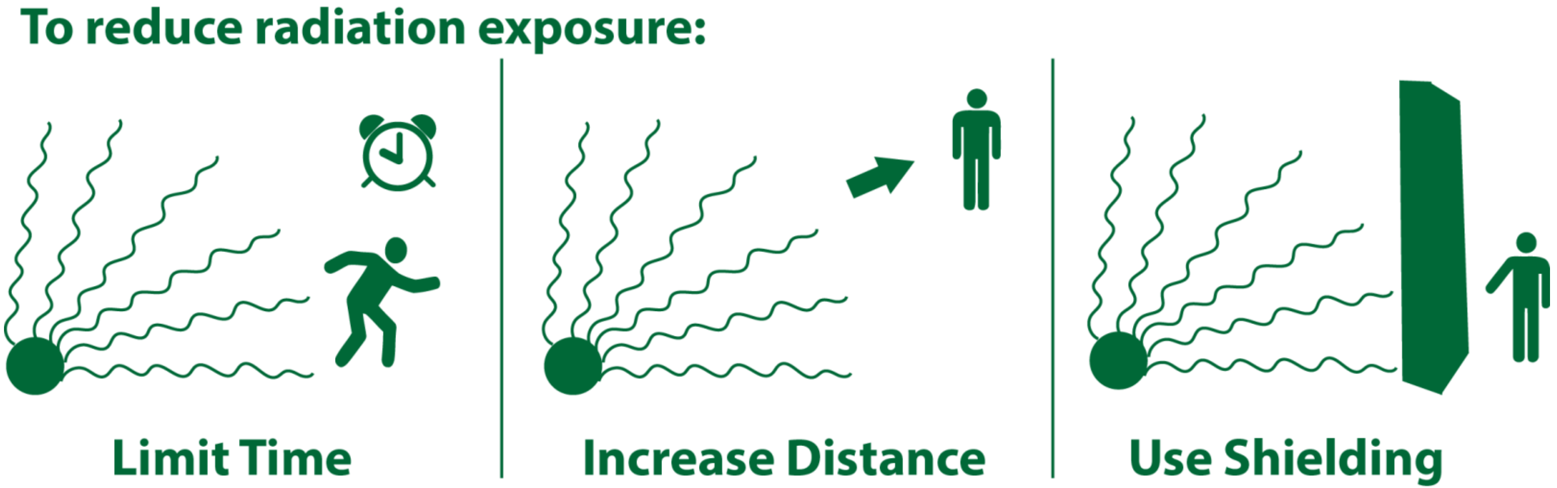
Radiation Biology, Protection and Applications

Radiation Shielding



https://www.epa.gov/radiation/protecting-yourself-radiation

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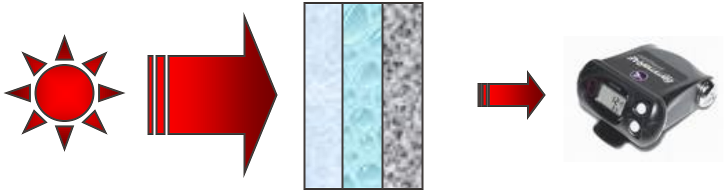
Radiation Shielding: Outline

- ☐ Concept and Basics
- ☐ Shielding of Alphas and Heavy Charged Particles
- ☐ Shielding of Beta Sources
- ☐ Shielding of Photons
  - Attenuation of narrow beams
  - Attenuation of broad beams: scattering and buildup factors
  - Distributed Sources
- ☐ Shielding of Protons and Light Ion Sources
- ☐ Shielding of Neutrons
- ☐ Monte Carlo Methods

The Concept of Radiation Shielding

- ☐ Purpose of radiation shielding:
  - Reduce the radiation exposure to persons and equipment (obvious).
- ☐ Radiation shielding design is **based upon the mechanisms by which different radiations interact** in an absorbing medium.
- ☐ **Radiation shielding is** a very **complex** discipline:
  - There are many radiation sources.
  - There is a wealth of materials and geometric configurations.



Source of Radiation **Source Intensity** **Shielding Material** **Attenuated Intensity**

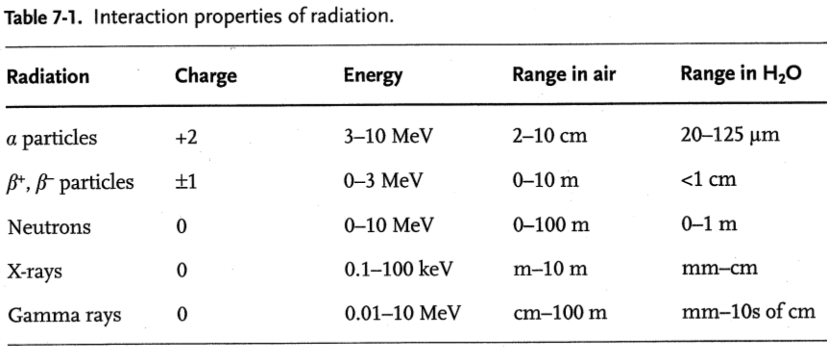
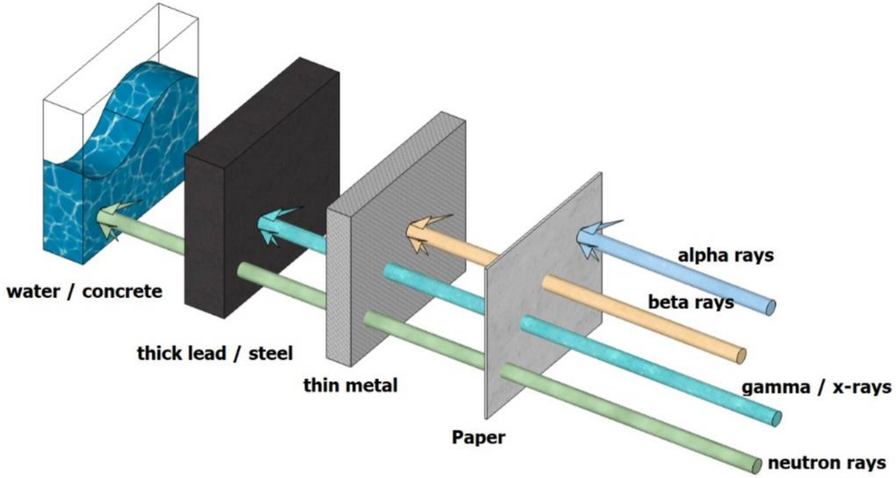
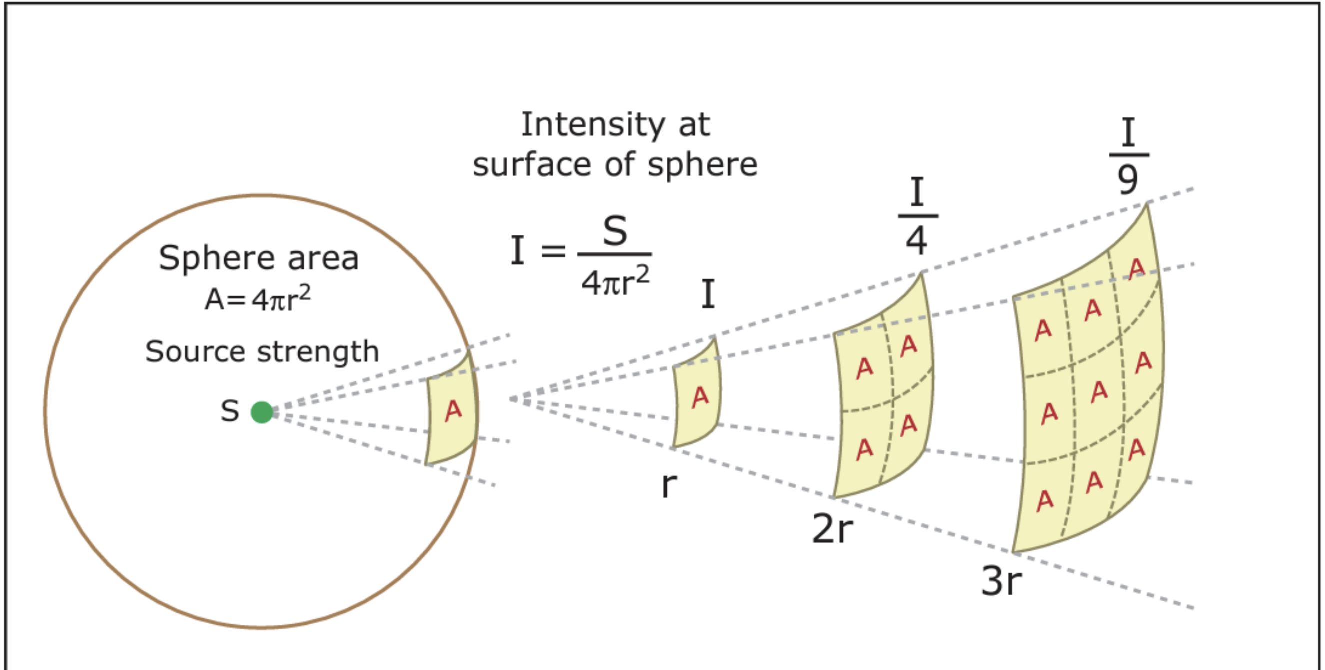


Table 7-1. Interaction properties of radiation.

Radiation	Charge	Energy	Range in air	Range in H_2O
α particles	+2	3–10 MeV	2–10 cm	20–125 μm
β^+, β^- particles	±1	0–3 MeV	0–10 m	<1 cm
Neutrons	0	0–10 MeV	0–100 m	0–1 m
X-rays	0	0.1–100 keV	m–10 m	mm–cm
Gamma rays	0	0.01–10 MeV	cm–100 m	mm–10s of cm



Reminder: Distance



Inverse square law: Doubling the distance from source, the energy is spread over four times the area, so intensity falls to one-fourth.

Image by MIT OpenCourseWare. After Hyperphysics.

Radiation Dose and Units (Reminder)

- The radiation **absorbed dose D** is the mean energy imparted to matter of mass M: $D=dE/dM$, unit gray, $1Gy=1J/kg$ (=100 rads, old unit).
- The radiation **dose equivalent H** is the product of the absorbed dose D and the quality factor w_R (or Q) characterizing the damage associated with each type of radiation: $H=w_R \cdot D$, unit Sievert, $1Sv=1Gy \cdot w_R$ (=100rem, old unit).
  - $w_R = Q = 1$ for X-rays, γ-rays, electrons
  - $w_R = Q = 20$ for α
  - $w_R = Q$ [2,10] for neutrons
- The **effective dose ε** is the equivalent dose H_T in organ or tissue T multiplied with a weight factor w_T describing the sensitivity of the tissue to radiation: $\varepsilon=\Sigma w_T \cdot H_T=\Sigma w_T\, \Sigma w_R \cdot D_{T,R}$
- Usually dose and exposure **rates** (per s, min, h) are of most interest !

More Basic Terms

- **Stopping Power** is defined as the total loss of energy from a particle over a path length dx:

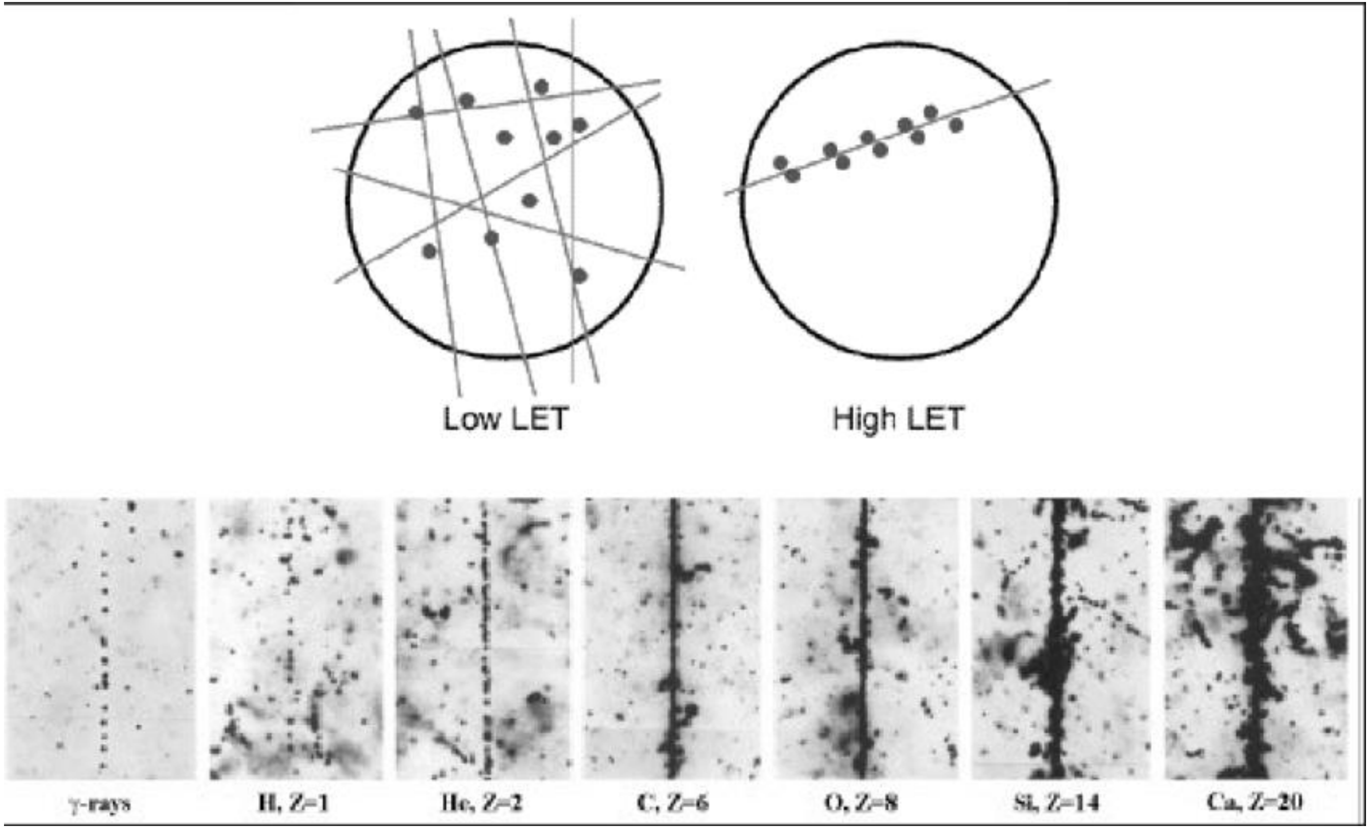
$$S = \left(-\frac{dE}{dx}\right)_{col} + \left(-\frac{dE}{dx}\right)_{rad}$$

Linear Energy Transfer →

← **Energy Loss by Radiation**

- **Linear Energy Transfer** (**LET**) is defined as the energy imparted to the medium per path length:
  - LET increases with MASS and CHARGE of the particle, e.g., LET of 1 MeV α in water is about 90 keV/μm, but for a 1 MeV electron it is only ~0.19 keV/μm.
  - High LET radiation: α-particles, fission products, heavy ions.
  - Low LET radiation: electrons, protons and positrons.
  - Neutrons are **High LET** (produce heavy ions), photons are **Low LET** (produce e^-).
- **KERMA** (kinetic energy released in material) is the energy transferred to matter per mass, $K=dE_{kin}/dM$, unit 1Gy=1J/kg. (Easy to measure and compute.)
- Note: KERMA ≥ absorbed Dose
  - (for low energies they are almost equal, for high energies secondary radiation often escapes the observed material)

Radiographic film exposure with different LET



C.F. Powell, P.H. Fowler, D.H. Perkins (Eds.) The study of elementary Particles by the Photographic Method, Pergamon Press, London New York Paris Los Angeles, 1959, pp. 669.

