

Part A. Dose magnitudes

1. Definitions

2. Effects of the ionization radiation

3. Natural background

4. Rules for workers & zones



1. Definitions

Ionizing radiation

- directly ionizing: charged particles (electrons, protons, ...)
- indirectly ionizing: photons, neutrons

of the order of 10 eV required to ionise an atom (**1 eV = 1.6022 10⁻¹⁹ J**)

electromagnetic radiation:

$$E = \frac{hc}{\lambda} \Rightarrow \lambda \approx 100 \text{ nm}$$

$$E = 12.4 \text{ eV}$$

(hard ultraviolet)

$$h = 6.626 \cdot 10^{-34} \text{ J s}$$

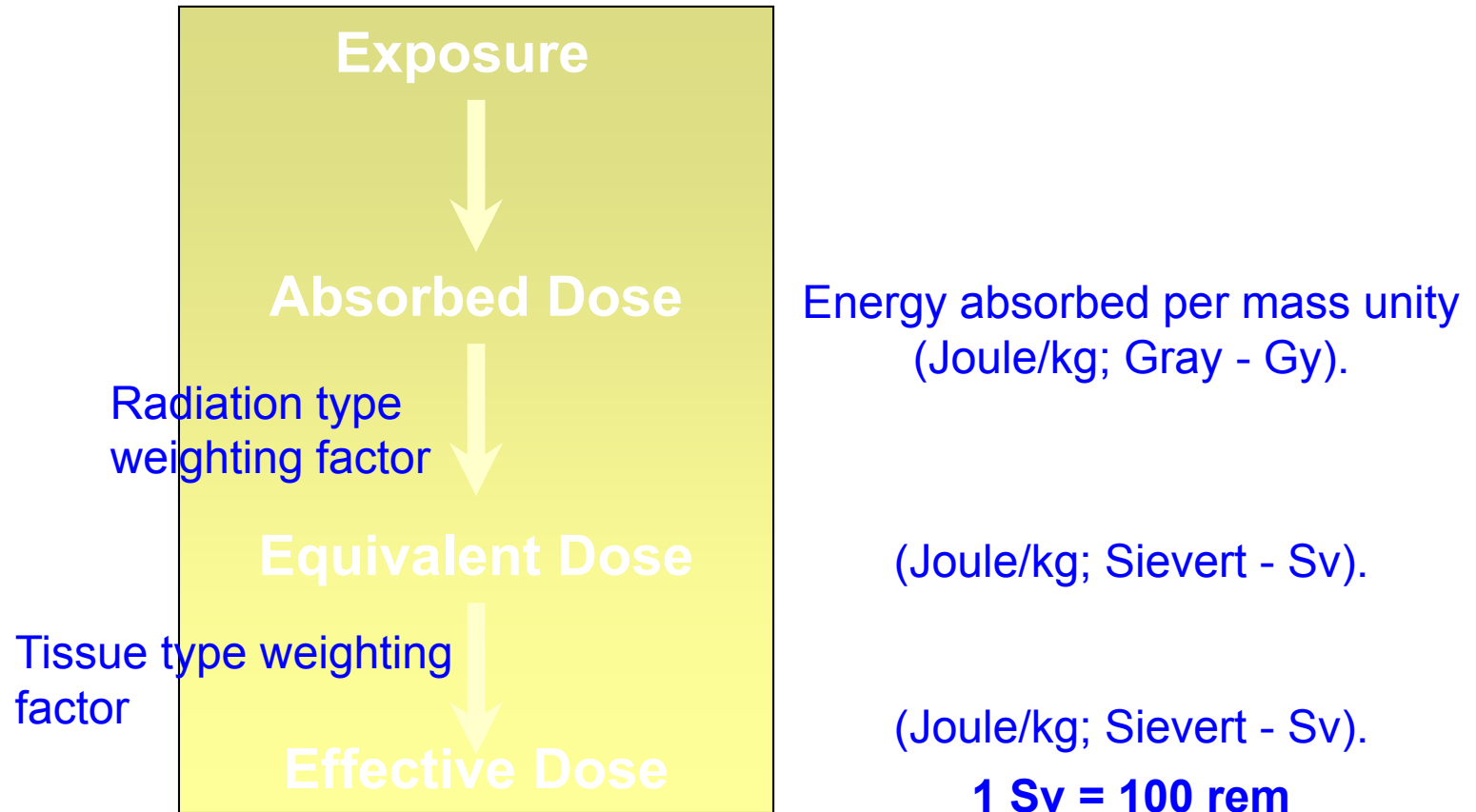
$$c = 2.998 \cdot 10^8 \text{ m s}^{-1}$$

	Ionization potential (eV)
carbon	11.260
oxygen	13.618
potassium	4.341
iron	7.870
lead	7.416



1. Definitions

Quantities and units used to quantify **stochastic effects**:



$$1 \text{ Sv} = 100 \text{ rem}$$

$$1 \text{ mSv} = 0.1 \text{ rem}$$



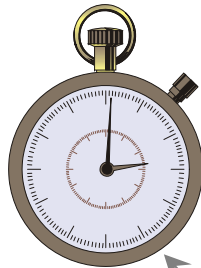
1. Definitions

$$\frac{dN}{dt} = -\lambda N(t)$$

$$N(t) = N(0)e^{-\lambda t}$$

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

$$\tau = 1/\lambda$$

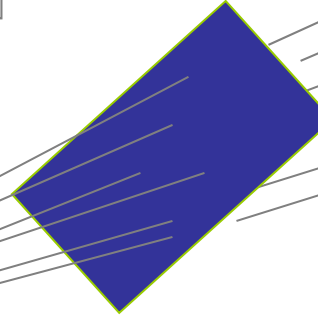
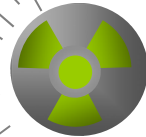


