MASTER DI II LIVELLO IN RADIOPROTEZIONE

Neutron attenuation

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Neutron Attenuation

It is practical, useful, and convenient to represent neutron intensity in terms of the number per unit area, either as a fluence (n cm^{-2}) or as a fluence rate or flux (n cm^{-2} s^{-1}).
The interactions that slow neutrons down and cause their eventual removal from a beam are probabilistic; they either occur or they don't.

Consequently, a flux of neutrons of intensity, *I,* will be diminished in a thickness x of absorber proportional to the intensity of the neutron source and the neutron removal coefficient, Σ_{nr} of the absorbing material, or $-dI/dx = \Sigma_{nr} I$ which, like photon attenuation, has the solution

$$I(x) = I_0 e^{-\Sigma_{nr} x}$$

where I_0 is the initial intensity and *I(x)* refers to those neutrons that penetrate a distance x in an absorber without a collision;
therefore, $e^{\Sigma_{nr} x}$

represents the probability that a given neutron travel a distance x without an interaction.

Σ_{nr} in this context resembles the attenuation coefficient for photons in good (or narrow-beam) geometry, and can be similarity developed and used for neutron shielding and dosimetry.

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The features of neutron beams, including the concept of narrow-beam effects, are shown schematically in the following figure.

The various interactions serve to remove a neutron from the beam such that it does not reach the receptor of interest (e.g., a detector or a person).

In this respect, elastic and inelastic scattering interactions deflect neutrons out of the beam, and Σ_{nr} accounts for all the processes that do so. However, neutrons scattered from the narrow beam are likely to undergo other scattering interactions and be deflected back into the beam and reach the receptor.

These more realistic, or poor geometry conditions, are accounted for with a neutron build up factor

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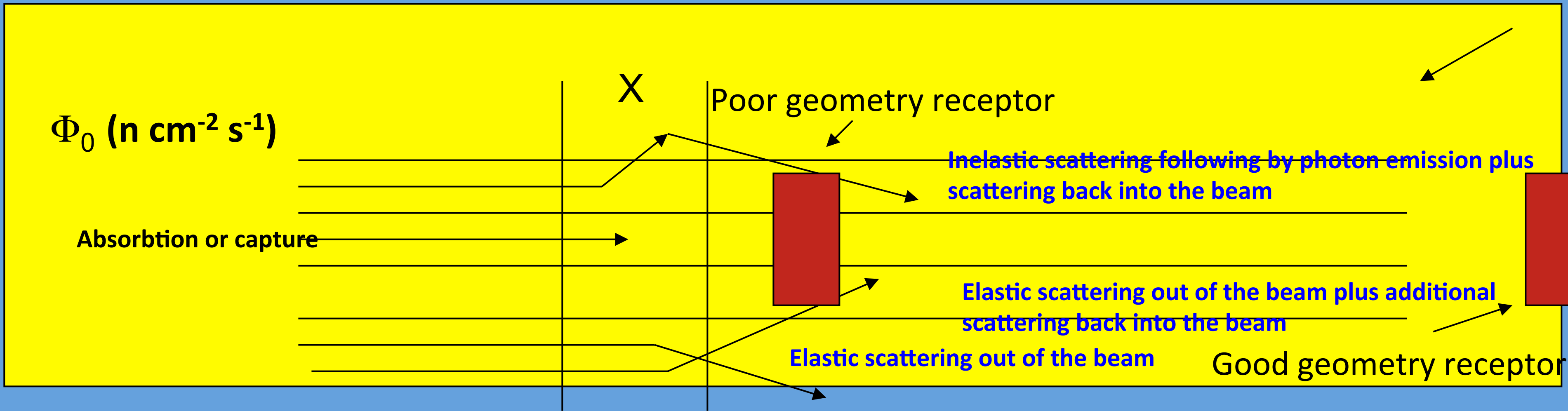