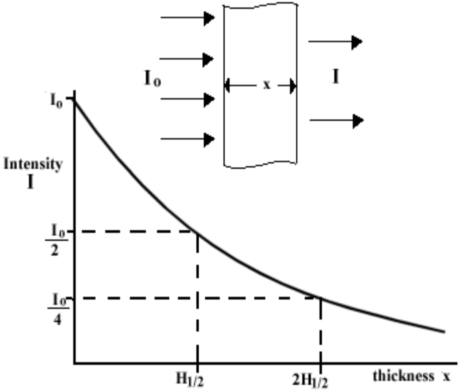
Attenuation and Range

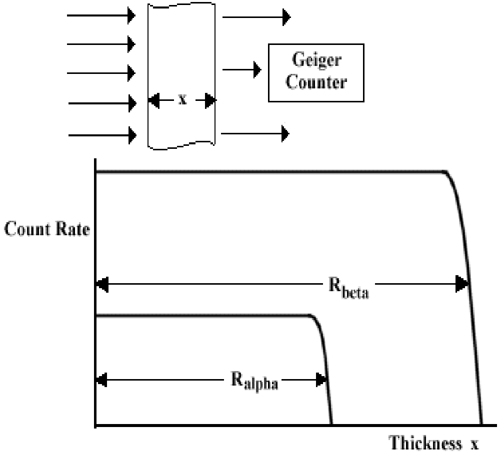
❑ Attenuation:

- A **reduction in intensity** of radiation with respect to distance traveled through a medium.

❑ Range $R_{particle}$:

- In passing through matter, charged particles ionize and thus lose energy in many steps, until their **energy is** (almost) **zero**. The distance to this point is called the range of the particle.
- The range depends on:
  1. The type of particle,
  2. its initial energy and
  3. the material which it passes through.
- The mean range can be calculated by integrating the inverse of the stopping power over energy.





Interaction of Alpha (and Heavy Charged) Particles

- The specific ionization of alpha particles follows a **Bragg curve**.
- Alphas are monoenergetic.
  - Each particle has the same range R_α in the medium.
  - Straggling may occur.
- R_a in cm of standard air is empirically given by (E_α in MeV):

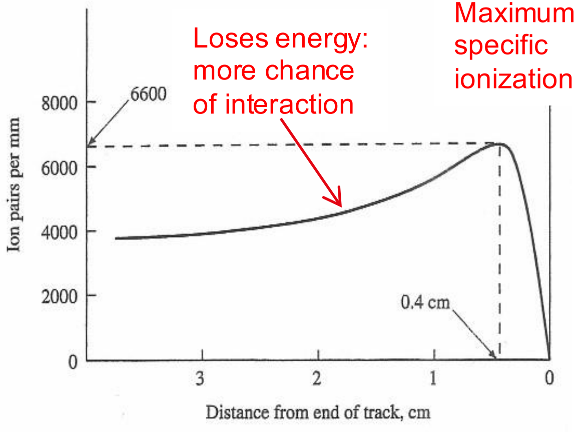
$$\boxed{R_a = 0.325\, E_\alpha^{3/2}}$$

- Its range in another medium can be estimated by the Bragg-Kleeman rule:

$$\boxed{R = R_a\left(\frac{\rho_a}{\rho}\right)\sqrt{\frac{M}{M_a}} = 3.2\cdot10^{-4}\,\frac{\sqrt{M}}{\rho}\,R_a}$$

- For biological tissue R_t is approximately:

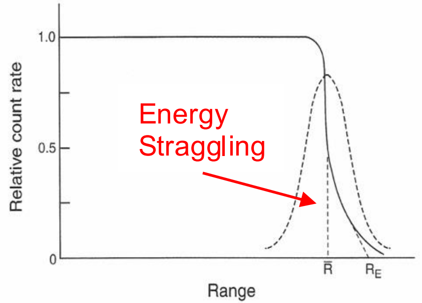
$$\boxed{R_t \approx \frac{\rho_a}{\rho_t}\,R_a}$$



Loses energy: more chance of interaction

Maximum specific ionization

Specific ionization of an α-particle in air.



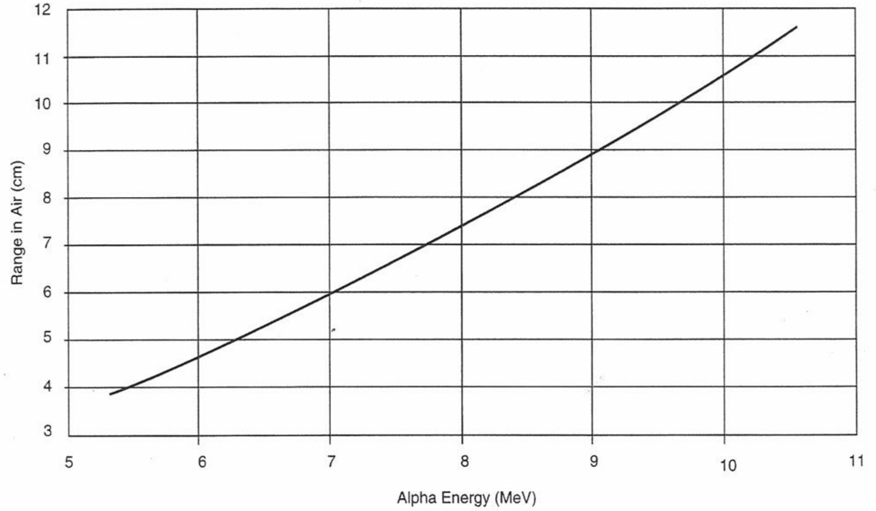
Energy Straggling

Range in air of a collimated monoenergetic source of alpha particles showing straggling that is normally distributed about the mean range at $\bar{R}$. An extrapolated range, R_E, can be obtained by extending the straight-line portion of the curve to the x-axis.

Shielding of Alpha (and Heavy Charged Particle) Sources

- ☐ Alpha particles are easy to shield due to their short and well predictable range.
- ☐ External radiation:
  - Absorbed by very **thin** layers of dense materials (range generally less than 1mm).
  - Stopped by dead skin layer.
- ☐ Internal Radiation:
  - Considerable damage to biological tissue: Large ionization.
  - High LET radiation.
- ☐ **“α-Shielding”: avoid spread and contact.**
- ☐ Very short range makes detection difficult:
  - Detector windows must be thin.
  - Highly contaminated areas may be missed by failing to get close enough.
- ☐ **Use proper detectors for alpha radiation!**
- ☐ Heavy charged particles have even shorter ranges!

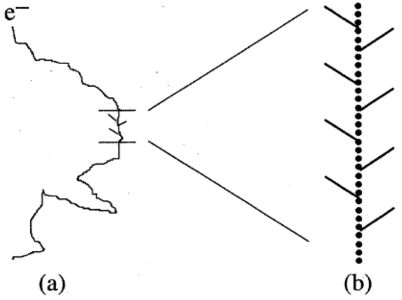
Range almost linear



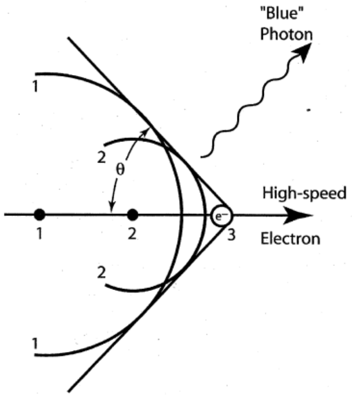
Range versus energy of alpha particles in air.

Interaction of Beta Particles with Matter

- Beta particles lose energy to a medium in four ways:
  - Direct ionization.
  - “Delta” rays from electrons ejected by ionization.
  - Bremsstrahlung.
  - Cherenkov radiation.
- Ionization:
  - Eject K,L or M shell electrons: characteristic X-rays are produced.
  - Beta particle paths are tortuous: low LET and stopping power.
  - Secondary ionizations are produced by “delta”-rays.
- Bremsstrahlung:
  - Continuous energy spectrum.
  - Important at high Z: up to 10% of 2 MeV β energy in Pb.
  - In tissue less than 1% is Bremsstrahlung with low probability of interaction (low Z).
- Cherenkov radiation: caused by high-speed beta particles in media if (v/c)>(1/n), n=refractive index of the medium.

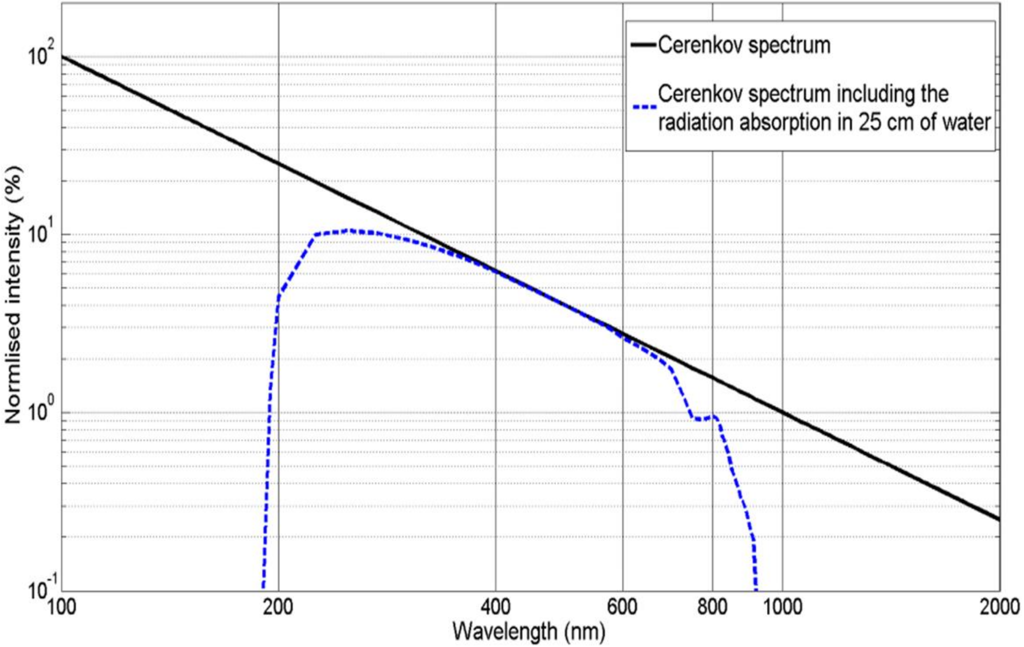


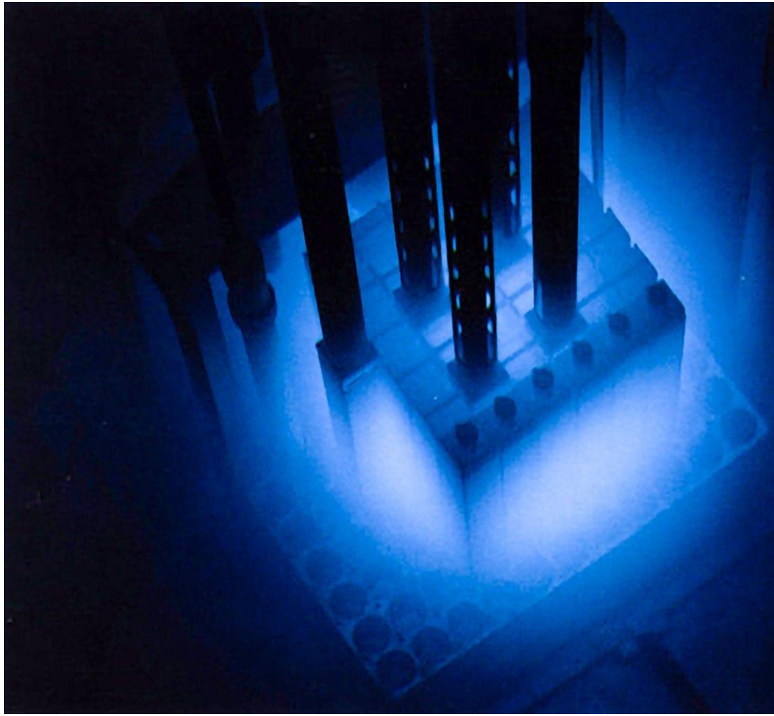
(a) Range and ionization path of a beta particle in an absorbing medium; (b) amplified segment of ionization track showing delta ray tracks produced by ejected electrons.



Wavefronts produced by a particle with velocity ≥ c/n constructively interfere to produce blue photons of light, or Cerenkov radiation.

Do you need to shield yourself from Cherenkov?



