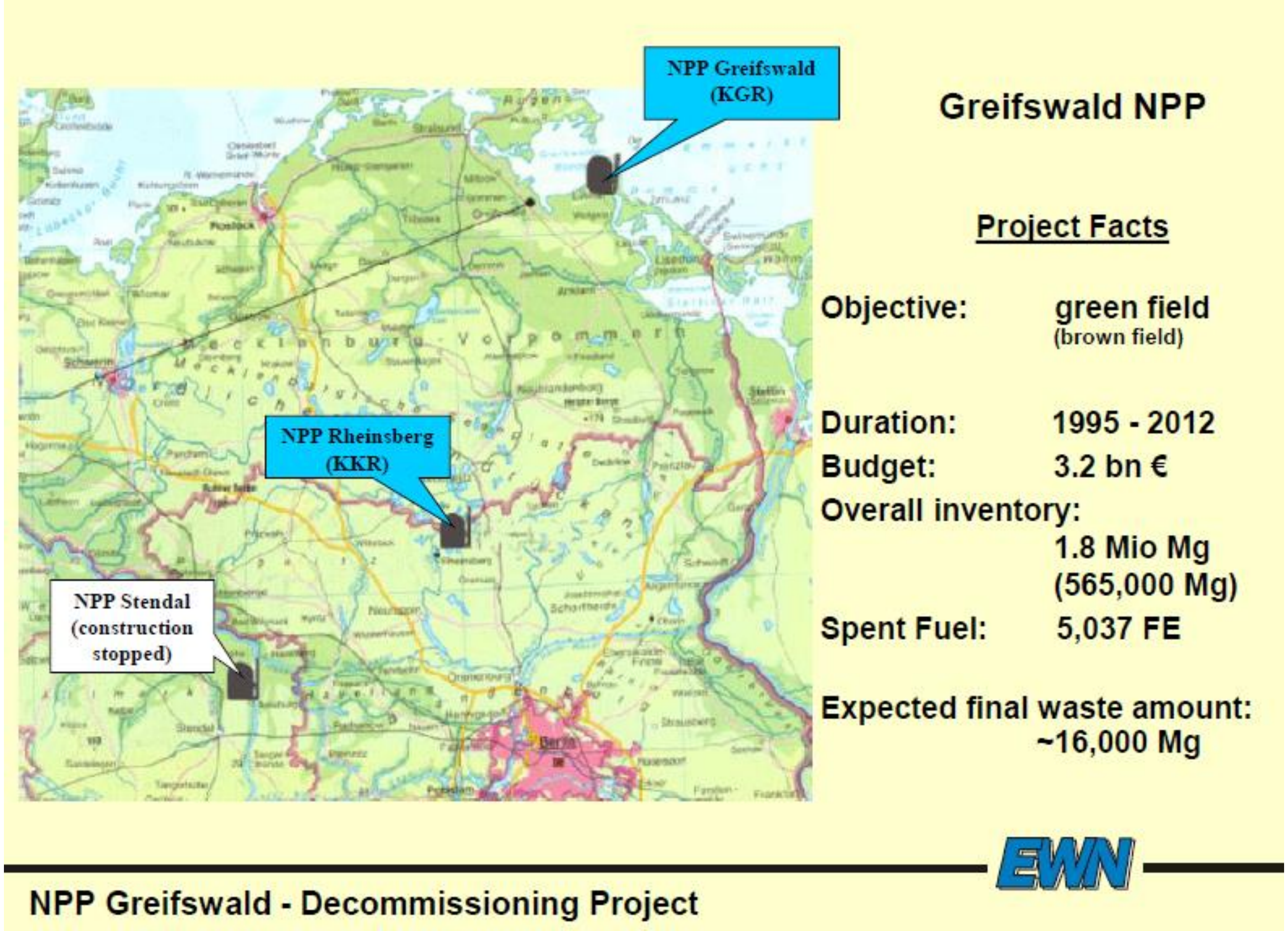


TABLE 1. RECOMMENDED D-VALUES.

Radionuclide[a]	D-value (TBq)	D_1-value (TBq)	D_2-value (TBq)
H-3	2.E+03	UL[b]	2.E+03[c]
Be-7	1.E+00	1.E+00	1.E+03
Be-10	3.E+01	3.E+02	3.E+01
C-11	6.E-02	6.E-02	4.E+02
C-14	5.E+01	2.E+05	5.E+01
N-13	6.E-02	6.E-02	UL
F-18	6.E-02	6.E-02	3.E+01
Na-22	3.E-02	3.E-02	2.E+0

Decommissioning of the Greifswald reactors



Greifswald NPP

Project Facts

Objective:	**green field** (brown field)
Duration:	**1995 - 2012**
Budget:	**3.2 bn €**
Overall inventory:	**1.8 Mio Mg** **(565,000 Mg)**
Spent Fuel:	**5,037 FE**

Expected final waste amount:
~16,000 Mg

NPP Greifswald - Decommissioning Project

Decommissioning of the Greifswald reactors

Case Study
Dismantling of the Reactors on the
Greifswald Nuclear Power Plant (KGR) Site
Axel Bäcker

IAEA Workshop on Decommissioning Planning and Licensing, Karlsruhe/Germany – November 2012

Decommissioning of the Greifswald reactors

Reactors on Greifswald site (KGR)

IAEA Workshop on Decommissioning Planning and Licensing, Karlsruhe/Germany – November 2012

Decommissioning waste of power reactors

Greifswald: Decommissioning of 5 VVER-440 reactor units (former DDR) – performed by EWN

„Nuclide vector for the whole site”:

- ^{60}Co – 17% - corrosion product
- ^{137}Cs – 2% - fission product
- ^{55}Fe – 71% - corrosion product
- ^{63}Ni – 10% - corrosion product

Management of radioactive wastes

Sequential steps of waste management:

1. **Collection, pre-classification**
2. **Classification I.**
3. **Storage, transporting**
4. **Waste processing operations:**
   - **preparatory procedures**
   - **volume reduction**
   - **conditioning**
5. **Classification II.**
6. **Temporary and/or final disposal (in repositories)**

Alternative solutions: reprocessing of spent reactor fuel, transmutation of long-lived waste components

Management of radioactive wastes

Temporary or final disposal (repositories)

Surface or near-surface disposal (above aquifers in use) – LLW (VLLW)

Deep (geological) disposal (below aquifers in use) – LLW,ILW,HLW

Characterization: RTOX (radiotoxicity index) [μSv/a]

$$RTOX = \sum_i A_i(t) \cdot \left(\sum_j mf_{i,j} \cdot Q_j \right) \cdot DCF_i$$

A_i: time-dependent inventory of radioactivity of i-th radioisotope [Bq]
Q_j: annual consumption of j-th diet item connected to potential input from repository [kg/year]
$mf_{i,j}$: mobility factor: transfer of radionuclide i into j-th diet item [(Bq/kg)/Bq]
DCF_i: respective dose conversion factors

RW repositories in Germany

RW Disposal in Germany

Konrad (close to Salzgitter) – Iron ore mine between 1961 – 1976. (Dry!)

1975 – 2002: explorations (thick surrounding clay layers)

2002: Licence for establishing LLW + ILW geological repository.

2006 – 2007: Lawsuits for the withdrawal of the licence – lost.

Licence for 303.000 m³ LLW + ILW, from this 88.000 m³ would come from other repositories that are decommissioned. Licensee: BGE

Costs: 945 M euro spent before 2008, further 900 M euro were expected till the end of construction. Disposal will start in 2027.

