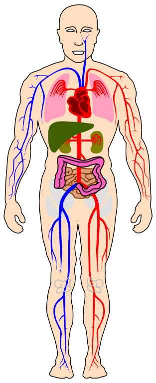
Dosimetry of External Exposures

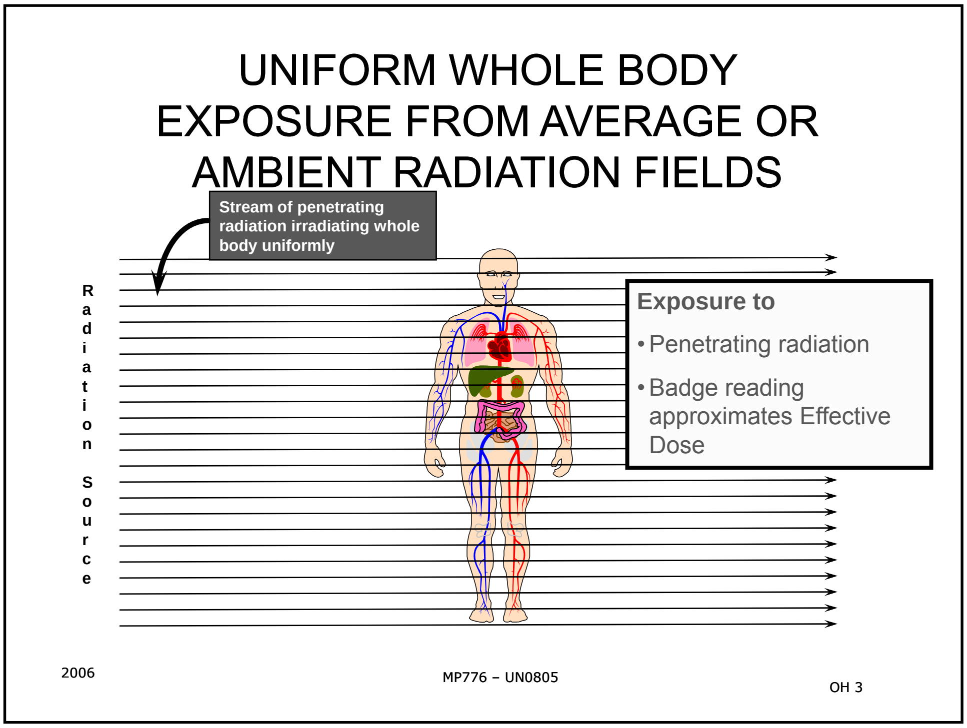
Med Phys 776 – UN0805

Dave Tucker

External Exposure

- Whole Body
- Skin
- Extremity
- Partial





UNIFORM WHOLE BODY EXPOSURE FROM AVERAGE OR AMBIENT RADIATION FIELDS

Stream of penetrating radiation irradiating whole body uniformly

Radiation Source

Exposure to

- Penetrating radiation
- Badge reading approximates Effective Dose

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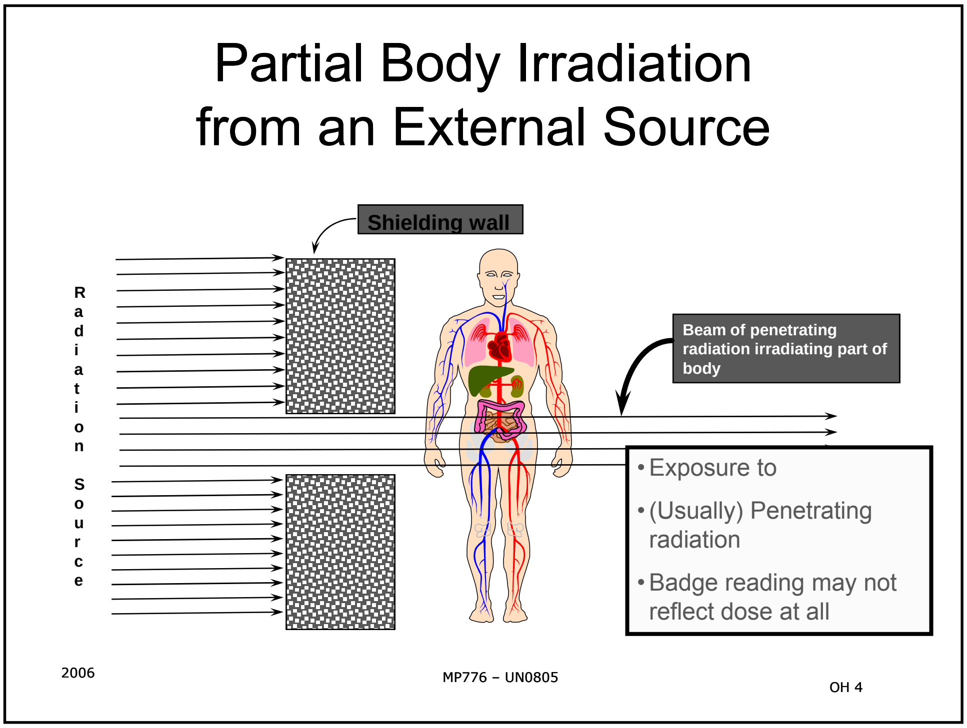

