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CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

Basic aspects of radiation protection for radiological incidents

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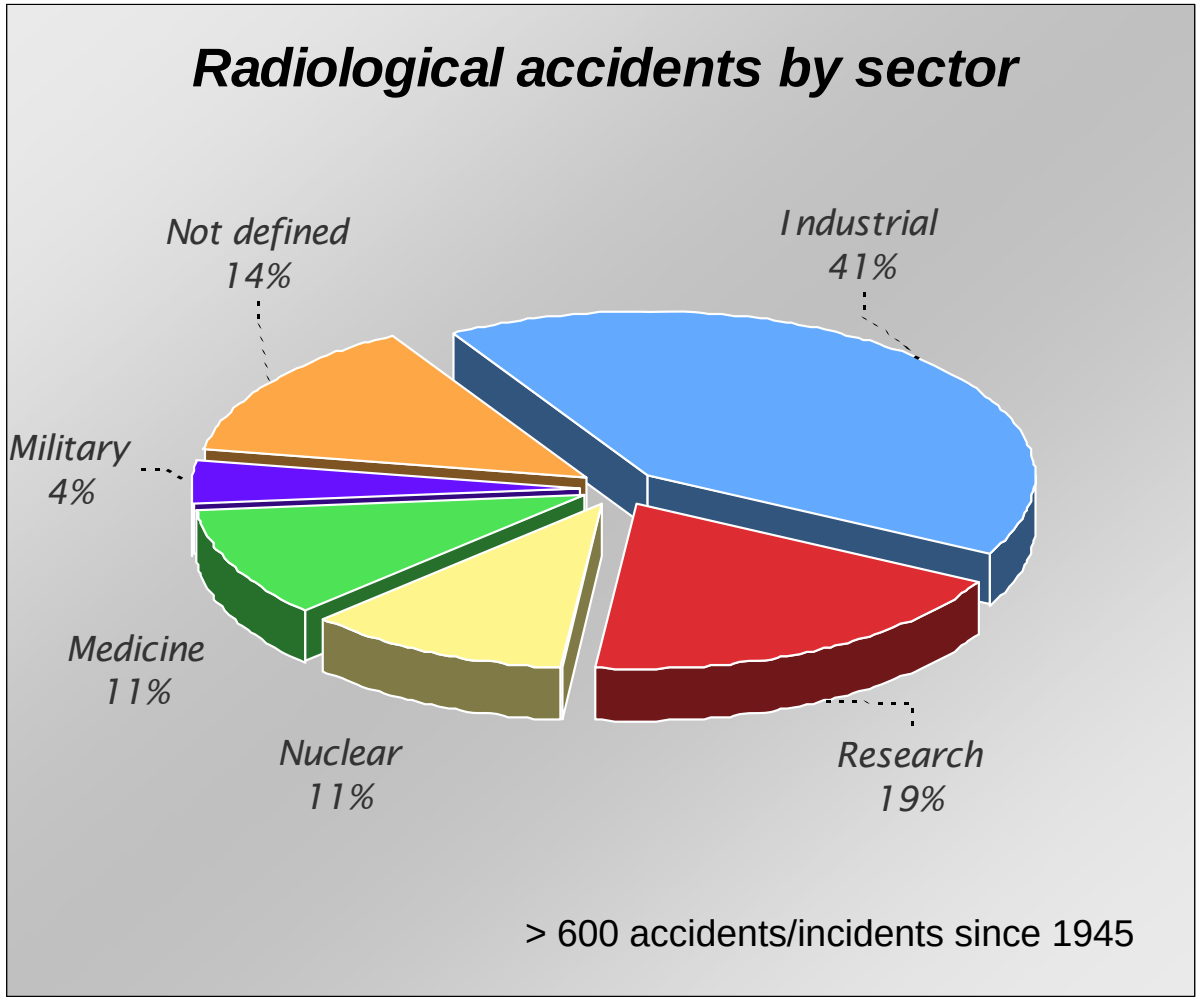
Introduction



Based on numbers from IRSN

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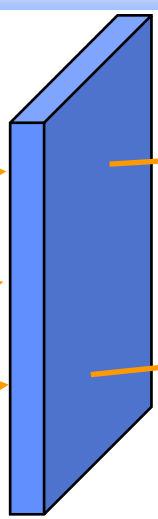
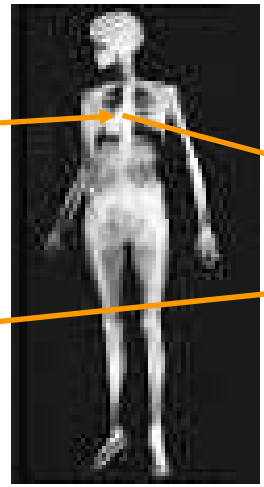
Outline of presentation





1. Sources of ionising radiation

Source characteristics

2. Interaction of ionising radiation with matter

Shielding of radiation

3. Exposure pathways & basic dose concepts

Risk associated with radiation exposure

4. Monitoring

Quantify source/dose

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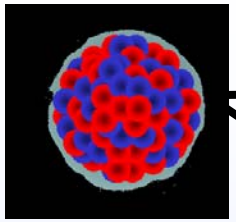
1. Sources and source characteristics

- Electrically generated ionising radiation
  - X-ray tubes
  - Accelerator beams ....
- Radioactive sources/material

  → different types of decay/radiation

	Nature	Rest Mass (MeV)	Charge (e)	Energy spectrum	Energy interval
α decay α radiation	Particles	3727.379	+ 2	Discrete	4-7 MeV
β decay β radiation	Particles positrons e^+ or electrons e^-	0.511	$\pm$1	Continuous	0–3 Mev
γ decay γ radiation	Photons	0	0	Discrete	1 keV – 10 MeV
Fission Neutrons	Particles	939.565	0	Function of source	0-10 MeV

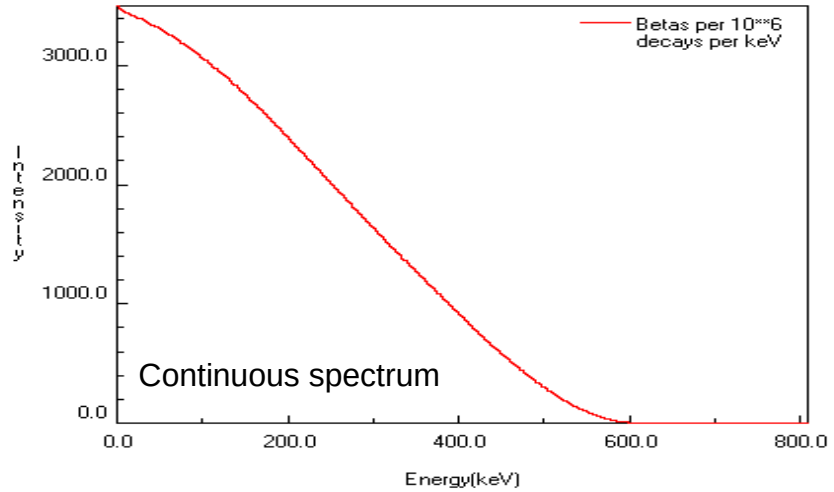
Radioactive decay: example



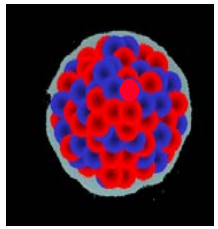
I-131

Example of the decay of I-131

Electron with energy between 0 en 800 keV



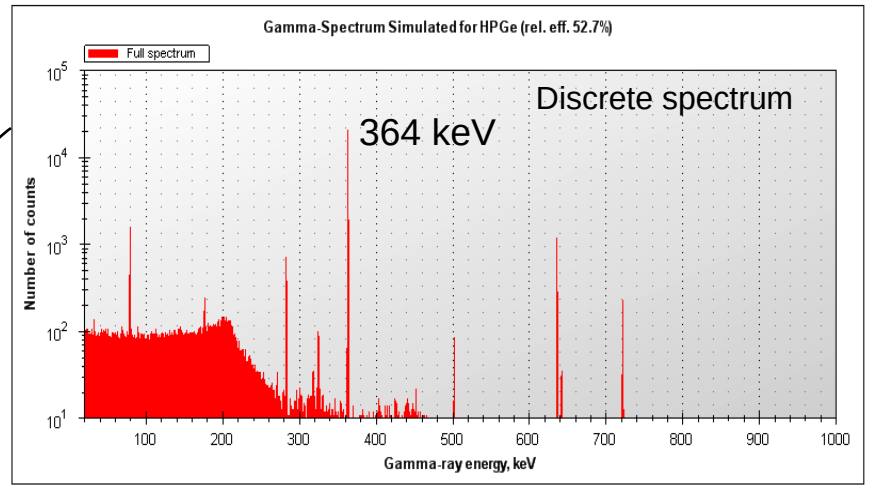
Beta decay

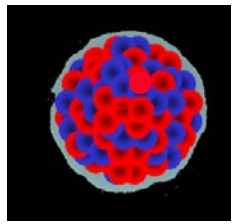


Xe-131*

gamma radiation

Gamma decay





Xe-131

$X^* \rightarrow X + \gamma$

γ no rest mass

γ no charge

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Activity

- Activity of a radioactive source
  = number of atoms that decay per unit of time
- Expressed in becquerel (Bq): 1 Bq corresponds to 1 disintegration per second
- Sources have typical an activity in kBq – PBq range

K-40 present in human body	3 kBq
I-131 for radiation treatment of the thyroid gland	2 GBq
1 million tonnes of uranium ore	10 TBq
Iodine and cesium released in the 1957 Windscale fire	720 TBq
Cs-137 released in Chernobyl reactor incident	89 PBq

Numbers taken from Radiation Protection 79. Radiation protection for emergency workers

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Specific activity

- Old unit of activity : curie (Ci)
- 1 Ci = activity of 1 g Ra-226
- 1 Ci= 3.7 10^{10} Bq
- Specific activity

  = activity in a unit quantity of the radioactive material (Bq/g)
  - Example 1: Pu-239 ($T_{1/2}$ = 2.4 10^4 y) has a specific activity of 2.3 GBq/g
  - Example 2: 2 GBq I-131 ($T_{1/2}$ = 8.02 d) correspond to 0.434 μg (stable iodine prophylaxis: 100mg for adult)
- !! Don't confuse with activity concentration !!
  - can also be expressed in Bq/kg (or Bq/m^3 for air conc.)
  - e.g. 4000 Bq/kg of Cs-137 in mushrooms

Half-life

half-life: time required to halve the amount of radioactivity

- Specific for each radionuclide (from ns to billions of years)

Example:

- Uniform deposit of **10 kBq/cm²** F-18 (**$T_{1/2}$=1.83h**)