Activity

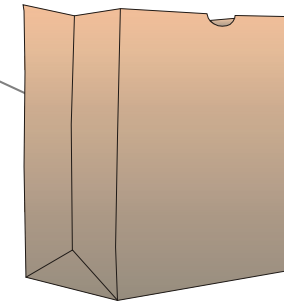
Becquerel (Bq):
1 Bq = 1 s⁻¹
(Curie (Ci):
1 Ci = 3.7 · 10¹⁰ Bq)

Fluence F

particles per cm²
~ 1/distance²



Absorbed dose D



$$D = \frac{d\varepsilon}{dm}$$

$$\dot{D} = \frac{dD}{dt}$$

Biological effects:
Effective dose E (Sv)

Ambient dose
equivalent H*(d)

gray (Gy): 1 Gy = 1 J.kg⁻¹
(rad: 1 rad = 0.01 Gy)



1. Definitions

Ionising Radiation Dose (Equivalent Dose):

is a measure of the radiation dose absorbed by a tissue depending on the different types of ionizing radiation.

$$1 \text{ mSv} = 0,001 \text{ Sv (Sievert)}$$

Energy absorbed per kilogram: $1 \text{ Sv} = 1 \text{ Joule} / 1 \text{ kg}$ (1 Joule = 0,25 calories)

Assuming that the hours per year for a worker is **2000 hours**:

$$0,001 \text{ Sv} / 2000 \text{ h} = 0,0000005 \text{ Sv/h} = 0,5 \mu\text{Sv/h}$$



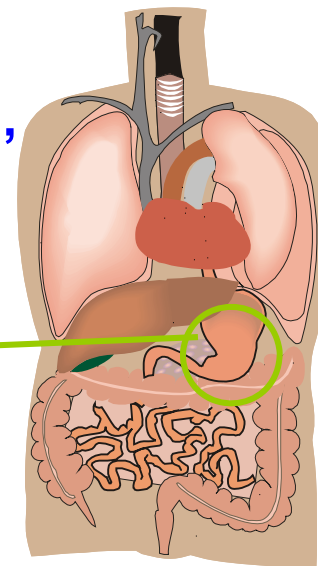
1. Definitions

ICRP Publication 60 (1991):

Organ dose D_T

$$D_T = \frac{1}{m_T} \int_{m_T} D dm$$

Individual organ,
e.g. stomach



Tissue or organ
equivalent dose $H_{T,R}$

$$H_{T,R} = w_R \cdot D_{T,R}$$

$$H_T = \sum_R w_R \cdot D_{T,R}$$

Unit of equivalent dose: $J \cdot kg^{-1}$
Special name: Sievert (Sv)
Old unit: rem (1 Sv = 100 rem)

Type and energy range of radiation	Radiation weighting factor
	w_R
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons	
< 10 keV	10
10 - 100 keV	5
> 100 keV to 2 MeV	10
> 2 - 20 MeV	20
> 20 MeV	10
Protons, energy > 2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20



1. Definitions

ICRP Publication 60 (1991):

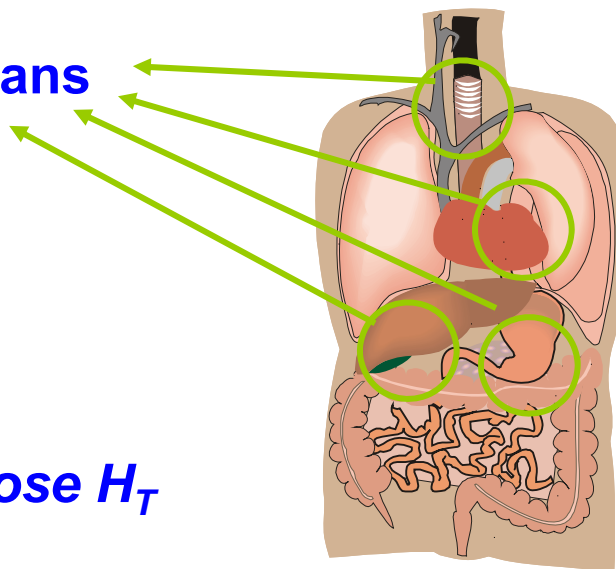
Effective dose E

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

Unit of effective dose: Sv

Tissue or organ	Tissue weighting factor w_T
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05

Σ different organs



Dose limits on:

- Effective dose E
- Tissue or organ equivalent dose H_T

Tissue weighting factor w_T

	ICRP 60	ICRP 103
Gonads	0.20	0.08
Bone marrow (red)	0.12	0.12
Colon	0.12	0.12
Lung	0.12	0.12
Stomach	0.12	0.12
Bladder	0.05	0.04
Breast	0.05	0.12
Liver	0.05	0.04
Oesophagus	0.05	0.04
Thyroid	0.05	0.04
Skin	0.01	0.01
Bone surface	0.01	0.01
Brain	-	0.01
Salivary gland	-	0.01
Remainder	0.05	0.12
Total	1	1

Radiation weighting factor w_R

$$2.5 + 18.2 e^{-[\ln E_n]^2 / 6}, \quad E_n < 1 \text{ MeV}$$

$$5.0 + 17.0 e^{-[\ln 2E_n]^2 / 6}, \quad 1 \text{ MeV} \leq E_n \leq 50 \text{ MeV}$$