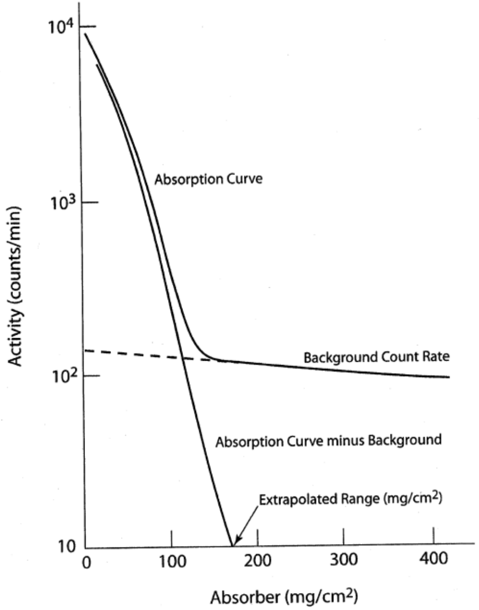


Typically: Not if there is water, like in a reactor.
Otherwise: UV radiation

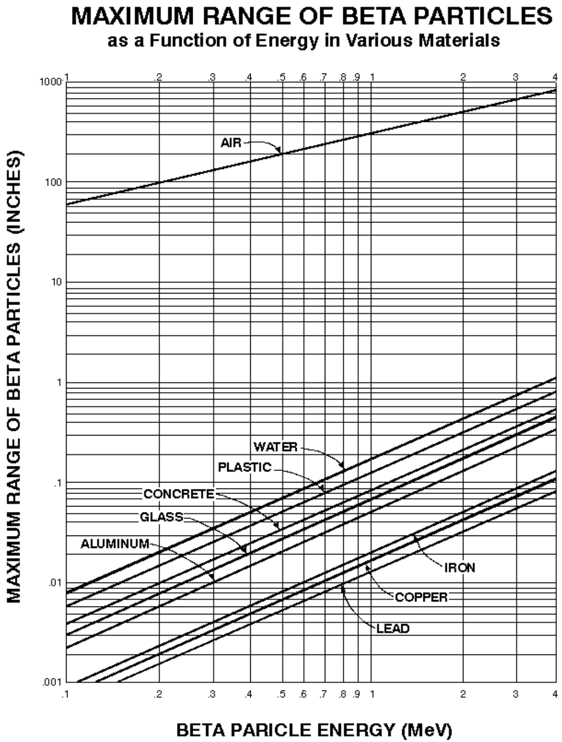
Attenuation and Range of Beta Particles

- The attenuation of beta particles in a medium is exponential:
- The range of beta particles is short (m in air, mm in dense materials)
- Depends on their kinetic energy E and Z of the material.

$$I(x)=I_0\, e^{-\mu_{\beta,i}(\rho x)}$$



Decrease in measured activity of a beta particle source versus mg/cm^2 of absorber thickness that trails off into the background of the detector system. Subtraction of the background portion from the total curve yields a curve that can be extrapolated to estimate the maximum range (in mg/cm^2) of the beta source.



Shielding of Beta Sources (empirical formulas)

- The intensity of a beta source is: $I(x) = I_0\, e^{-\mu_{\beta,i}(\rho x)}$
  - Approximations for the mass attenuation coeff. $m_{\beta,i}$ (in units of cm^2/g) in some media as a function of the maximum β-particle energy $E_{\beta,max}$ (in units of MeV) are given by:

$$\mu_{\beta,air} = 16\,(E_{\beta,\max} - 0.036)^{-1.4}$$

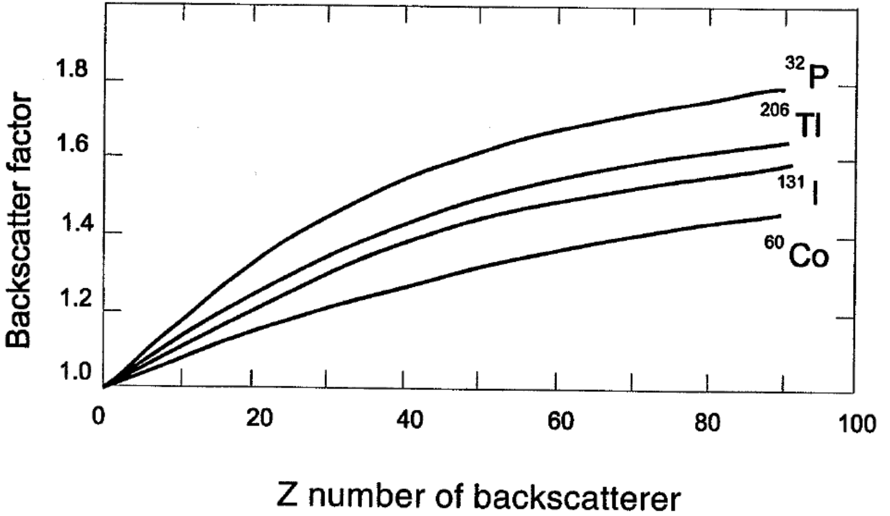
$$\mu_{\beta,tissue} = 18.6\,(E_{\beta,\max} - 0.036)^{-1.37}$$

$$\mu_{\beta,solid} = 17\,(E_{\beta,\max})^{-1.14}$$

- All attenuating materials between the source and the receptor must be considered, as well as geometric configuration and backscatter.
- External exposure: Shields are chosen “a bit” thicker than maximum range of most energetic β.
- Internal exposure: Prevent ingestion & control surfaces (**smear tests**).

Basics (Supplement): Backscattering

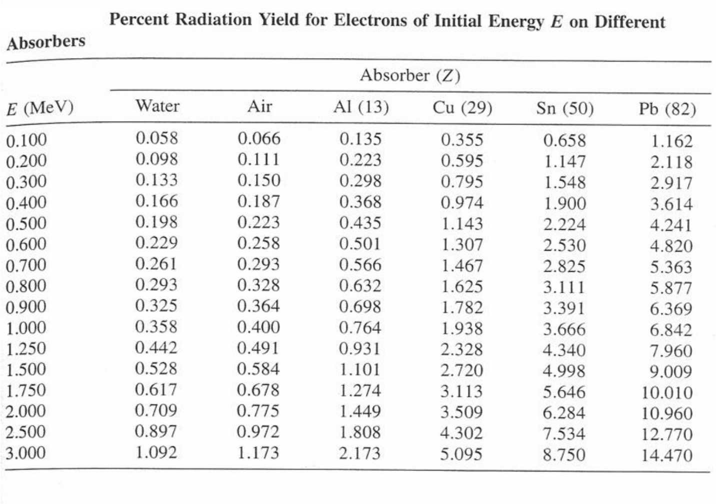
- ☐ Backscatter may occur for all sorts of radiation, however with different intensities.
- ☐ Backscattering most efficient for identical scattering partners or partners with similar mass:
  - **β-radiation is backscattered with intensity ~ Z**
  - **neutrons are effectively backscattered by Hydrogen**
- ☐ Backscattering depends also on the geometry (incident angle on surface) and the energy of the radiation beam.
- ☐ The backscattering material should not transmit radiation, i.e. must have saturation thickness.



Backscatter factors (relative values), for β particles emitted from ^{32}P (695 keV), ^{206}Tl (540 keV), ^{131}I (182 keV), ^{60}Co (96 keV), as functions of the *Z* number of the backscatterer. The energies are the averages of each particle spectrum (based on Shapiro, 1972, Figure 4.4).

Shielding of Beta Sources with Bremsstrahlung

- Important for high Z materials.
- Shield design must account for the fraction Y_i of total energy transformed into photons by Bremsstrahlung.
- Empirical formulas and tables are based on monoenergetic e^-.
- For β sources it is difficult to compute accurate bremsstrahlung yields Y_i:
  - Continuous energy spectra.
  - Average β-energy is ~1/3 $E_{\beta,max}$.
  - Empirical relations were developed for Y_i.
  - Adjustment: multiply Y_i calculated for monoenergetic $E=E_{max}$ on an absorber by a factor of 0.3
- High Z materials (Pb) should not be used for high activity sources (^{32}P, ^{90}Sr-Y)
  - Stop β with low Z element (plastic, Al).
  - Use high Z to trap any Bremsstrahlung γ.



Percent Radiation Yield for Electrons of Initial Energy *E* on Different Absorbers

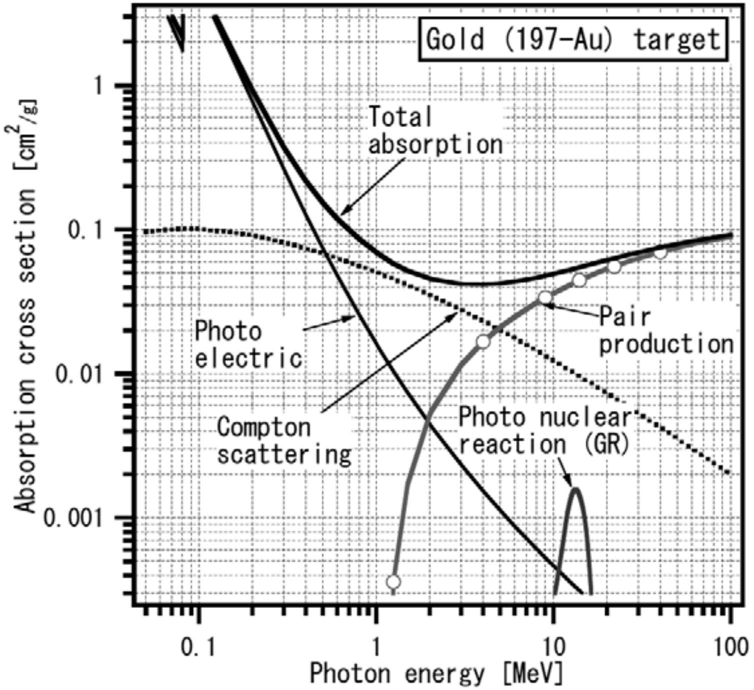
	Absorber (*Z*)					
E (MeV)	Water	Air	Al (13)	Cu (29)	Sn (50)	Pb (82)
0.100	0.058	0.066	0.135	0.355	0.658	1.162
0.200	0.098	0.111	0.223	0.595	1.147	2.118
0.300	0.133	0.150	0.298	0.795	1.548	2.917
0.400	0.166	0.187	0.368	0.974	1.900	3.614
0.500	0.198	0.223	0.435	1.143	2.224	4.241
0.600	0.229	0.258	0.501	1.307	2.530	4.820
0.700	0.261	0.293	0.566	1.467	2.825	5.363
0.800	0.293	0.328	0.632	1.625	3.111	5.877
0.900	0.325	0.364	0.698	1.782	3.391	6.369
1.000	0.358	0.400	0.764	1.938	3.666	6.842
1.250	0.442	0.491	0.931	2.328	4.340	7.960
1.500	0.528	0.584	1.101	2.720	4.998	9.009
1.750	0.617	0.678	1.274	3.113	5.646	10.010
2.000	0.709	0.775	1.449	3.509	6.284	10.960
2.500	0.897	0.972	1.808	4.302	7.534	12.770
3.000	1.092	1.173	2.173	5.095	8.750	14.470

$$Y_i = \frac{6 \cdot 10^{-4}\, E_{\beta,max}\, Z}{1 + 6 \cdot 10^{-4}\, E_{\beta,max}\, Z}$$

10 min break

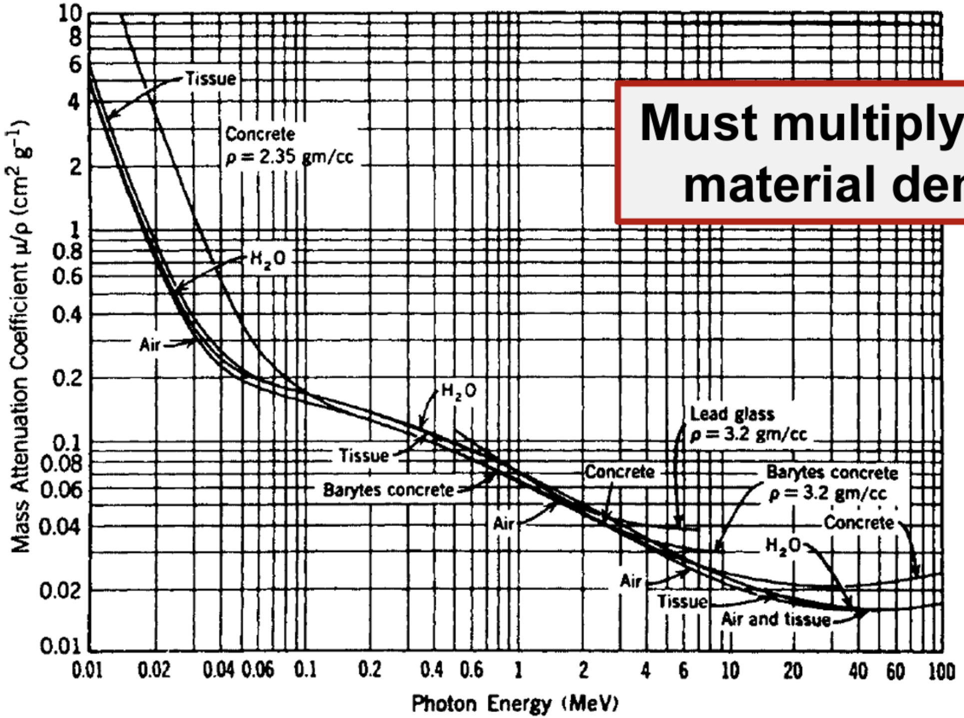
Interaction of Photons with Matter

- Photons lose energy interacting with matter **mainly** by:
  - **Photoelectric effect (low energy < 0.5 MeV), $\sigma_{pe} \sim Z^n/E^3$ (n=4-5)**
  - **Compton Scattering (medium energy 0.5-1.0 MeV), $\sigma_C \sim Z/E$**
  - **Pair Production (high energy > 1.022 MeV), $\sigma_{pp} \sim Z^2 \cdot (E-1.022)$**
- Attenuation coeff.: $\mu_{tot}=\mu_{pe}+\mu_C+\mu_{pp}$
  - Linear attenuation coefficient: $\mu=N \cdot \sigma$
  - Mass attenuation coefficient: $\mu_m=\mu/\rho$



Attenuation Coefficients

Note μ has units of cm^{-1}, yet tables give values in units of $\frac{cm^2}{g}$



Must multiply by the material density!