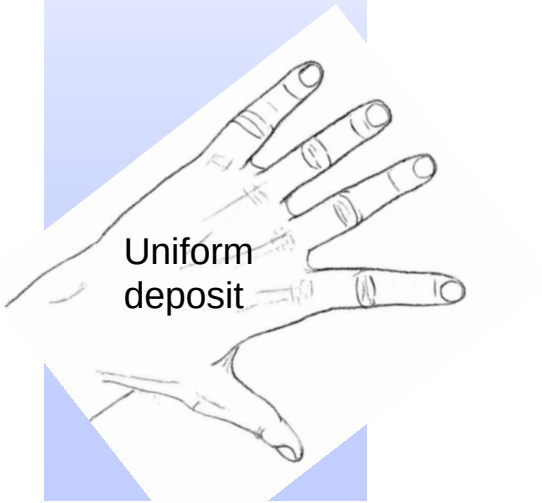
→skin dose rate of **19.5 mSv/h**

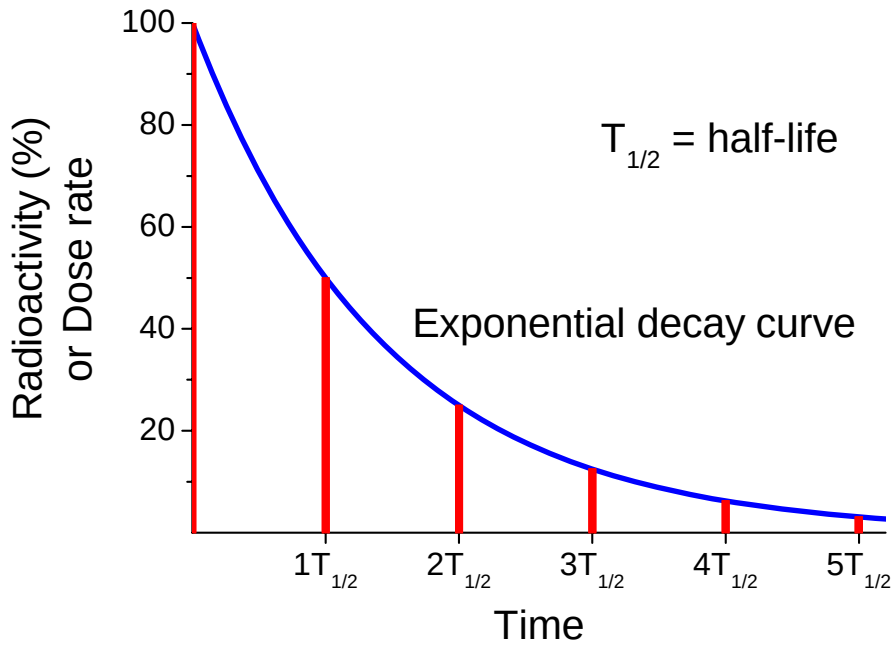
→ After 1.83 h activity reduced to 5 kBq/cm²

→ Total skin dose =19.5/λ mSv

with λ=0.379 h^{-1} for F-18:

51.5 mSv





$$A(t=T_{1/2}) = A(t=0)/2$$

$$A(t) = A(t=0)\cdot e^{-\lambda t} \quad with \quad \lambda = \frac{\ln 2}{T_{1/2}}$$

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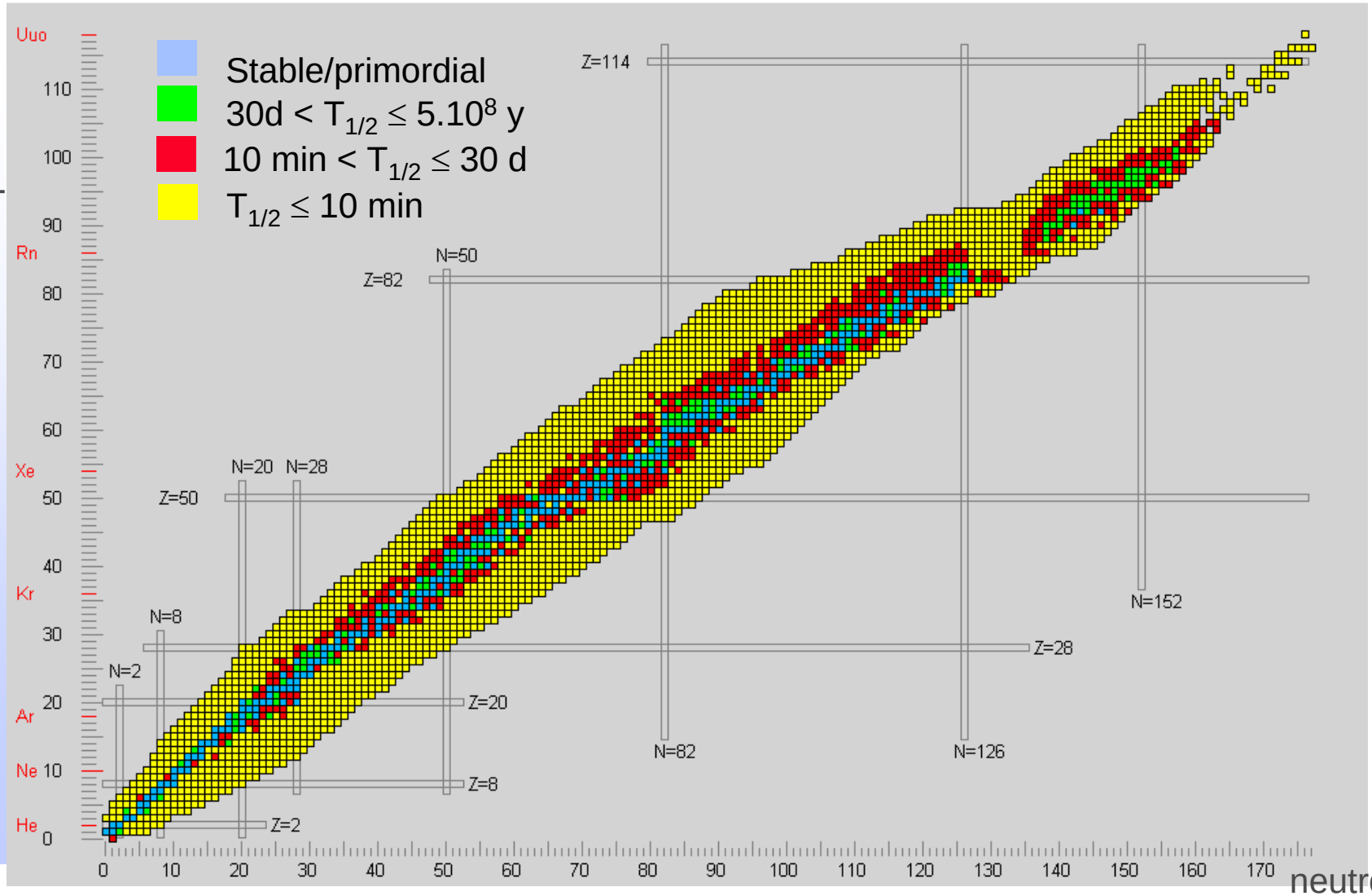
Half-life of radionuclides



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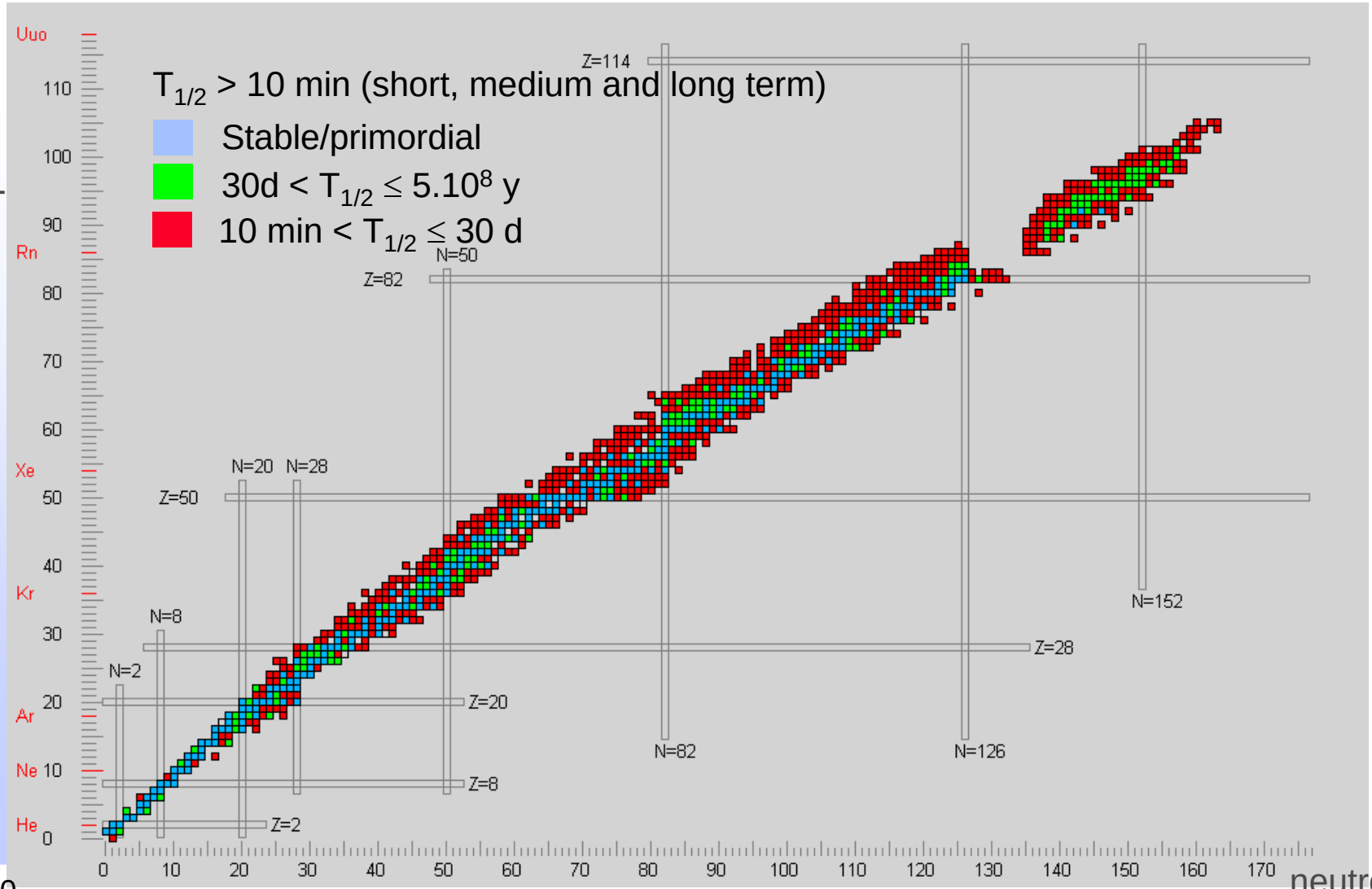
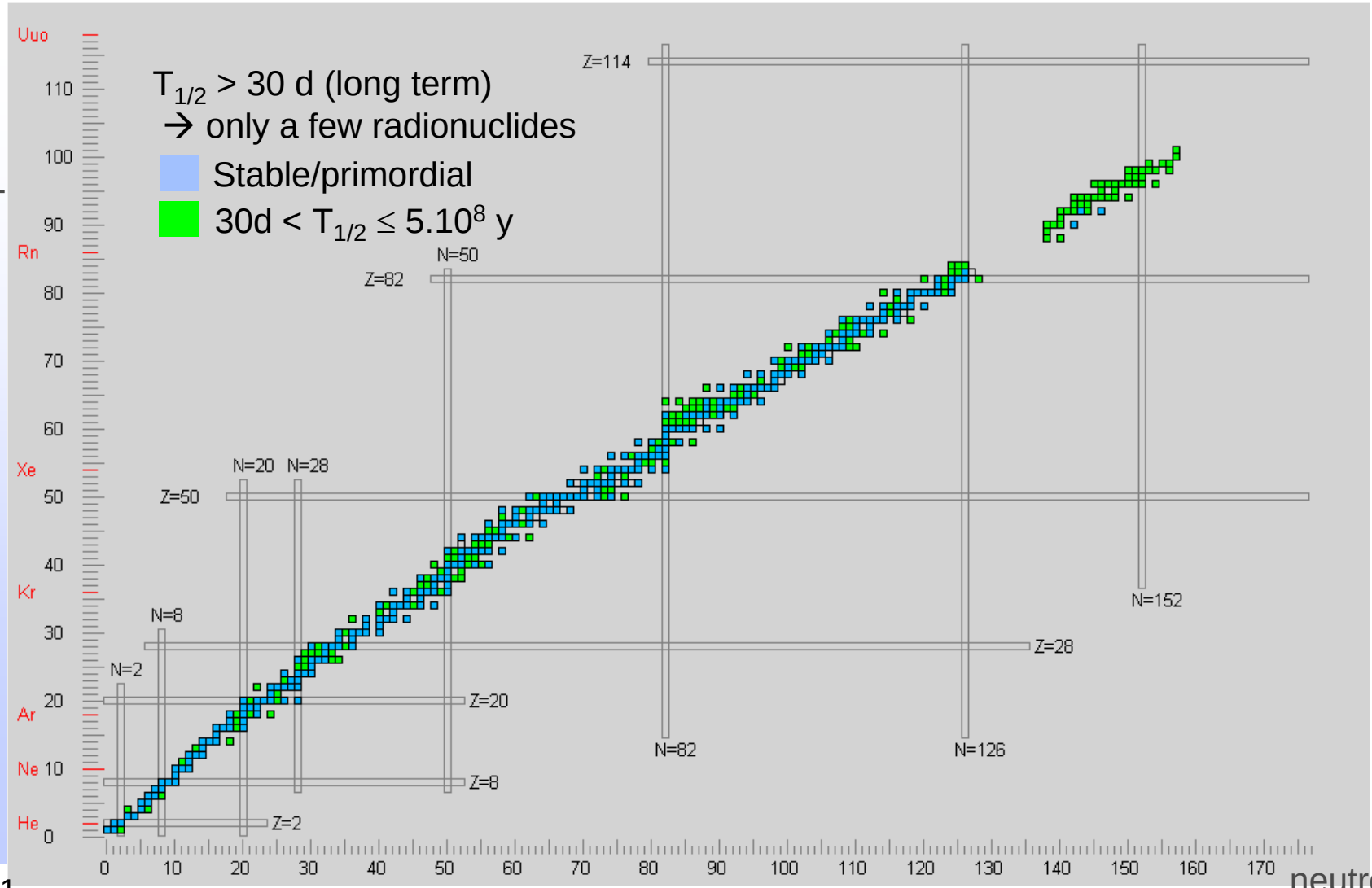