$$2.5 + 3.25 e^{-[\ln 0.04E_n]^2 / 6}, \quad E_n > 50 \text{ MeV}$$

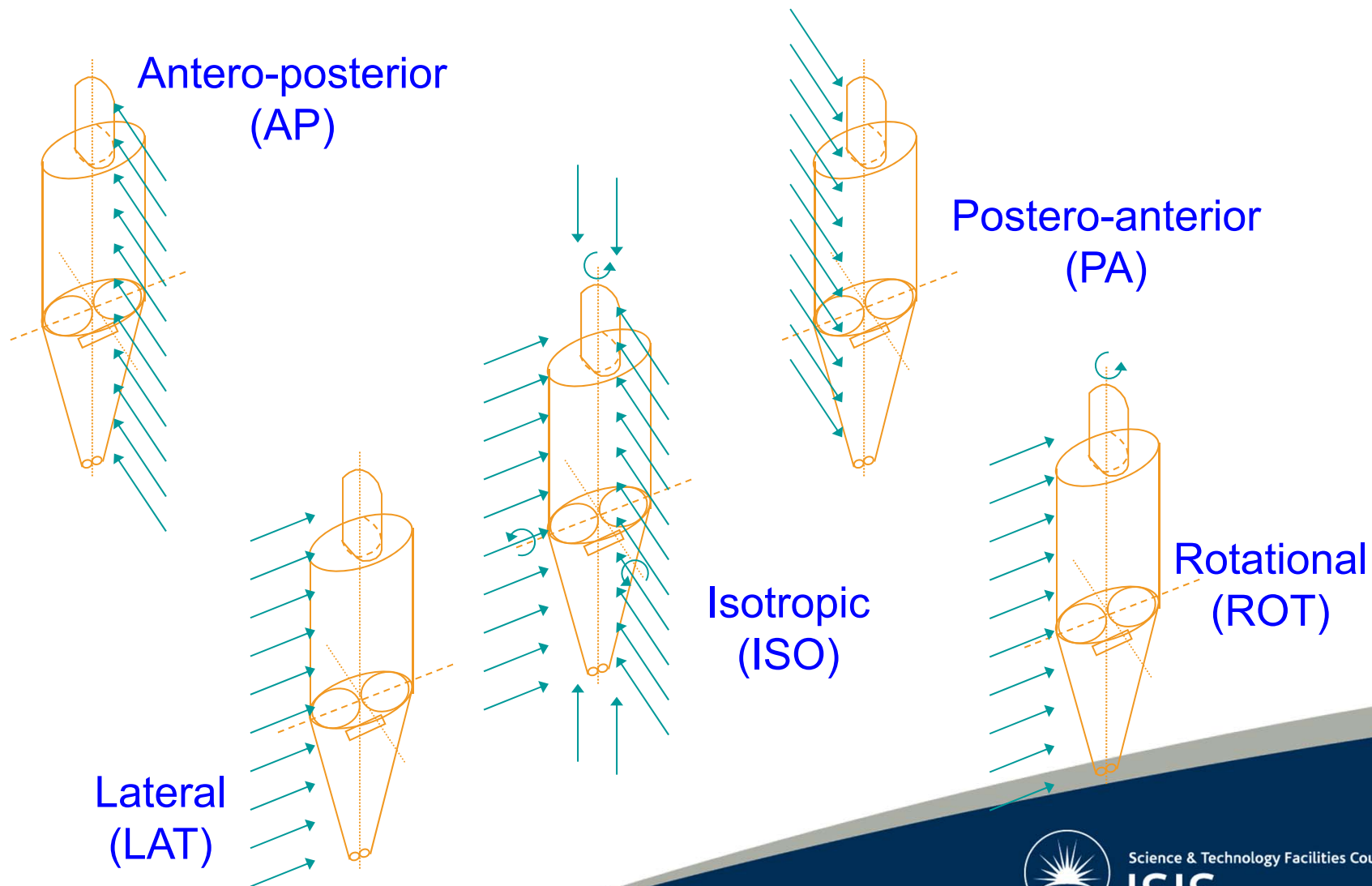
neutrons

protons: 2



1. Definitions

ICRP Publication 60 (1991): Irradiation geometries



1. Definitions

ICRU Report 51 (1993):

