University of Pittsburgh

ME/ENGR 2100 Fundamentals of Nuclear Engineering

Radiation Protection

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Relevant Reading Assignments

- Chapter 9 of "Introduction to Nuclear Engineering," Lamarsh and Baratta, 3rd edition, Prentice-Hall (2001)
- Chapter 3 of "Nuclear Engineering: Theory and Technology of Commercial Nuclear Power," Knief, 2nd edition, American Nuclear Society (1992, reprint by ANS 2008)

Learning Objectives

- Explain basic radiation terminology, radiation interactions with matter, and common radiation dose units.
- Describe radiation damage effects in biological systems
- Define LD50/30. State the value of LD50/30 for whole-body radiation to humans.
- Describe current US radiation protection standards
- Explain the three primary and two subordinate dose reduction principles.
- Estimate radiation dose and dose rate from specified alpha, beta, and gamma sources.
- Identify the major purposes of reactor shielding and explain secondary radiation.

The basic physics of radiation: terminology

- Radiation: energy emitted from a nucleus or atom (typically, gamma-rays or x-rays, electrons, neutrons, alpha-particles)
- Radioactivity: the process of emission of radiation due to nuclear instability
- Radiation is energy; radioactive material is matter that emits radiation
- Activity is measured in disintegrations per unit time. The historical unit is the Curie, defined as 3.7×10^{10} disintegrations per second (= 2.22×10^{12} disintegrations per minute). The SI unit is the Becquerel: 1Bq=1dps.

Macroscopic Effects of Radiation

- Ionization events are the root cause behind **ALL** observable effects of radiation [except neutron disruption of material lattices (e.g., in steels), and even there one finds ionizations]
  – Ionization reactions damage materials by breaking chemical bonds and disrupting normal chemical processes (material embrittlement [e.g., in polymers], biological damage, etc.)
- The rate of ionization (damage) depends on the type and energy of the radiation, as well as the constituent atoms in the target material.
- Note that radiation “damage” can also be beneficial – e.g., hardening of tool steel surfaces using ion beams