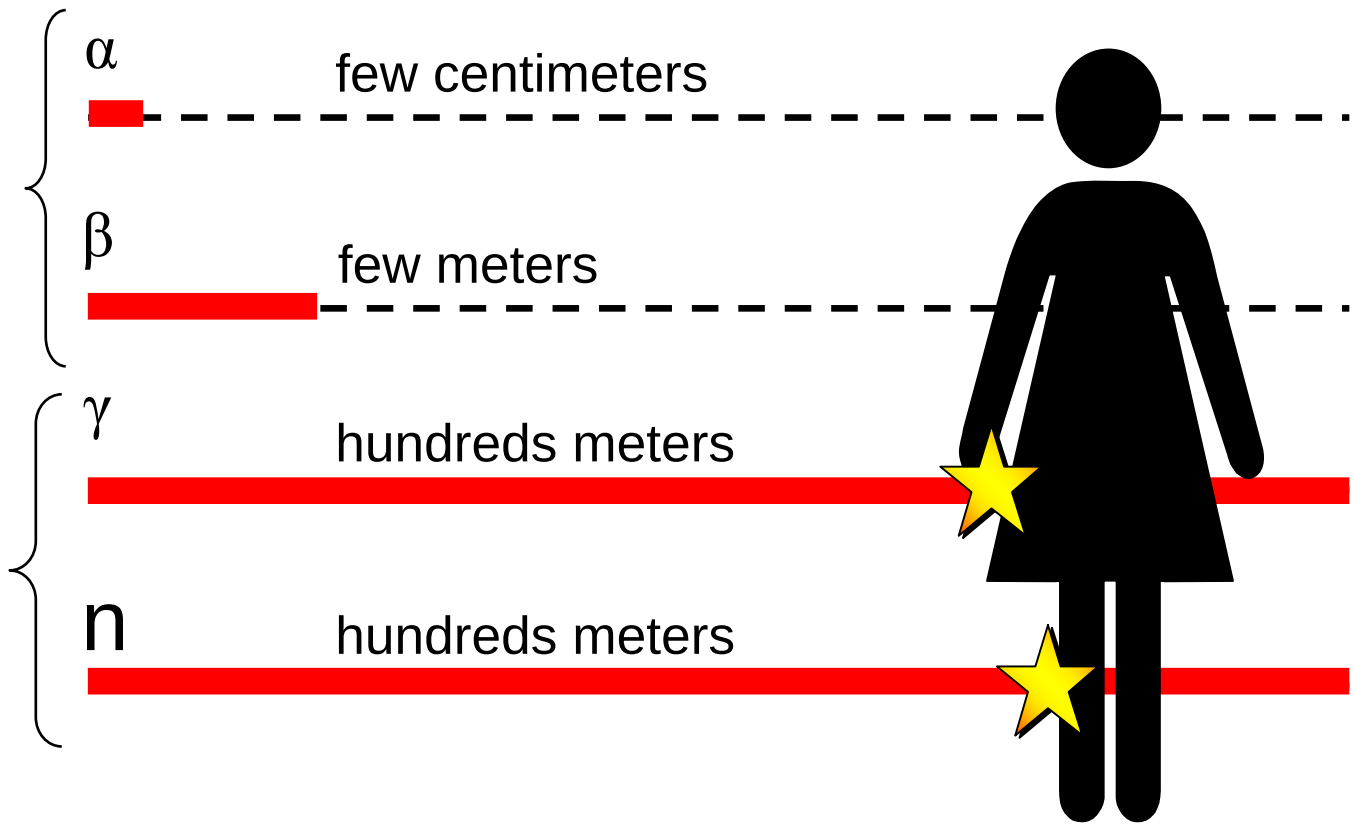
Half-life of radionuclides



2. Interaction and shielding of radiation

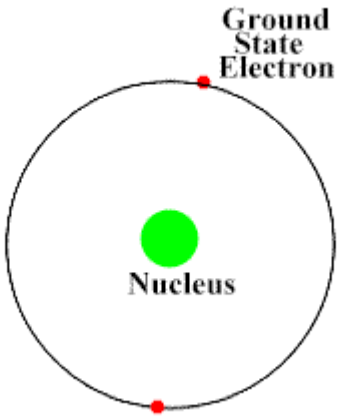
Direct interactions (charged particles)

Indirect interactions (uncharged particles)



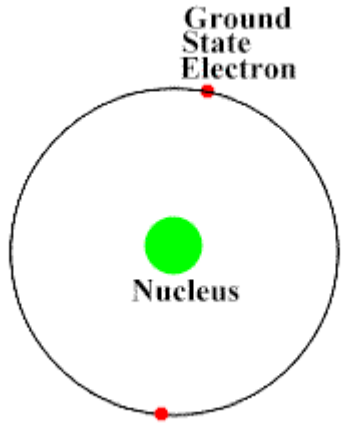
Kind of interactions (direct interactions)

Ionisations
Energy > ionisation energy
(typical few tens eV)



→ions
→free electrons which can interact again with atoms

Excitations



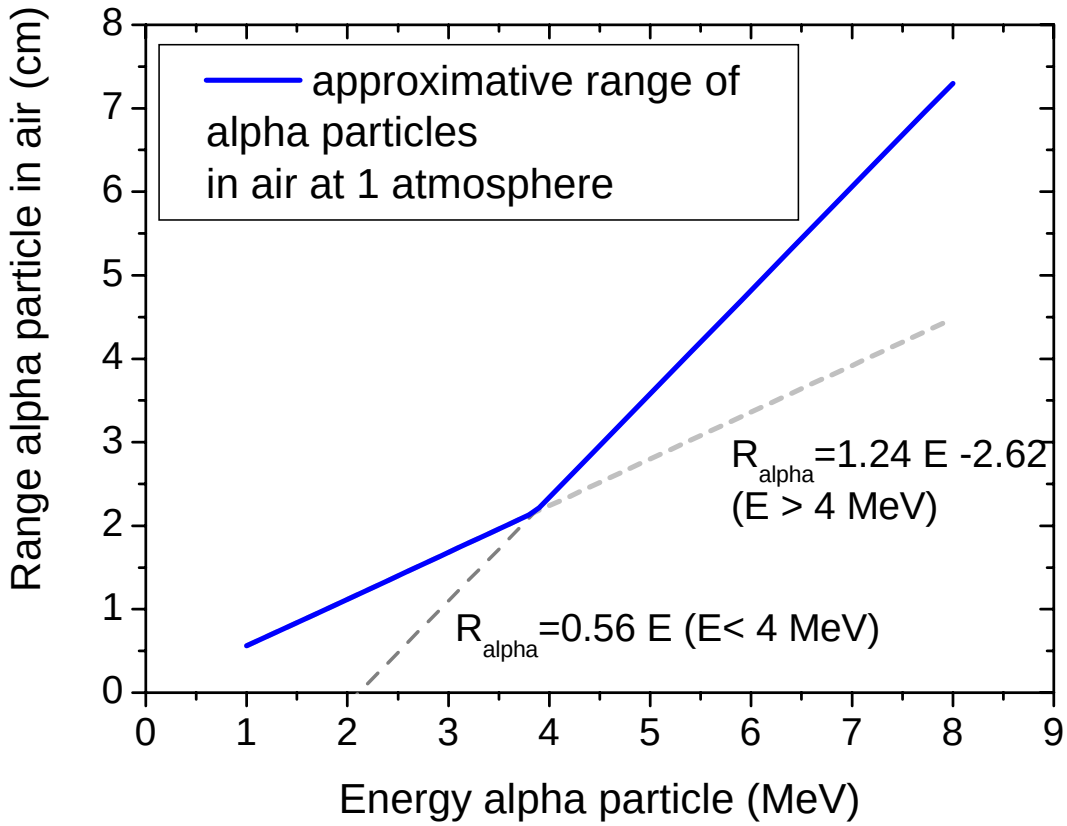
→Excitation state
→photons
→Heat production (e.g. Radioisotope thermoelectric generators)
→0.142 W/g Sr-90 (β^-)
→0.567 W/g Pu-238 (α)