Partial Body Irradiation from an External Source

Shielding wall

Beam of penetrating radiation irradiating part of body

Radiation Source

- Exposure to
- (Usually) Penetrating radiation
- Badge reading may not reflect dose at all

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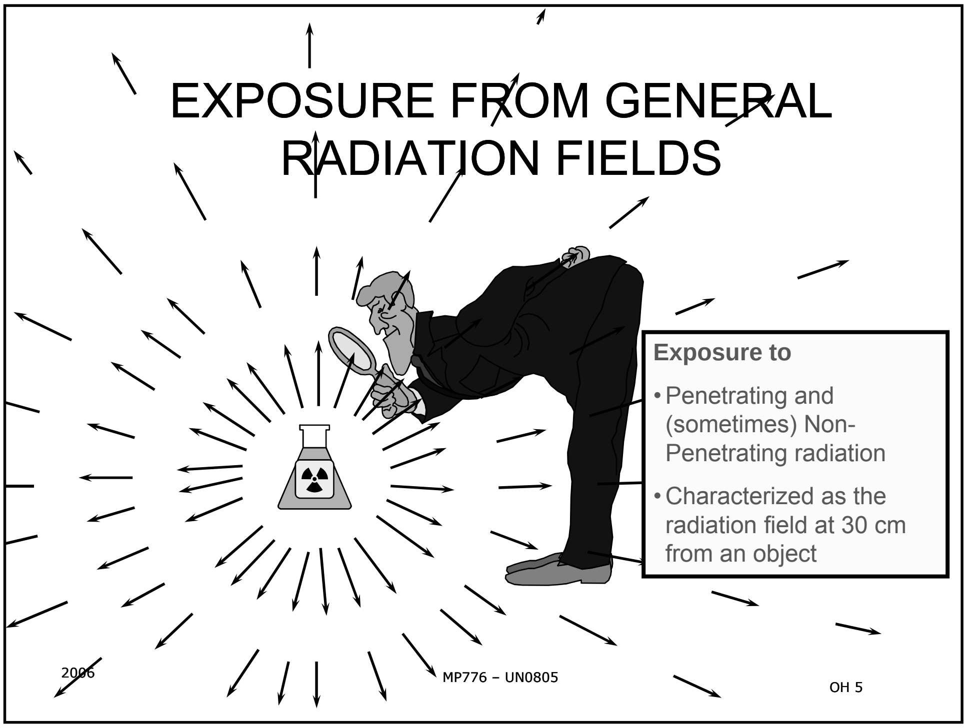
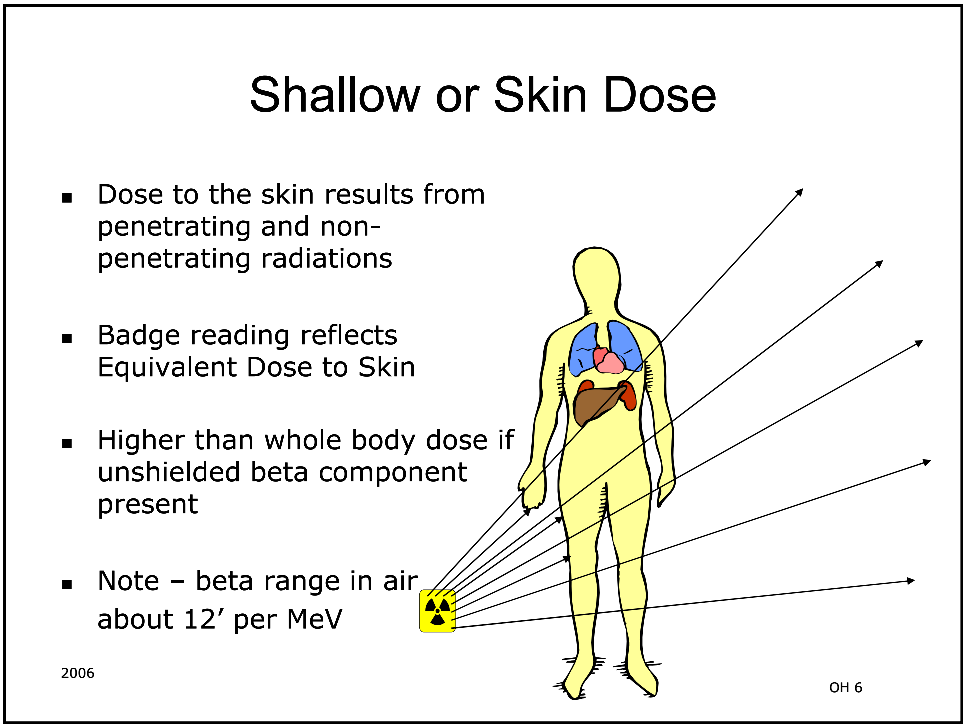