Ionization Density

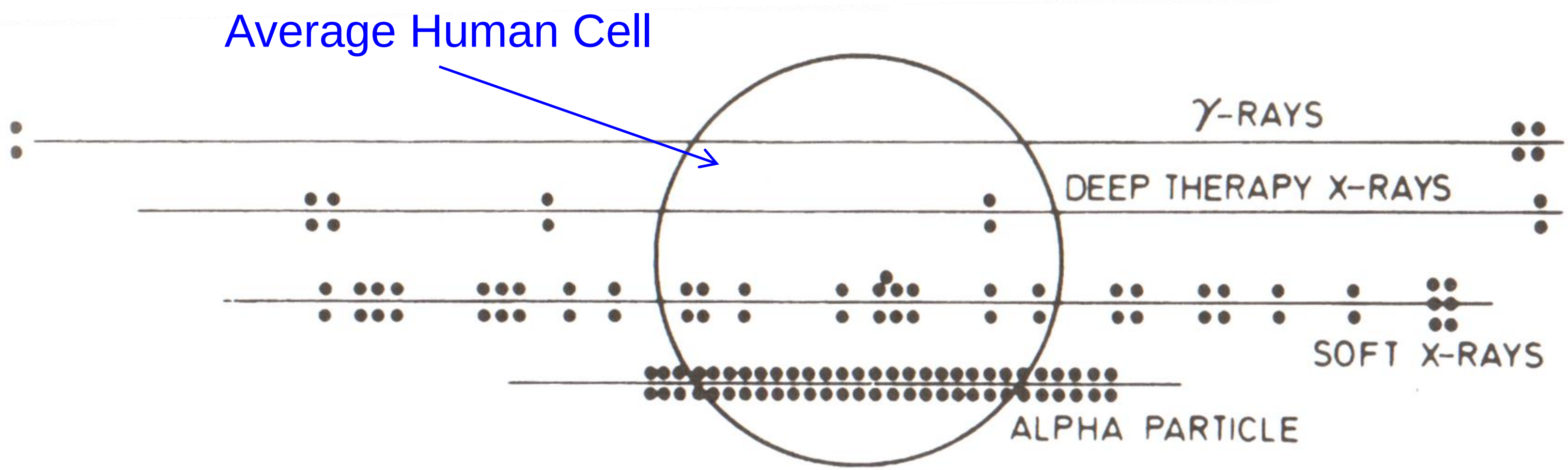
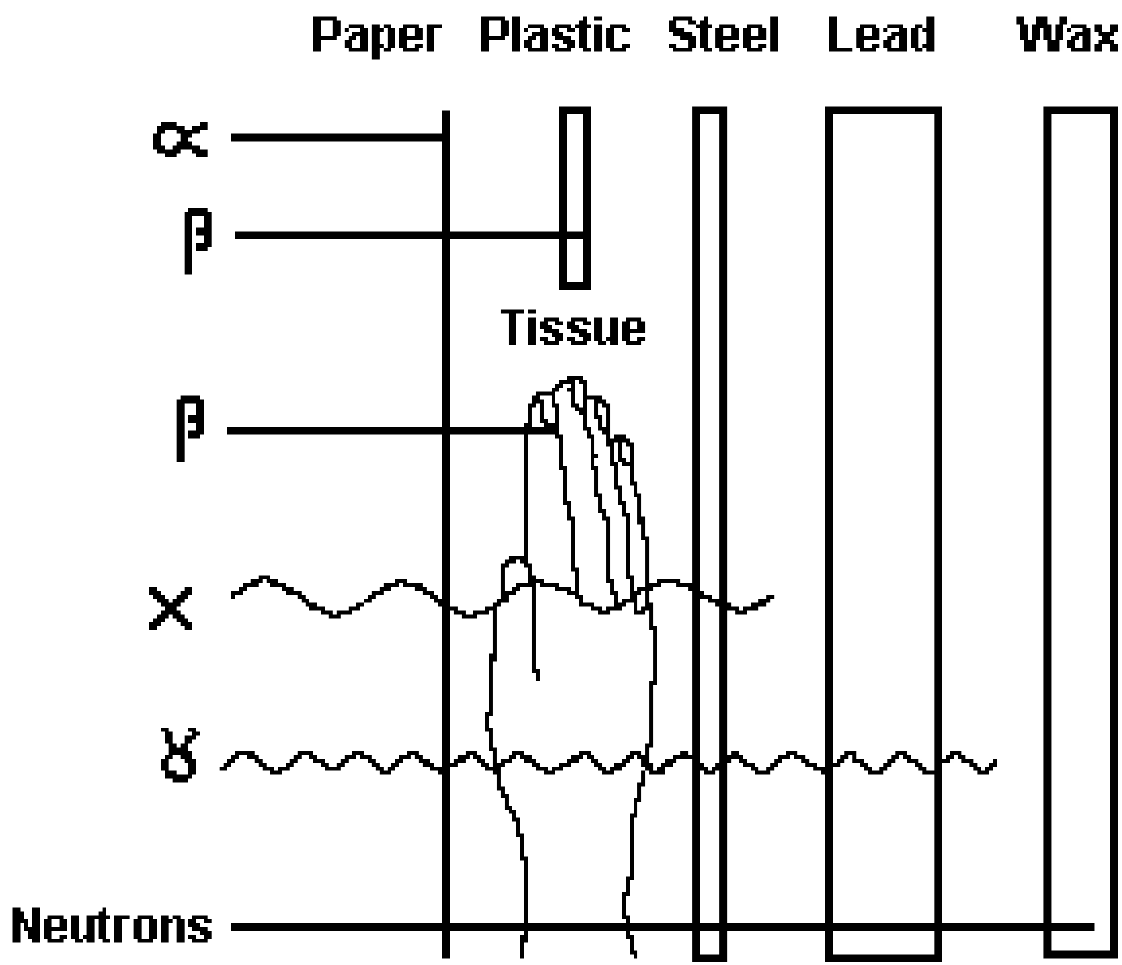


Figure 4.4. Separation of ion clusters in relation to the size of a biological target. (Reproduced from Gray, 1946, *Br. Med. Bull.* by permission of the author.)