RW Disposal in Germany

Gorleben – exploration from 1973: 140 salt lenses were examined.
Costs: 1973 – 2000: 1.5 B euro.
Opponents: „Lack of transparency and controllability”
1996: Two exploration shafts down to 840 m depth.
Owing to fractured neighbouring rock bodies explorations were suspended in 2000 „at most for 10 years”.

BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

Asse II. (in 490 m depth) – present licensee: BfS
Salt dome – Exploration shaft drilled in 1965, 1967 – 1978: LLW + ILW disposal, mostly from Karlsruhe reprocessing plant WAK (shut down in 1990)
Closure decision: 1995; 1995 – 2004 vaults are backfilled with salt (halite)
2008: Brine intrusion was observed (12 m^3*/year) owing to a possible diapir*

Morsleben: former DDR - LLW + ILW repository established from former salt mine. Disposal: 1971-1998: 40,000 m^3
Present intention: Decommissioning, clearance of site

BfS Bundesamt für Strahlenschutz

Germany – Reports on Asse

Erhöhte Krebs-Raten rund um die Asse

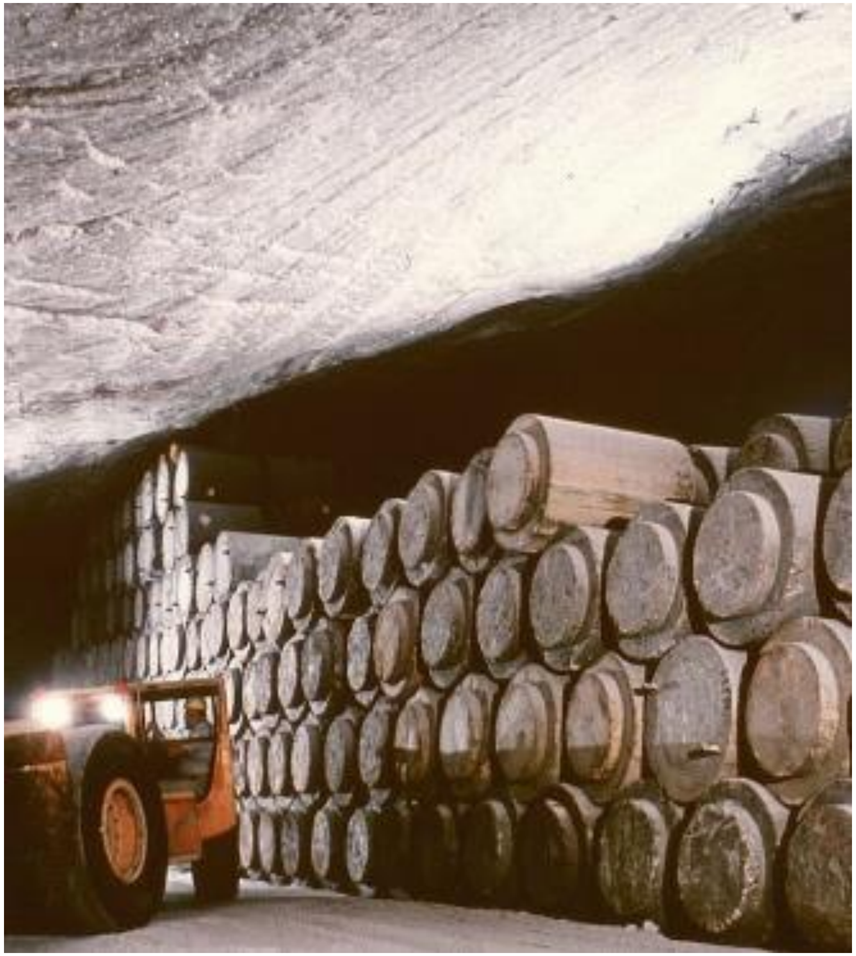
Donnerstag 25.11.2010, 20:23

Reuters Atomendlager: Erhöhte Zahl von Leukämie-Fällen im Umfeld der Asse

Im Umfeld des maroden Atomendlagers Asse bei Wolfenbüttel ist eine erhöhte Zahl von Leukämie-Fällen bei Männern festgestellt worden. Frauen erkranken dort weit öfter an Schilddrüsenkrebs als anderswo. Die Gründe sollen nun erforscht werden.

Dies teilte das niedersächsische Umweltministerium am Donnerstagabend in Hannover mit und bestätigte damit einen Bericht des regionalen NDR-Fernsehmagazins „Hallo Niedersachsen“. Ministeriumssprecher Thomas Spieker sagte, Auswertungsergebnisse des Epidemiologischen Krebsregisters des Landes hätten Hinweise auf ein gehäuftes Auftreten von Leukämie-Erkrankungen insbesondere bei Männern ergeben.

„Eine Ursache dafür kann bisher nicht festgestellt werden“, sagte Spieker. Die Auswertung sei noch nicht abgeschlossen: „Wir wissen daher noch nicht, welchen Einfluss zum Beispiel Lebensalter und Berufstätigkeit auf Erkrankungen haben.“



RW management in Hungary
Intermediate Spent Fuel Storage Facility - KKÁT Paks

Dry storage vaults with mixed ventilation (natural convection with active supplement)

Püspökszilágy – „A” type vaults before deing covered with soil; „wells” (steel container tubes) for spent radiation sources

Model of Bátaapáti NRWD site

Shafts leading to drifts in „fresh" granite body. Closure: backfill, field concrete

RHK = PURAM

Commissioning of Bátaapáti NRWD repository: December 11, 2012

First concrete container with conditioned waste in drift #1

Operational radiation protection

Monitoring

On-site monitoring at controlled and supervised areas, monitoring releases, off-site (environmental) monitoring

On-site: personal dose meters, area dose rate meters, measurement of surface contamination.

Environmental: system of local (controlling emissions) and regional/national (controlling immission) networks.

Radioactive waste management, decontamination

Waste processing technologies: see separate slides

Decontamination: selective removal of radioactive material from surfaces by dissolution producing the least reasonable amount of liquid waste.

