Dosimetry and Radiation Safety

“My head bounded against a pointed rock, and I lost all knowledge of existence."

—Henry Lawson in “Journey to the Center of the Earth” by Jules Verne.

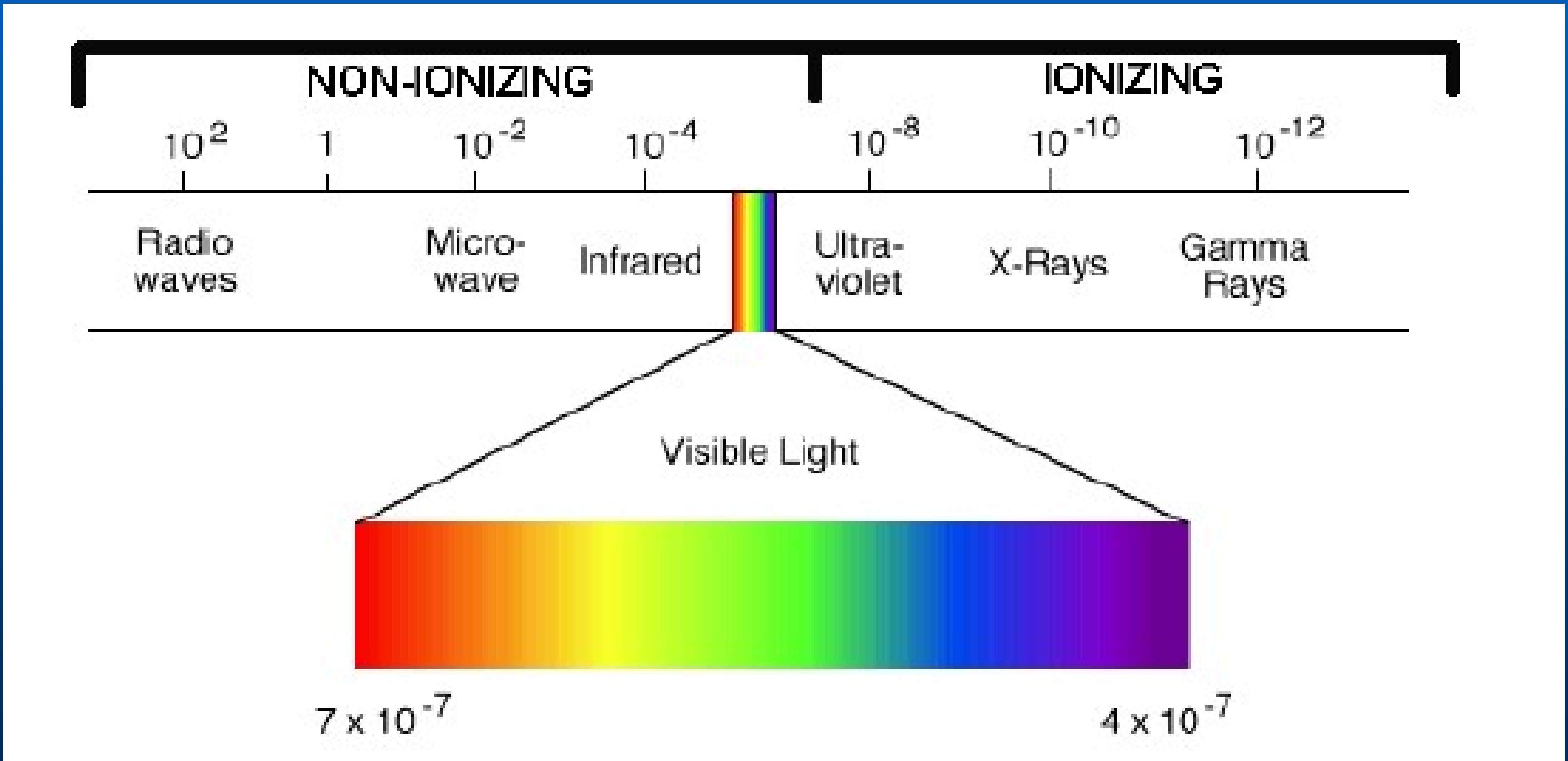
Exposure and Dose

Radiation: The transfer of energy in the form of the movement of particles or electromagnetic waves.

Exposure: When any material is subjected to *any* type of radiation. For radioactive wastes, the concern is ionizing radiation.

Particles having enough kinetic energy to remove an electron from an atom of molecule, this ionizing it.

The energy needed to remove a valence electron is about 4 to 25 eV.