Protection quantities (ICRP) → operational quantities

Dose equivalent

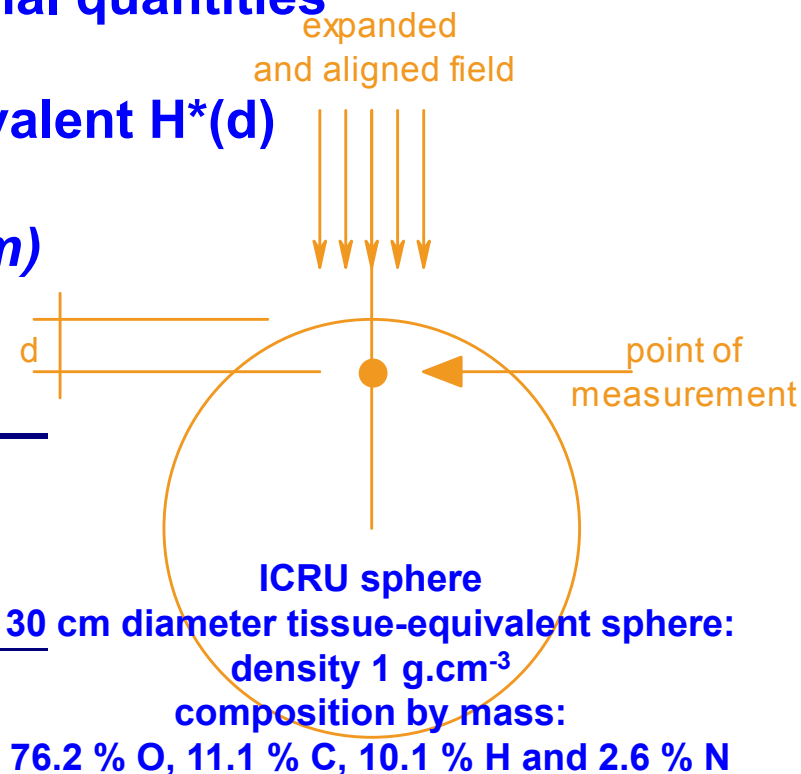
Ambient dose equivalent $H^*(d)$

$$H = Q \cdot D$$

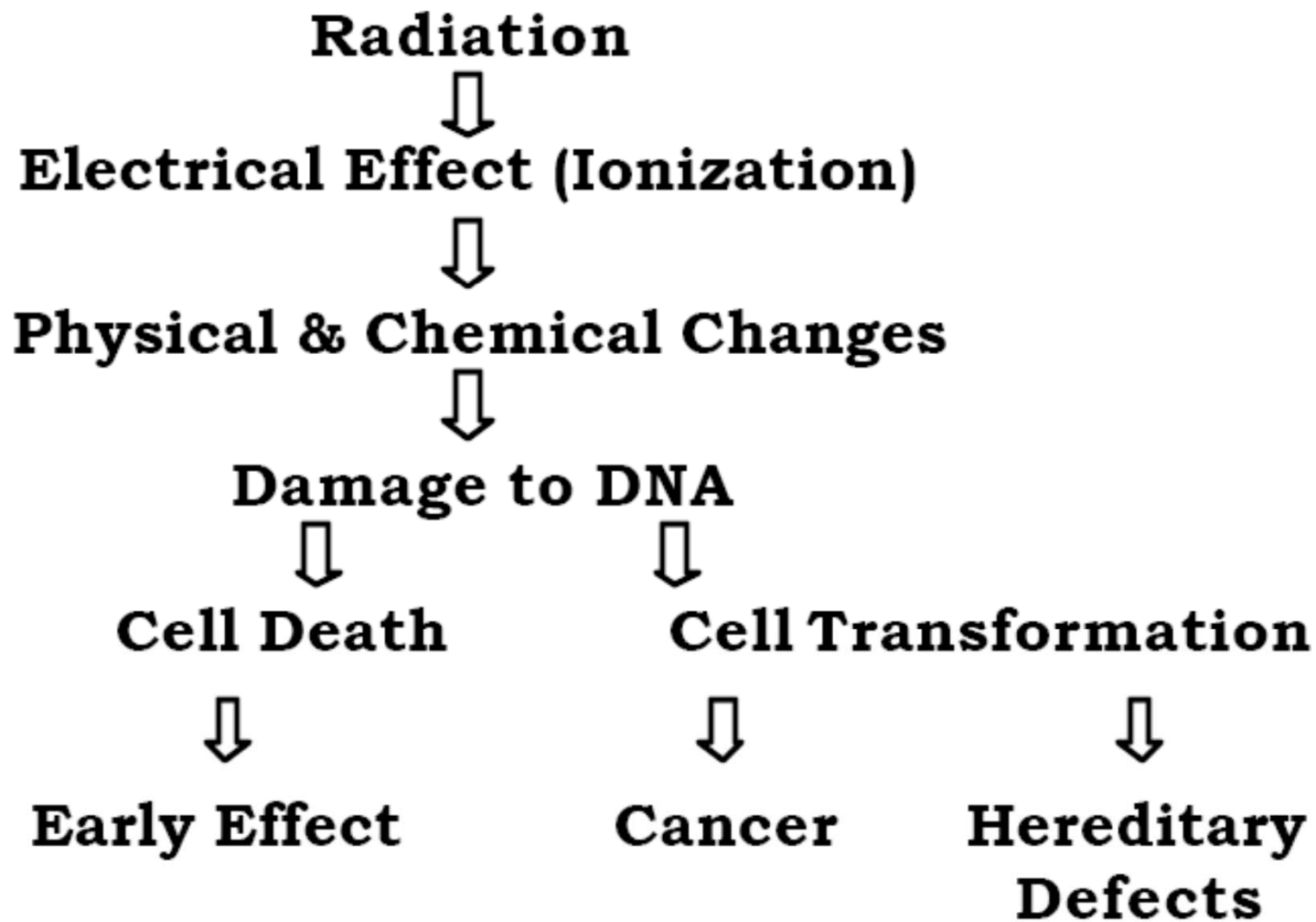
$$\rightarrow H^*(10) \quad (d = 10 \text{ mm})$$

Unit of dose equivalent: Sv

Unrestricted linear energy transfer L (keV· μm^{-1})	Quality factor Q
$L < 10$	1
$10 \leq L \leq 100$	$0.32 L - 2.2$
$L > 100$	$300 / L^{1/2}$