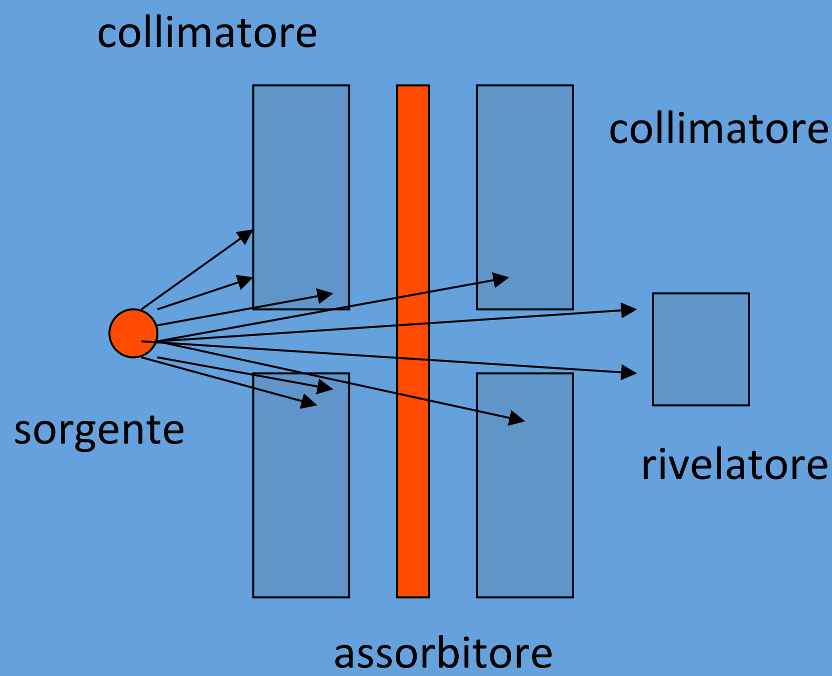

Only in good geometry

$$\phi(x) = \phi_0 e^{-\Sigma_{nr} x}$$

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When no hydrogenous materials are present, **the neutron removal coefficient** Σ_{nr}, *is* determined by the macroscopic cross section, $\Sigma = N\sigma_t$ where N is the number of atoms per cubic centimeters in an absorber and σ_t is the total cross section in barn for each atom (10^{-24} cm^2/atom) in a unit volume of absorber.

Therefore, Σ_{nr} has units of cm^{-1} and is closely related physically to the attenuation coefficient for photons (and the beta absorption coefficient for electrons), and is in fact used in a similar way;
it can be converted to a neutron mass coefficient (cm^2/g) by dividing by the density of the absorber, or

neutron mass coefficient (cm^2/g) $= \Sigma_{nr}/\rho$

A related concept is the mean free path, which is the average distance a neutron of a given energy will travel before it undergoes an interaction. The mean free path can also be thought of as the average thickness of a medium in which an interaction is likely to occur and is similar to the mean life of a radioactive atom. It has the value

Mean free path $= 1/\Sigma_{nr}$

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Neutron Shielding Materials

If the cost and convenience were no criteria, any material in sufficient quantity may be used for shielding against radiation

Many practical constraints limit materials to those most commonly used in construction

- Concrete
- Steel
- Earth

Other materials may be more advantageous under certain circumstances But the following factor should be evaluated

- Thickness and weight
- For shielding and structural purposes
- Effective against photons and neutrons
- Uniformity consistency homogeneity
- Permanence of capability of shielding
- Cost of material
- Cost of installation of material
- Possibility of inducing radioactivity

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Neutron Shielding Materials

Many shielding materials produce capture gamma rays or photons from inelastic scattering interactions. These can be minimized by adding lithium or boron to the shield. Lithium-6, which has a large (n thermal, α) cross section of 941 barn does not yield capture gamma rays by neutron absorption, and the helium and tritium atoms, that are formed, are easily absorbed.

Natural boron contains 20% ^{10}B and is a very effective shielding material for thermal neutrons through $^{10}B(n, \alpha)^7Li$ reactions. About 96% of the ^7Li atoms created in these reactions are in an excited state which is relieved promptly by emission of a 0.48 MeV gamma ray, but these are easier to shield than the 2.225 MeV gamma rays from hydrogen capture and boron is commonly used in neutron shields.