Exposure

Roentgen (runt-gin). The amount of ionizing energy needed to produce 1.0 electrostatic unit of charge per cubic centimeter of air at 0° C; or the amount required to 2.58 Coulombs of charge per 1.0 kg of dry air (i.e. external radiation; external to the body).

Abbreviated as R.

Background radiation is about 23 μR.

The term is not often used.

Dose

Dose: The amount of radiation energy "deposited" on/in the material, or the amount of radiation energy absorbed by the body.

Ultimately, a measure of *risk* by the exposure of ionizing radiation.

For external radiation, the U.S. term is rad (radiation absorbed dose): a unit of energy absorbed from ionizing radiation, equal to 100 ergs per gram of irradiated material. In SI units, Gray (Gy) which is 1 Joul/kg. 1 Gy = 100 rads.

Dose Equivalent

Radiation can be composed of different types of particles with different properties and/or particles with different kinetic energies. Also their effects on biological tissues can vary from one organ to another. ***This complicates an assessment of dose from exposure.***

In order derive some type of useful measure of health risk, we calculate a dose equivalent.

LET

Linear energy transfer (LET): the rate at which a charged particle deposits energy as a travels through matter. Expressed as MeV or keV/µm.

Related to "stopping power" as LET/ρ (density of the solid material).

Of all radiation types, the concept of LET is most applicable to alpha particles, and fission fragments. Less so for beta and gamma radiation.

Low and High LET

“Low LET” beta and gamma

“High LET” alpha and fission fragments.

Radiation	Typical LET values
1.2 MeV ^{60}Co gamma	0.3 keV/µm
250 kVp x rays	2 keV/µm
10 MeV protons	4.7 keV/µm
150 MeV protons	0.5 keV/µm
14 MeV neutrons	12 keV/µm
Heavy charged particles	100-2000 keV/µm
2.5 MeV alpha particles	166 keV/µm
2 GeV Fe ions	1,000 keV/µm

Relative biological effectiveness (RBE)

When comparing different types of radiation, it is often accomplished by using x-rays as a standard:

RBE = dose of x-rays /dose of a given radiation.

X-rays (0.01 to 10 ηm) from electronic transitions.

Gamma radiation/rays (< ≈ 10 ηm) from nuclear re-arrangements.

Relative biological effectiveness (RBE)

RBE is evaluated when the amount of biological damage caused by the test radiation is the same as that caused by the reference radiation. The energies applied for each type of radiation may be different.

RBE is experimentally evaluated by exposing living cells in a culture medium such as bacteria. The end-point is the LD-50 (the median lethal dose for half the population).

Relative biological effectiveness (RBE)

The RBE is represented by a radiation weighting factor (W_R), formerly called the "quality factor" (Q). Note that RBE $\neq W_R$

The conversion of the experimental data into these factors is complicated, and beyond the scope of NPRE 442. They are best estimates that are derived by the consensus of radiation safety regulators in concert with industrial interests, and governmental directives.

Equivalent dose (H_T)

The equivalent dose is calculated by multiplying the absorbed dose, by the radiation weighting factor appropriate to the type tissue (T) and type of radiation (R).

To obtain the equivalent dose for a mixture of radiation types and energies, a sum is taken over all types of radiation energy dose.

$$H_T = \sum W_R \times D_{T,R}$$

Radiation Weighting factors

Radiation Type and Energy Range	**Radiation Weighting Factor, W_R**
X and γ rays, all energies	1
Electrons positrons and muons, all energies	1
Neutrons:	
< 10 keV	5
10 keV to 100 keV	10
> 100 keV to 2 MeV	20
> 2 MeV to 20 MeV	10
> 20 MeV	5
Protons, (other than recoil protons) and energy > 2 MeV,	2-5
α particles, fission fragments, heavy nuclei	20

[ICRU 60, 1991]

Equivalent dose units

W_R is unitless.

H_T is rem in the U.S. (from **r**oentgen **e**quivalent in **m**an).

The S.I. unit is sievert (Sv) which is equal to 1 Joul/kg.

1.0 Sv = 100 rem

1 Gray (Gy) of α radiation is more harmful than 1 Gy of β radiation, but 1 Sv of β radiation causes as much biological damage as 1 Sv of α radiation.

Introductions

Prof. Rolf M. Sievert

(1896 – 1966)

Swedish medical physicist

Dr. Louis H. Gray, FRS

(1905 – 1965)

English physicist

BED

The Banana Equivalent Dose (BED)

About 0.1 μSv (0.01 mrem).

Radioactivity from potassium-40.

The term is used informally.