2. Effects of the ionization radiation

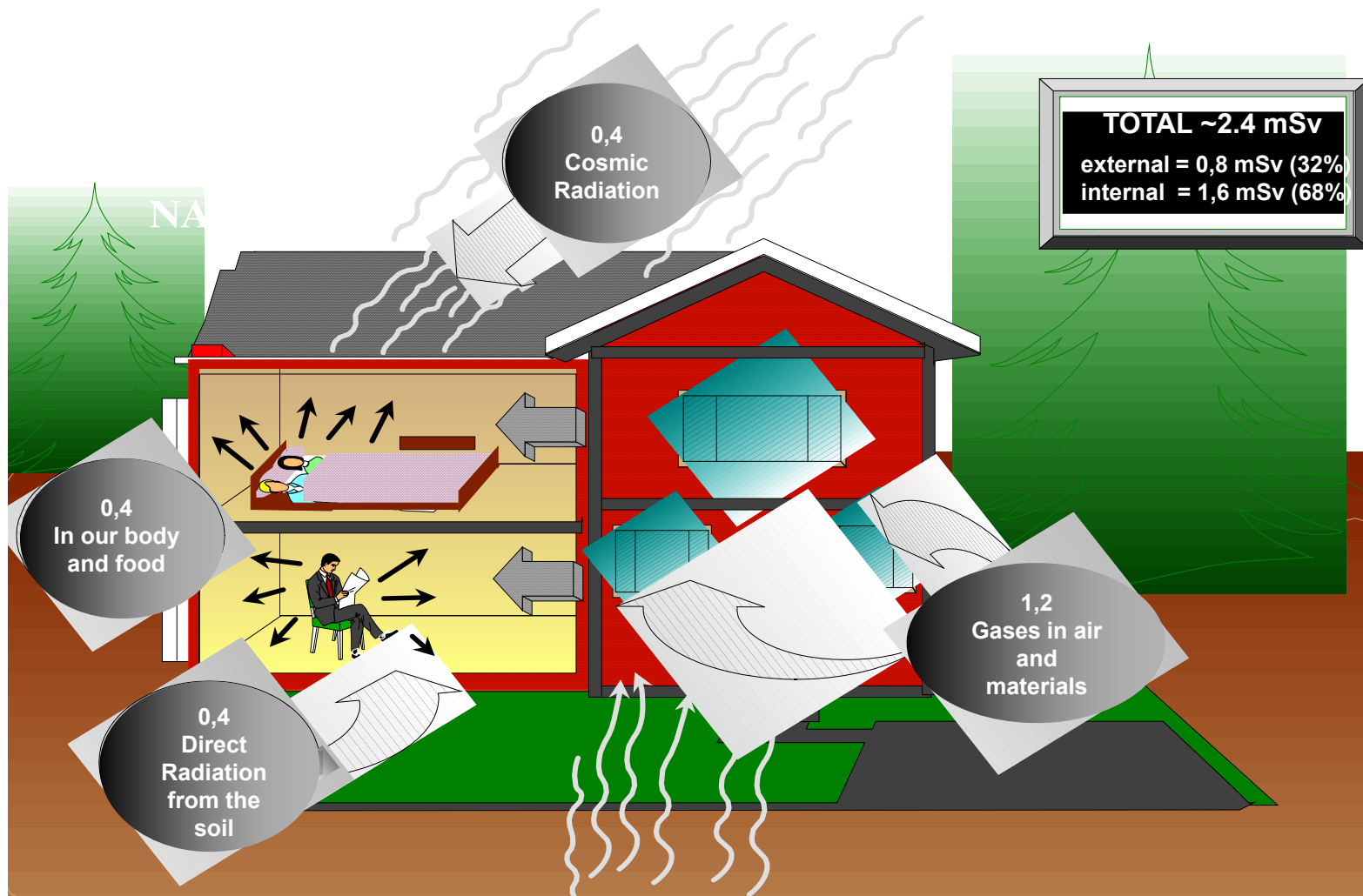


2. Effects of the ionization radiation

Effect	Population	Exposure period	Probability/Sv
Hereditary effects	Whole population	Lifetime	1 % (all generations)
Fatal cancer	Whole population	Lifetime	5 %
	Working population	Age 18-65	4 %
Health detriment	Whole population	Lifetime	7.3 %
	Working population	Age 18-65	5.6 %