- ***Hydrogenous materials* such as paraffin and water make efficient neutron shields because of the effectiveness of elastic scattering with hydrogen atoms but not without potential problems. Paraffin is flammable, water can leak and evaporate, and thermal neutron capture produces 2.225 MeV gamma rays. When H_20 is used as a neutron shield, it is necessary to prevent leakage, minimize corrosion, and keep contaminants out, which is generally done by demineralization.**

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➢ ***Metals*** **such as lead, iron, tungsten, and depleted uranium are relatively poor shield materials for neutrons; however, they are often used as a gamma shield, especially around nuclear reactors, and their neutron shielding properties are important because of such uses. Lead and iron can produce capture gamma rays of 7.4 and 7.6 MeV, respectively, although with low probability and (n, γ) interactions in ^{58}Fe produce radioactive ^{59}Fe ($T_{1/2}$= 44.51 d), which emits 1.1 and 1.29 MeV gamma rays.**

Tungsten **is dense and is almost as effective as lead as a gamma shield. It is much better than lead for neutron attenuation, although secondary gamma radiation is produced due to capture reactions.**

Depleted uranium, **which is readily available from nuclear fuel enrichment processes, is very dense (ρ = 19 g/cm^3) and is the best attenuator available on a volume basis for gamma rays. Neutron attenuation in U is about the same as in lead, and even though it doesn't produce significant capture gamma rays, fast fission reactions may yield gamma-emitting fission products.**

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Lithium and Boron are often incorporated into neutron shields because of its absorption cross section ^{6}Li (760 barn) and the large (n,γ) cross section of ^{10}B (3840 barn).

The alpha particles from ^{10}B reactions are easily absorbed and the 0.48 MeV gamma rays from the excited ^{7}Li product, which occurs in 96% of the interactions, is not too difficult to shield.

Borax (sodium borate) is a crystalline powdery material that is easily shaped into various shield configurations, is not subject to leakage, and is cheap and effective.

Borated water and borated polyethylene are useful, as are boron oxide, boric acid, and boron carbide (B_4C). A sandwich material called boral is available that consists of an Al-B_4C mixture clad in aluminum. Boron has also been added to various steels to absorb thermal neutrons and reduce activation products and associated gamma rays.

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- Concrete and earth are many times the shield materials of choice for neutron sources, especially around nuclear reactors and accelerators since they are dense, contain hydrogen and other light materials that promote neutron capture, and can be shaped easily.

- Barytes, iron-portland, and Colemanite-aggregate are some of the many varieties of concrete that are used in neutron shields.

- Barytes concrete contains boron for neutron absorption and hydrogen for moderation of fast neutrons; it also is a good gamma shield.

- Colemanite is used as an aggregate and contains hydrated calcium borate, which enhances neutron capture because of the boron it contains.

- Additives that promote neutron capture can be incorporated into concrete; however, care must be taken to assure that cracks, access ports, ducts, or other penetrations do not permit the escape of neutrons.

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- *Polyethylene* is a pure hydrocarbon that contains 18% more hydrogen per unit volume than water (about 8 x 10^{22} atoms of H/cm^3 versus 5.98 x 10^{22} atoms of H/cm^3 for H_2O). Unfortunately, it softens at about 100 ºC and will burn; a more dense (p = 0.96 g/cm^3) variety is available that softens at about 200 ºC but with slightly diminished neutron removal properties. Boron can also be added to polyethylene to absorb thermal neutrons from hydrogen interactions. Water extended polyethylene (or WEP) is a special formulation of polyethylene that is an especially effective neutron shield.

- *Lithium hydride* contains about 12.6% H by weight and is a very effective material for neutron attenuation. It is, however, difficult to fabricate into solid shields. It also actively combines with water, and because of this property needs to be protected from water by encapsulation or other means. Lithium hydroxide is often mixed with water to absorb thermal neutrons and has been used as a burnable reactivity shim in nuclear reactors or added to water shields to absorb thermal neutrons after they are slowed down. Capture reactions in lithium do not produce gamma rays, but absorption of neutrons by ^{6}Li in natural lithium produces tritium, which can be minimized by using lithium depleted in ^{6}Li.