Effective dose (H_E or E)

Effective dose is the equivalent dose weighted to take into account the susceptibility of different tissues and organs. Effective dose is defined as sum of equivalent doses in particular tissue multiplied by dimensionless tissue weighting factor, W_T:

$$H_E = \Sigma\, W_T\, \Sigma W_R D_{T,R} = \Sigma\, W_T H_T$$

The origins of the tissue factors are the same as those for the radiation factors.

Tissue weighting factors

Tissue	Tissue Weighting Factor, W_T
Gonads	0.20
Red bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surfaces	0.01
Remainder	0.05

(ICRU 60, 1991; NCRP 116, 1993)

Example of effective dose

Suppose that a person held a GTCC waste container in his lap, and his stomach was exposed to 110 mSv equivalent dose and his bladder received 70 mSv. The effective dose is (110 mSv x 0.12) + (70 mSv x 0.04) = 16 mSv.

The risk of harmful effects from the radiation is 16 mSv received uniformly throughout the whole body. Why?

Example of effective dose

The summation of all the tissue weighting factors must equal to 1.0. In this example, only two organs were exposed. Therefore, for the sake of clarity, we can add

$$0 \text{ mSv} \times (1.0 - 0.17) = 0 \text{ mSv}.$$

This addition of course does not change the effective dose calculation, but it illustrates that the effective dose (16.0 mSv) can be called the *whole-body effective dose*. The whole-body effective dose is the summation of the effective doses to each region of the human body.

Effective Dose

In practice, effective dose is calculated and not measured.

Computer software

Monte Carlo simulations

ImPACT

ImpactDose

RESRAD-BUILD

Converting activities/concentrations to dose

https://www.epa.gov/radiation/tools-calculating-radiation-dose-and-risk

https://www.epa.gov/radiation/calculate-your-radiation-dose

https://www.ornl.gov/crpk/software

Dosimetric Quantities

Quantity	**Definition**	**New Units**	**Old Units**
Exposure	Charge per unit mass of air $1\ R = 2.58 \times 10^{-4}\ C/kg$	---	Roentgen (R)
Absorbed dose to tissue T from radiation of type R $D_{T,R}$	Energy of radiation R absorbed per unit mass of tissue T 1 rad = 100 ergs/g 1 Gy = 1 joule/kg 1 Gy = 100 rads	gray (Gy)	Radiation absorbed dose (rad)
Equivalent dose to tissue T H_T	Sum of contributions of dose to T from different radiation types, each multiplied by the radiation weighting factor (w_R) $H_T = \Sigma_R\ w_R\ D_{T,R}$	Sievert (Sv)	Roentgen equivalent man (rem)
Effective Dose E	Sum of equivalent doses to organs and tissues exposed, each multiplied by the appropriate tissue weighting factor (w_T) $E = \Sigma_T\ w_T\ H_T$	Sievert (Sv)	rem

Committed equivalent dose and committed effective dose

The dose to a specific organ or tissue that is received from an intake of radioactive material by an individual over a specified time after the intake. After, ingestion, one could be “committed” to internal exposure for years.

Collective effective dose (S)

Collective dose is the sum of all the effective doses received by an exposed population and can be used to estimate the total health effects of a process or accidental release involving ionizing radiation.

$$S = \sum_i E_i \times N_i$$

Where N is the number of individual in the population.

Deep and Shallow Dose

Shallow-Dose Equivalent (SDE)

The external exposure dose equivalent to the skin or an extremity at a tissue depth of 70 µm averaged over an area of 1 cm^2

Deep-Dose Equivalent (DDE)

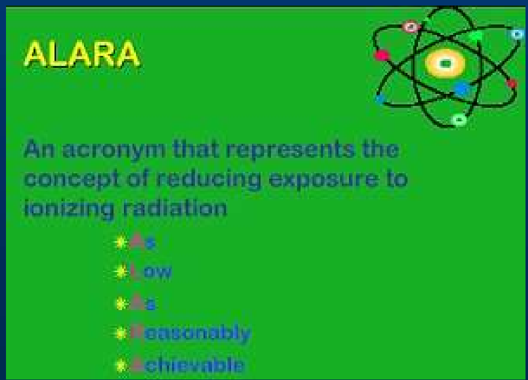
The external whole-body dose exposure equivalent at a tissue depth of 1 cm.

How to minimize exposure and dose: ALARA

As Low As Reasonably Achievable

For protection in practical terms:

- **<u>Distance</u> (maximize distance between source and worker).**
- **<u>Shielding</u> (maximize blocking).**
- **<u>Duration</u> (minimize amount of time of exposure).**



Stay time

The amount of radiation that an individual accumulates will depend on how long the person stays in the radiation field.

Dose = dose rate x time.

Stay time = limit (mrem)/dose rate (mrem/hour)

How long can a worker remain in a 1.5 rem/hour radiation field if we need to limit the dose to 100 mrem?