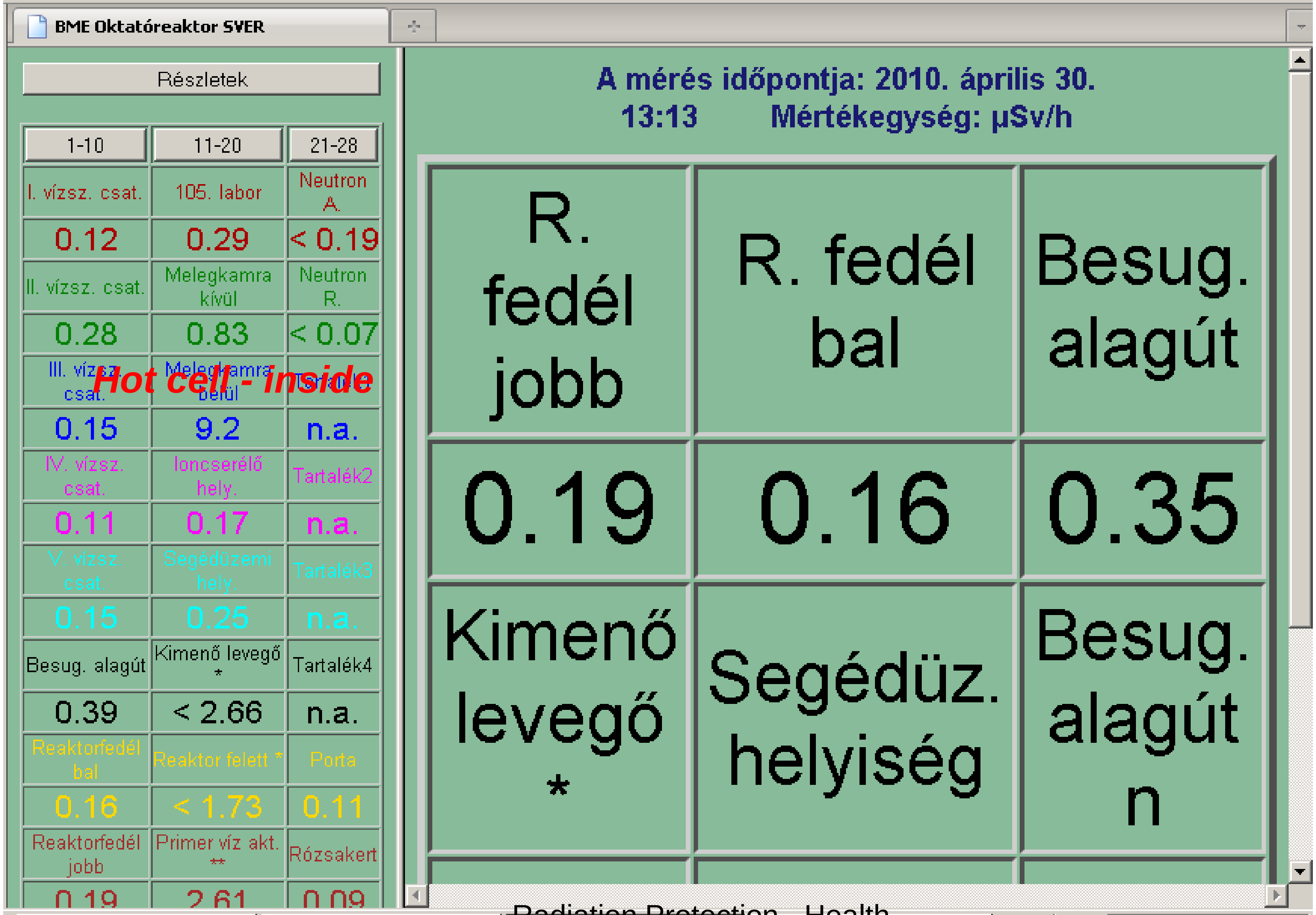
Shielding: personal radiation protection by absorbing gamma- or neutron radiation in shielding material

Gamma-shielding: by high-Z material, considering generation of secondary radiations as well

Neutron-shielding: by non-activating low-Z material

Further protective measures: protection by time, distance and clothing

On-site area monitoring at BTU - TR



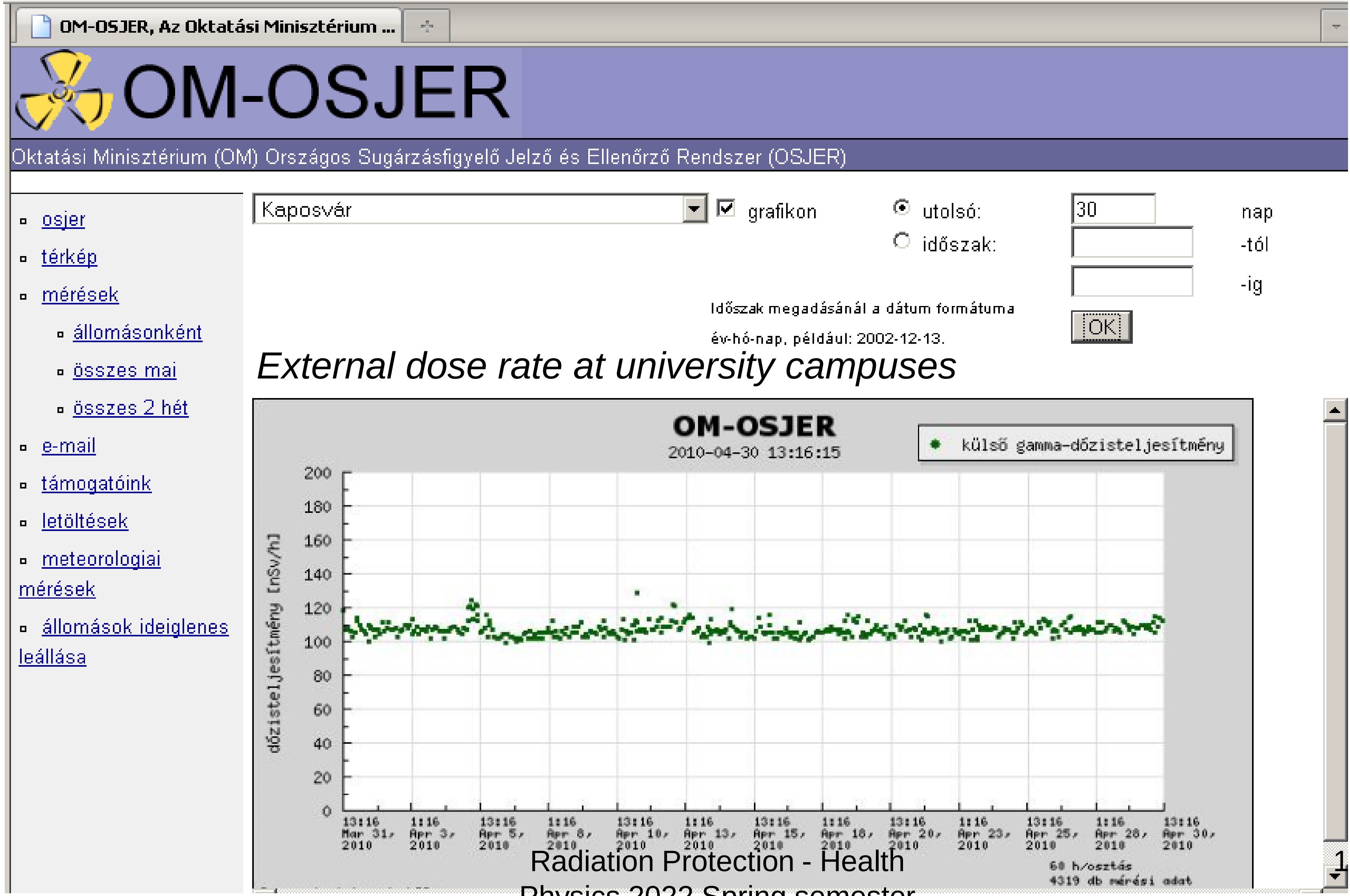
1-10	11-20	21-28
I. vízsz. csat.	105. labor	Neutron A.
0.12	0.29	< 0.19
II. vízsz. csat.	Melegkamra kívül	Neutron R.
0.28	0.83	< 0.07
III. vízsz. csat.	Melegkamra belül	Tartalék
0.15	9.2	n.a.
IV. vízsz. csat.	Ioncserélő hely.	Tartalék2
0.11	0.17	n.a.
V. vízsz. csat.	Segédüzemi hely.	Tartalék3
0.15	0.25	n.a.
Besug. alagút	Kimenő levegő *	Tartalék4
0.39	< 2.66	n.a.
Reaktorfedél bal	Reaktor felett *	Porta
0.16	< 1.73	0.11
Reaktorfedél jobb	Primer víz akt. **	Rózsakert
0.19	2.61	0.09

Hot cell - inside

A mérés időpontja: 2010. április 30. 13:13 Mértékegység: μSv/h

R. fedél jobb	R. fedél bal	Besug. alagút
0.19	0.16	0.35
Kimenő levegő *	Segédüz. helyiség	Besug. alagútn

Environmental monitoring http://omosjer.reak.bme.hu/



Oktatási Minisztérium (OM) Országos Sugárzásfigyelő Jelző és Ellenőrző Rendszer (OSJER)