EXPOSURE FROM GENERAL RADIATION FIELDS

Exposure to

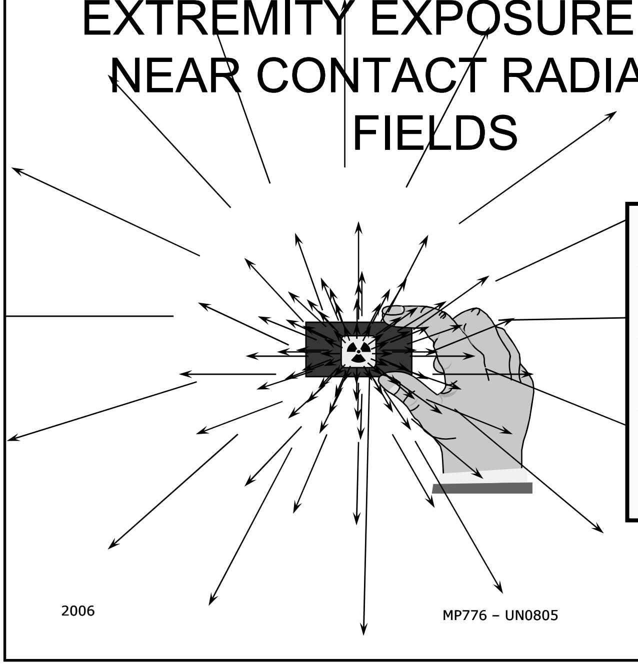
- Penetrating and (sometimes) Non-Penetrating radiation
- Characterized as the radiation field at 30 cm from an object



Shallow or Skin Dose

- Dose to the skin results from penetrating and non-penetrating radiations
- Badge reading reflects Equivalent Dose to Skin
- Higher than whole body dose if unshielded beta component present
- Note – beta range in air about 12’ per MeV

EXTREMITY EXPOSURE FROM NEAR CONTACT RADIATION FIELDS



Exposure to

- Penetrating and Non-Penetrating radiation
- High intensity of radiation due to geometry
- Ring badge reading reflects Equivalent Dose to extremity

Photons

$$\dot{D} = \phi E_\gamma \frac{\mu_{en}}{\rho}$$

$\phi =$ the photon fluence rate

$E_\gamma =$ the photon energy

$\frac{\mu_{en}}{\rho} =$ the mass energy absorption coefficient (cm^2/g)

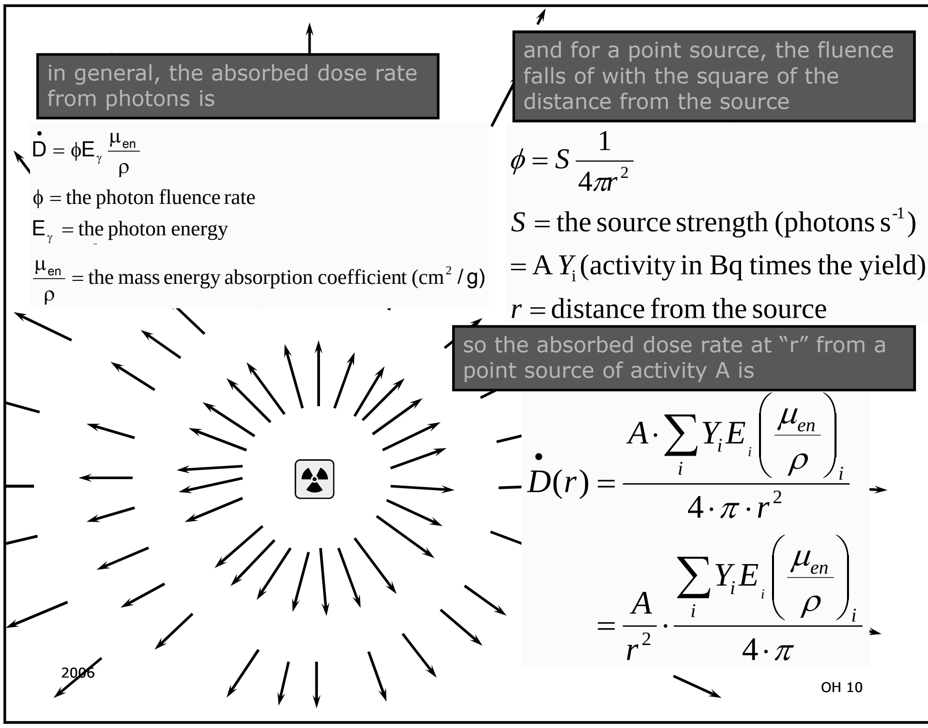
For a point source…

$$\phi = S\,\frac{1}{4\pi r^{2}}$$

S = the source strength (photons s^{-1})