Source: Morgan, K. Z., and J. E. Turner, eds. *Principles of Radiation Protection*. Wiley, 1967.

How do you deal with multicomponent materials?

Composites, alloys, foams, concrete…

$$N(x) = N_0 e^{-\left(\frac{\mu}{\rho}\right)\rho x} \quad \Rightarrow \quad N(x) = N_0 e^{-\sum_{i=1}^{n}\left[\left(\frac{\mu}{\rho}\right)_i \rho_i\right]x}$$

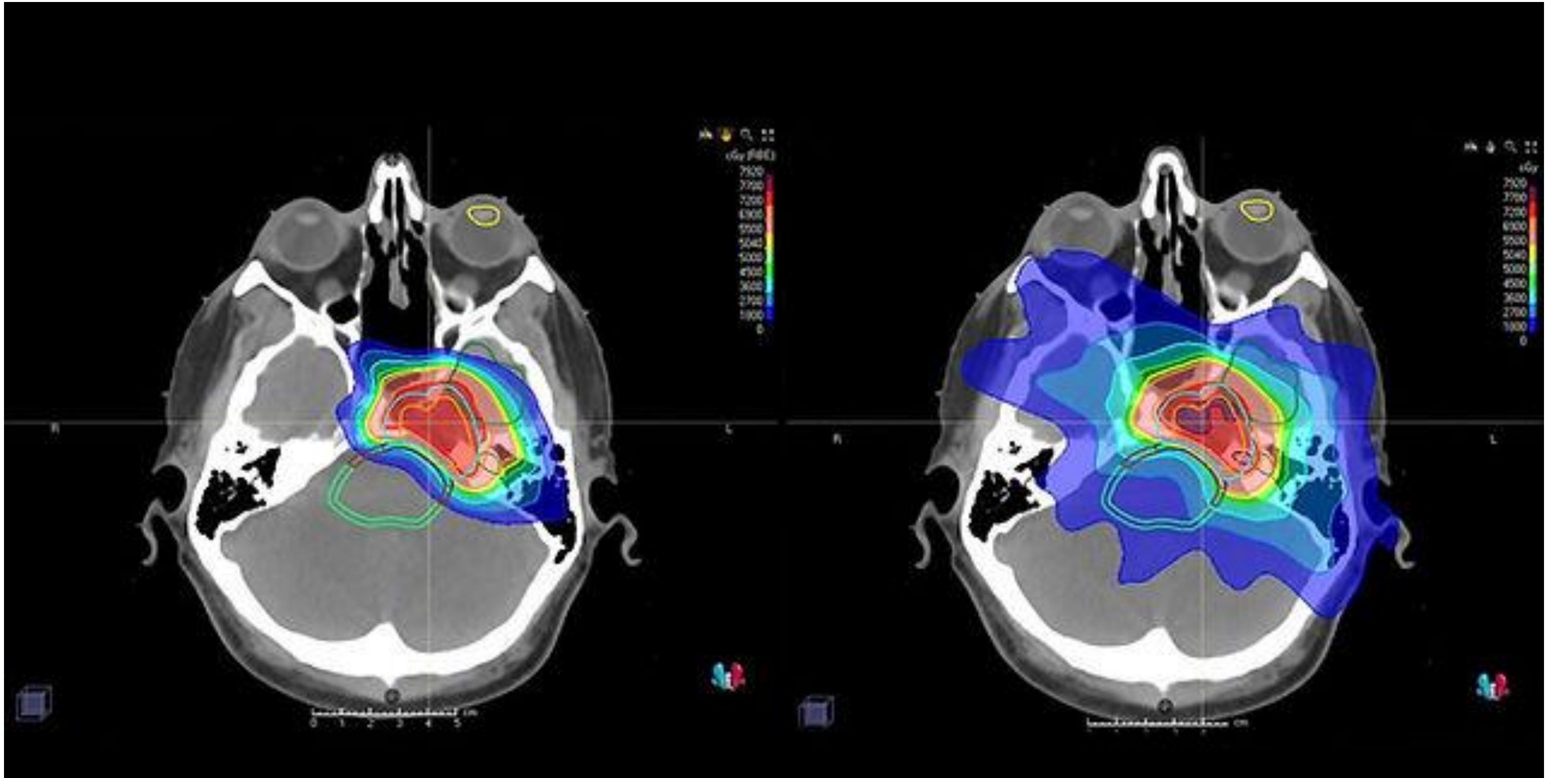
Each component *i* combines additively in the exponential

Now, where to find values of $\left(\frac{\mu}{\rho}\right)$?

http://www.nist.gov/pml/data/xraycoef/index.cfm

NIST (National Institute of Standards and Technology) maintains an active database!

Range vs. Attenuation



Patient brain scans show how proton therapy (left) specifically targets tumors with minimal radiation going to surrounding tissue and structures, whereas traditional photon radiation (right) can damage surrounding tissues and structures.

https://www.theuglycword.com/post/proton-v-photon-radiation-therapy

BJC

MINIREVIEW

British Journal of Cancer (2013) 108, 1225–1230 | doi: 10.1038/bjc.2013.100

Keywords: proton beam; radiation; prostate cancer; quality of life; cost; evidence

Proton beam therapy and localised prostate cancer: current status and controversies

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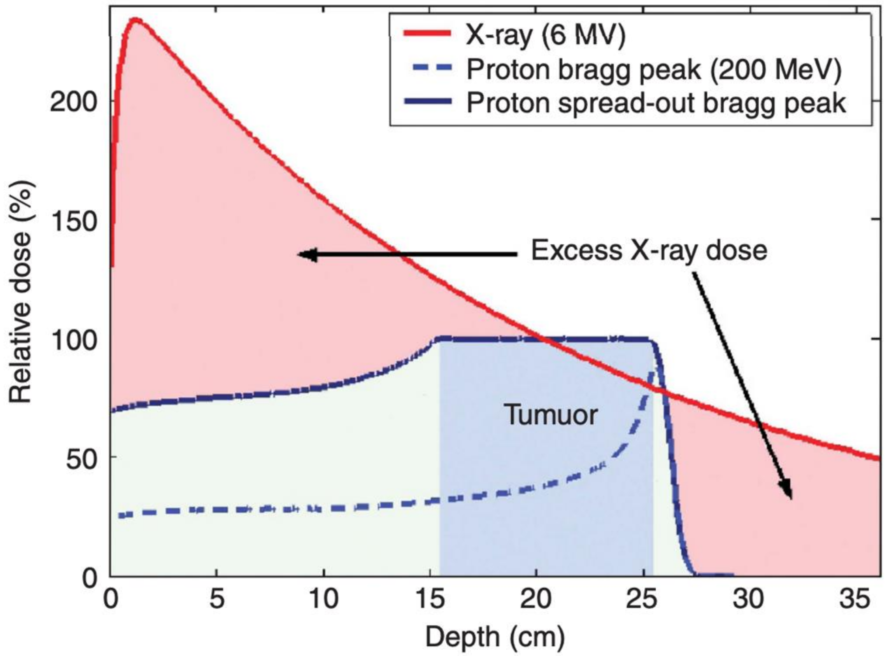
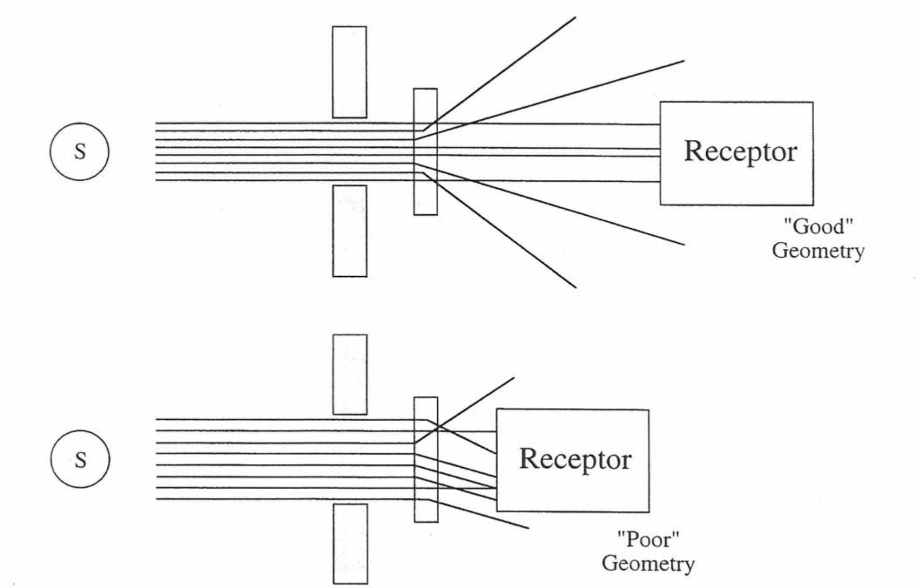


Figure 1. Radiation dose delivered at a certain depth in the body for a X-ray photon beam (red), the Bragg peak of an individual proton beam (dashed blue), and a spread-out Bragg peak combining multiple proton beams to cover the target (solid blue). The excess X-ray dose at entrance and at exit is highlighted.

Attenuation of Photon Sources depends on “Geometry”

❑ Commonly used terms: “Good” and “Bad” geometry

- **“Good” geometry** (**narrow-beam**): Mostly non-scattered (primary) photons reach the target.
- **“Bad”** (**broad-beam**) **geometry**: Significant amount of scattered (secondary) photons of lower energy can reach the receptor → complex energy spectrum.
- Shield design must tend to “good” geometry.



Shielding of Good Geometry Photons

- ☐ The attenuation obeys an exponential law:
- ☐ The attenuation coefficient μ (cm^{-1}) is the sum for all interactions:
  - Depends on photon energy and Z of the absorber medium:
    - => Pb is often used as shield for X-rays.
  - μ grows with Z because of rising importance of photoelectric effect and pair production.
- ☐ Tables for μ and μ/ρ in various materials exist.
- ☐ Half-and Tenth-Value Layers:
  - HVL: Intensity decreased by half
  - TVL: Intensity decreased by ten.
  - Used for fast estimations of dose and shielding.

Attenuation of Photons

$$\boxed{I(x) = I_0\, e^{-\mu x}}$$

Half-Value Layer (HVL)

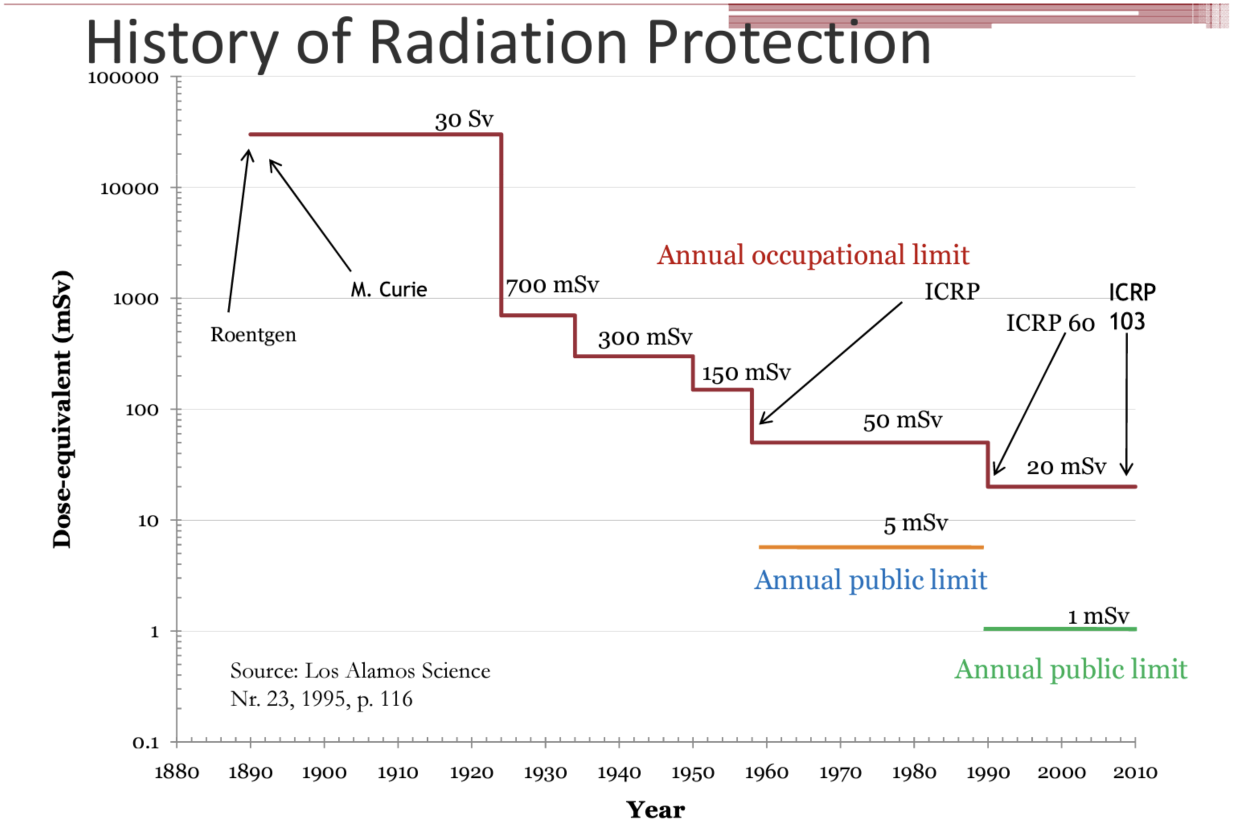
$$\boxed{\frac{I(x_{1/2})}{I_o} = \frac{1}{2} = e^{-\mu x_{1/2}}}$$

$$\boxed{x_{1/2} = \mathrm{HVL} = \frac{\ln 2}{\mu}}$$

Tenth-Value Layer (TVL)

$$\boxed{x_{1/10} = \mathrm{TVL} = \frac{\ln 10}{\mu}}$$

Trivia



History of Radiation Protection

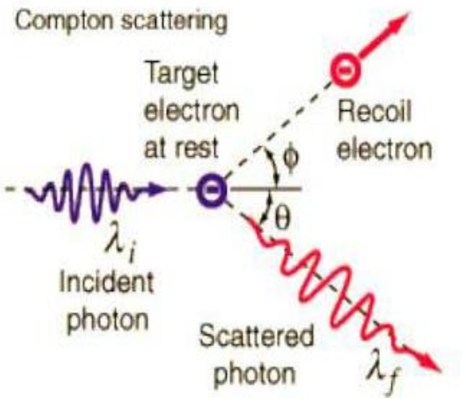
Source: Los Alamos Science
Nr. 23, 1995, p. 116

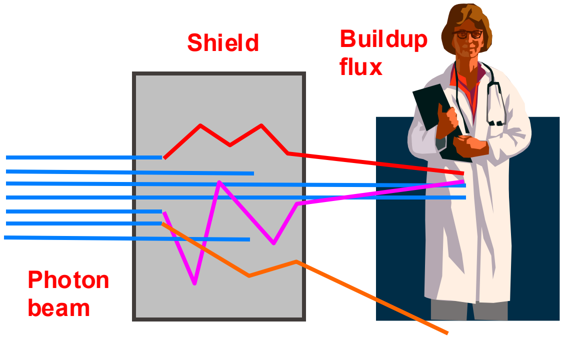
INTERNATIONAL COMMISSION ON
RADIOLOGICAL PROTECTION

Shielding of Photons with Scattering (1)

- Problem: Thick shields produce large amount of lower-energy scattered photons.
- The flux of photons reaching the receptor is a function of:
  - Beam size.
  - Photon energy distribution.
  - Absorber material.
  - Geometry.
- I(x) based only on μ underestimates the flux reaching the receptor.