Kaposvár ☑ grafikon

● utolsó: 30 nap

○ időszak: -tól

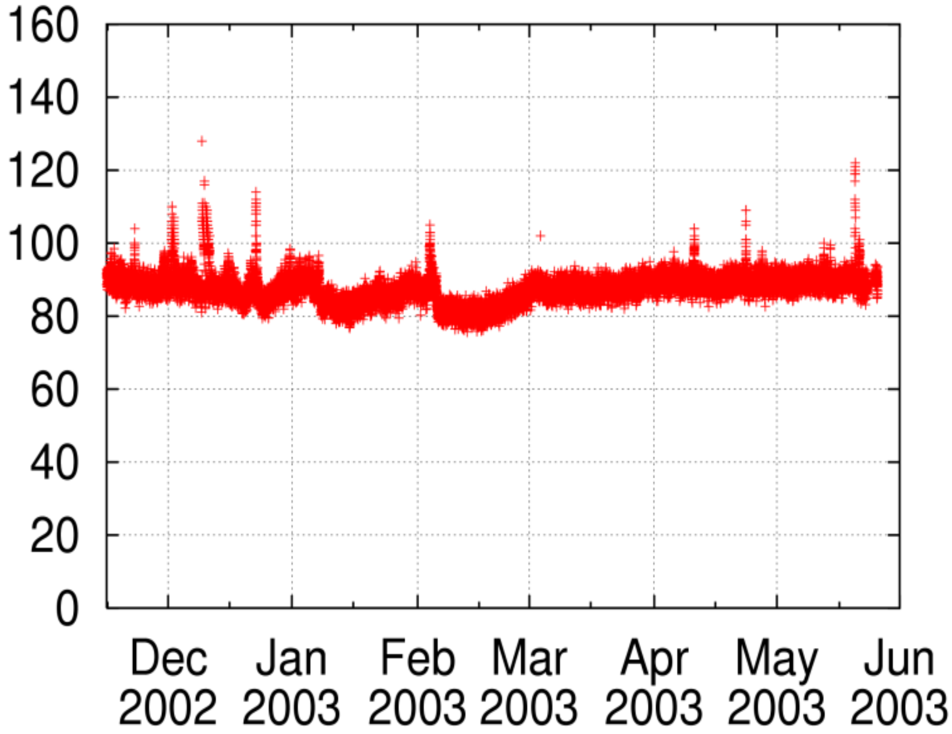
-ig

Időszak megadásánál a dátum formátuma év-hó-nap, például: 2002-12-13.

External dose rate at university campuses

EARLY WARNING SYSTEM – response of BTU TR environmental monitoring station in 6 months

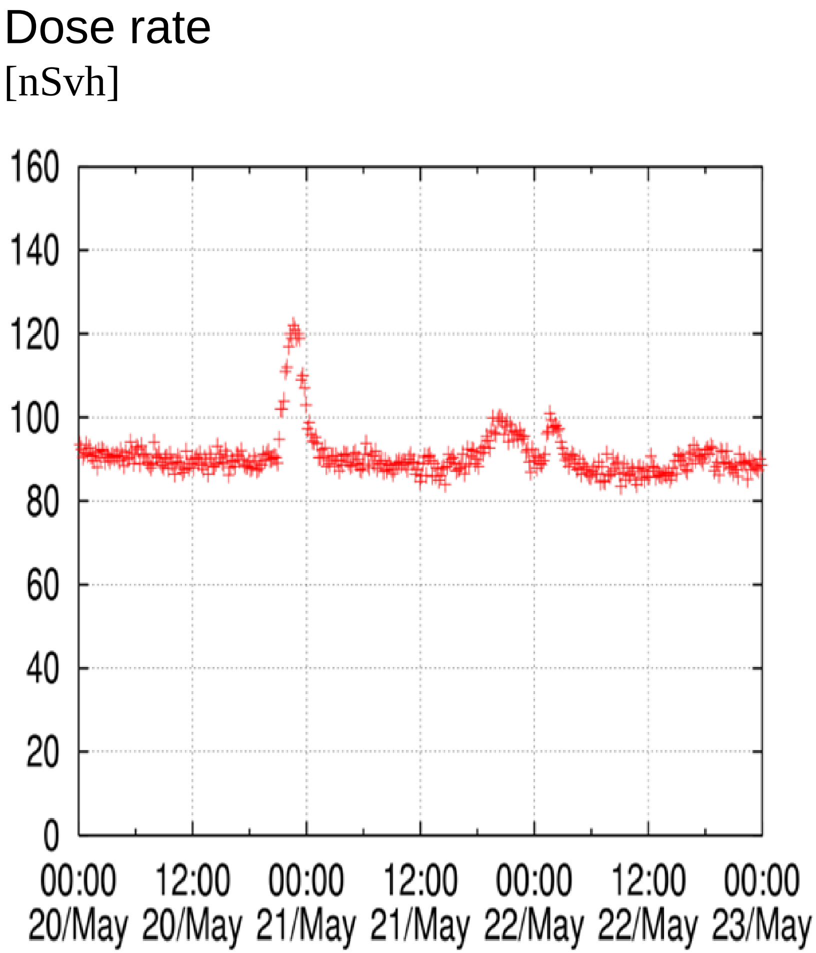
dose rate
[nSvh]



Long term record shows 3 possible effects:

- local effect (release),
- rapid environmental effect (precipitation or radiocontamination),
- slow (seasonal) change

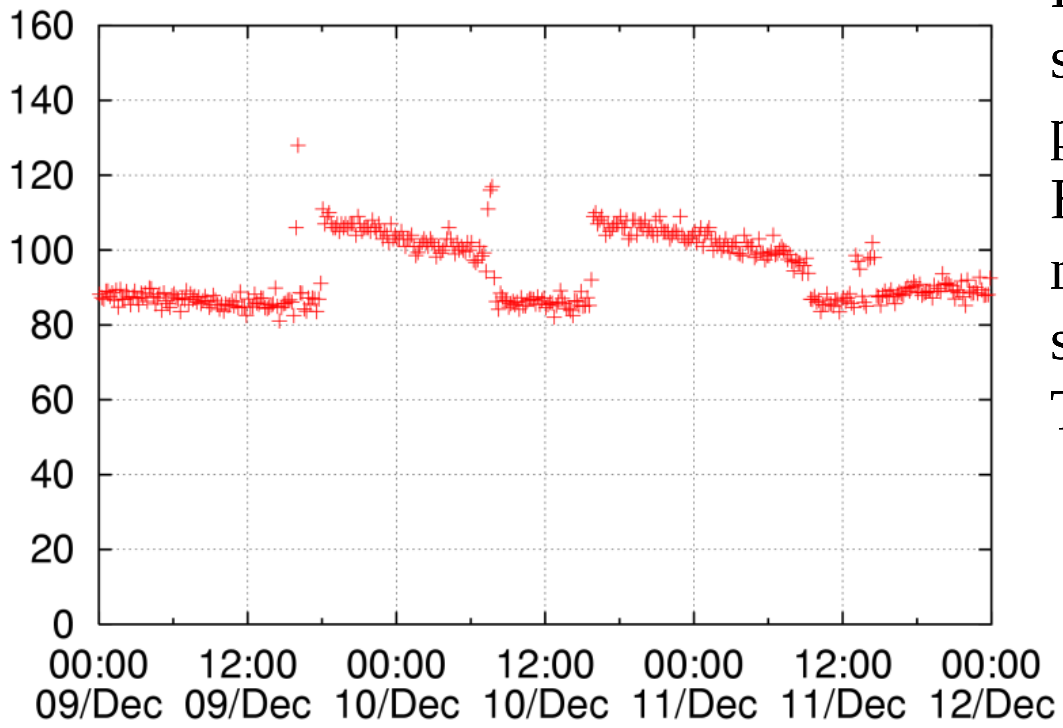
Environmental monitoring – precipitation „peaks”



Rain or snow removes floating particles (aerosol) from the air. The precipitate rich in short-lived ^{222}Rn- and ^{220}Rn-progeny comes down and is detected with improved efficiency compared to conditions in dry weather. Decay curve of progeny is characterized by their half-life. Similar patterns with different (less steep) descending side may occur in case of artificial radiocontamination migrating in the atmosphere.