Figure taken from Nias, 1997, *An Introduction to Radiobiology, 2nd Ed.*

Penetrating Properties of Radiation



Reproduced from Knief, 1992, *Nuclear Engineering*

Question: Multiple Choice

- A rule of thumb for the penetrating power of radiation is that the relative range for radiation in a specified material decrease from high to low as:

a) Gamma, Beta, Alpha
b) Alpha, Beta, Gamma
c) Alpha, Gamma Beta
d) Beta, Gamma, Alpha

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Absorbed dose

- Radiation damage to matter results from the absorption of energy from radiation.
- The *absorbed dose* is described by the ***deposited energy per unit mass*** of material.
- Applicable to all ionizing radiation, from external or internal sources.

- The cgs unit is the rad, for "*radiation absorbed dose*": 1 rad = 100 ergs/gm

SI units for radiation quantities

- In the late 1980's, Standard International units for radiation were introduced by the European community, which were based on the original units of Curie (radioactive decay rate), rad (deposited energy) and rem (radiation effects in "man").

- Decay rate: Becquerel (Bq): 1Bq = 1 disintegration/second (dps), whereas 1 Curie = 3.7 x 10^{10} dps
- Deposited energy: Gray (Gy): 1 Gy = 100 rads = 1 joule/kg *
- Biological radiation effect: Sievert (Sv): 1 Sv = 100 rem

* Recall 1 erg = 10^{-7} joule

Equivalent Dose

- The upper limit of the RBE for a specific type of radiation is called the **quality factor** (QF) for the radiation.
- Multiplying absorbed dose by the quality factor for the type of radiation gives the effective or **equivalent** dose.

$$\boxed{\text{equivalent dose (rem)} = \text{QF} \times \text{absorbed dose (rad)}}$$

- Equivalent dose in rem is a common unit of measurement for comparing unique exposure events.
- In SI and traditional units:
  - 1Sv (sievert) = D (Gy) x QF
  - 1 rem = D (rad)x QF,   where 1 Sv = 100 rem and 1 Gy = 100 rad

Equivalent Dose

- Because the quality factor is an upper limit, equivalent dose is considered a measure of the potential damage from a radiation exposure.
- Simultaneous doses from multiple types of radiation are additive.
- The weighting factor, determined by the International Commission on Radiation Protection (ICRP), is closely related to the "Quality Factor".

TABLE 9.2 QUALITY FACTORS FOR VARIOUS TYPES OF RADIATION*

Type of radiation	Q	W_R
x-rays and γ-rays	1	1
β-rays, $E_{max} > 0.03$ MeV	1†	
β-rays, $E_{max} < 0.03$ MeV	1.7†	
Naturally occurring α-particles	10	
Heavy recoil nuclei	20	20
Neutrons:		
Thermal to 1 keV	2	5
10 keV	2.5	10
100 keV	7.5	10
500 keV	11	20
1 MeV	11	20
2.5 MeV	9	5
5 MeV	8	5
7 MeV	7	5
10 MeV	6.5	5
14 MeV	7.5	5
20 MeV	8	5
Energy not specified	10	

*Based on 10CFR20 (Q) and ICRP 60 (W_R).
†Recommended in ICRP Publication 9.

Cell Functions

- All cells perform basic tasks:
  - Metabolism: Cells break down complex nutrient molecules to release energy.
  - Reproduction: Cells reproduce by division.
  - Protein synthesis: Protein molecules take part in all biochemical processes in the cell. The cell builds proteins required to perform its specialized tasks of the cell.
- Every cell contains specialized "organelles," which are responsible for performing these tasks.

Every cell is 70% to 90% water

Cell Damage

- Ionization can disrupt any of the three major functions of cells:
  - Metabolism
    - Cell cannot produce the energy that it needs and dies.
  - Protein synthesis
    - Cell cannot create protein needed for cell survival. -or-
    - Cell cannot create protein required for its specialized task; cell is alive but useless.
  - Reproduction
    - Cell cannot reproduce or reproduces incorrectly.

Cell Damage

- Many ionizations within a single cell typically results in enough damage to disrupt metabolism or protein synthesis and immediately kill the cell.
- For radiation damage, this requires a lot of energy to be deposited within a single cell:
  - Direct radiation damage
    - High LET charged particles ionize biological molecules directly.
  - Indirect radiation damage
    - High-energy γ and X-Rays produce strongly oxidizing free-radicals by radiolysis. The free radicals then travel through the cell destroying molecules. Because cells are mostly water, indirect damage due to radiolysis of water is the most common mechanism.