Interaction of alfa particles

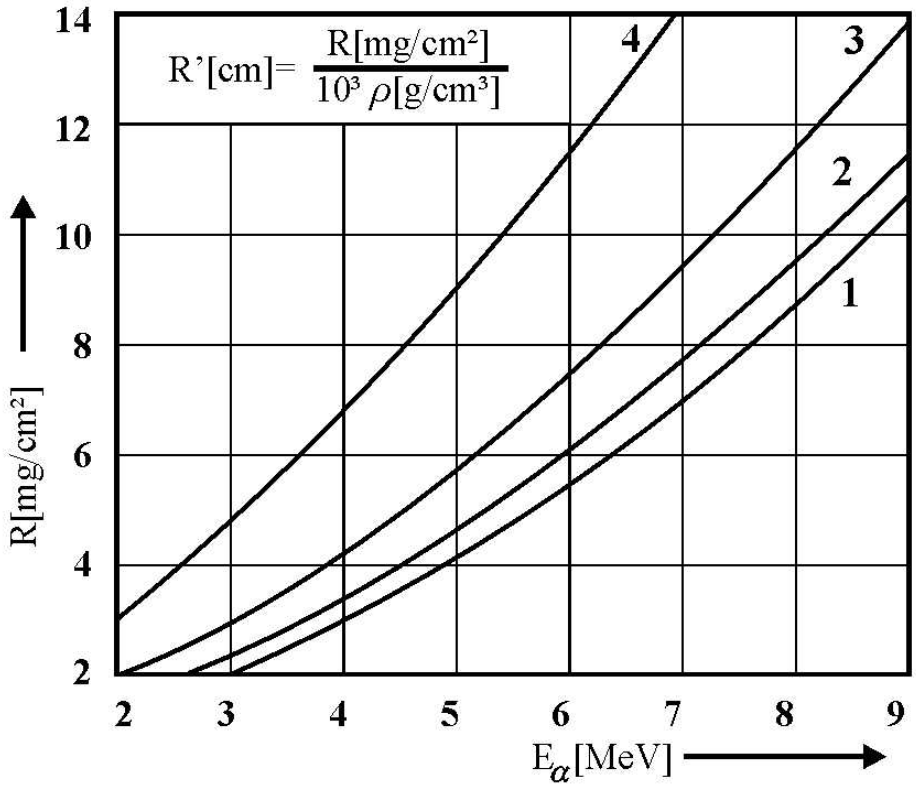
- Range of a few cm in air
- Range of up to 50 μm in tissue
- Do not penetrate outer layer of skin (epidermis) if energy < 7.5 MeV

→ Radiation effects from external source or external contamination limited

→ Danger comes from internal contamination (e.g. by ingestion, inhalation, wounds, …)



Example



Range of α-particles in	:	1 Air	2 Tissue	3 Al	4 Cu
ρ[g/cm³]		0,0013	~ 1,0	2,70	8,96

Pu-239
En = 5,14 MeV

R_{air} = 4.5 mg/cm²
R_{tiss} = 5.2 mg/cm²
R_{Al} = 6.5 mg/cm²
R_{Cu} = 10 mg/cm²

R'_{air} = 34.6 mm
R'_{tiss} = 0.05 mm
R'_{Al} = 0.02 mm
R'_{Cu} = 0.01 mm

Stopping power, range alpha particles: NIST database **astar**

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Interaction of beta particles

- Range of meters in air
- Range of several mm in tissue
- Penetrate the skin and can cause skin burns

→ External β source can be easily shielded (attention for Bremsstrahlung)

→ External contamination can cause high skin dose (>70kEV-> penetration epidermis)

→ Important danger from internal contamination

Remark:

→ interaction of positrons similar as electrons

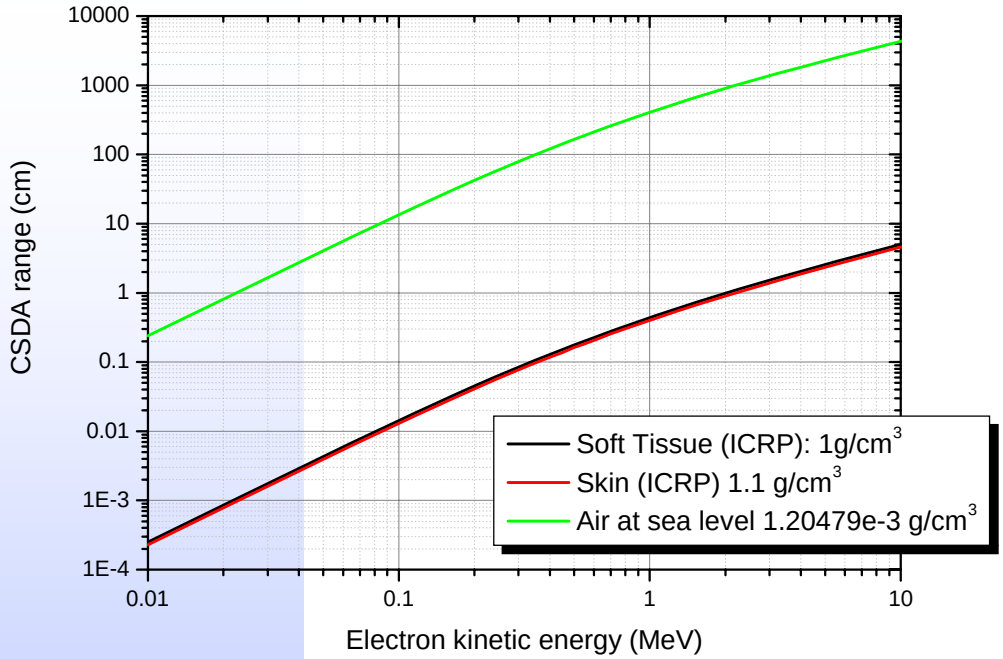
→ after stopping down of positrons: annihilation with electron: 2 annihilation photons of 511 keV

Range of 1 MeV electrons

Material	Range (cm)
air	380
water	0.43
Al	0.56
Plexiglas	0.45
Pb	0.065

Example Range - Bremsstrahlung

Example range electrons



Stopping power, range of electrons in different materials can be found in NIST database **estar**

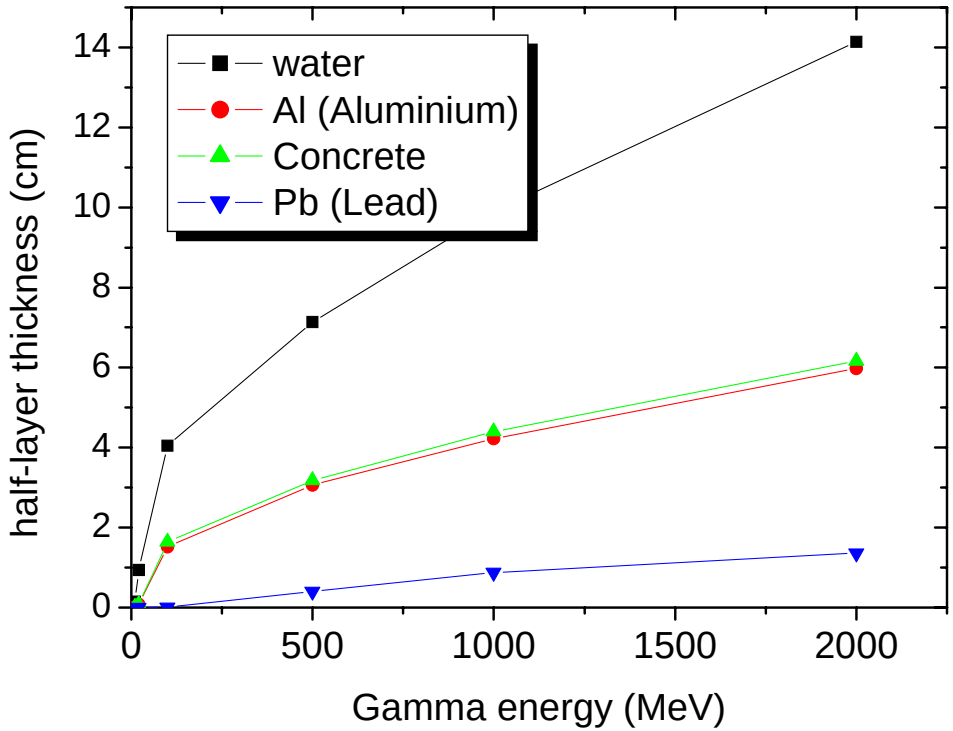
- Bremsstrahlung:
  - Energy loss:

$$-\frac{dE}{dx} \propto \frac{EZ^2}{m_e^2}$$

  - Strongly Z dependent
  - Use low-Z material to shield strong electron sources

Interaction of gamma's

- Indirect interactions via specific processes
  - photo-electric effect (low energy gammas)
  - Compton effect (medium energy gammas
  - Pair production (E > 1022 keV)
- Interaction produces electrons and secondary photons (stray radiation, …)
- Depending on energy: heavy shielding material required
- Exposure danger from external source(s)
- Can penetrate all parts of the body



- $I = I_0 \exp(-\mu x)$ with
  - x the thickness of absorber
  - μ the attenuation coefficient (depending on energy and material)

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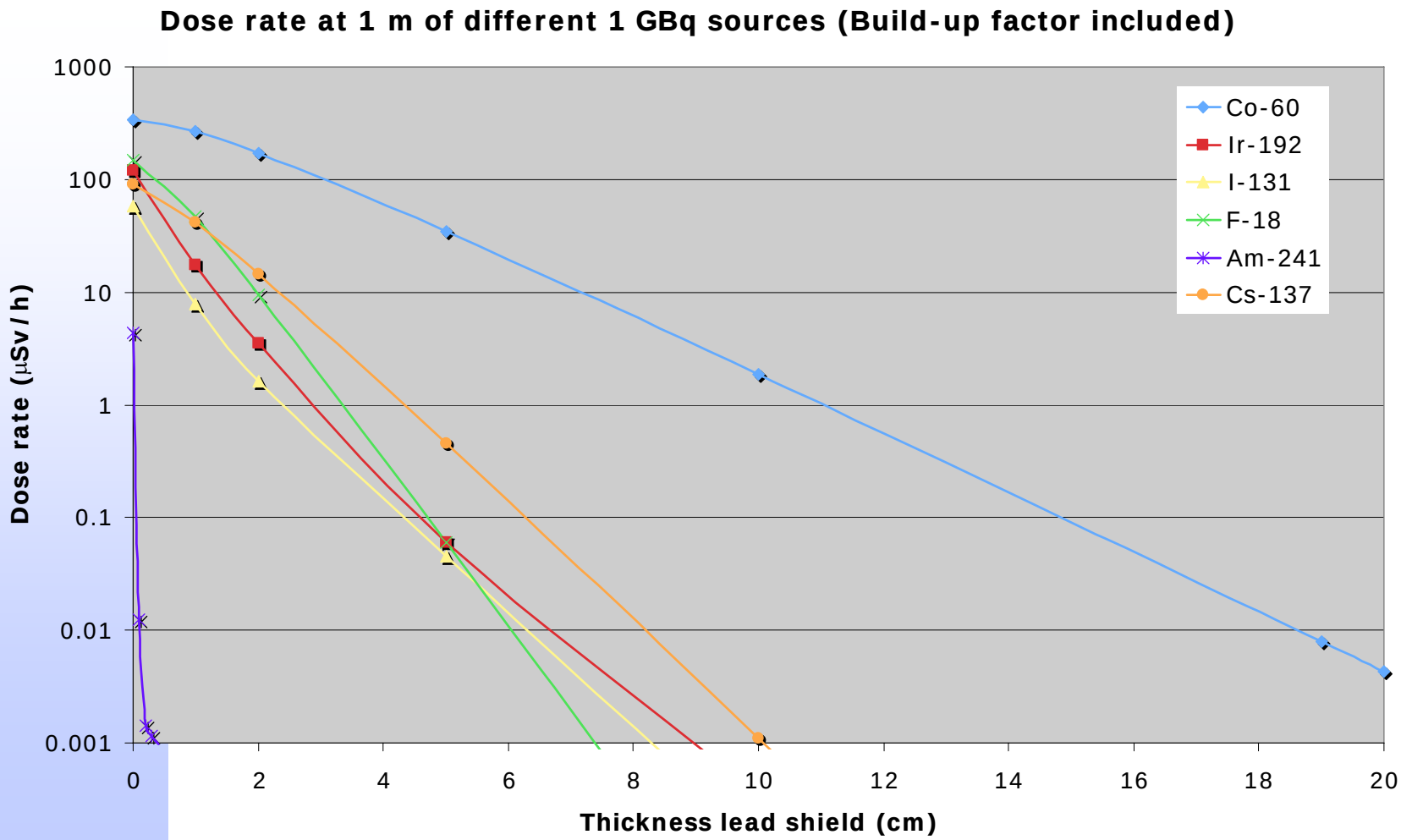
Example of effect of shielding on dose rate