3. Natural background



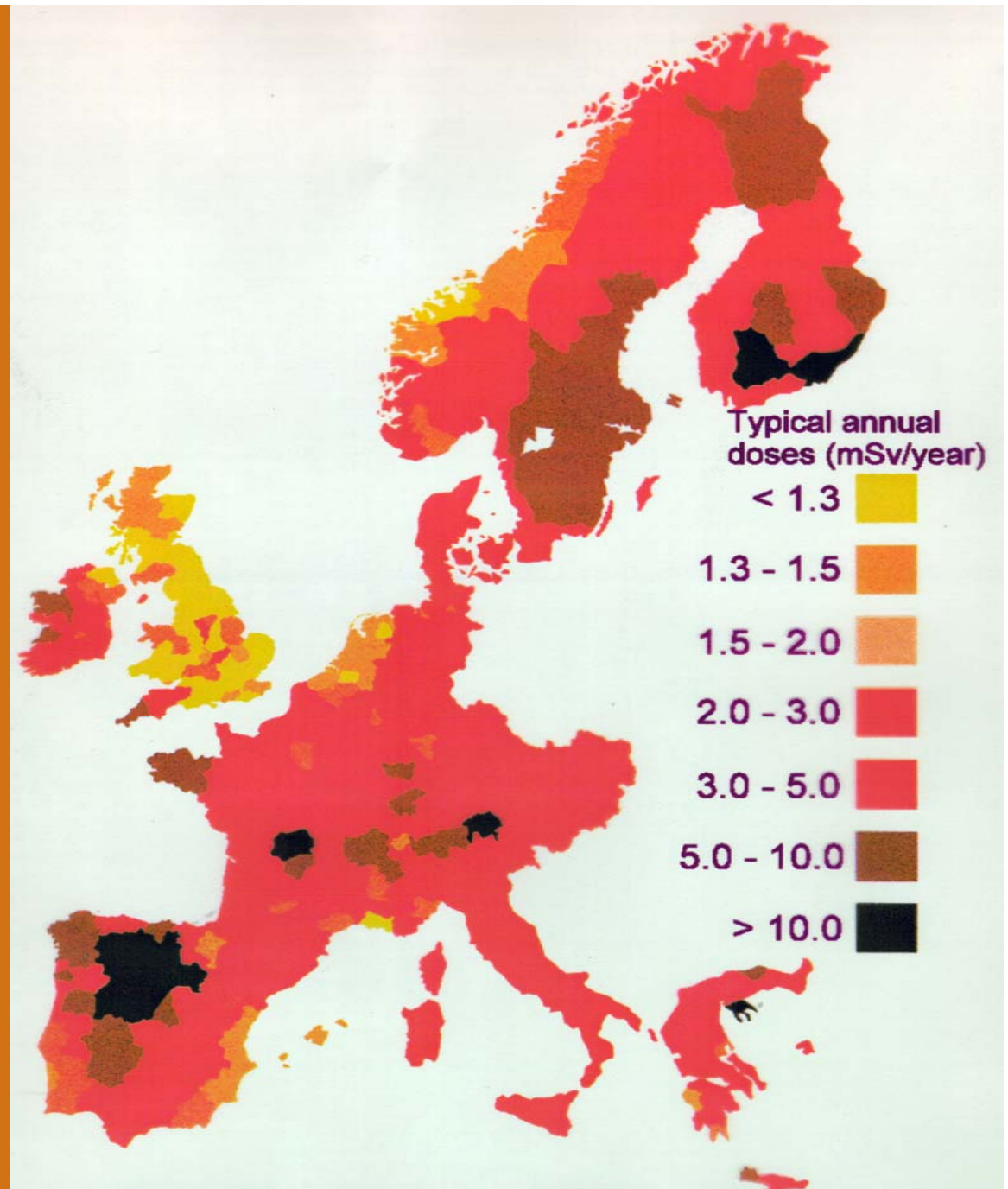
3. Natural background

WORLDWIDE AVERAGE DOSES

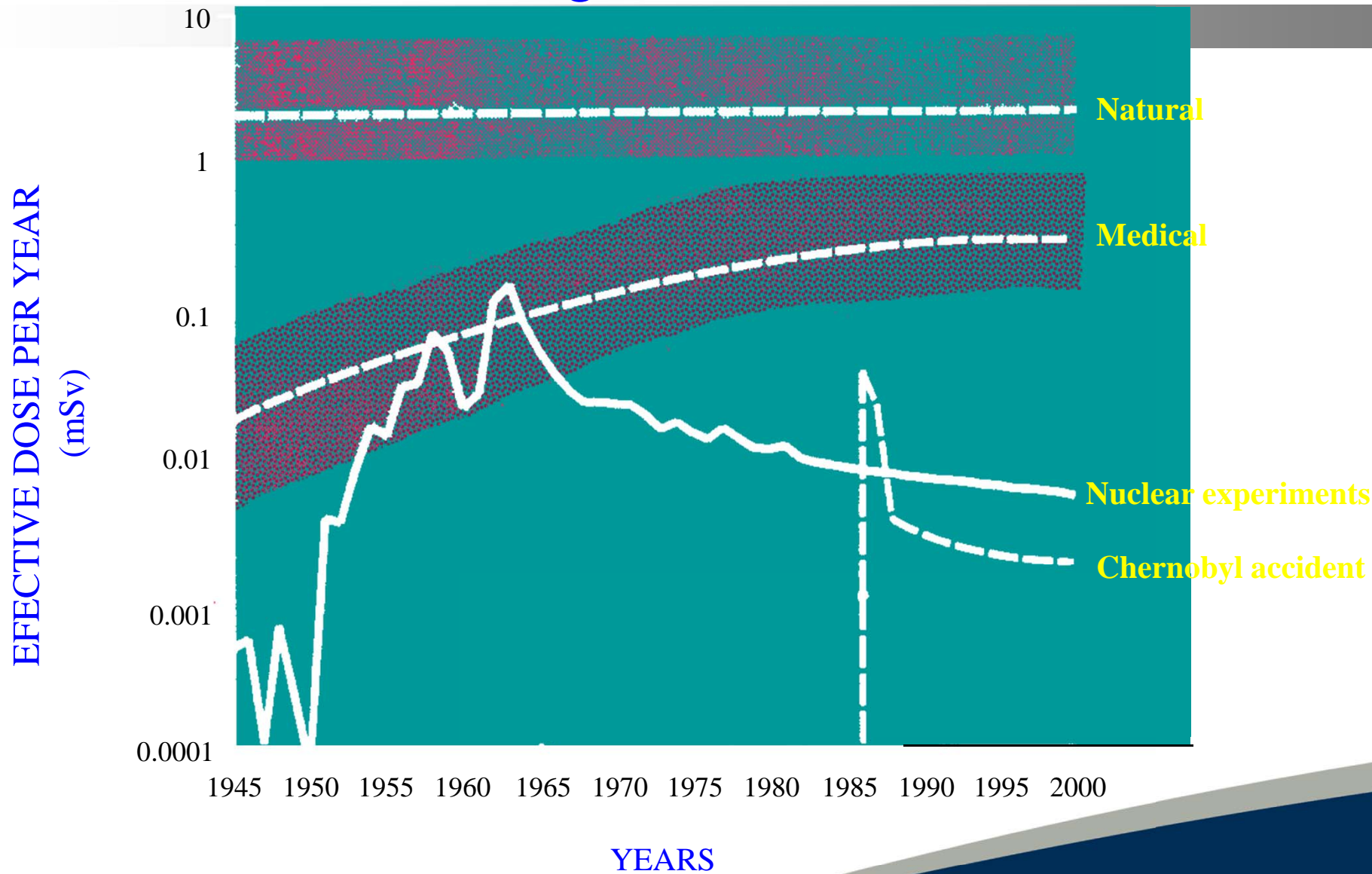
<i>Source</i>	<i>Effective dose (mSv per year)</i>	<i>Typical range (mSv per year)</i>
External exposure		
• Cosmic rays	0.4	0.3-1.0
• Terrestrial gamma rays	0.5	0.3-0.6
Internal exposure		
• Inhalation	1.2	0.2-10
• Ingestion	0.3	0.2-0.8
Total	2.4	1–10