Short-Term Radiation Effects

- Immediate Effects (hours to days)
  - Skin reddening, inflammation
  - Immune suppression
  - Sterility
  - Blood chemistry changes
  - Loss of hair
  - Gastrointestinal syndromes
  - Central nervous system syndromes

Increasing Dose

Long-Term Radiation Effects

- Long term effects (months to years)
  - Cancer / leukemia
  - Cataracts
  - Genetic defects
  - Blood disorders
  - Lifespan shortening
- Scientific consensus on high dose effects.
- Lack of consensus on low dose effects.

Radiation Dose Effects

Equiv Dose Sv (Rem)	Symptoms	Lethality
0.05-0.2 (5-20)	None	0%
0.2-0.5 (20-50)	No external. Temporary reduction in red blood count	0%
0.5-1 (50-100)	Mild radiation sickness	0%
1-2 (100-200)	Nausea and vomiting. Immune system depressed	LD10/30
2-3 (200-300)	Nausea and vomiting. Loss of hair, loss of white blood cells.	LD35/30
3-4 (300-400)	Uncontrollable hemorrhaging	LD50/30
4-6 (400-600)	Widespread internal bleeding. Near shutdown of immune system	LD60/30
6-10 (600-1000)	Complete destruction of bone marrow. Widespread damage to organs	LD100/14
10-50 (1000-5000)	Direct damage to central nervous system. Direct burning damage to skin.	LD100/7
>50 (>5000)	Increased severity of symptoms listed above	LD100/2

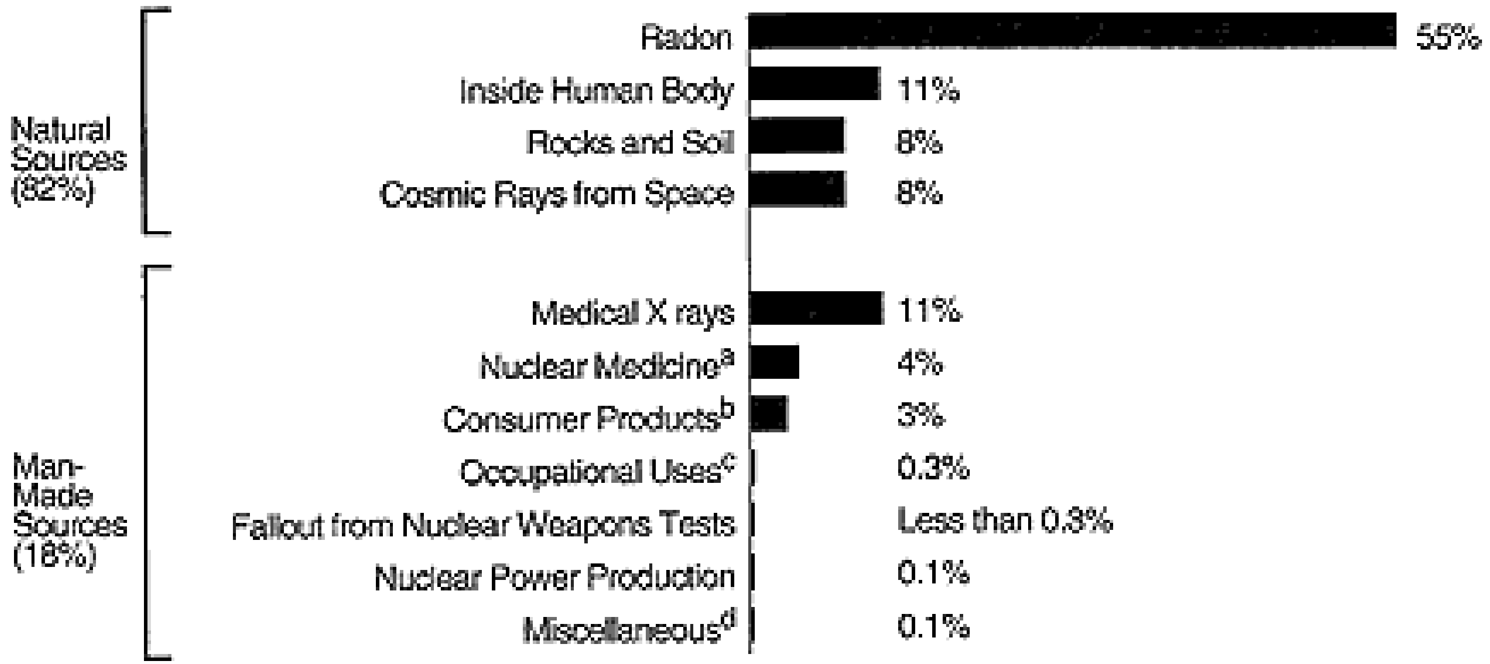
No detectable response
<0.25 Sv (25 rem)