Stay time = 100 mrem/1500 mrem/hour = 4 minutes.

Distance

The Inverse Square Law: the intensity of radiation decreases in proportion to (1/distance)^2.

$I_1 d_1^2 = I_2 d_2^2$ where I = radiation intensity.

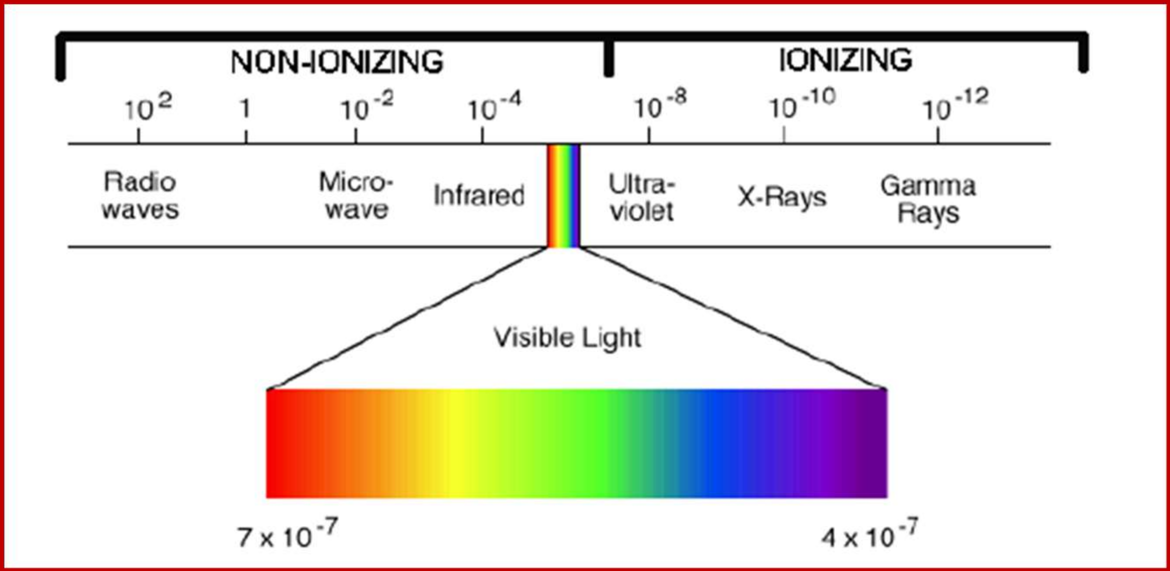
The exposure rate 1.0 foot from a waste container is 710 mrem/hour of gamma radiation. What would be the exposure rate 20 feet from the container?

$I_2 =$ (710 mrem/hour) (1 foot)^2/(20 feet)^2 = 1.78 mrem/hour

Exposure (rem)	**Health Effect**	**Time to Onset** (without treatment)
5 to 10	changes in blood chemistry	
50	nausea	hours
55	fatigue	
70	vomiting	
75	hair loss	2-3 weeks
90	diarrhea	
100	hemorrhage	
400	possible death	within 2 months
1,000	destruction of intestinal lining	
	internal bleeding	
	and death	1-2 weeks
2,000	damage to central nervous system	
	loss of consciousness;	minutes
	and death	hours to days

IAEA (2014). Occupational exposure limits for workers over the age of 18 years.
(a) An effective dose limit of 20 mSv per year, averaged over five consecutive years.
(b) An equivalent dose limit to the lens of the eye of 20 mSv per year, averaged over 5 consecutive years.
(c) An equivalent dose of 500 mSv in a year to the extremities (hands and feet) or to skin.
US NRC (2019). Subpart C. Occupational dose limits for adults.
1. An annual dose limit of which of the following is the most limiting: **a. An effective dose equivalent (or whole-body) limit of 5 rem (0.05 Sv) per year.** **b. The sum of the deep-dose equivalent plus the committed dose equivalent to any organ or tissue limited to 50 rem (0.5 Sv).**
2. The annual limits to the lens of the eye, whole-body skin, and skin of extremities: **a. A lens dose equivalent of 15 rem (0.15 Sv) per year** **b. A shallow-dose equivalent of 50 rem (0.5 Sv) per year to the whole-body skin or to the skin of any extremity.**

Questions?



NON-IONIZING
IONIZING
10^2
1
10^{-2}
10^{-4}
10^{-8}
10^{-10}
10^{-12}
Radio waves
Micro-wave
Infrared
Ultra-violet
X-Rays
Gamma Rays
Visible Light
7×10^{-7}
4×10^{-7}