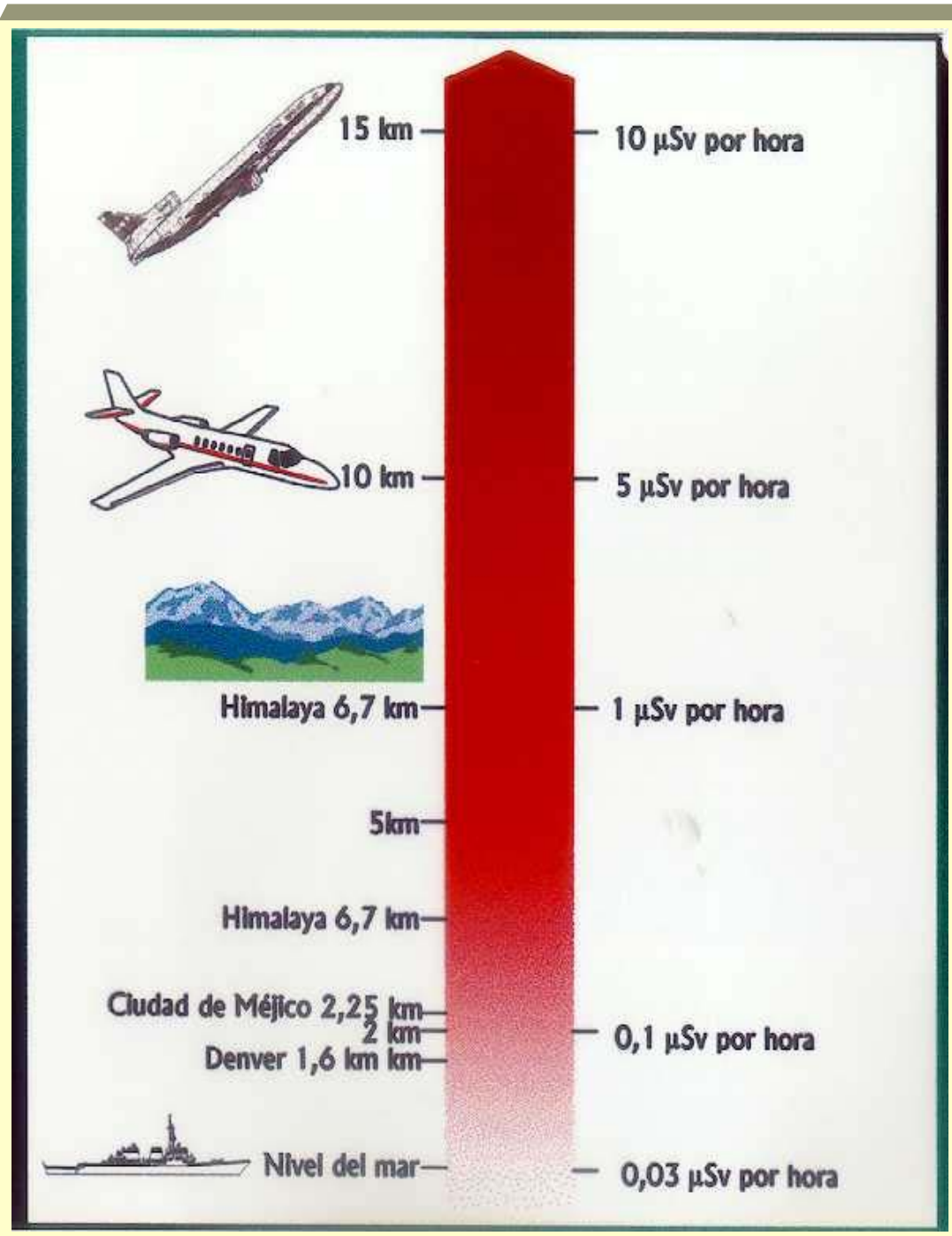
Natural
background
radiation
exposure
in Europe



3. Natural background



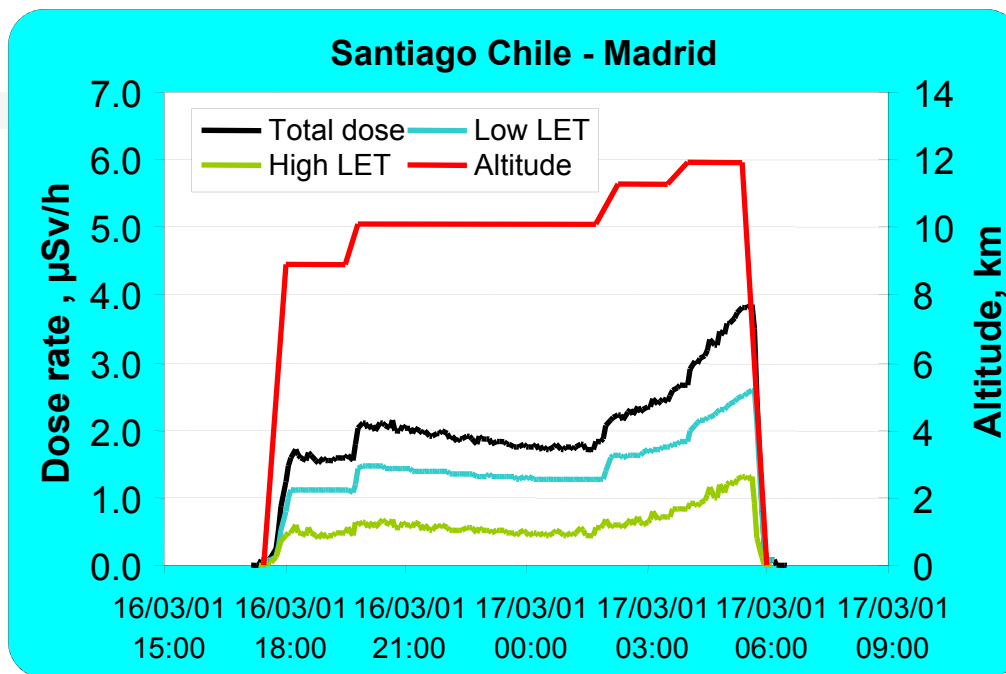
3. Natural background



Cosmic Radiation



3. Natural background



3. Natural background

AVERAGE DOSES TO WORKERS

<i>Radiation source</i>	<i>Number of workers</i>	<i>Average dose</i> <i>(mSv per year)</i>
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Enhanced natural sources

- | | | |
|-----------------------------------|-----------|-----|
| • Mining (excluding coal) | 760,000 | 2.7 |
| • Coal mining | 3,900,000 | 0.7 |
| • Air travel (crew) | 250,000 | 3 |
| • Mineral processing | 300,000 | 1.0 |
| • Above ground workplaces (radon) | 1,250,000 | 4.8 |

Total	6.500,000	1.7
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4. Rules for workers & zones

DOSE LIMITS - PERSONAL

➤ WORKERS :

1. For Exposed Workers - A: maximum dose 50 mSv per official year (100 mSv for 5 years)
2. For Exposed Workers - B: maximum dose 6 mSv per official year
3. For None Exposed Workers: 1 mSv per official year
4. For women during pregnancy (*): 1 mSv
5. For general public: 1 mSv per official year



4. Rules for workers & zones

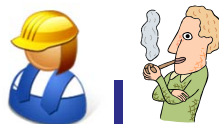
Application	Dose Limit	
	Workers	Public
Effective Dose	20 mSv/year averaged for 5 years periods ¹	1 mSv/year ²
Equivalent Dose (/year):		
Lens (Crystalline)	150 mSv	15 mSv
Skin ³	500 mSv	50 mSv
Hands and foot	500 mSv	-----

- 1 The effective dose will be below 50 mSv any year.
- 2 Under exceptional situations a higher effective dose could be accepted, if the average in 5 years is not above 1mSv/year.
- 3 These dose limits (equivalent dose) prevent deterministic effects after local exposures.