EARLY WARNING SYSTEM – local effects

Dose rate
[nSvh]



Freshly activated ^{24}Na radiation sources were prepared and their presence in a laboratory of BTU TR was observed by a monitoring station positioned some meters away from BTU TR building.

Shielding calculations

Attenuation of dose rate is approximated by the attenuation equation of primary parallel photon beam:

$$\dot{D} = \dot{D}_0 \cdot B \cdot \exp(-\mu \cdot x)$$

B: build-up factor: Compton-scattered radiation contribute to primary (unattenuated) photon intensity; B depends on:
- (μx), it increases with depth of material,
- atomic number of shielding material (increased probability for Bremsstrahlung)
- reversely proportional with radiation energy as μ (absorption coefficient) decreases with energy.

Dependence of build-up factor on quality and thickness of matter

54 EXPONENTIAL ATTENUATION

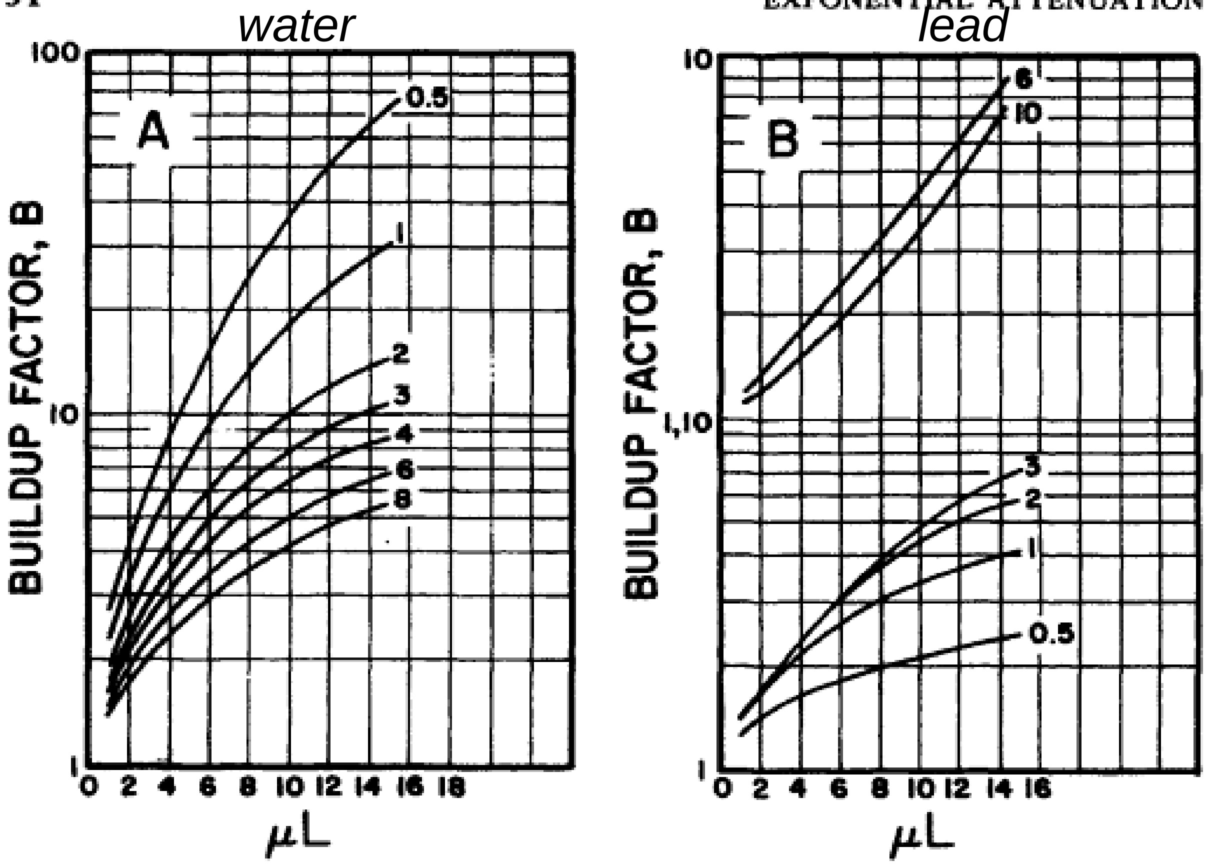


FIGURE 3.6. Exposure buildup factors for a plane, infinitely wide beam of photons perpendicularly incident on semi-infinite media of (*A*) water and (*B*) lead. Curves are labeled with photon energies in MeV. Abscissae indicate the depth in units of the mean free path 1/μ. (Goldstein, 1957.) Reproduced with the author's permission.

Source:
google books
Introduction to Radiological Physics and Radiation Dosimetry
F. H. Attix (2008)

Calculation of shielding

Example: What is the thickness of a lead brick wall required for „free” working area in the vicinity of a waste package? The waste contains ^{60}Co, „free working area” is considered below 1 μSv.h^{-1} at NPP Paks. The measured value is 15 μSv.h^{-1}, linear absorption coefficient of lead for the 1.25 MeV average gamma energy of ^{60}Co is 0.47 cm^{-1}, B will approximately be ≤3

$D=D_0*B*\exp(-\mu x)$

$1=15*3*\exp(-0.47*x)$

$x=-1*\ln(45)/(-0.47)$

x= 8.1 cm

Operational radiation protection

Physical protection: precluding entrance of trespassers

Emergency preparedness and response: (EPR)