- Cadmium has a high (n, γ) neutron capture cross section (2450 barn) and is frequently used as a neutron absorber, but like hydrogen has the disadvantage of emitting energetic 9.05 MeV capture gamma rays, which themselves require shielding.

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TABLE 4.8—*The elemental composition of representative soils.*[a]

Element	Global Average[b] (Chilton *et al.*, 1984) (percent)	Wilson and Karcher (1966) Average[c] (percent)
Oxygen	43.77	50.2 ± 2.2
Silicon	28.1	26.5 ± 9.2
Aluminum	8.24	6.7 ± 2.9
Iron	5.09	5.5 ± 9.0
Manganese		0.07 ± 0.06
Titanium		0.45 ± 0.43
Calcium	3.65	5.0 ± 6.6
Magnesium	2.11	1.3 ± 1.5
Potassium	2.64	1.4 ± 0.7
Sodium	2.84	0.6 ± 0.5

[a] Based on a dry-weight percentage basis. The total does not add to 100 percent.
[b] This is a mixture approximating the relative abundance of the eight most common elements in Earth's crust.
[c] These are means and standard deviations of compositions of 28 soils selected from throughout the United States.

TABLE 4.9—*Typical compositions of representative concretes after curing (Chilton et al., 1984).*

Concrete Type	Ordinary	Magnetite[a]	Barytes[b]	Magnetite and Steel	Limonite and Steel[c]	Serpentine[d]
Density ($g\ cm^{-3}$)	2.35	3.53	3.35	4.64	4.54	2.1
Element	Partial Density ($g\ cm^{-3}$)					
Hydrogen	0.013	0.011	0.012	0.011	0.031	0.035
Oxygen	1.165	1.168	1.043	0.638	0.708	1.126
Silicon	0.737	0.091	0.035	0.073	0.067	0.460
Calcium	0.194	0.251	0.168	0.258	0.261	0.15
Carbon						0.002
Sodium	0.04					0.009
Magnesium	0.006	0.033	0.004	0.017	0.007	0.297
Aluminum	0.107	0.083	0.014	0.048	0.029	0.042
Sulfur	0.003	0.005	0.361			
Potassium	0.045		0.159		0.004	0.009
Iron	0.029	1.676		3.512	3.421	0.068
Titanium		0.192		0.074		
Chromium		0.006				0.002
Manganese		0.007				
Vanadium		0.011		0.003	0.004	
Barium			1.551			

[a] Magnetite ($FeO \cdot Fe_2O_3$) as aggregate.
[b] Barytes, a $BaSO_4$ ore, as aggregate.
[c] Limonite, a hydrated Fe_2O_3 ore, plus steel punchings, as aggregate.
[d] Serpentine ($3MgO \cdot 2SiO_2 \cdot 2H_2O$) as aggregate; a concrete usable at high temperatures with minimal water loss.