3. Exposure pathways & dose concepts

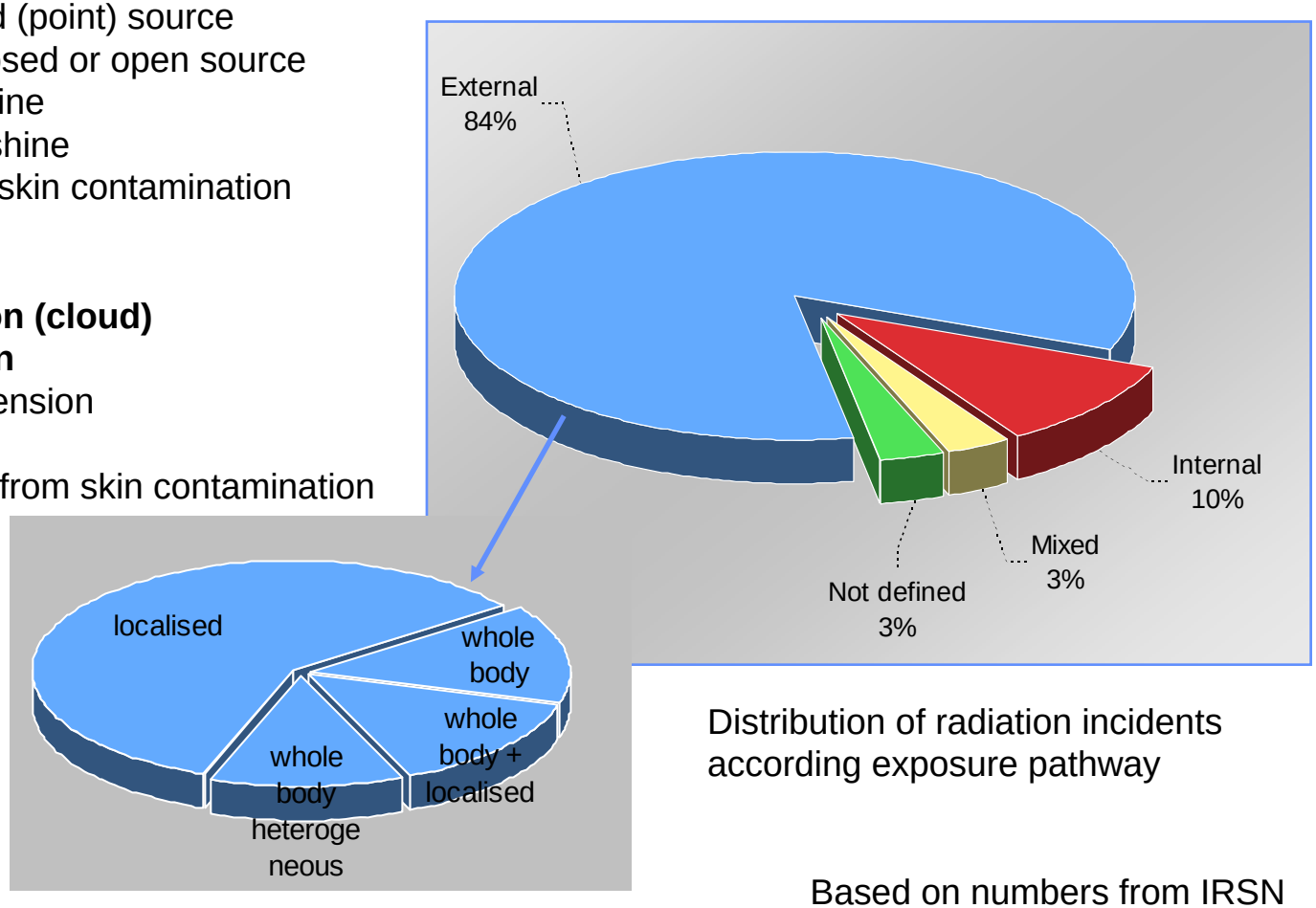
Exposure pathways:

External

- Localized (point) source
  - Closed or open source
- Cloud shine
- Ground shine
- External skin contamination

Internal

- **Inhalation (cloud)**
- **Ingestion**
- Re-suspension
- Wounds
- Transfer from skin contamination



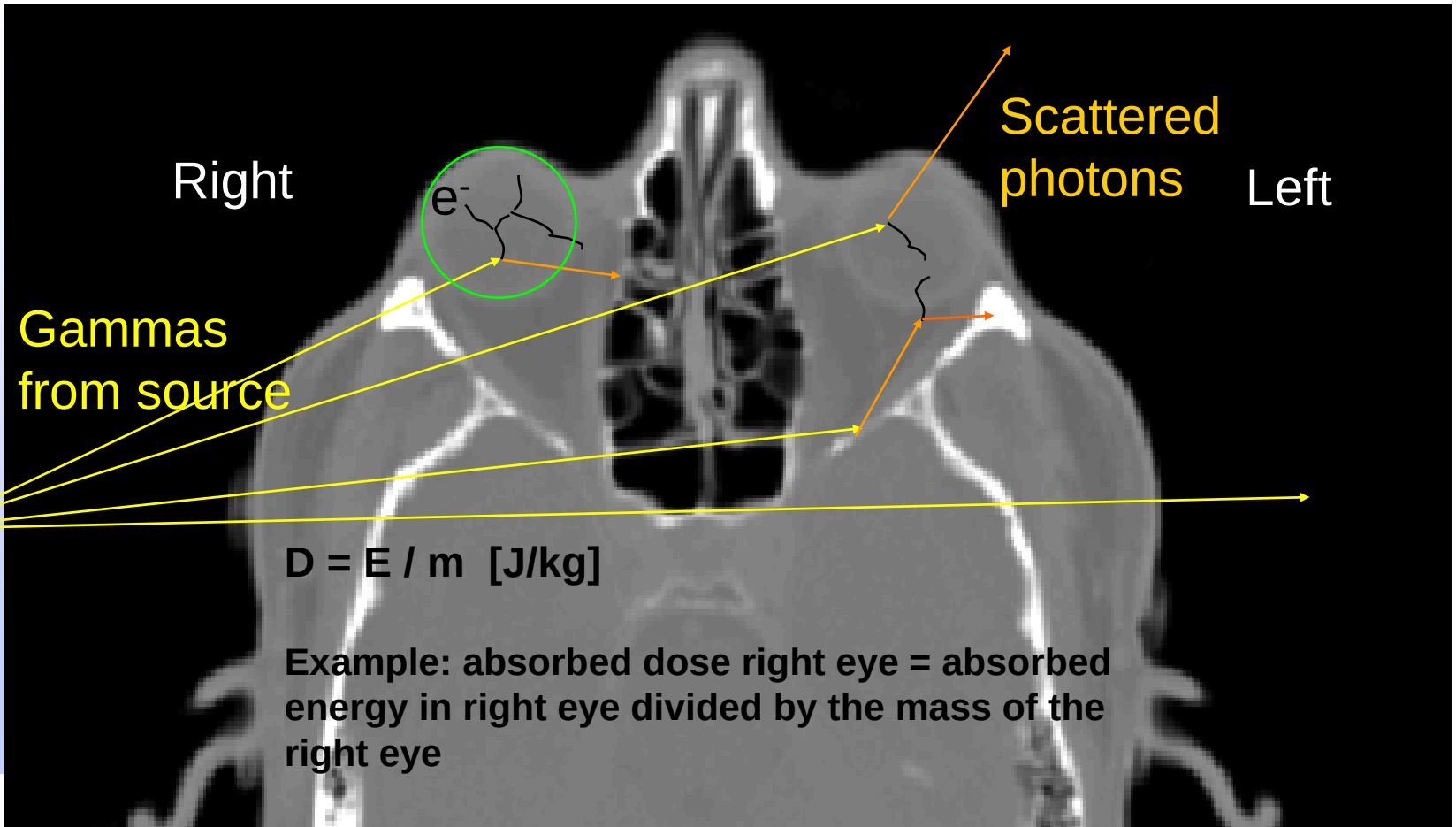
Distribution of radiation incidents according exposure pathway

Based on numbers from IRSN

Dose concepts – absorbed dose

- Absorbed dose

  = measure of energy deposited in a medium by ionising radiation



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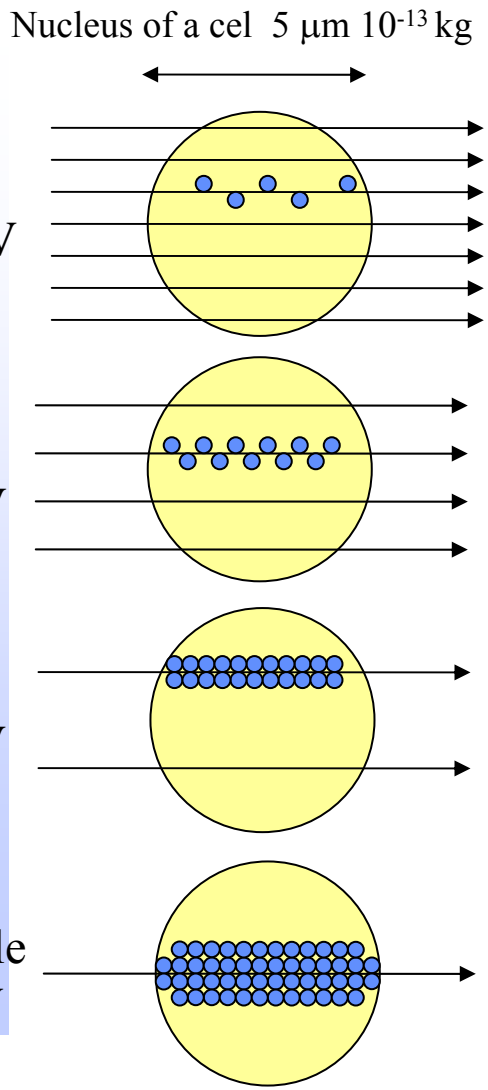
Absorbed dose

- Organ dose (example previous slide) and total absorbed dose (= energy absorbed by whole body divided by mass of body)
- Absorbed dose is not restricted to humans or animals (e.g. prevention of sprouting of potatoes by food irradiation: typical 0.1 kGy)
- Expressed in gray: 1 Gy = 1 J/kg is a big unit:
  - 4-5 Gy: lethal dose (LD50) without treatment of the person and given to the entire body in a short period
  - Illustrates the hazard of the ionisation effect of ionizing radiation: energy absorbed by an adult from a normal diet = 9600 kJ/day >>> 1 J/kg
- Absorbed dose rate (dose received per unit of time) expressed in Gy/s or mGy/h …

Influence of type and energy of radiation



	Energy loss and number of ionisations per µm and particle	**Total number of ionisations in cel**	**Absorbed dose**
670 electrons energy 1 MeV	200 eV 6 ionisaties	±20.000	1 Gy
135 electrons energy 30 keV	1 keV 30 ionisaties	±20.000	1 Gy
5 protons energy 1 MeV	27 keV 800 ionisaties	±20.000	1 Gy
1 alpha-particle energy 3 MeV	120 keV 4000 ionisaties	±20.000	1 Gy

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Equivalent dose

- Effect of radiation depends also on type and energy of radiation (not only on the absorbed dose)

  → equivalent dose

$$H = \sum_R w_R \cdot D_R$$

With w_R the weighting factor
D_R absorbed dose
} for radiation type R

Table 2. Recommended radiation weighting factors.