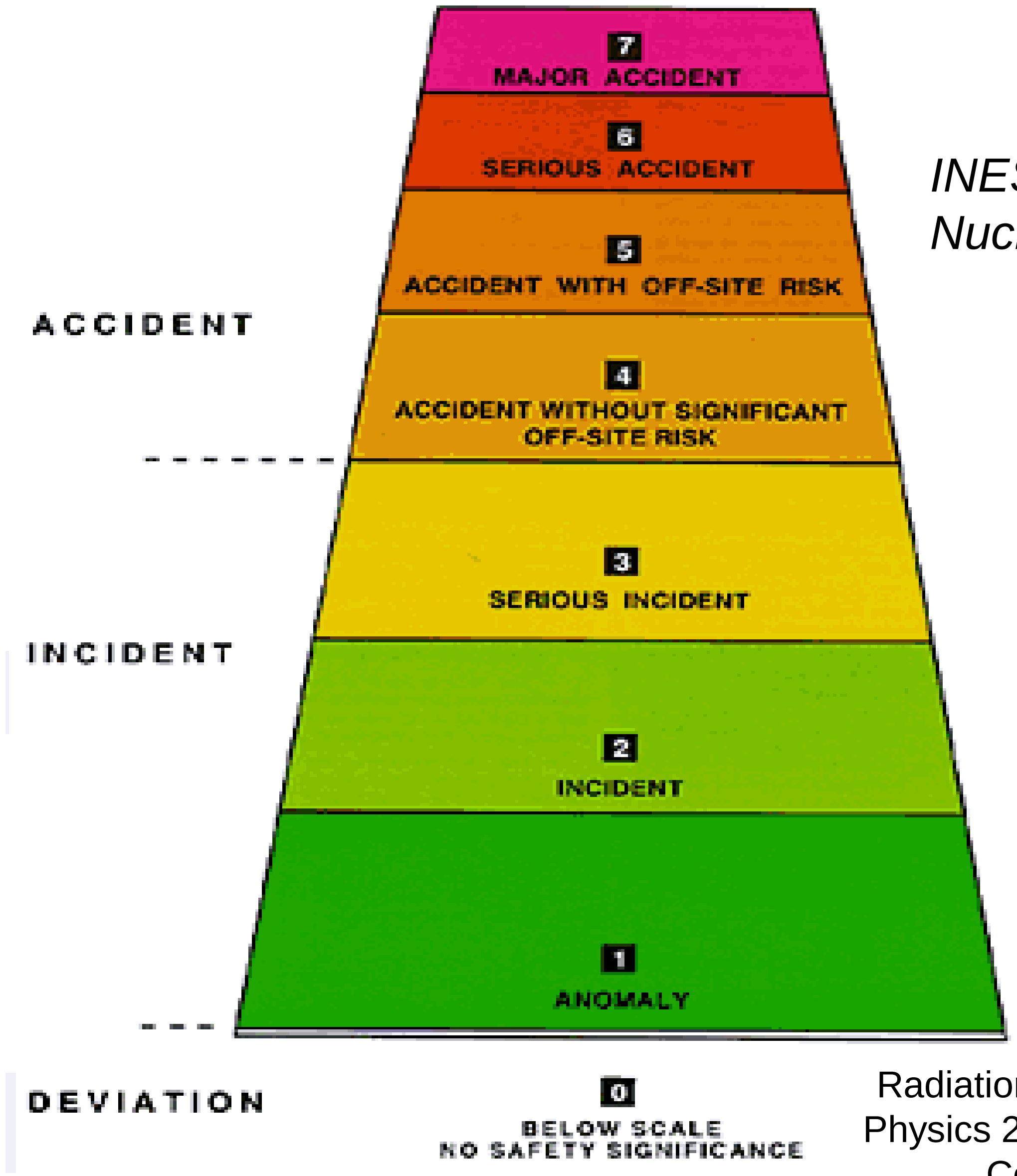
Guidance on doses during emergency (occupational dose: dose limits higher than that of planned exposures; public: generic criteria for protective measures)

Nuclear/radiological accidents: Windscale, Three Mile Island, Chernobyl, Goiania, Fukushima.

Accidents with overexposure

>95 % of accidents leading to overexposure occurred with industrial and medical radiation sources and not with nuclear facilities – owing to violation of rules and/or inadequate planning

Nuclear and radiological accidents– INES categories



INES = International Nuclear Event Scale

Nuclear and radiological accidents

1957 Windscale (United Kingdom) → Sellafield

In a military fast breeder (^{239}Pu-producing) reactor graphite reflector rods were overheated = prompt release of heat due to Wigner-discomposition and reordering (exothermic process)

Core meltdown, graphite fire

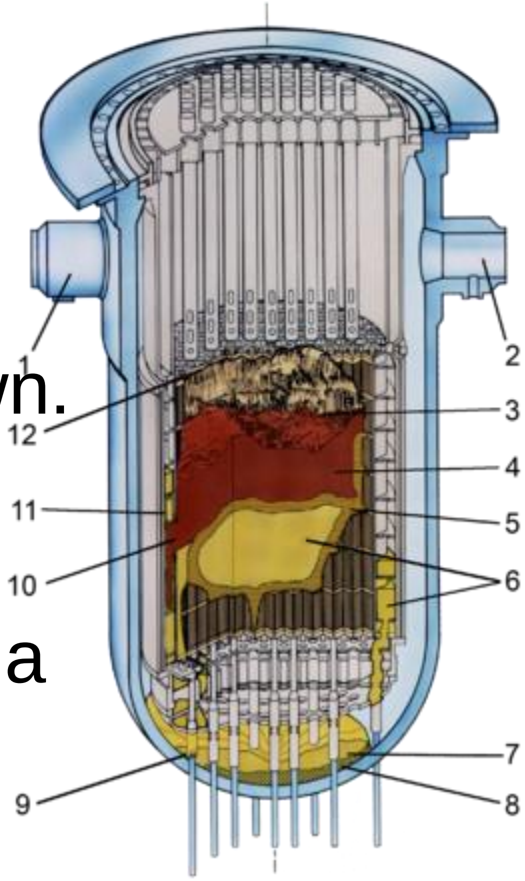
Fission products were released into the environment contaminating and area of 700 km^2. Consumption of milk from grazing cows was forbidden. (In order to avoid ^{131}I intake)

Total emitted activity: 4.10^{16} Bq

https://www.youtube.com/watch?v=vZ4vtUzG6sQ

Nuclear accidents

1979 Three Mile Island (Middletown, USA) – LOCA: loss-of-coolant accident



Following multiple failure of valves and erroneous operator decisions active core was dried and partially melt down. Only volatile noble gases and radioiodine escaped. Contaminated water was released into Susquehanna river.

Total emitted radioactivity: 10^{15} Bq

http://www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Three-Mile-Island-accident/

Nuclear accidents

1986 Chernobyl (Soviet Union, now Ukraine = Chornobil)
RBMK: water-cooled, graphite moderated reactor
RIA: reactivity insertion accident

An experiment was performed in the operating reactor in the course of which emergency cooling pumps and emergency shutdown system were intentionally switched off. Owing to insufficient cooling reactor water got boiling and due to unsafe design (positive void coefficient) reactor power increased. Reactor became uncontrollable, shutdown efforts failed . Graphite fire and hydrogen explosions occurred.

Huge amount of radioactive material was released to an elevation of several km, thus the radioactive plume could spread over the whole Europe. Emission lasted for several days. 47 dead: operators, firemen, emergency responders.

Total emitted radioactivity: 2.10^{18} Bq

Radiological accident

Goiania (Brazil) 1987: accident from an uncontrolled radiation source

A 50 TBq ^{137}Cs source was left at an abandoned hospital department originally used for teletherapy. Scavengers found it and took to a waste dump where tried to disassemble it.

„Bright blue powder" – it was distributed to friends.