Human
LD 50/30
≈4.5 Sv (450 rem)

Selected data from Wikipedia: “Radiation poisoning”, 8-26-2007, GDFL

*Symptoms are cumulative to maximum equivalent dose received.
† LD xx/yy gives the percentage of fatalities (xx%) within yy days, without medical attention.

Sources of Radiation Exposure



[a] Involves the use of radioactive materials in diagnosing and treating patients with cancer and other diseases.
[b] Building materials, tobacco, mining and agricultural products, water supplies, etc.
[c] Uranium mines, industrial and medical users, etc.
[d] Department of Energy facilities, smelters, transportation, etc.

* Source: National Council on Radiation Protection and Measurements, Report No. 93.
(Total adds up to more than 100% due to rounding off of percentages.)

From: *National Institutes of Health:* *Look up XKCD chart*

External Radiation Standards

- Universal annual radiation dose limits

	Occupational	Public
Whole body	5 rem	0.1 rem
Lens of the eye	15 rem	5 rem
Other tissues	50 rem	5 rem

- Special situations
  - 25 rem “Lifesaving” (on voluntary basis)
  - 10 rem “Equipment/Property saving”
  - Remember: “no observable effects below 25 rem”

Dose Reduction

- How do we optimize radiation exposure to get it as low as reasonably achievable?
- Three basic principles
  - Restrict proximity ***TIME***
    - Dose = Dose Rate × Time
  - Increase the ***DISTANCE*** from the source
    - For example, Point source: "1-over-r-squared" reduction
  - Use ***SHIELDING*** material

Dose Estimates

- Charged particles (α and β)

$$R_p(t) = \frac{Q(t)\, E¢}{m}$$

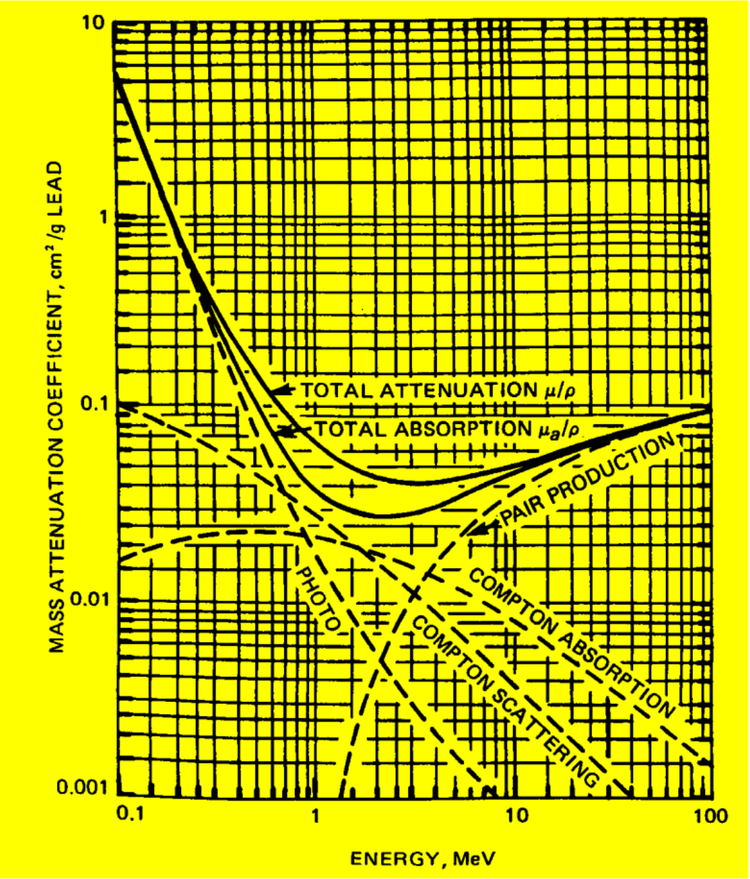
$$Q(t) = Q_0 e^{- / t}$$

- Photons

$$R_g = \mathrm{F}(t)\, E\, \frac{m_a}{r}$$

- Fast Neutrons

$$R_{fn}(t) = \frac{\mathrm{F}(t)\, E\, \mathrm{S}_s\, f}{r} = \frac{\mathrm{F}(t)\, E\, \mathrm{S}_s}{r}\, \frac{2A}{(A+1)^2}$$