Radiation type	Radiation weighting factor, w_R
Photons	1
Electrons and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous function of neutron energy

Taken from the review paper, "New ICRP recommendations" by A.D. Wrixon, J. Radiol. Prot. 28 (2008) 161-168

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Equivalent dose

- Expressed in sievert: Sv (1 Sv=1J/kg)
- Examples:
  - 50 mGy absorbed dose by skin due to contamination of skin by β-emitter gives an equivalent skin dose of 50 mSv
  - 50 mGy absorbed dose by lungs due to contamination of lungs by an α-emitter gives 20 x 50 mGy = 1 Sv equivalent lung dose
- Equivalent dose rate (equivalent dose per unit of time) expressed in Sv/s or μSv/h …
  - Absorbed dose rate of 50 μGy/h from whole body irradiation by a gamma emitter due to a Cs-137 contamination of a surface gives a total equivalent dose of 8.4 mSv after 1 week.
- Measurement devices give often values in equivalent dose rates (e.g. mSv/h). Type of radiation is inherent assumed to be photons and/or electrons (w_R=1)

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Effective dose

- Sensitivity of different tissues/organs to ionising radiation can be different

  → effective dose (tissue weighting factors)

$$E = \sum_T w_T \cdot H_T$$

For estimation of stochastic effects!

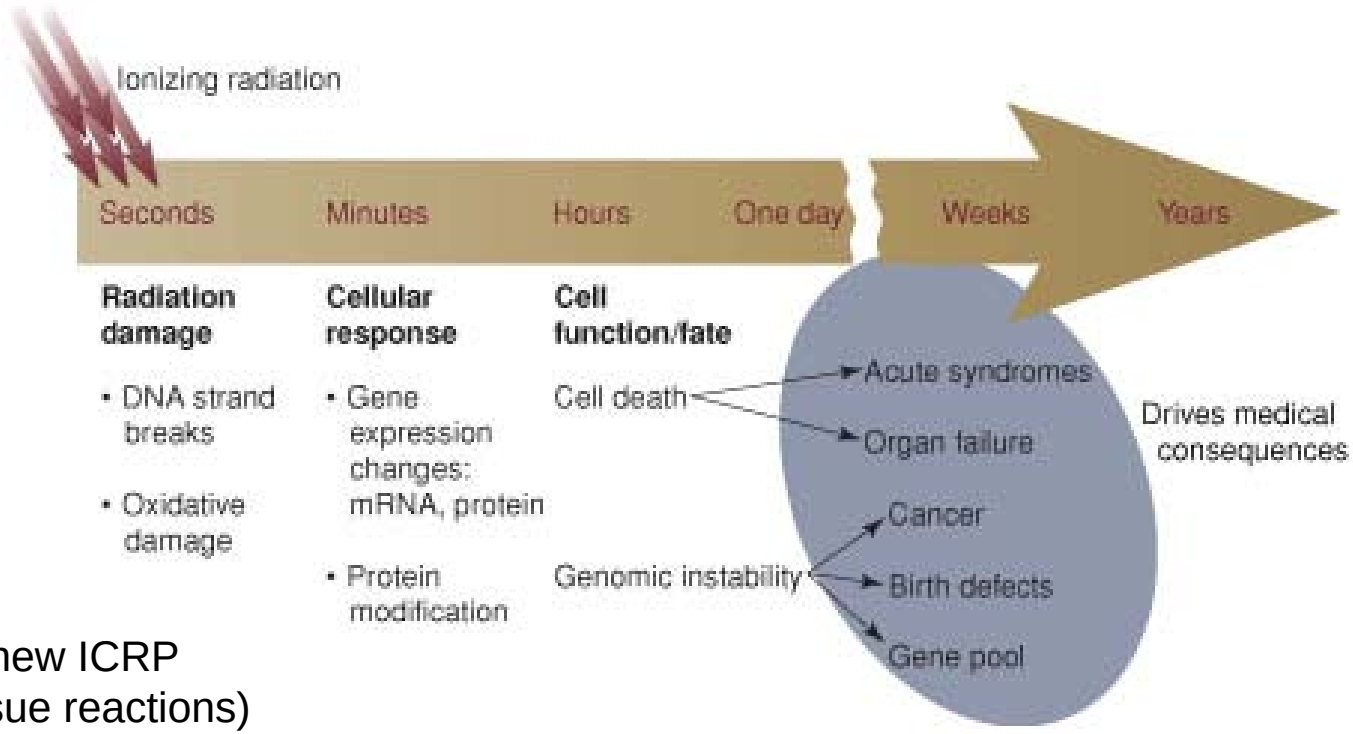
Table 3. Recommended tissue weighting factors.

Tissue	Tissue weighting factor, w_T	Sum of w_T values
Bone-marrow (red), colon, lung, stomach, breast, remainder tissues[a]	0.12	0.72
Gonads	0.08	0.08
Bladder, oesophagus, liver, thyroid	0.04	0.16
Bone surface, brain, salivary glands, skin	0.01	0.04
Total		1.00

[a] Remainder tissues: Adrenals, extrathoracic (ET) region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate (♂), small intestine, spleen, thymus, uterus/cervix (♀).

Taken from the review paper, "New ICRP recommendations" by A.D. Wrixon, J. Radiol. Prot. 28 (2008) 161-168

Biological effects of ionising radiation



- Deterministic effects (new ICRP recommendations: tissue reactions)
  - Acute syndromes
  - Organ failure

⟵ Absorbed dose (Threshold >100 mGy)

- Stochastic effects
  - Induction of cancer
  - Hereditary effects

⟵ Effective dose (no threshold)

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Effective dose and risk

- Effective dose expressed in Sv, mSv
- Estimation of stochastic risks at low dose rate (dose-rate effectiveness factor DDREF of 2)

Table 1. Detriment-adjusted nominal risk coefficients for stochastic effects after exposure to radiation at low dose rate (10^{-2} Sv^{-1}).

Exposed population	Cancer		Heritable effects		Total detriment	
	2007	1990	2007	1990	2007	1990
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

age, …

→ Detriment from stochastic effects around 5 % /Sv for low dose rates (e.g. by the continuous radiation by internal contamination)

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Collective dose

- Collective dose
  = total of all individual doses received by a group of people

- Special unit: mansievert (manSv) or personsievert
  - 1 manSv= 1000 people receiving 1 mSv
    or 100 people receiving 10 mSv …

- Example Risk: if a population of 20 000 affected by a radiological emergency receives 100 manSv this means that 100x0.057 (see table)=5.7 people will develop a stochastic effect

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Summary dose concepts

Basic physical dose	Absorbed dose → Tissue reactions	gray (Gy)
Biological effect of type of radiation and energy	Equivalent dose → Measurement devices	sievert (Sv)
Sensitivity of different tissues/organs	Effective dose → Stochastic effects (cancer, ..)	sievert (Sv)
Additional factors: e.g. dose rate	Risk	Sv^{-1}
Exposure of population	Collective dose	mansievert (manSv) personsievert

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Examples

- Effective dose from dental X-ray = 0.01 mSv
- Effective dose from flight of +/- 5000 km = 0.02 mSv (from cosmic radiation)
- Effective dose from living one month on a Cs-137 contaminated surface of 1 MBq/m^2 (only external radiation, no inhalation, no ingestion) = 1 mSv
- Annually effective dose from all sources of natural radiation = 2.5 mSv (average for world population)
- Skin dose from 2 hours uniform skin contamination of 1 kBq/cm^2 Sr-90: 2hx1.8 mSv/h= 3.6 mSv
- Effective dose from a 1 TBq Co-60 point source at 1 m distance for 6 minutes = 40 mSv
- Effective dose from living 50 years on a Cs-137 contaminated surface of 1 MBq/m^2 (only external radiation, no inhalation, no ingestion) = 130 mSv
- Temporal decrease of lymphocytes = 100mGy absorbed dose
- Lethal dose (LD50): 4,5 Gy (absorbed dose)

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Relation between source activity and dose

- Relation between source strength or activity and dose depends on:
  - Radionuclide and type of radiation
  - Geometry (point source, contaminated surface, volume source, …)
  - Shielding
  - Exposure pathway
    - Only external irradiation by e.g. point source, cloud or ground shine
    - Skin contamination
    - Internal contamination (chemical form, particle size, …)

    → different dose conversion factors (radionuclide specific, way of exposure, age, …)

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Example

- Co-60 (0.1 MBq) – $T_{1/2}$ = 5.27y
  - 30 cm from point source of 0.1 MBq
    - Skin dose from electrons: 1.26 μSv/h
    - Equivalent dose from gammas: 0.386 μSv/h ($1/r^2$ law)
  - Droplet on hand of 0.1 MBq
    - Skin dose 22.2 mSv/h
  - Contaminated floor of laboratory (0.1 MBq/m^2)
    - Dose rate at 1m (only photons) 1 μSv/h
  - Inhalation of 0.1 MBq by adult
    - Effective dose conversion factor 1.7E-8 Sv/Bq_{intake} (AMAD of 5μm)
    - (Committed) Effective dose of 1.7 mSv

4. Monitoring of radiation

Two groups (methods/instruments)

Two groups (application):

Characterization of source

Assessment of individual dose

Dose related measurements

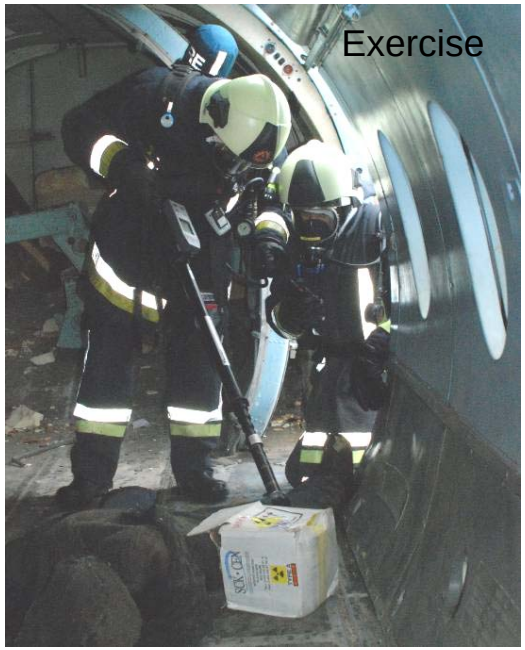
- Devices calibrated to give dose parameters (absorbed dose, equivalent dose)
- Dose rate meters
- Personal dose meters (Film/TLD/…)
- But also biodosimetry, retrospective dosimetry