250 persons were overexposed, 50 persons showed serious radiation sickness, 4 dead because of damage to red bone marrow. (Maximum estimated dose was 5 Gy)

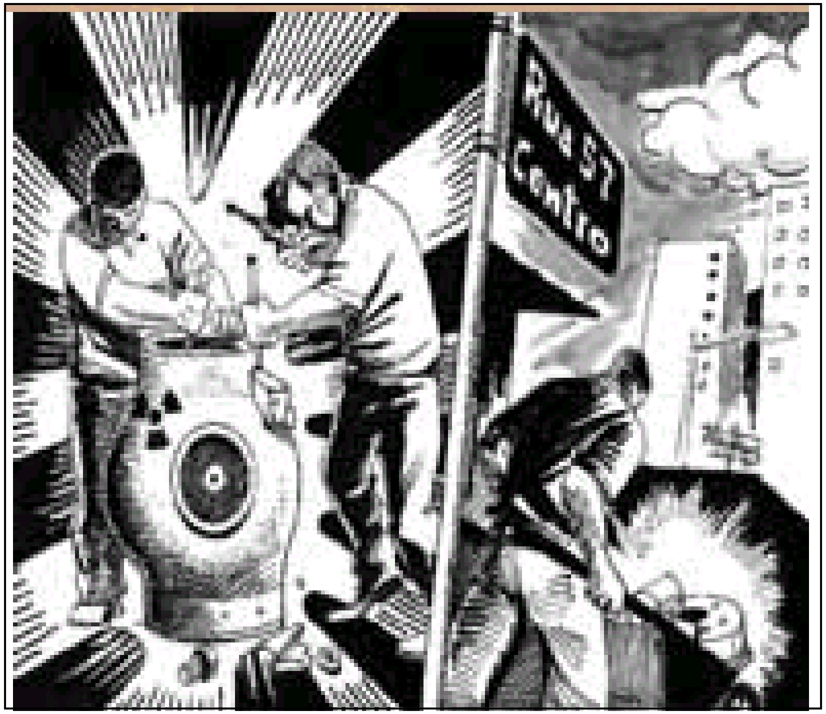
7 houses were demolished, 3000 m^3 radioactive waste was generated and disposed of.

https://www.youtube.com/watch?v=fh-VqehmgCQ

Radioactive waste from radiological accident with an abandoned medical source: 1987, Goiânia (Brazil)

The following slides are shown from the courtesy of International Atomic Energy Agency.

The Accident's History



On September 13, 1987, two scavengers entered the abandoned premises of a radiotherapy clinic in Goiânia and removed the rotating assembly of a ^{137}Cs radiotherapy device (Activity: 50.9 TBq). At the house of one of them, they managed to break open the shutter of the collimator orifice and were exposed to radiation.

The Accident's History

Five days later, the violated equipment was sold to a junkyard. During the next days, fragments of Cs were given to many persons and pieces of the equipment were sold to two other junkyards.

Some people put fragments of Cs in pockets or rubbed them on the skin.

The Accident’s History

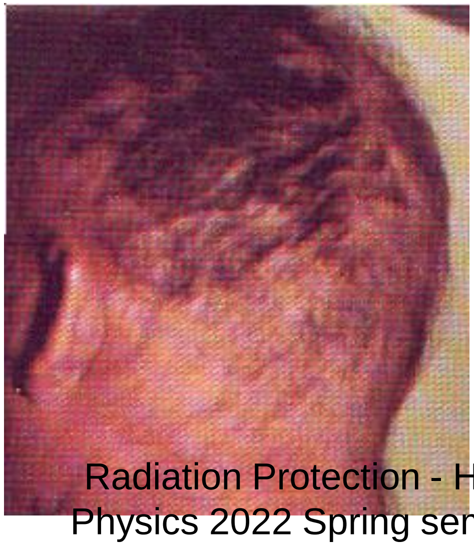
- During the next days, people developed prodromal manifestations of ARS (acute radiation syndrome) and local radiation injuries (CRS – cutaneous radiation syndrome).
- Manifestations were not recognised by local physicians as radiation induced ones.

The Identification of the Accident

- On September 28, 1987, the wife of the owner of the junkyard suspected the manifestations people were presenting were caused by exposure to “the object”
- She and another individual took it to the Secretary of Sanitary Surveillance of Goiânia

Misdiagnosis of injuries


© 1996, Dermatology, University of Iowa



The Immediate Medical Impact

<table>
<tr><th>Hospitalisation</th><th>ARS</th><th>CRS</th><th>Death toll</th></tr>
<tr><td>20
(ARS/CRS/Contamination/ Association)</td><td>8</td><td>20</td><td>4</td></tr>
<tr><td colspan="4">Screened people</td></tr>
<tr><td>112800</td><td colspan="3">~15%
of population</td></tr>
</table>

ARS: acute radiation syndrome
CRS: cutaneous radiation syndrome

The Environmental Impact: Waste Generation of 3500 m^3

- 1347 boxes;
- 4223 drums;
- 10 marine containers and
- 8 concrete drums;
- 7 houses demolished

Nuclear accidents

1999 Tokai-mura (Japán) – Criticality accident

At JCO reactor fuel plant three workers poured into a vessel <u>mistakenly</u> uranium solution enriched enough to reach criticality, so chain reaction started. Workers saw blue flashes then became very sick.

Radiation sickness (deterministic effect): 2 dead (gastro-intestinal system destroyed), 1 survivor (lung damage)

Description of a „moderate” radiological event

Event date: 2010-04-20

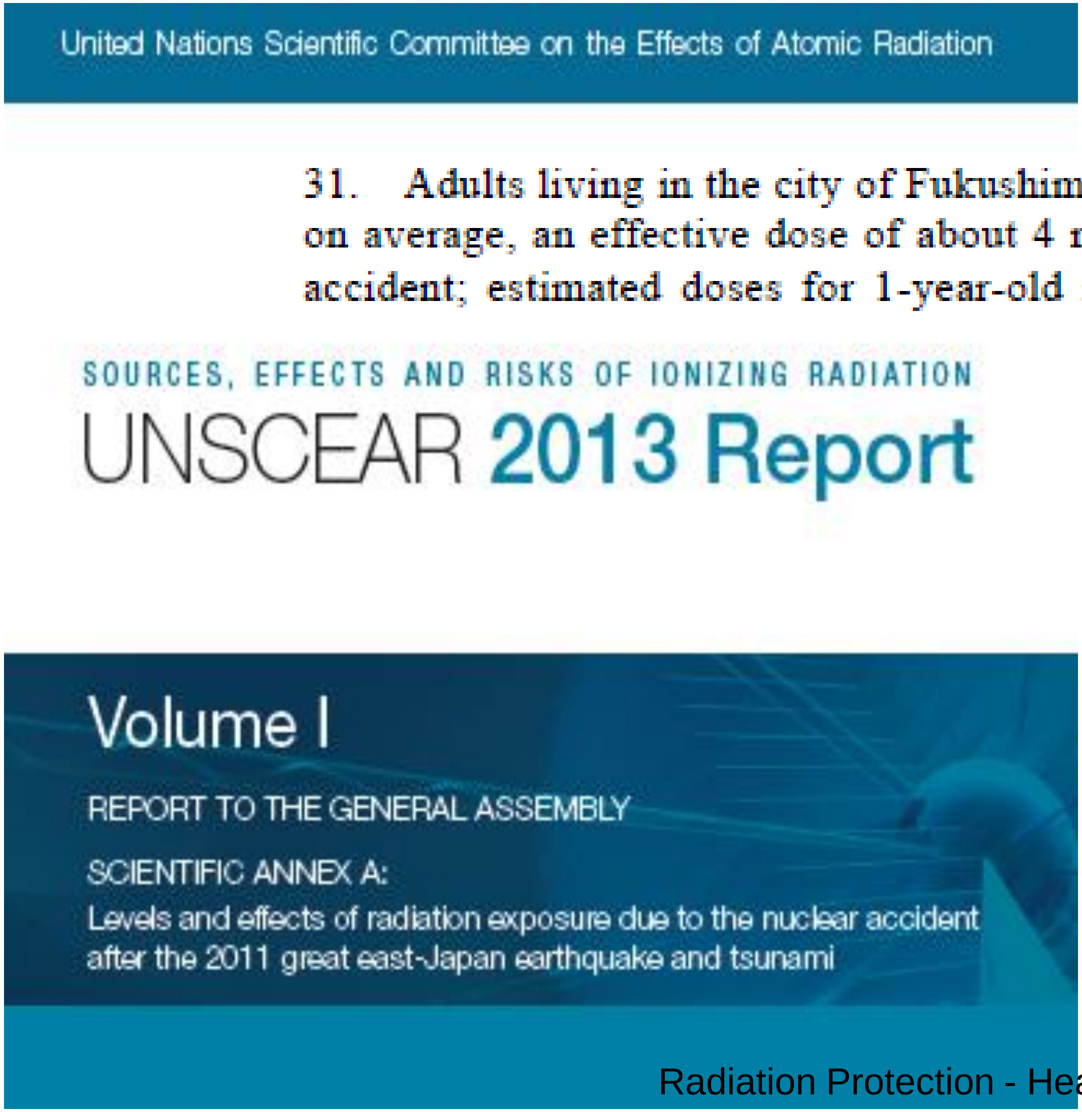
Location/facility: Ohio State University,Columbus Ohio, USA