= A Y_i (activity in Bq times the yield)

r = distance from the source



in general, the absorbed dose rate from photons is

$$\dot{D} = \phi E_{\gamma}\,\frac{\mu_{en}}{\rho}$$

ϕ = the photon fluence rate

E_{γ} = the photon energy

$\frac{\mu_{en}}{\rho}$ = the mass energy absorption coefficient (cm^{2}/g)

and for a point source, the fluence falls of with the square of the distance from the source

$$\phi = S\,\frac{1}{4\pi r^{2}}$$

S = the source strength (photons s^{-1})

= A Y_i (activity in Bq times the yield)

r = distance from the source

so the absorbed dose rate at "r" from a point source of activity A is

$$\dot{D}(r) = \frac{A\cdot\sum_{i} Y_i E_i \left(\frac{\mu_{en}}{\rho}\right)_i}{4\cdot\pi\cdot r^{2}}$$

$$= \frac{A}{r^{2}}\cdot\frac{\sum_{i} Y_i E_i \left(\frac{\mu_{en}}{\rho}\right)_i}{4\cdot\pi}$$

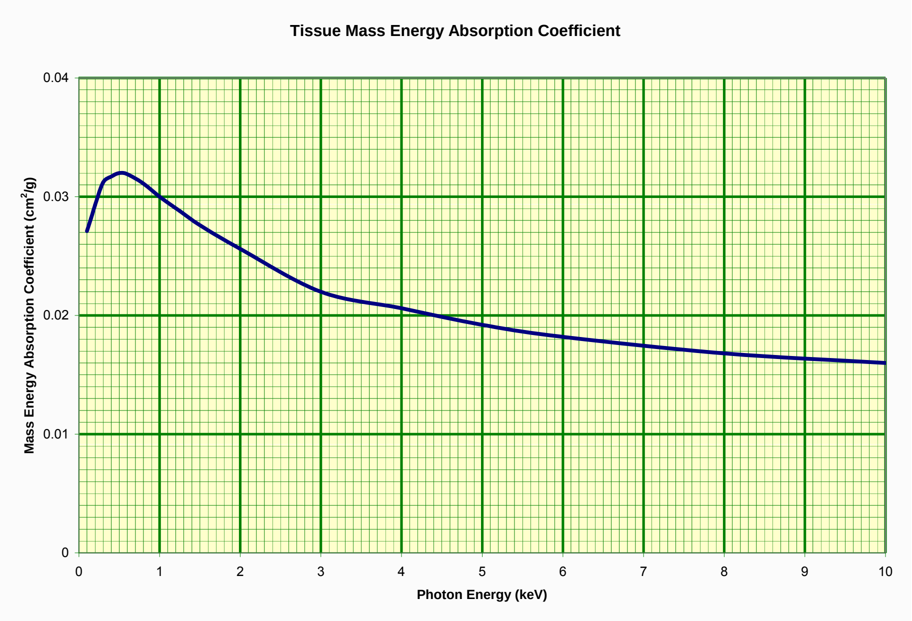
The Gamma Specific Dose Constant

$$\dot{D}(r) = \frac{A}{r^2} \cdot \boxed{\frac{\sum_i Y_i E_i \left(\frac{\mu_{en}}{\rho}\right)_i}{4 \cdot \pi}}$$

$$= \frac{A}{r^2} \cdot \boxed{\Gamma}$$

all constant for a given radionuclide

The gamma specific dose constant



From www.hps.org “Ask the Expert”

Answer to Question #932 Submitted to "Ask the Experts"

Category: ***Doses and Dose Calculations — Basic dose information, dose quantities, units***

The following question was answered by an expert in the appropriate field:

Example: Dose Rate from 1 Ci Cu-64 at 1m

- Cu-64 Decay Data from ICRP 38
  - E_1=1.346 MeV Y_1= 0.0049 (μ_{en}/ρ) = 0.032 cm^2/g
  - $E_\pm$=0.511 MeV $Y_\pm$= 0.358 (μ_{en}/ρ) = 0.029 cm^2/g
  - So – for 1 Ci = 3.7E10 Bq

$$\dot{D}(r) = \frac{A \cdot \sum_i Y_i E_i \left(\frac{\mu_{en}}{\rho}\right)_i}{4 \cdot \pi \cdot r^2}$$

$$= \frac{(3.7E10 s^{-1})}{4 \cdot \pi \cdot (100cm)^2} \begin{bmatrix} \left(0.0049 \times 1.346 MeV \times 0.029 cm^2 g^{-1}\right) + \\ (0.358 \times 0.511 MeV \times 0.032 cm^2 g^{-1}) \end{bmatrix}$$

$$= 1.8E3 MeV\ g^{-1}\ s^{-1} \left[\frac{3600s}{h}\right]\left[\frac{1.6E-13J}{MeV}\right]\left[\frac{1000g}{kg}\right]$$