Effective Half-Life for isotopes taken internally

- Once a radionuclide has crossed the biological boundary, it will continue to emit radiation and damage nearby tissue until it is removed from the body.
- Two main removal mechanisms:
  - Radioactive decay
    - Eventually all atoms of the radioisotope will decay away.
  - Biological removal
    - The body can flush elements out of the body through normal excretion processes (sweat, tears, urine, feces).

So $\lambda^{eff} = \lambda^{rad} + \lambda^{biol}$; or equivalently:
Half-life: $1/T^{eff} = 1/T^{rad} + 1/T^{biol}$; or
Mean lifetime: $1/T_{1/2}^{eff} = 1/T_{1/2}^{rad} + 1/T_{1/2}^{biol}$

$$N(t) = N_0 e^{-\lambda_r t} e^{-\lambda_b t} = N_0 e^{-(\lambda_r + \lambda_b)t}$$

Radiation Shielding

- Purpose of radiation shielding
  - Protect personnel and/or equipment ("behind" the shield) from radiation exposure
    - Absorb *primary radiation* incident on the shield
    - Reduce primary radiation energy (usually through scattering) to produce *secondary radiation* that is less damaging / easier to absorb.
    - Absorb *secondary radiation* generated within the shield material.

Shielding Effects

- Radiation *Buildup*
  - Absorption/scattering collisions
  - Secondary radiations
- Secondary Radiation
  - Scattered gamma rays
    - Compton scattering
  - Capture gamma rays
    - Neutron capture (n, γ)
  - *Secondary radiation can dominate over primary radiation*

Radiation Shielding

- Alpha / beta radiation
  - Short range, small thickness of any material will work.
  - Requires only simple shielding (Layer of skin / piece of foil).
- Gamma / neutron radiation
  - Extremely penetrating, reaction rates are highly material dependent (preferred shielding materials).
  - Shielding
    - Have to worry about both primary and secondary radiations
    - Usually requires composite shields containing several different materials.

Radiation Shield Types

- Simple
  - Lead — "Hazardous" (toxic), so handle carefully
  - Concrete — General Purpose
  - Water — Research Reactor "Pool"
- Composite (for mixed n, γ radiations)
  - Optimize gamma & neutron attenuation
  - Minimize thickness / weight
- Specialized shields
  - "Lead" Glass for use in shielded "hot cells" that workers must see inside of.

Shield Attenuation

$$\frac{I}{I_0} = \left(\frac{1}{2}\right)^{\left[\frac{x}{X_{1/2}}\right]}$$

Half thickness attenuation formula

$$\frac{I}{I_0} = \left(\frac{1}{10}\right)^{\left[\frac{x}{X_{1/10}}\right]}$$

Tenth thickness attenuation formula

I Intensity
x Distance (Thickness of Shield)

$X_{1/10}$ X_{TT} Tenth Thickness [cm]
$X_{1/2}$ X_{HT} Half thickness [cm]

Tenth Thickness Values

TENTH THICKNESSES (X_{TT}) FOR MATERIALS USED FOR RADIATION SHIELDING

Material	Density [g/cm^3]	Tenth Thickness [cm]		
		Fast Neutrons	Gamma	
			1 MeV	Reactor (w/ Buildup)
Water	1.0	23	34	69
Graphite	1.62	21		44
Be	1.85	21		42
BeO	2.3	21		32
Concrete	2.3-4.3	38-14	17-11	34-18
Al	2.7	23	14	30
Iron	7.8	14	5.1	8.5
Lead	11.3	21	2.9	5.8
Glass	2.7-6.2		15-5.6	
Air	0.0011		0.88 km	

Source: Etherington, 1958