Shield design MUST account for scattered photons.





Shielding of Photons with Scattering (2)

- The effect of scattered photons is accounted for by using a buildup factor B > 1.
- The radiation intensity with buildup is:

$$\boxed{I(x) = I_0\, B(E, \mu x)\, e^{-\mu x}}$$

- Buildup factors are determined experimentally and tabulated for point sources.
- B depends on:
  - The absorbing medium *Z*.
  - The photon energy *E*.
  - The attenuation coefficient μ.
  - The absorber thickness *x*.
- Mathematical approximations for B have been developed from fits to the experimental data for particular absorbers and E_{photon}.

Mathematical Formulations:

Taylor Form *(caution for low energy and Z)*

$$\boxed{B(E, \mu x) = A e^{-\alpha_1 \mu x} + (1 - A) e^{-\alpha_2 \mu x}}$$

Single Term Taylor Form, precise for *(3< μx < 8)*

$$\boxed{B(E, \mu x) \approx A_1\, e^{-\alpha_x \mu x}}$$

Linear Form *(generally acceptable results)*

$$\boxed{B(E, \mu x) = 1 + \alpha_l (\mu x)}$$

Shielding of Photons for Distributed Sources: Point Kernel

- Many shielding calculations are easy once the flux is known.
- For a point source, the flux at a location *r* attenuated by an absorber μx is given by:

$$\boxed{\phi(x,r)=\phi_o\,\frac{e^{-\mu x}}{4\pi r^2}}$$

Attenuation

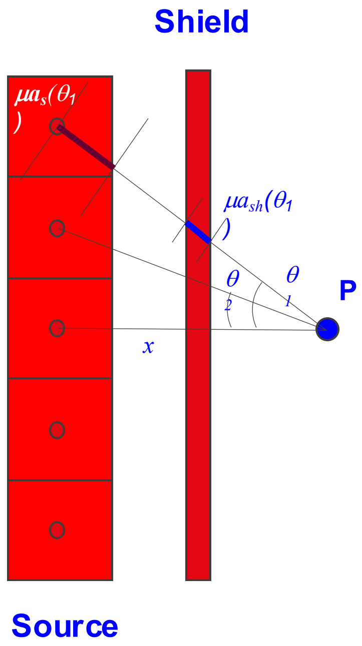
Point Kernel

- The Point Kernel is used to develop relationships between flux and exposure for various source geometries and absorbing media.
- Real-world exposure conditions have varied geometrical shapes, but the total flux can be determined assuming point kernels spread over the geometries.

Shielding of Photons for Distributed Sources: Volume Source

- Examples are large drums or tanks of radioactive materials.
- Complex accurate calculations:
  - Self-absorption.
  - Different materials.
  - Scattering.
- Approximate solutions can be calculated by dividing them up into several point-sources.
  - Tend to overestimate exposure.
- This method is ‘old-school’ / analytical

⇒Volumetric sources are best analyzed by using Monte Carlo transport codes.



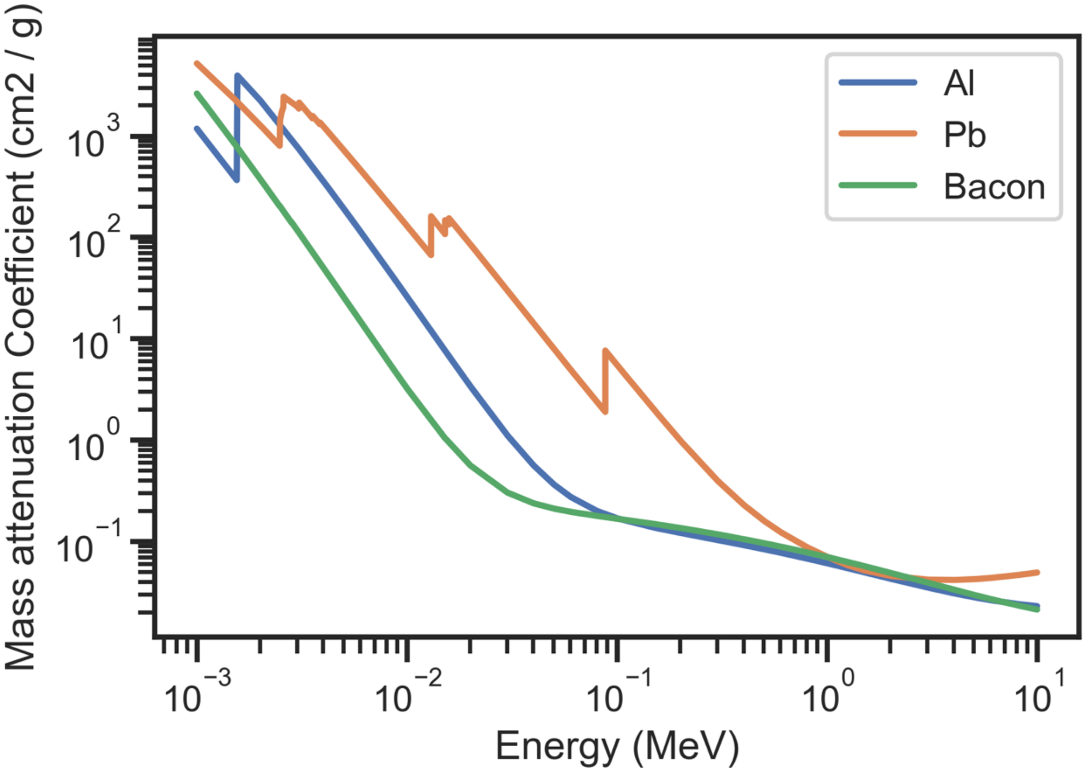
Quiz

- Which of the materials has the highest mass attenuation coefficient for:
    - 2 keV X-rays
    - 10 keV X-rays
    - 1.5 MeV gamma rays
    - 10 MeV gamma rays

- Materials: Pb, Al, Bacon

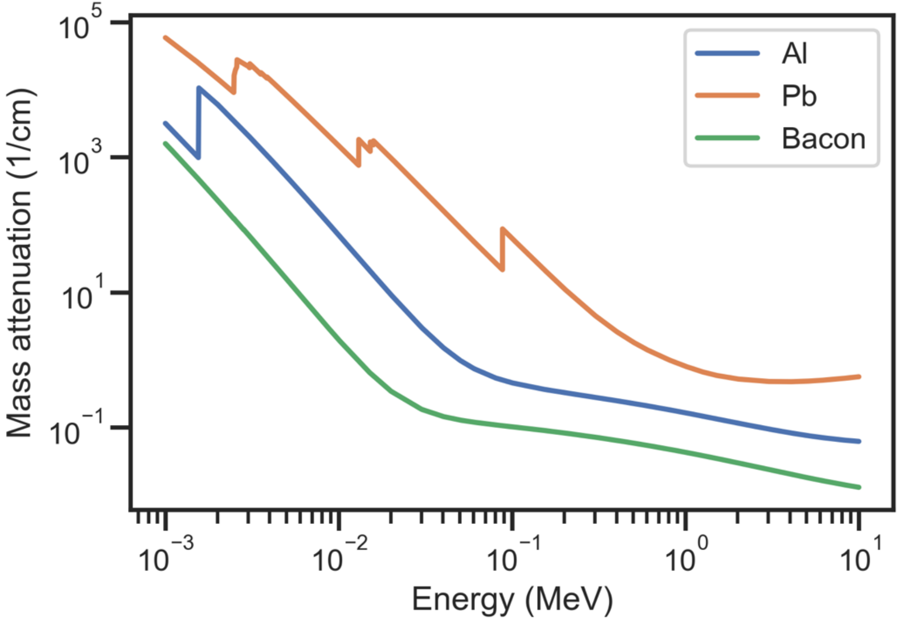
Which of the materials has the highest mass attenuation coefficient for:

- 2 keV X-rays - Al
- 10 keV X-rays - Pb
- 1.5 MeV gamma rays - Bacon
- 10 MeV gamma rays - Pb



Quiz

- Which of those materials has the highest mass attenuation?

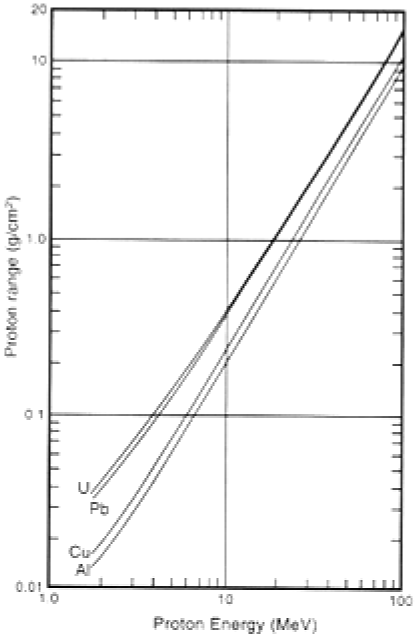


- Multiplied by density:
- Al 2.7 g/cm^3
- Pb 11.4 g/cm^3
- Bacon 0.61 g/cm^3

→ Even high-density bacon is not as good as Pb

Shielding of Protons and Light Ion Sources

- ❑ Beams of protons, deuterons, tritons, and helium ions can be present around accelerators.
- ❑ The range is definite:
  - Range calculated as a function of the most energetic particles in the beam.
- ❑ Design for shielding of light ions is based on the thickness of penetration R_p of a proton of a given energy.

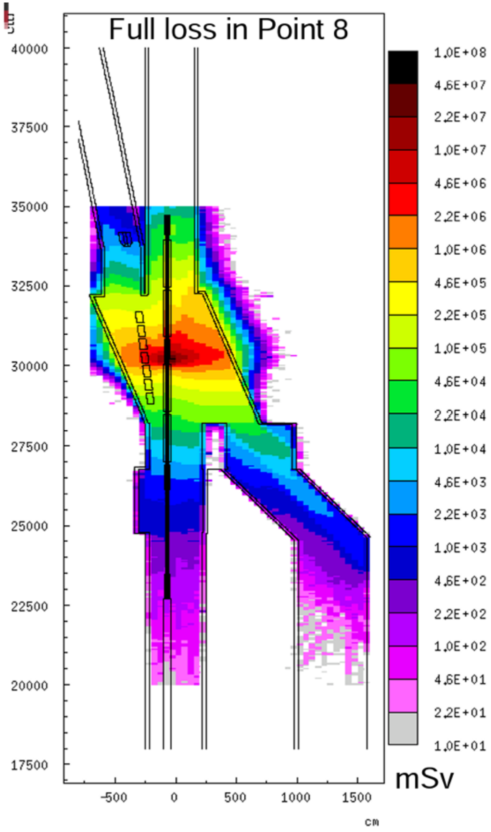


$$\mathrm{R}(^{2}\mathrm{H}^{+}) = 2\times(R_p(E/2))$$

$$\mathrm{R}(^{3}\mathrm{H}^{+}) = 3\times(R_p(E/3))$$

$$\mathrm{R}(^{4}\mathrm{He}^{2+}) = (R_p(E/4))$$

Example: Beam loss at CERN, dose maps



Distance to beam line (without shielding)	Dose for full beam loss (Gy)	Dose rate at quench limit (Sv/h)	Dose rate caused by beam gas interactions (mSv/h)	
			ultimate	nominal
1 m	5500	10	20	14
2 m	2500	5	10	7
3 m	1200	3.3	7	5
5 m	500	2	4	3

Remark: all dose and dose rates have to be doubled inside and increased by a factor of 20 % to 30 % outside due to photonic contribution

Quench limit: 1E7 protons/(m s)

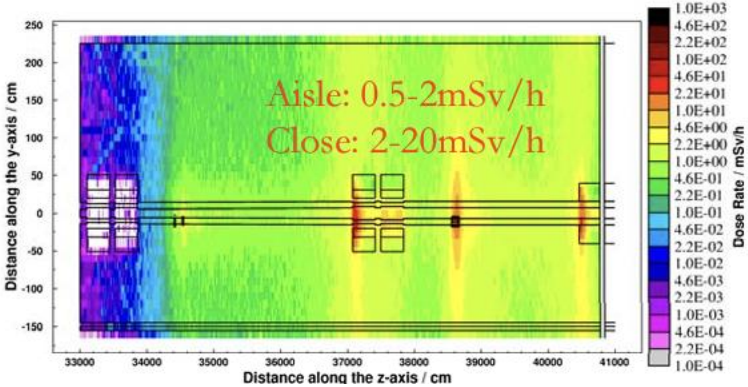
Beam gas interactions (ultimate): ~1E16/year (200 days) ➔ 21400/(m s)