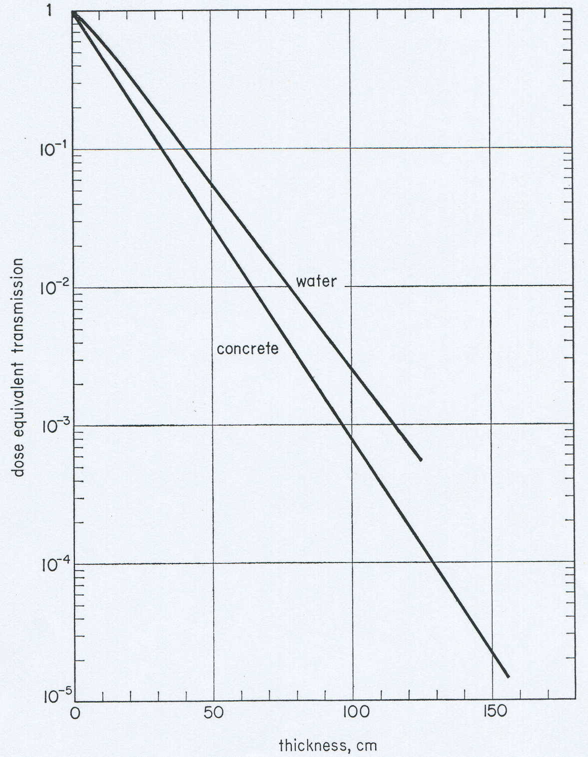

FIG. 19. Broad-beam dose equivalent transmission of 14–15 MeV neutrons through slabs of concrete, density 2.4 g/cm³, and water.

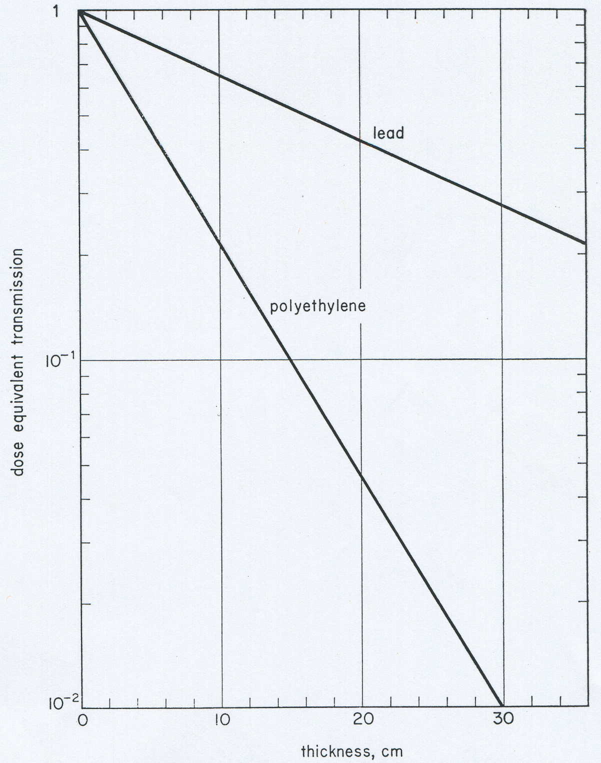

FIG. 22. Broad-beam dose equivalent transmission of ²⁵²Cf neutrons through slabs of lead (density 11.35 g/cm³) and polyethylene (0.96 g/cm³).

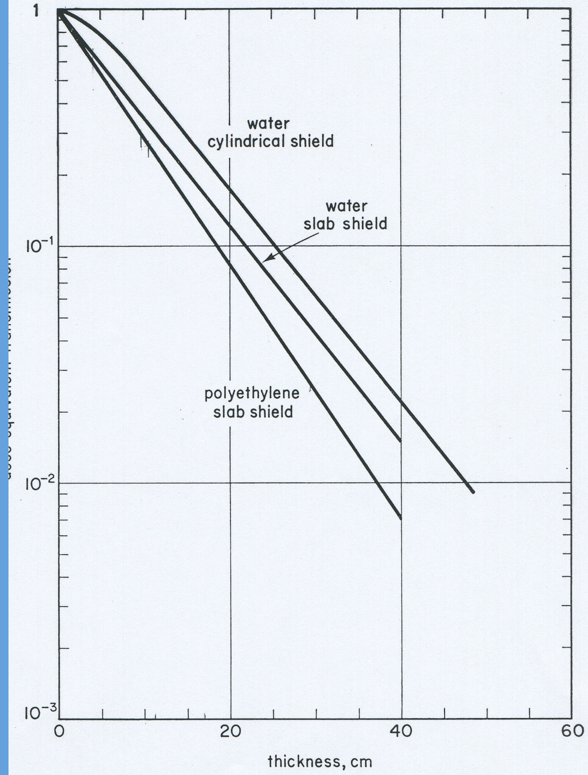

FIG. 21. Broad-beam dose equivalent transmission of ²⁴¹Am–Be neutrons through water and through polyethylene, density 0.94 g/cm³.

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