The potentially overexposed individual may have spent a significant amount of time visiting his fiancée who was receiving a temporary implant of ^{137}Cs and ^{192}Ir seeds via low dose-rate remote afterloader brachytherapy. The licensee instructed the patient's visitor to visit no longer than 2 hours and to stay behind the bedside shield during these visitations. On Tuesday, April 20, 2010, the Assistant Nurse Manager informed the licensee that the visitor claimed to have spent the night in the bed with the patient on two consecutive nights. A preliminary and conservative dose estimate for the visitor is 60 mSv whole body exposure, based on a 16-hour stay time (8 hours each night for two nights) and an estimated distance of 15.2 cm from the sources. Investigation of the event continues.

Fukushima 2011

- Loss of heat removal of shutdown reactor units and cooling ponds
- Accident was initiated by a tsunami following a huge (9.0 magnitude) „megathrust” earthquake
- NPP design deficiencies: too low protective wall against tsunami → lasting failure of heat removal → diesel generators were positioned to a low place
- NPP design benefits: effective containment
- INES scale = 7 = worst possible accident (?)

Fukushima - evaluations



United Nations Scientific Committee on the Effects of Atomic Radiation

31. Adults living in the city of Fukushima were estimated to have received, on average, an effective dose of about 4 mSv in the first year following the accident; estimated doses for 1-year-old infants were about twice as high.

SOURCES, EFFECTS AND RISKS OF IONIZING RADIATION

UNSCEAR 2013 Report

Volume I

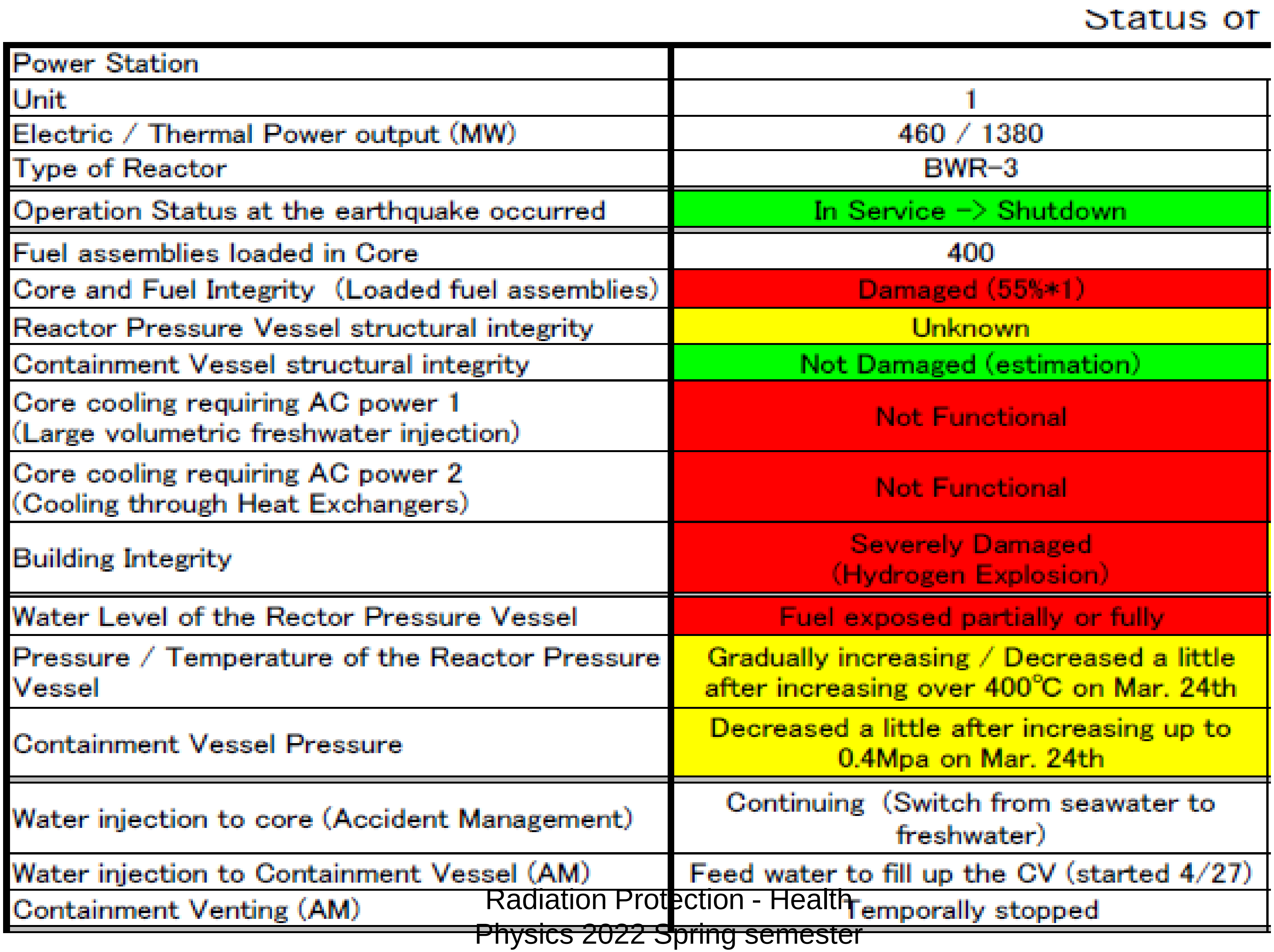
REPORT TO THE GENERAL ASSEMBLY

SCIENTIFIC ANNEX A:

Levels and effects of radiation exposure due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami

Effective dose of the most affected population in the 1st year was 4 – 8 mSv = 2 – 3 times the natural background.

Fukushima 2011.



Status of

Power Station	
Unit	1
Electric / Thermal Power output (MW)	460 / 1380
Type of Reactor	BWR-3
Operation Status at the earthquake occurred	In Service -> Shutdown
Fuel assemblies loaded in Core	400
Core and Fuel Integrity (Loaded fuel assemblies)	Damaged (55%*1)
Reactor Pressure Vessel structural integrity	Unknown
Containment Vessel structural integrity	Not Damaged (estimation)
Core cooling requiring AC power 1 (Large volumetric freshwater injection)	Not Functional
Core cooling requiring AC power 2 (Cooling through Heat Exchangers)	Not Functional
Building Integrity	Severely Damaged (Hydrogen Explosion)
Water Level of the Rector Pressure Vessel	Fuel exposed partially or fully
Pressure / Temperature of the Reactor Pressure Vessel	Gradually increasing / Decreased a little after increasing over 400℃ on Mar. 24th
Containment Vessel Pressure	Decreased a little after increasing up to 0.4Mpa on Mar. 24th
Water injection to core (Accident Management)	Continuing (Switch from seawater to freshwater)
Water injection to Containment Vessel (AM)	Feed water to fill up the CV (started 4/27)
Containment Venting (AM)	Temporally stopped