$$= 1.03\ mGy\ h^{-1} \approx 1.03\ mSv\ h^{-1}$$

Example: Dose Rate from 1 Ci Cu-64 at 1m

- Cu-64 Γ=3.566E-5 mSv h^{-1} MBq^{-1} m^2
  - So – for 1 Ci = 3.7E4 MBq

$$\overset{\bullet}{H}(r) = \frac{A}{r^2} \cdot \Gamma$$

$$= \frac{3.7E4\ MBq}{(1m)^2}\ (3.566E-5\ mSv\ h^{-1}\ MBq\ m^2)$$

$$= 1.32\ mSv\ h^{-1}$$

Point Source Approximation

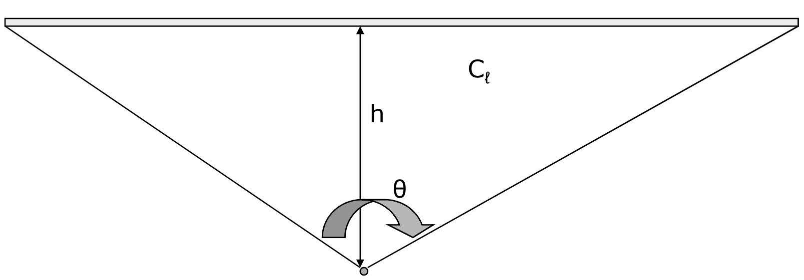
- An unshielded point source displays "1/r^2" drop off in dose rate with distance.
- You can use a point source approximation when your distance from the source is a least three times the greatest dimension.

$$\frac{\overset{\bullet}{D}_A}{\overset{\bullet}{D}_B} = \frac{r_B^2}{r_A^2}$$

"The Inverse Square Law"

Line Source

- A common problem in Health Physics
  - Example – pipe filled with radioactive liquid

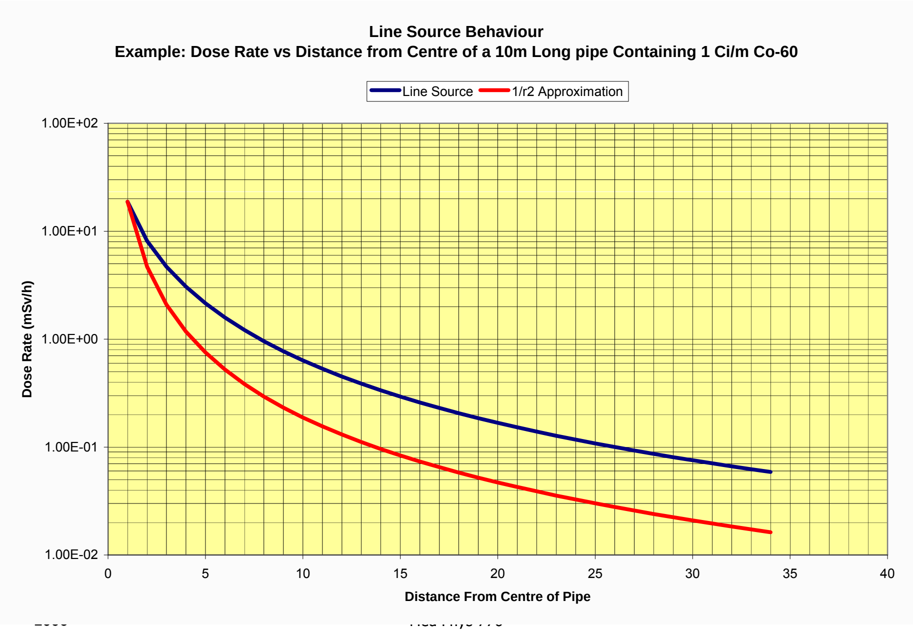


$$\dot{D} = \frac{\Gamma \times C_\ell \times \theta}{h}$$

C_ℓ = The activity per unit length

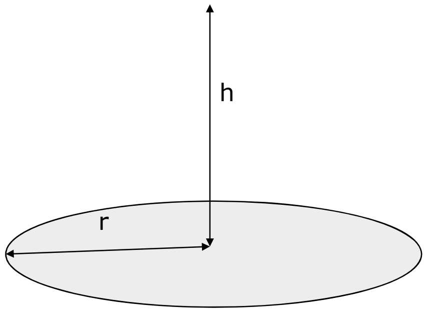
θ = Angle subtented by the line in radians

h = distance from the line



Plane Source

- A common problem in Health Physics
  - Example – spill on floor
  - Reactor Face