Activity related measurements

- Devices calibrated to give activity (e.g. NaI, HPGe)
- Deposited activity (e.g. ground contamination, skin contamination)
- Activity concentrations (e.g. air, water, soil, food samples, human body)
- Direct measurement or laboratory measurements on samples

Remark: some instruments are calibrated for dose and activity measurements

Dose/dose rate meters



Mainly for gamma/neutron radiation

- Personal dose meters
  - Passive (Film/TLD badges)
  - Electronic devices (dose and dose rate, alarm level)
- Portable dose rate meters
- Survey of laboratory/environment

Remarks:

- Not nuclide specific
- No direct relation with health impact (e.g. dose in rate in cloud can be limited)
- Specific dose (rate) and energy range (cf. Goiana incident)

Contamination monitors

Typical example

Isotoop	Efficientie van 2π
Am-241	40% (α)
Co-60	17% (β)
Sr/Y-90	56% (β)

- Alpha & Beta contaminations:
- Measurement in counts/second (cps)
- Not nuclide specific
- Example:
  - Scintillation counter on the left
  - Surface 125 cm^2
  - γ-response (Cs-137)

    ~60 cps/μSv/h
  - Contamination of 50 kBq/m^2 I-131 → ~ 100 cps (β eff. 30% van 2π). Background: 5-10 cps
  - Dose rate at 1 m: 70 nSv/h (Background 50-100 nSv/h)

Interpretation - example

- Radiological incident
  - Wounded and contaminated people
  - Measurement team checks radioactive contamination of victims who don’t require direct medical care

Photo from exercis

Interpretation – example (2)

Highly?
5000 cps x ε x Ω /S_{probe}
= 125 Bq/cm^2
→ x DCF= skin dose of 0.2 mSv/h

People are clearly highly contaminated, what are the health consequences for these people?

Our measurement team confirms that the people are contaminated, we will advice decontamination measures ….

Photo from exercise

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Plume survey with contamination monitor

Measurement at 1 m		Measurement at ground level	Interpretation
$\beta+\gamma \approx \gamma$	AND	$\beta+\gamma \approx \gamma$	Plume above you
$\beta+\gamma > \gamma$	AND	$\beta+\gamma > \gamma$	Plume at ground level
$\beta+\gamma \approx \gamma$	AND	$\beta+\gamma > \gamma$	No plume, only contamination

Based on IAEA-TECDOC-1092. Generic procedures for monitoring in a nuclear or radiological emergency.

Instrumentation for identification

- Sampling and measurement in laboratory/measurement van SCK•CEN
- Portable devices for identification of radionuclides:
  - Gamma- energy sensitive probe (NaI, electrically cooled Ge, …)
  - Identification soft-ware
- Characterisation of large area contaminations:
  - AGS (Aerial gamma spectrometer system, 4x4 l NaI coupled to GPS) equipment of Ministry of Interior Affairs at IRE and SCK•CEN

Anthropogammametry

Calibration of whole body counter

Preparation of thyroid measurement during I-131 measurement campaign Fleurus incident

Direct (in-vivo) measurement of enhanced levels of radioactivity in body (after incident)

Laboratory at SCK•CEN:

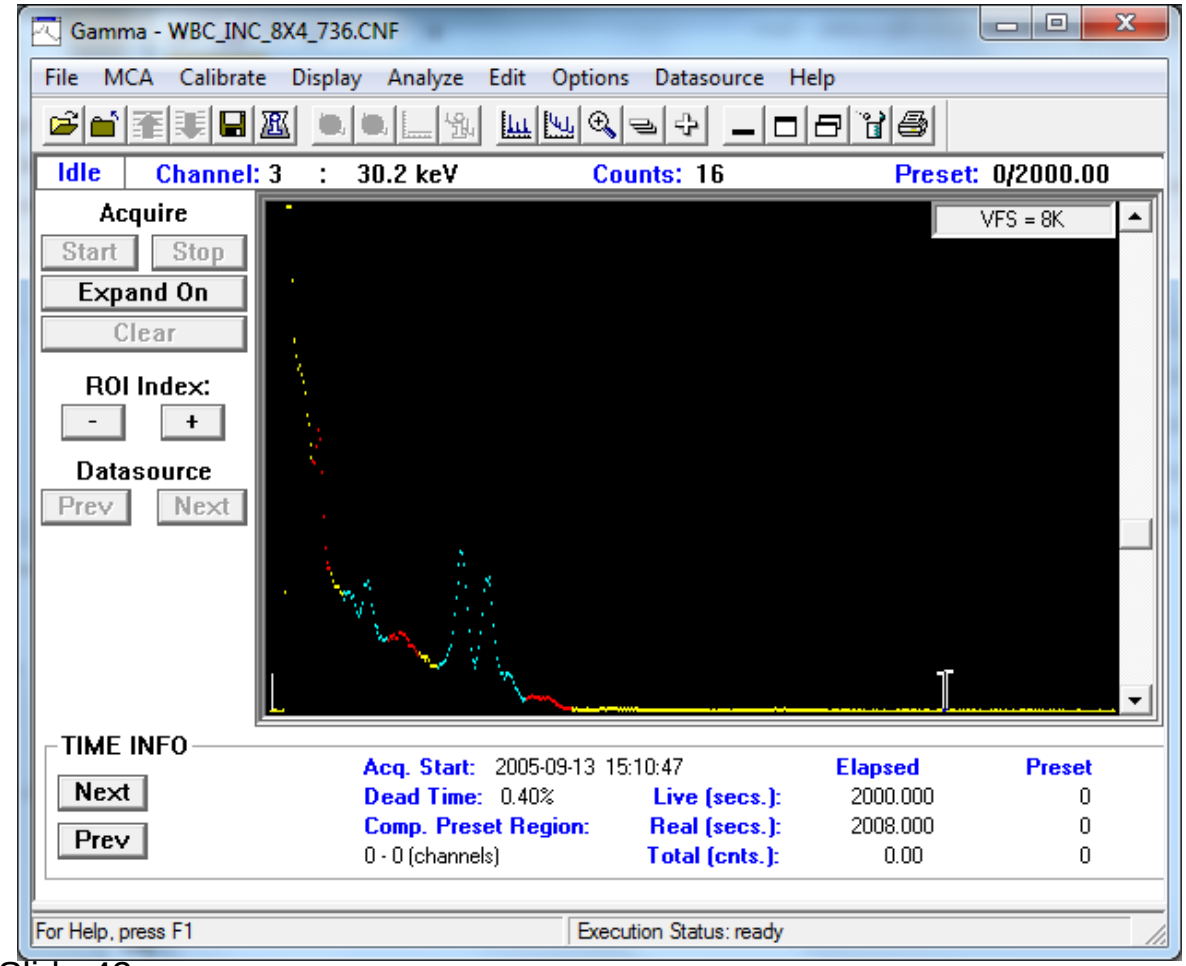
- Whole body counting (8”-12” NaI)
  - → 25 Bq for e.g. Co-60, Cs-137 (30’)
- Lung counting (low energy HPGe)
  - → 8 Bq Am-241 (50’)
- Wound counting (low energy HPGe)
- Thyroid counting (NaI – HPGe)
  - → 25 Bq I-131 (10-20’)
  - → <100 Bq I-131 (non-laboratory conditions - 1’)

Accreditation BELAC

Contact: Anne-Laure Lebacq - Filip Vanhavere

Example whole body

Contamination incident BR2 (2005)



Measured retention:

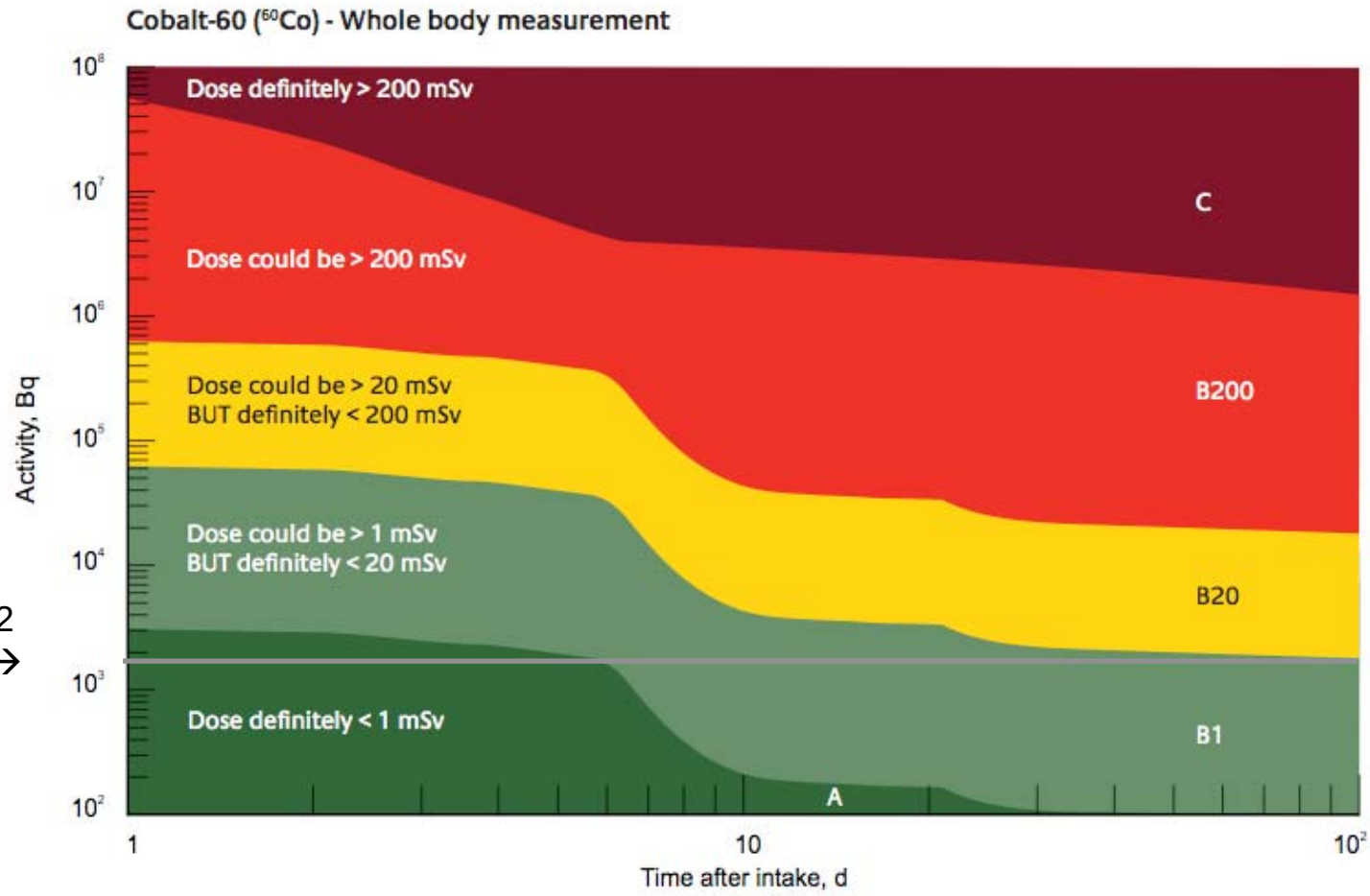
Co-60	1869±36	Bq
Cr-51	4060±200	Bq
K-40	3450±150	Bq
Mn-54	201±18	Bq
Sb-124	308±12	Bq