Attenuation of concrete:

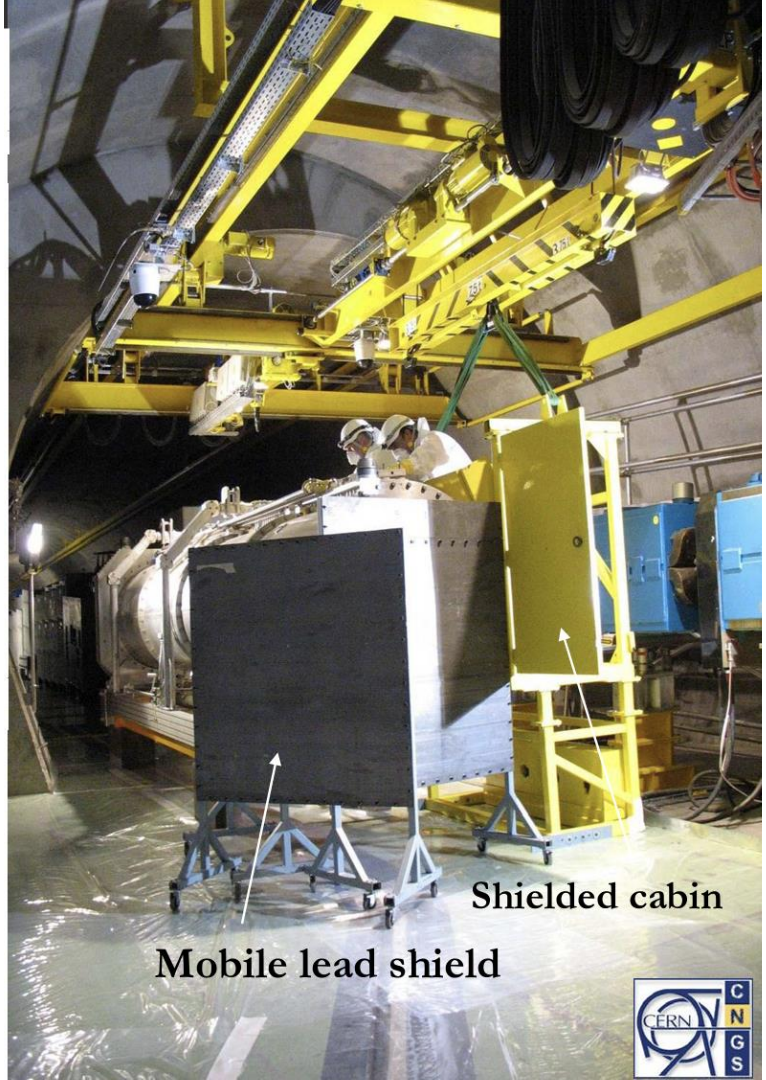
100 cm concrete ➔ factor ~ 10
200 cm concrete ➔ factor ~ 100
300 cm concrete ➔ factor ~ 1000

Sv/Gy: approximated with 5

Heinz Vincke, 'Radiation Protection at High Energy Accelerator Laboratories'



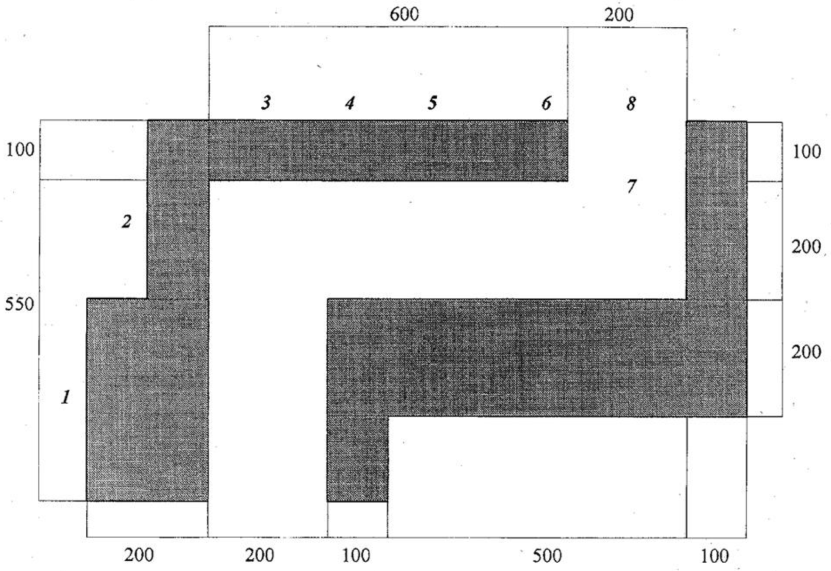
Heinz Vincke, ‘Radiation Protection at High Energy Accelerator Laboratories’



Example

Shielding Design for a Proton Medical Accelerator Facility

S. Agosteo, M. G. Corrado, M. Silari, and P. Tabarelli de Fatis



Maze geometry. The points at which the dose equivalent rate was scored are shown (Table V). The maze height is 3.0 m.

- Concrete ‘maze’ for acces

10 min break

Neutron Interactions and Attenuation

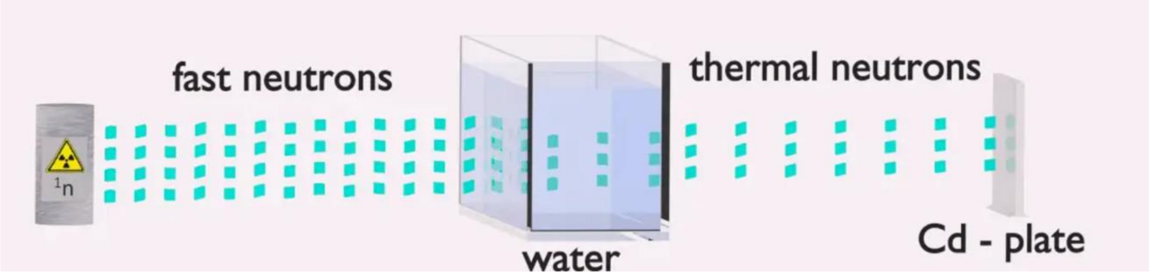
- Neutrons (n) interact with matter (nuclei) in many ways:
  - Elastic scattering: $^{A}Z(n,n)^{A}Z$; NB energy loss of n is highest for low Z scatter targets
  - Inelastic scattering: $^{A}Z(n,n')^{A}Z^*$
  - Radiative capture: $^{A}Z(n,\gamma)^{A+1}Z$
  - Nuclear reactions: $^{A}Z(n,p)$, $^{A}Z(n,\alpha)$, $^{A}Z(n,2n)$, ...
  - Fission of heavy nuclei: $^{A}Z(n,f)$
- Neutron attenuation under "good" geometry conditions:

$$I(x) = I(0)\cdot\exp(-\Sigma_t\cdot x), \qquad \Sigma_t = N\cdot\sigma_t = N\cdot(\sigma_e+\sigma_i+\sigma_\gamma+\sigma_r+\ldots)$$

- Otherwise, buildup factors can be significant, e.g., B~5.0 for 20cm or more water or paraffin.

Shielding of Neutrons

- ☐ Fast neutrons:
  - **First** moderation: elastic and inelastic scattering (γ-rays).
  - **Then** absorption of thermal neutrons.
- ☐ Thermal neutrons:
  - Absorption: (n,γ)-reactions, but not (n,2n), (n,3n), (n,f), …
- ☐ Best moderating materials are those with:
  - Low Z: higher energy loss per collision, e.g., H_2 (1/2E loss per interaction).
  - High elastic scattering X-sections.
- ☐ Best absorbing materials are those with large absorption cross sections for thermal neutrons: e.g., ^{10}B, Cd, H, Li, Gd, …

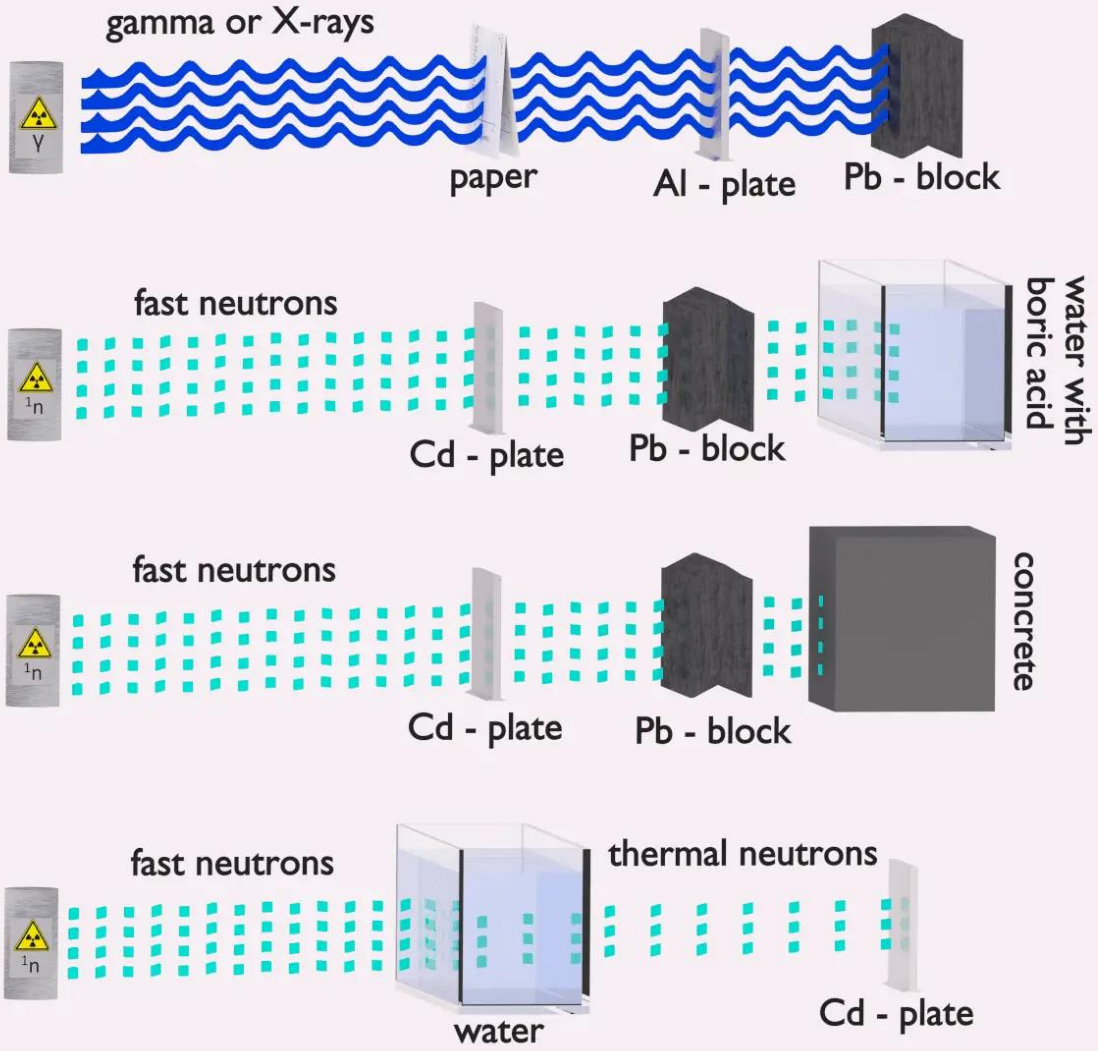


Shielding of Neutrons (Materials)

- ☐ Hydrogenous materials (moderators)
  - **Water** (but: corrosion, leakage, contamination, etc.)
  - **Paraffin** (but: flammable)
  - **Polyethylene,** larger volume than water.
  - **LiH**: no γ from neutron capture, but Tritium formation from ^{6}Li.
- ☐ Elements used as shielding materials in NPP
  - **Pb, Fe**: Capture γ-rays, ^{59}Fe activation.
  - **W**: Better than Pb. Secondary γ-radiation from neutron capture.
  - **U (depleted)**: best attenuator for γ-rays, low neutron capture γ, but high γ flux from fast fission reactions.
  - **B**: incorporated in Boron based shields. High thermal absorption cross section.
  - **Concrete and earth**: high H content; added B, cheap.
  - **Cd**: large n_th absorption cross-section; but high capture γ-photons (9.05 MeV).