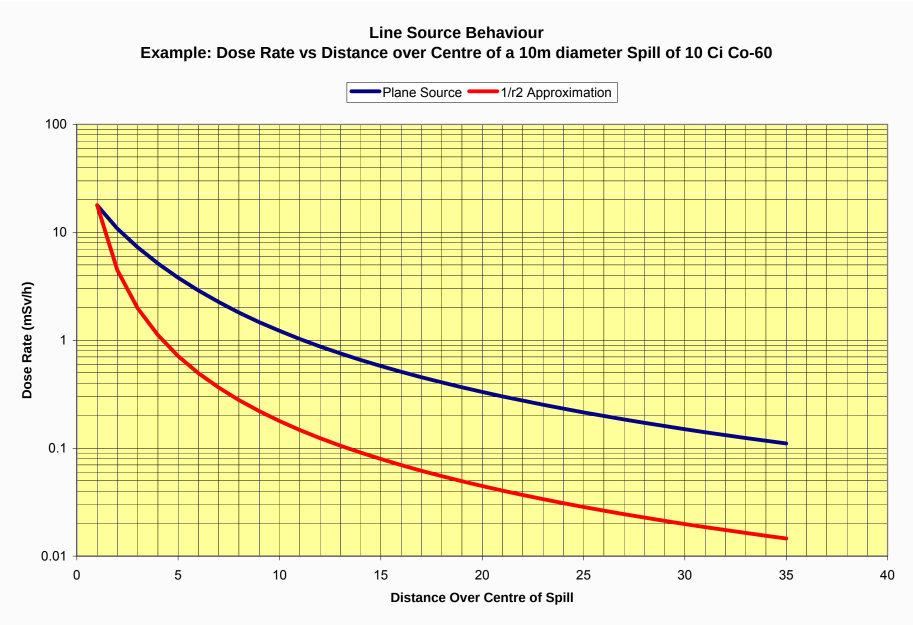


$$\dot{D} = \pi \, \Gamma \, C_a \, \ln\left[\frac{\left(r^2 + d^2\right)}{d^2}\right]$$

C_a = The activity per unit area

r = The radius of the source

d = The distance over the centre of the source



Line Source Behaviour
Example: Dose Rate vs Distance over Centre of a 10m diameter Spill of 10 Ci Co-60

Immersion Exposures

- Exposure in a cloud of radioactive material
  - Examples are dose to public from air effluents or accidental releases
  - Dose due to airborne noble gas activity
    - Noble gases are an external hazard only
  - Both gamma and beta exposures must be considered
    - Potential for significant surface exposures

Rate of Energy Absorption at the Centre of a Sphere of Radius X

$$R_{prim} + R_{se} = \frac{n \cdot E_{\gamma}}{\mu_0}(\mu_a \cdot (1 - e^{-\mu_0 X}) + \sigma_s[1 - e^{-\mu_0 X}(1 + \mu_0 X)]$$

μ_a = mass absorption coefficient
σ_s = Compton scattering coefficient
μ_o = total attenuation coefficient
$\mu_a = \mu_o - \sigma_s$
n = photons/s.g of energy $E\gamma$(MeV)

R_{prim} is the rate of energy absorption from primary photons
R_{se} is the rate of energy absorption from scattered photons

From Evans, "The Atomic Nucleus"

What happens if the sphere gets very large?

For large X, $\mu_o X >> 1$

$$R_{prim} + R_{se} = \frac{n \cdot E_\gamma}{\mu_0}(\mu_a \cdot (1) + \sigma_s(1))$$
$$= n \cdot E_\gamma$$

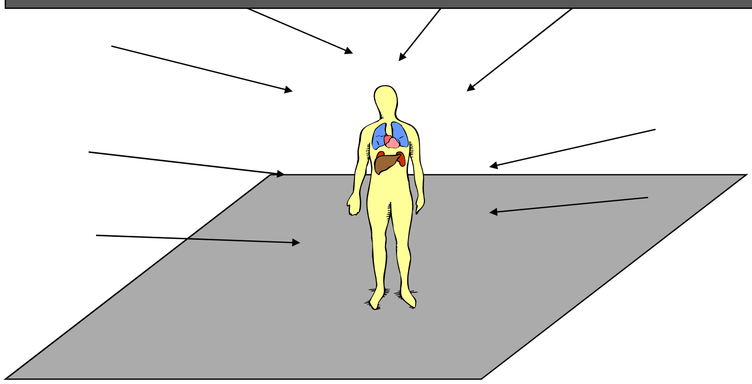
That is, the rate of energy absorption per gram is equal to the rate of energy emission per gram.

How large is large?

- In air, for 1 MeV, $\mu_o = 8.25\text{x}10^{-5}\text{ cm}^{-1}$
- For $\mu_o X$»1 X»$1/\mu_o = 1.2\text{x}10^4$ cm = 120 m
- Thus for distances much greater than this (say, greater than about 0.5 km), the geometry can be considered an infinite sphere.
- For beta particles, radii of greater than about a few meters can be considered infinite;
  - one invariably has infinite geometry for beta particles.

Semi-Infinite Geometry

Need to divide infinite geometry answers by 2 to reflect situations in which the exposure occurs only from above



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^{41}Ar Example

- Nuclear reactors release ^{41}Ar, an activation product of argon in air, which has a gamma-ray of 1.29 MeV (100%). What dose rate would be received by an individual exposed at ground level to a very very large cloud of 1 Bq/m^3?

^{41}Ar Solution:

What happens when the sphere gets small?