1 mSv/year is the annual limit for
public due to artificial radiations

Exposed Worker



Annual dose (2000 h/year):

< 1 mSv/year

Dose per day:

< 12 μ Sv

Dose rate @ public areas:

< 0.5 μ Sv/h

The smoker case

Annual dose (1.5 pack/day):

13 mSv/year

Dose per cigarette:

~ 1.2 μ Sv/cigarette

Dose rate (5min/cigarette):

~ 14.4 μ Sv/h



4. Rules for workers & zones

AREA DOSE LIMITS

➤ ZONE CLASIFICATION:

1. **Controlled Zone:** dose higher than 6 mSv (per official year)

i. Limit Access Zone: dose higher than 100 mSv (for 5 years)

ii. Ruled Access Zone: high dose rate (short period)

iii. Prohibited Access Zone: high dose (single exposition)

2. **Watched Zone:** dose lower than 6 mSv (per official year)

Always ANNUAL DOSE is ABOVE the background LEVEL



4. Rules for workers & zones

DOSE LIMITS - SIGNALS

WATCHED ZONE > 0,5 μ Sv/h up to 3 μ Sv/h



CONTROLLED ZONE > 3 μ Sv/h up to 25 μ Sv/h



LIMIT ACCESS ZONE

> 25 μ Sv/h up to 1 mSv/h

RULED ACCESS ZONE

> 1 mSv/h up to 100 mSv/h



PROHIBITED ACCESS ZONE

> 100 mSv/h



4. Rules for workers & zones

Passive personnel dosimeters

- Thermoluminescence
- Based on detectors TLD-100 (LiF: Mg, Ti):
 - Equivalent dose
 - Range of usage: 10 μ Gy-10Gy.
- The filter system allow to distinguish the energy radiation



Whole body dosimeter

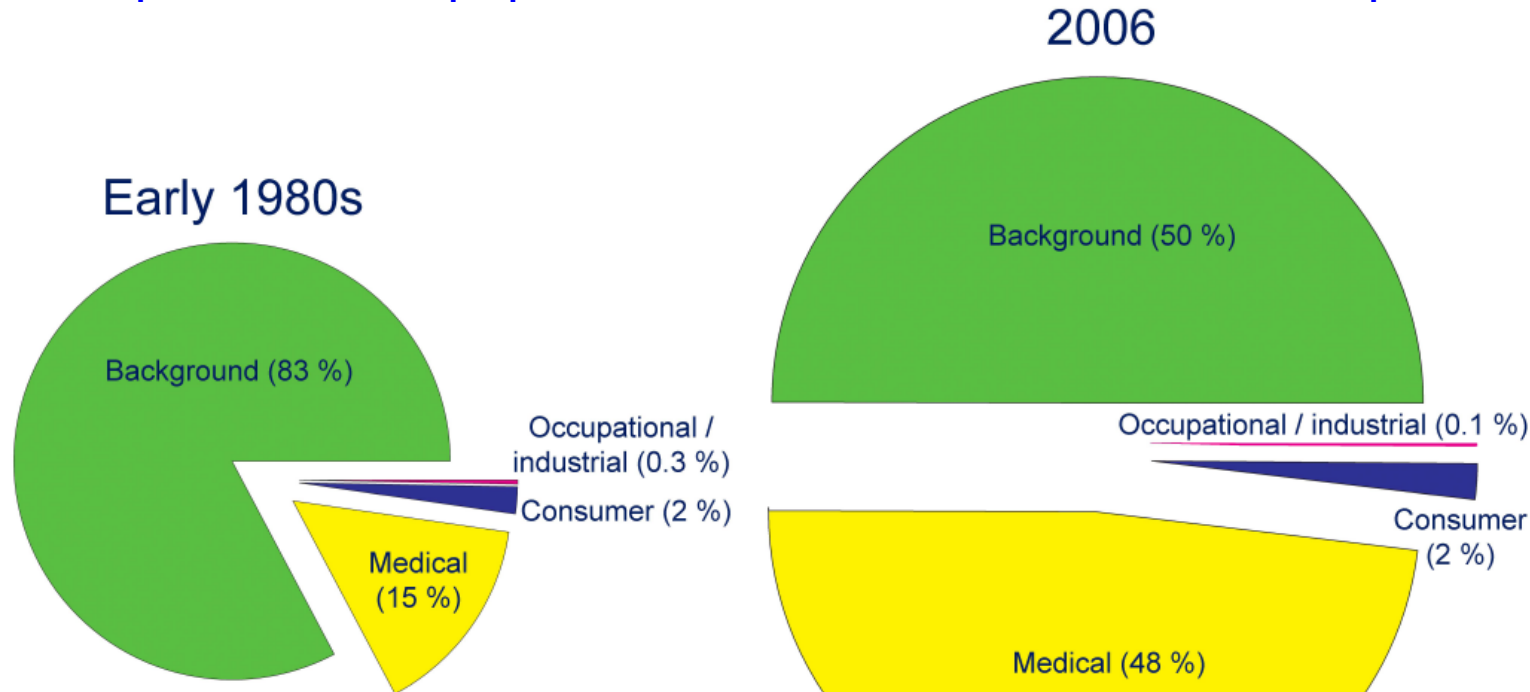
4. Rules for workers & zones

Different passive dosimeters configurations



4. Rules for workers & zones

Radiation exposure to US population from all sources. NCRP 160 published 2009



	Early 1980s	2006
Collective effective dose (person-Sv)	835,000	1,870,000
Effective dose per individual in the U.S. population (mSv)	3.6	6.2

Medical dose per capita (mSv) .54 3.0 has increased 560%