Neutron shielding

- First fast neutrons need to be slowed down, then (once thermalized) absorbed

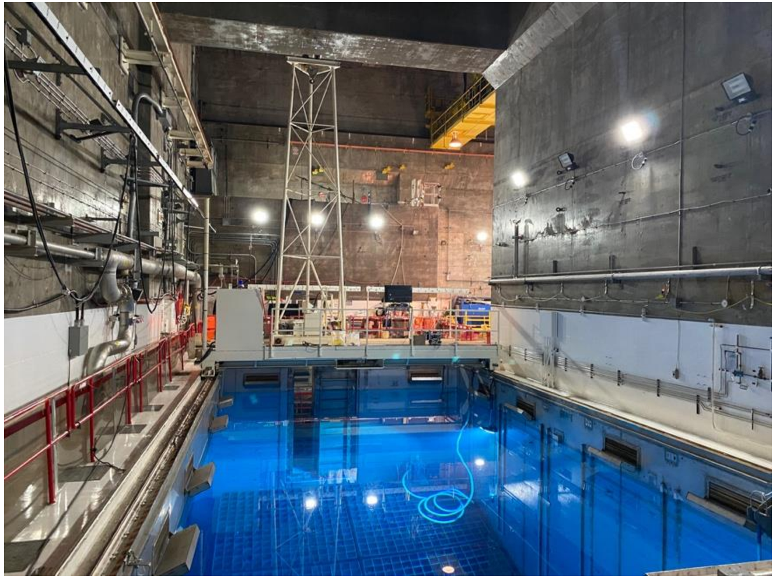


https://www.nuclear-power.com/nuclear-power/reactor-physics/atomic-nuclear-physics/fundamental-particles/neutron/shielding-neutron-radiation/

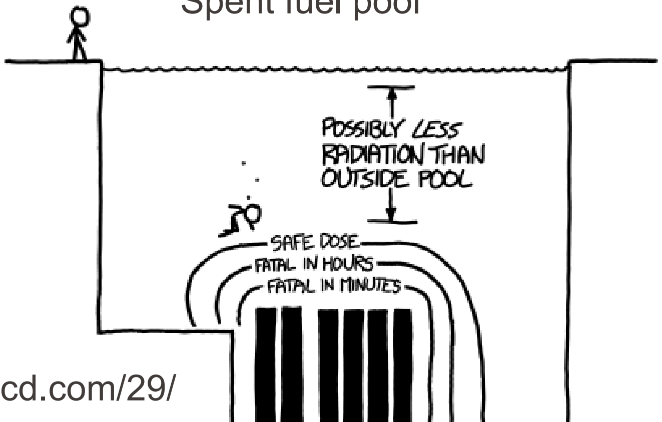
Most commonly used neutron shields

Water:
High H content, availability
Low Z (bad for gamma ray shielding)
2.2 MeV gammas from H(n,ɣ)
Option:
Add boric acid. B(n,ɑ) emits 477 keV gamma ray

Concrete:
High H content (less than water), higher density (good for gammas)
No need for maintenance
Option: ‘Heavy concrete’ with BaS or Pb additives for even higher density



Spent fuel pool



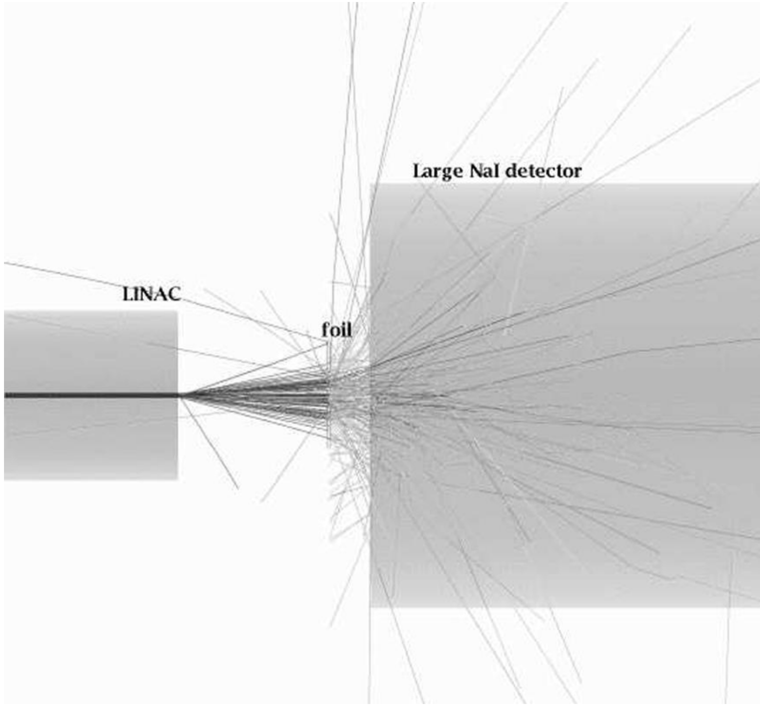
https://what-if.xkcd.com/29/

Speaker

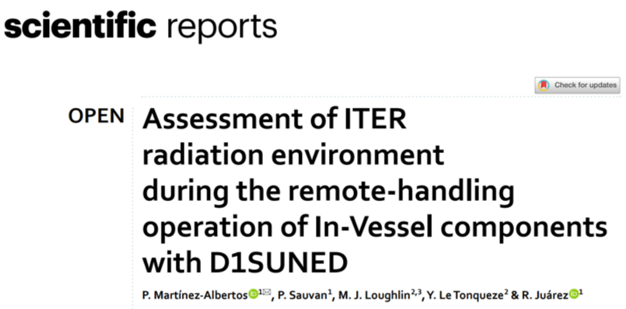
The modern way: Monte Carlo Methods

- Monte Carlo Radiation Transport:
  - Calculates individual particle tracks traversing a medium.
  - Individual interactions are sampled from nuclear data

- Advantages:
  - Monte Carlo methods allow for very complicated 3D geometries.
  - Classical radiation protection relies on ‘rule of thumb’ equations, empirical relations, and analytical formulae
  - →‘True(r)’ representation of particle transport
- Disadvantages:
  - Computationally expensive (slow)
  - Geometry generation can be slow



Example: Monte Carlo model for radiation protection at ITER



scientific reports

Check for updates

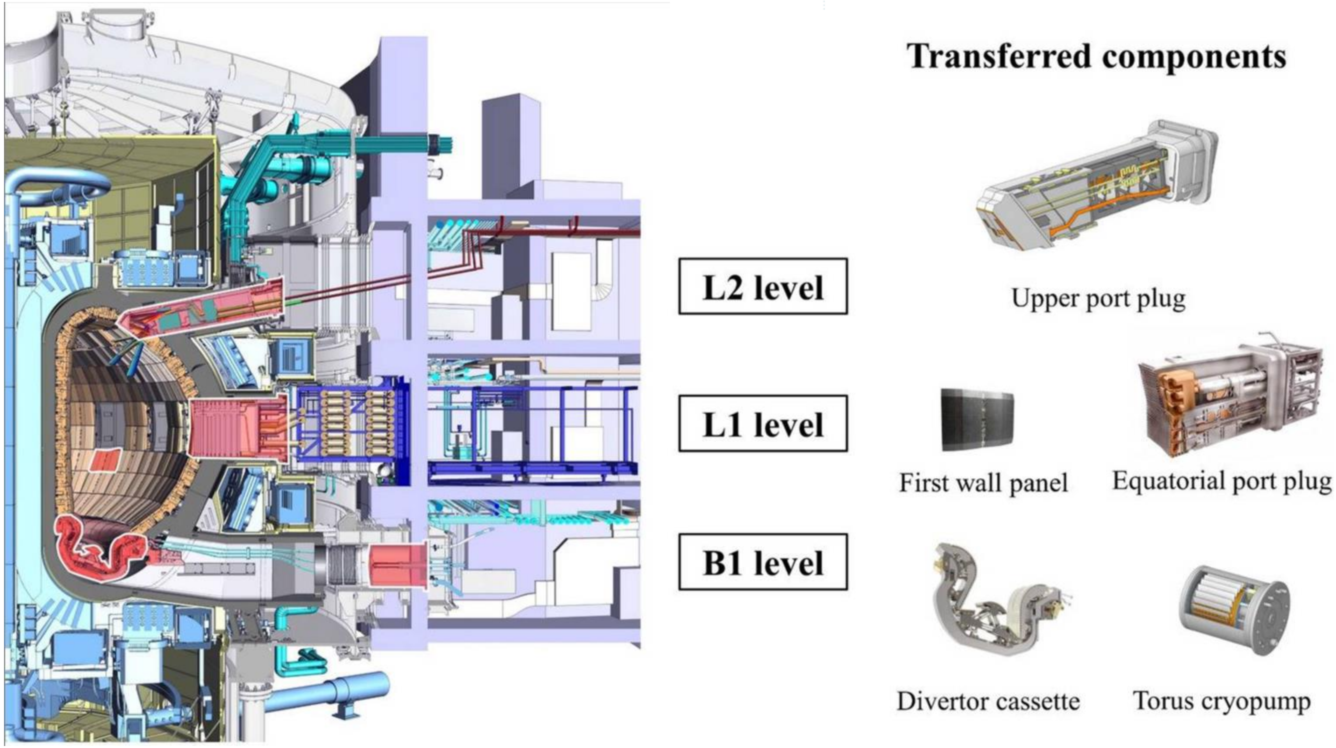
OPEN

Assessment of ITER radiation environment during the remote-handling operation of In-Vessel components with D1SUNED

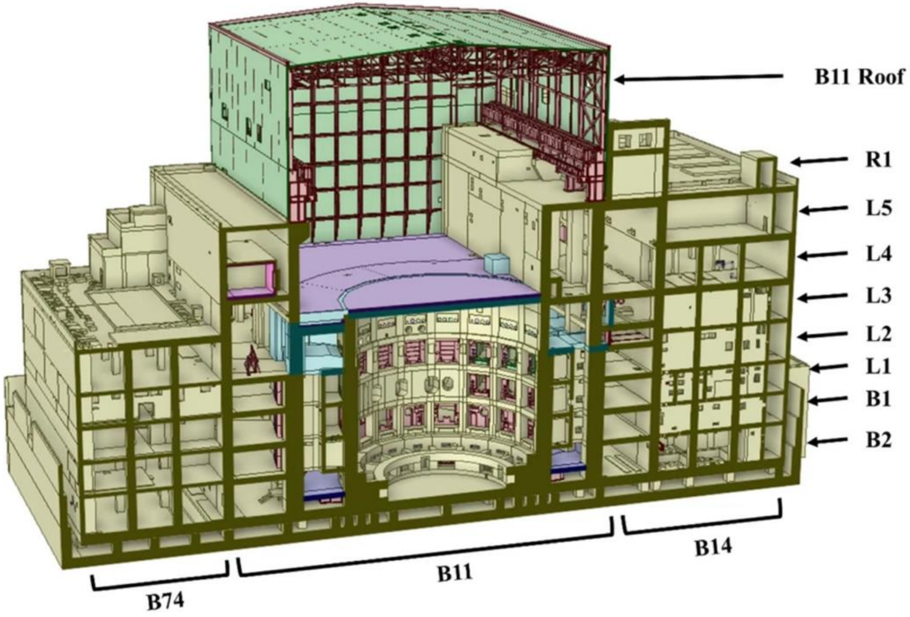
P. Martínez-Albertos[1✉], P. Sauvan[1], M. J. Loughlin[2,3], Y. Le Tonqueze[2] & R. Juárez[1]

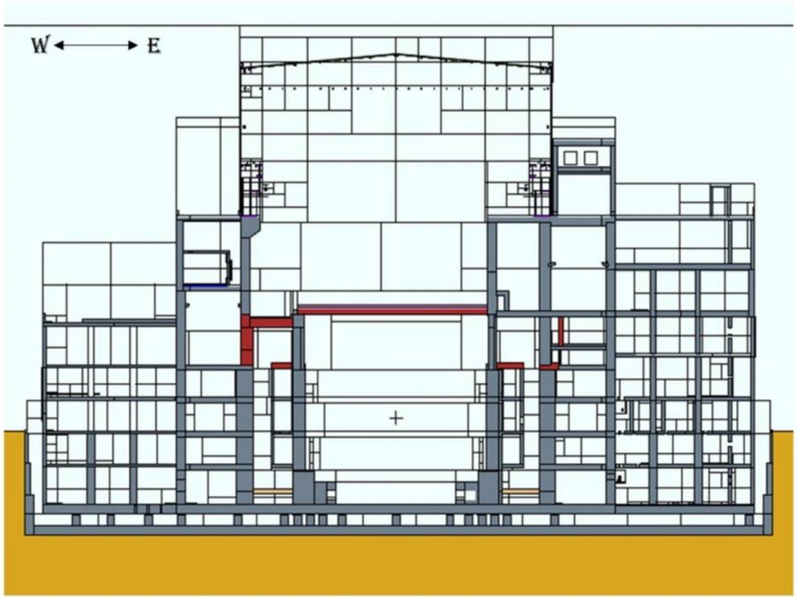
Fusion reactor radiation protection challenges:

- Complex geometry
- 14 MeV fusion n
- Bremsstrahlung from plasma
- Activation of structures

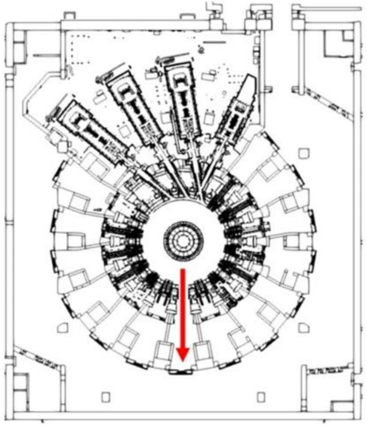


First: 3D model of building

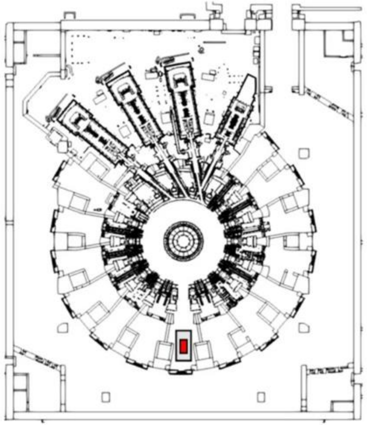




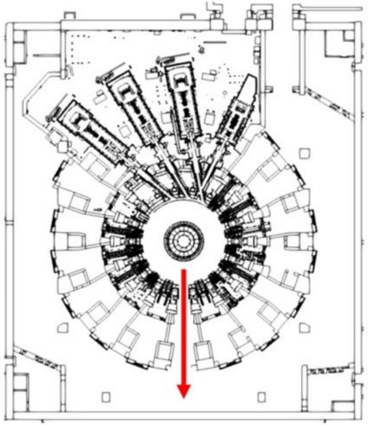
Sample extraction procedure



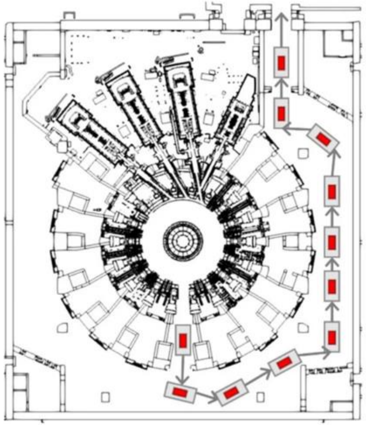
Contribution #1
In-Vessel remaining components during stage 3 (16h).



Contribution #2
Component to be transferred during stage 3 (16h).