For SMALL X, $\mu_o X << 1$

$$R_{prim} + R_{se} = \frac{n \cdot E_\gamma}{\mu_0}(\mu_a \cdot (1 - e^{-\mu_0 X}) + \sigma_s[1 - e^{-\mu_0 X}(1+0)]$$

$$= \frac{n \cdot E_\gamma}{\mu_0}(\mu_a \cdot (1 - e^{-\mu_0 X}) + \sigma_s(1 - e^{-\mu_0 X}))$$

$$= \frac{n \cdot E_\gamma}{\mu_0}\mu_0 \cdot (1 - e^{-\mu_0 X})$$

$$= R_\infty (1 - e^{-\mu_0 X})$$

Noble Gas DAC

- DAC will depend upon the geometry of the room.
- It is common to take the volume of the room and then determine the radius of a hemisphere that would have the same volume and use this for "X" in the preceding equation. The ICRP used to give the DAC for a selection of room volumes. Dose coefficients are now provided for infinite cloud exposure (see handout) and it is left to the user to correct for geometry if appropriate or required.
- One correction is nearly always appropriate – at ground level a person is only exposed from the cloud above. This is the semi-infinite sphere geometry and the dose rate (neglecting reflection from the ground) is half of that from an infinite sphere.

From ICRP 68

Note: the values are given for a 24 hour day.

To obtain the effective dose rate per second, divide by 8.64E4 s d^{-1}

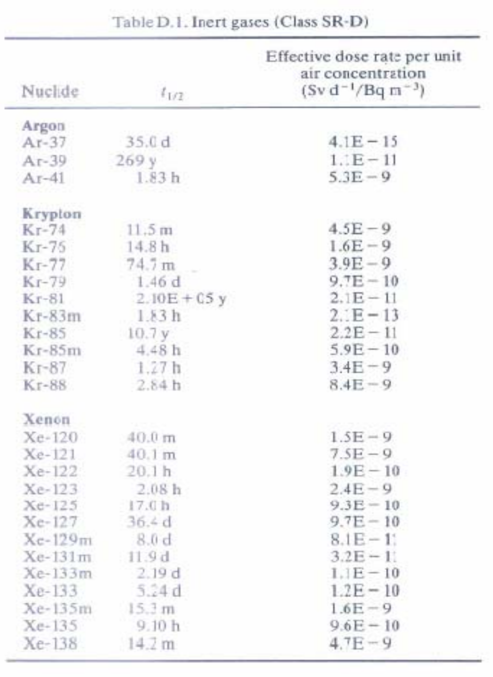


Table D.1. Inert gases (Class SR-D)

Nuclide	$t_{1/2}$	Effective dose rate per unit air concentration ($Sv\ d^{-1}/Bq\ m^{-3}$)
Argon		
Ar-37	35.0 d	4.1E − 15
Ar-39	269 y	1.1E − 11
Ar-41	1.83 h	5.3E − 9
Krypton		
Kr-74	11.5 m	4.5E − 9
Kr-75	14.8 h	1.6E − 9
Kr-77	74.7 m	3.9E − 9
Kr-79	1.46 d	9.7E − 10
Kr-81	2.10E + 05 y	2.1E − 11
Kr-83m	1.83 h	2.1E − 13
Kr-85	10.7 y	2.2E − 11
Kr-85m	4.48 h	5.9E − 10
Kr-87	1.27 h	3.4E − 9
Kr-88	2.84 h	8.4E − 9
Xenon		
Xe-120	40.0 m	1.5E − 9
Xe-121	40.1 m	7.5E − 9
Xe-122	20.1 h	1.9E − 10
Xe-123	2.08 h	2.4E − 9
Xe-125	17.0 h	9.3E − 10
Xe-127	36.4 d	9.7E − 10
Xe-129m	8.0 d	8.1E − 11
Xe-131m	11.9 d	3.2E − 11
Xe-133m	2.19 d	1.1E − 10
Xe-133	5.24 d	1.2E − 10
Xe-135m	15.3 m	1.6E − 9
Xe-135	9.10 h	9.6E − 10
Xe-138	14.2 m	4.7E − 9

Beta Exposures

$$\dot{D} = \phi\left(\frac{S}{\rho}\right)_{col}$$

$\phi =$ the charged particle fluence rate ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)

$\left(\frac{S}{\rho}\right)_{col} =$ the collision mass stopping power ($\mathrm{MeV\ cm^2/g}$)

$$\dot{H}(\mathrm{Sv/h}) = 8E-12 \cdot n \cdot C \cdot d^{-2}\ \mathrm{Sv/h\ Bq^{-1}m^2}$$