Effective dose coefficient

- for inhalation
- integration time 50 years (committed effective dose)
- AMAD of 5 µm

Co-60	1.7e-008	Sv/Bq_{intake}
Cr-51	3.6e-011	Sv/Bq_{intake}

Relation with time (of measurement) after intake



Example BR2 incident →

From “Dose Assessment of Inhaled Radionuclides in Emergency Situations”, Health Protection Agency, August 2007

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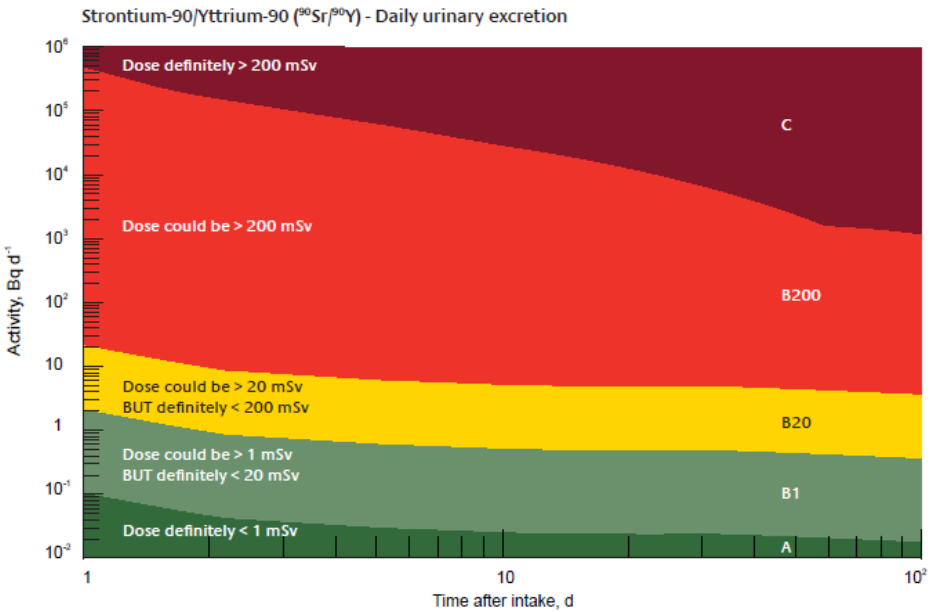
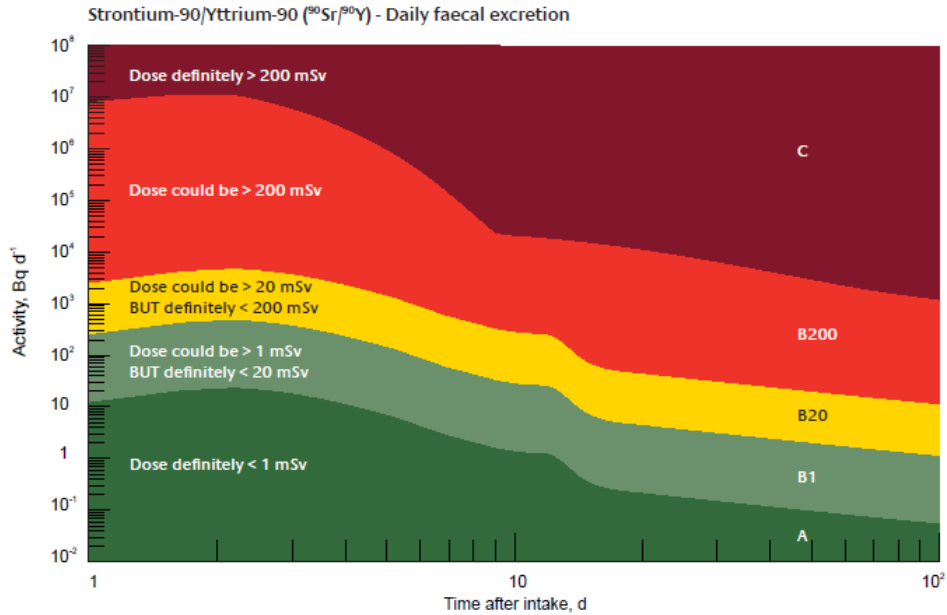
Collection of samples

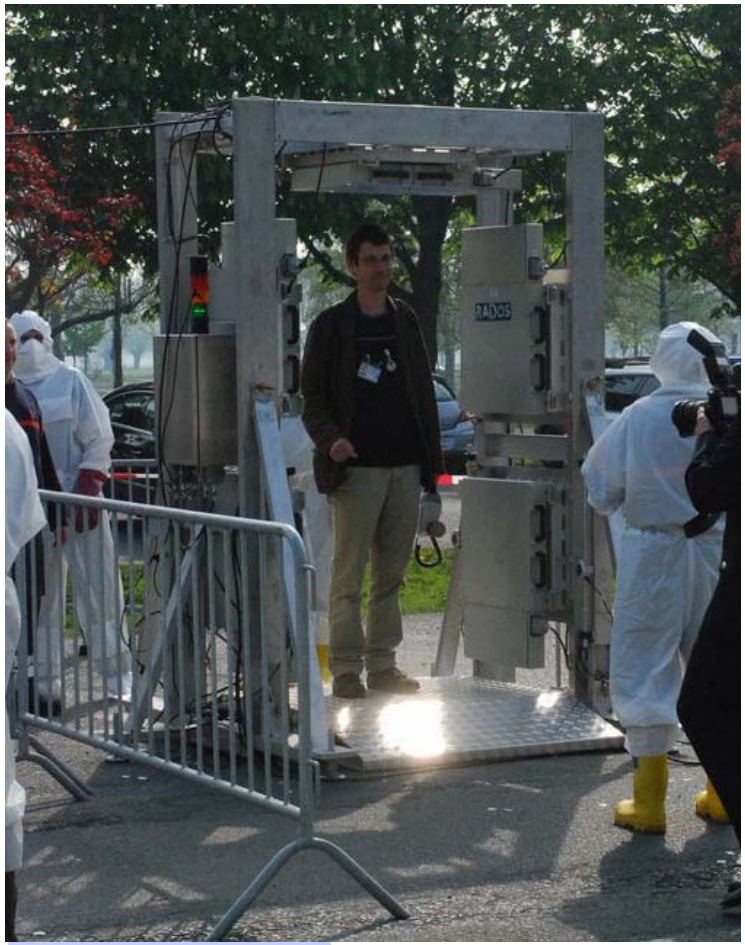
- Daily urinary excretion
- Daily faecal excretion
- Nasal swab
- …





From "Dose Assessment of Inhaled Radionuclides in Emergency Situations", Health Protection Agency, August 2007

Triage of contaminated people



Evacuation exercise (Puyenbroeck)

- Large groups of potentially contaminated people
- Fast triage with portals
- Example:
  - Portals from civil protection
  - Typical detection limits (depending on settings) of order of 10-50 kBq of typical fission products(Cs-137, I-131)
  - Typical capacity 40 persons/hour
- More localized measurement of external contamination with contamination probes

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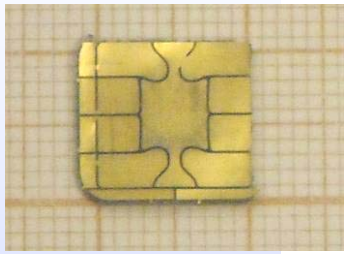
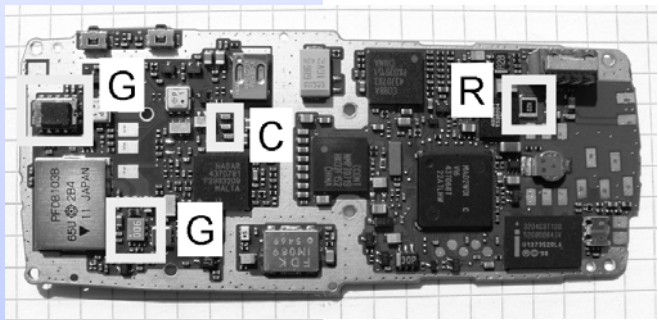
Accident dosimetry





Circuit board of a Nokia 5210 mobile phone, with useful components for OSL dosimetry

Reconstruction of received dose

- Clinical symptoms (tissue reactions)
- Biodosimetry
  - Cytogenetic biodosimetry …
  - Electron paramagnetic resonance (e.g. teeth): typical from 0.5 Gy on
- Retrospective dosimetry
  - Neutron activation (neutron dose)
  - Optically Stimulated Luminescence (OSL) dosimetry on personal objects:
    - Epoxy containing silica in e.g. chip cards (electronic identity card), cell phone components …
    - Low detection limits (3 mGy, depending on sample)
    - Fast (post calibration required) and large capacity possible
    - Limited time after exposure (days) due to fading of signal

Contact: Vanessa Cauwels – Filip Vanhavere

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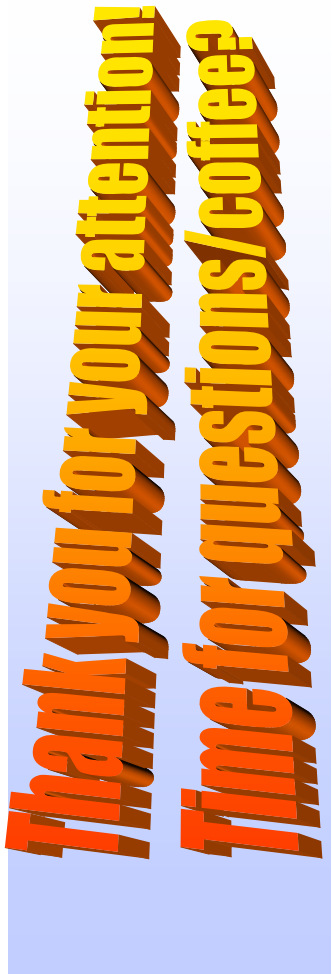
Some interesting references



- ICRP2007: “New ICRP recommendations” by A.D. Wrixon, J. Radiol. Prot. 28 (2008) 161-168
- Stopping-power and range tables for electrons and alpha particles (estar & astar)
  http://physics.nist.gov/PhysRefData/Star/Text/contents.html
- Nucleonica – web driven nuclear science (JRC-ITU)
  http://www.nucleonica.net (free login required)
- Radionuclide and radiation protection data handbook – Radiation protection dosimetry
- TMT handbook – Triage, Monitoring and Treatment of people exposed to ionising radiation following a malevolent act
  http://www.tmthandbook.org/
- isRP courses: International School for Radiological Protection

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