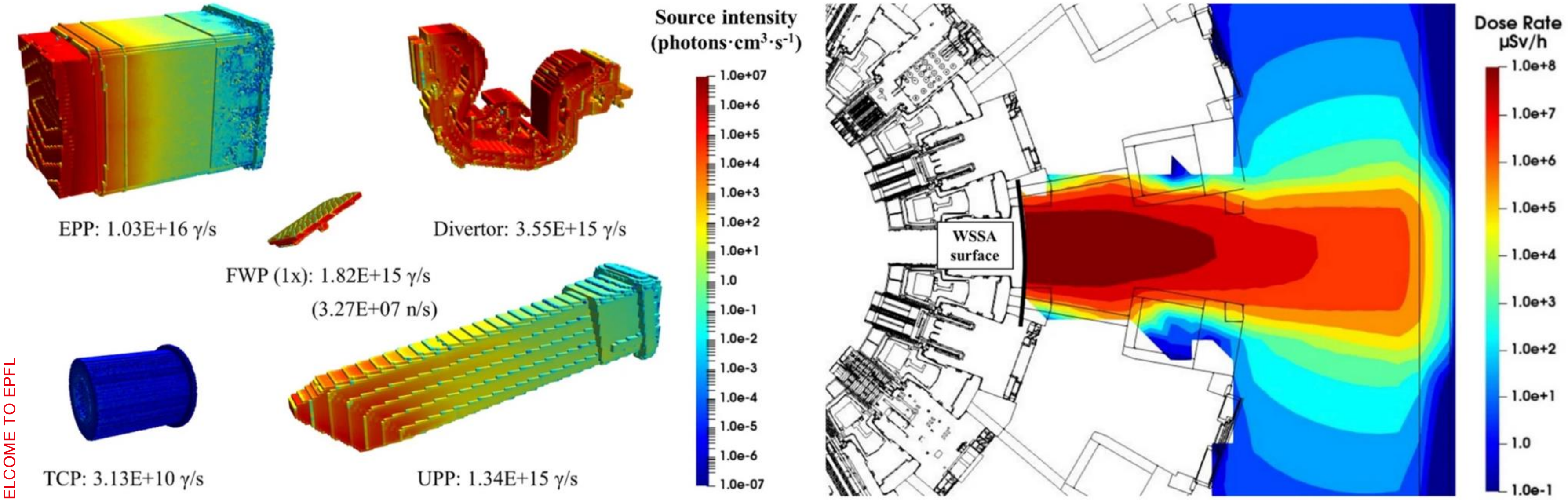


Contribution #3
In-Vessel remaining components during stage 4 (30 min).

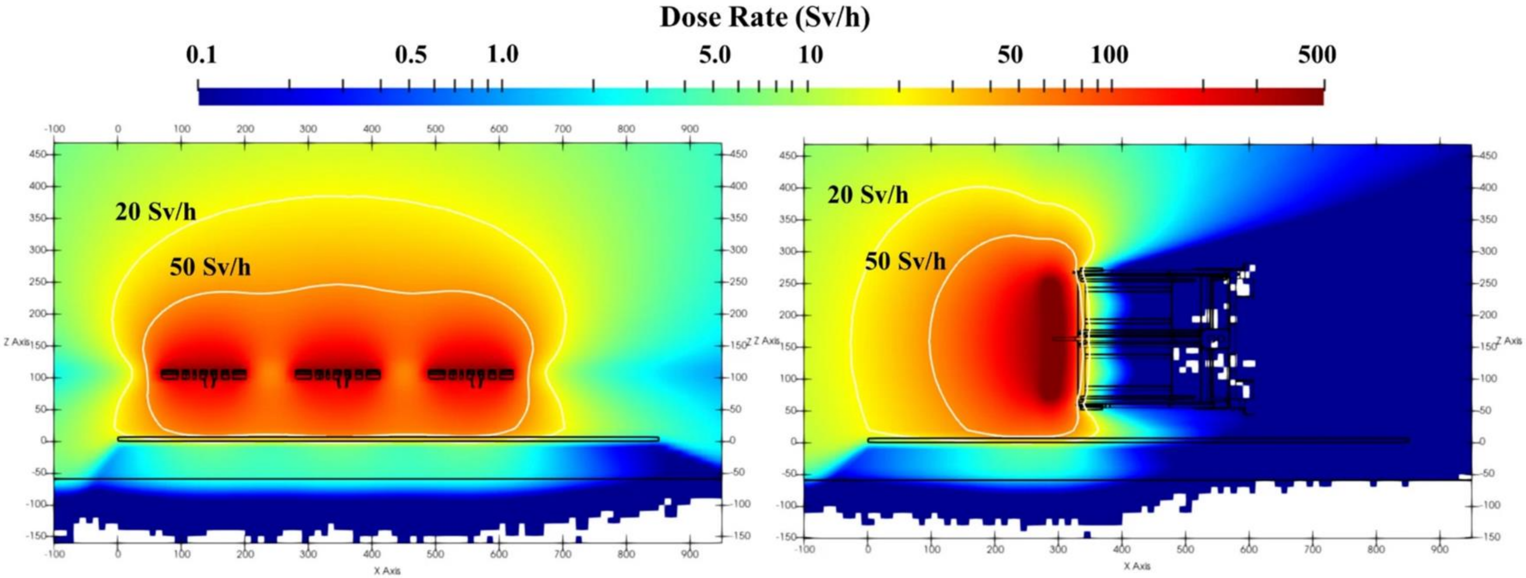


Contribution #4
Transferred component during stages 4 and 5 (1-6 h).

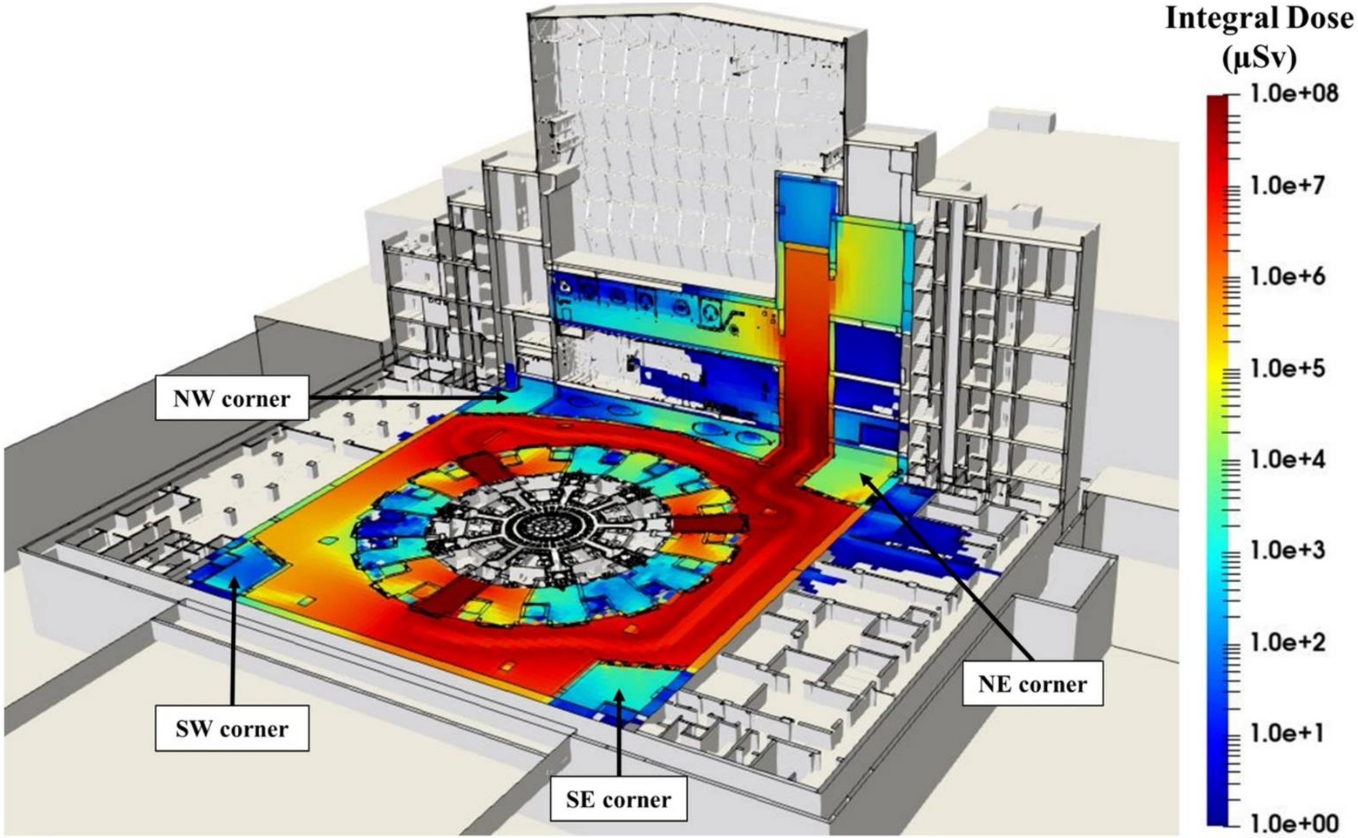
Dose rate


EPP: 1.03E+16 γ/s
Divertor: 3.55E+15 γ/s
FWP (1x): 1.82E+15 γ/s
(3.27E+07 n/s)
TCP: 3.13E+10 γ/s
UPP: 1.34E+15 γ/s
Source intensity
(photons·cm³·s⁻¹)
1.0e+07
1.0e+6
1.0e+5
1.0e+4
1.0e+3
1.0e+2
1.0e+1
1.0
1.0e-1
1.0e-2
1.0e-3
1.0e-4
1.0e-5
1.0e-6
1.0e-07
WSSA
surface
Dose Rate
µSv/h
1.0e+8
1.0e+7
1.0e+6
1.0e+5
1.0e+4
1.0e+3
1.0e+2
1.0e+1
1.0
1.0e-1

Sample dose rates



Vertical view of the dose rate (in Sv/h) for the 3 first wall panels and the equatorial port plug cask. The 20 and 50 Sv/h contour lines are shown.



Integral total dose map (in µSv) produced by the extraction of the 54 divertor cassettes. Each of the 18 operations from port cells #2, #8 and #14, comprises contributions #2, #3 and #4 from Fig. 5. B1 level shielded corners are marked.

Secondary particles..

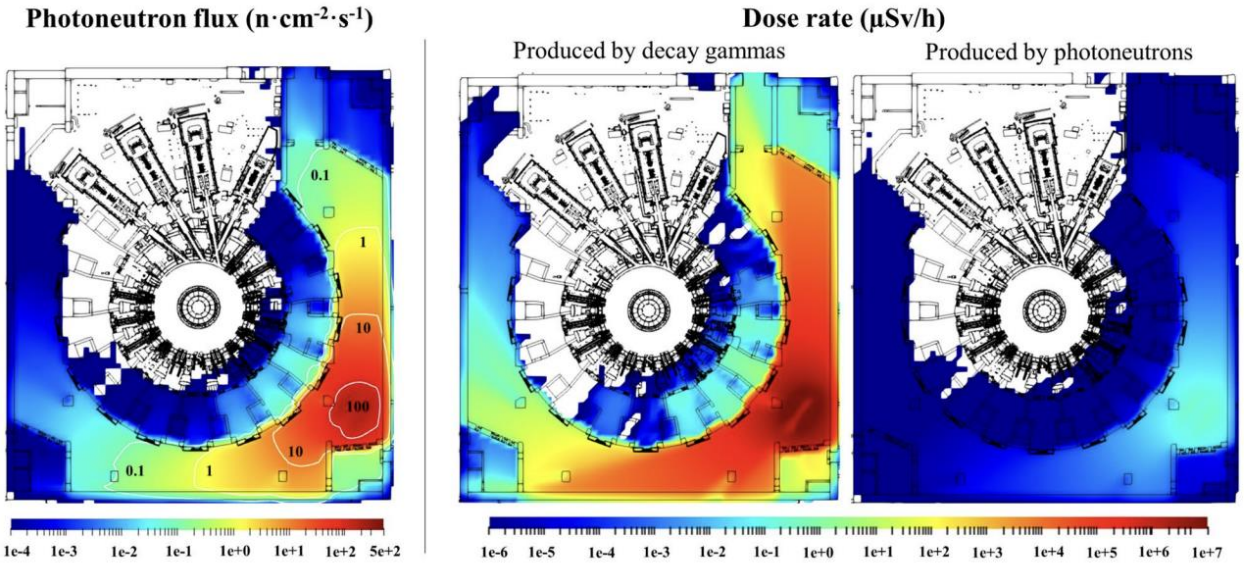


Figure 12. Radiation maps from the first wall panels cask in front of the L1 south-east shielded corner. Left: Photoneutron flux (in n·cm^{-2}·s^{-1}) and contour lines. Centre: Dose rate (in µSv/h) produced by decay gammas. Right: Dose rate (in µSv/h) produced by photoneutrons.

Check out the paper for details: https://doi.org/10.1038/s41598-023-30534-x

Final reminder

Time

Shielding

Distance

Summary

- ☐ Radiation Shielding is a very complex discipline.
- ☐ It is a form of radiation protection:
  - Source Intensity.
  - Shielding Material.
  - Radiation Energy.
  - Geometry.
- ☐ Alpha particles and light ions can be shielded by a sealer (very short ranges in most media).
- ☐ Beta particle shield requires selection of material and thickness to stop highest energy beta and Bremsstrahlung (high energy, high Z). Strategy : Low Z + High Z
- ☐ Photon shields governed by exponential (probabilistic) attenuation.
  - Flux is a complex mixture of scattered and unscattered photons.
  - Need the use of buildup factors (B > 1.0) to account for scattering effects.
- ☐ Neutrons must be slowed down and then absorbed.
  - Shield is governed by exponential attenuation.
  - Also need to account for scattering back into the beam in low Z elements (water, paraffin): B>5

Literature

- ☐ James E. Martin, *“Physics for Radiation Protection”*, Wiley-VCH (2nd edition, 2006)
- ☐ J. Kenneth Shultis and Richard E. Faw, “Radiation Shielding”, ANS Publication (2000)
- ☐ J.R. Lamarsh, A.J. Baratta, “Introduction to Nuclear Engineering”, Prentice Hall (3rd edition, 2001)
- ☐ Michael Short, ‘DIY Geiger counter’, MIT Opencoursewave, https://ocw.mit.edu/courses/22-s902-do-it-yourself-diy-geiger-counters-january-iap-2015/