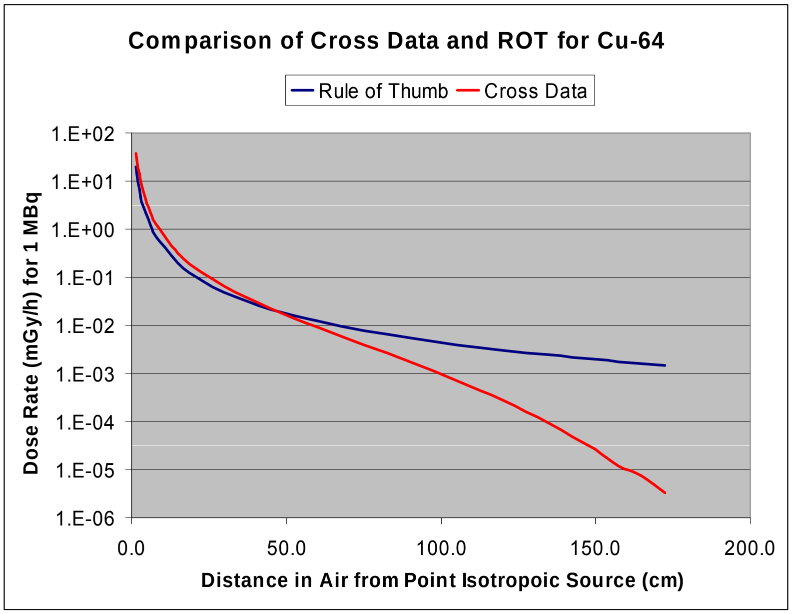
or in "old" units

$$\dot{D}(\mathrm{rad/h}) = \frac{300 \cdot C \cdot n}{d^2}\ \mathrm{rad/h\ Ci^{-1} \cdot ft^2}$$

$n =$ number of beta particles per decay

$C =$ source activity in appropriate units

$d =$ distance from the source in appropriate units



Comparison of Cross Data and ROT for Cu-64

Neutrons

$$\dot{H} = \phi \bullet DCF$$

$\phi =$ the neutron fluence rate ($cm^{-2}s^{-1}$)

DCF = the dose conversiuon factor in appropriate units,

for the neutron energy of concern

Specific values are provided in ICRP 51 or approximations (old units) are :

$$\mathrm{DCF_{thermal}} = \frac{2.5 mrem/h}{670 cm^{-2} s^{-1}}$$

$$DCF_{fast} = \frac{2.5 mrem/h}{17 cm^{-2} s^{-1}}$$

Beta Exposures from Noble Gases

Absorbed Beta dose rate in air from an infinite cloud – from Cember

$$\dot{D}_{\beta,\inf}\left(\frac{mGy}{h}\right) = \frac{C\left(\frac{Bq}{m^3}\right)\cdot 1\left(\frac{s^{-1}}{Bq}\right)\cdot \overline{E}(MeV)\cdot 1.6E-13\frac{J}{MeV}\cdot 3600\frac{s}{h}}{1.293\frac{kg}{m^3}\cdot 1\frac{J}{kg\cdot Gy}\cdot\frac{1Gy}{1E3mGy}} = 4.45E-7\cdot C\cdot \overline{E}\left(\frac{mGy}{h}\right)$$

Correcting for the irradiation from one side only and the fact that tissue absorbs about 10% more energy per kilogram than does air, and correcting for attenuation of the beta particles to the depth of the basal layer (7 mg cm^{-2})

$$\begin{aligned}\dot{D}_{\beta,\infty/2} &= 0.5\times 1.1\times \dot{D}_{\inf}\times e^{-\mu_{\beta,t}\times 0.007}\ \frac{mGy}{h}\\ &= 2.45E-7\cdot C\cdot \overline{E}\times e^{-\mu_{\beta,t}\times 0.007}\ \frac{mGy}{h}\end{aligned}$$

$$\mu_{\beta,t} = 18.6(E_{\max}-0.036)^{-1.37}\,cm^2 g^{-1}$$

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Beta Approximation

From USNRC Reg Guide 1.4

$$\dot{D}_{\beta,surface} = 0.23\,\overline{E}_{\beta}\ \chi$$

$\dot{D}_{\beta,surface}$ = The beta dose rate to skin from an infinite cloud in rad/s

$\overline{E}_{\beta}$ = The average beta energy per decay in MeV

χ = The activity concentration in the cloud in Ci/m^3

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^{85}Kr Example

- Calculate the equivalent dose rate to the skin of a person immersed in a large cloud of Kr-85 at a concentration of 37 kBq/m^3.
  - The average beta energy per decay is 0.246 MeV. The maximum beta energy is 0.672 MeV.
- Compare with the approximation.

^{85}Kr Solution:

Example A

- A powdered Cu-64 in the reactor broke open and spilled on the floor.
- The sample activity was 1 Ci (37 GBq).
- An operator just reporting for work cleaned up the spill, forgetting that he was not yet wearing his dosimetry
- Assume it took 10 minutes to wipe up the powder and deposit it in a shielded container using wet wipers held with 30 cm tweezers
- Assume the body is 1m away from the sample throughout the work
- Estimate the relevant doses and compare with the corresponding ICRP recommended dose limits

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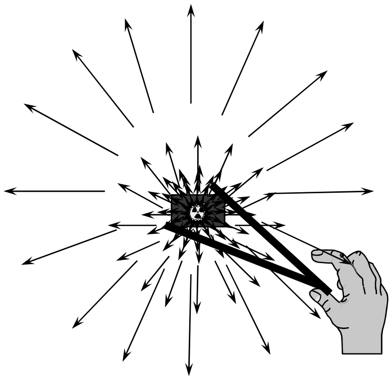
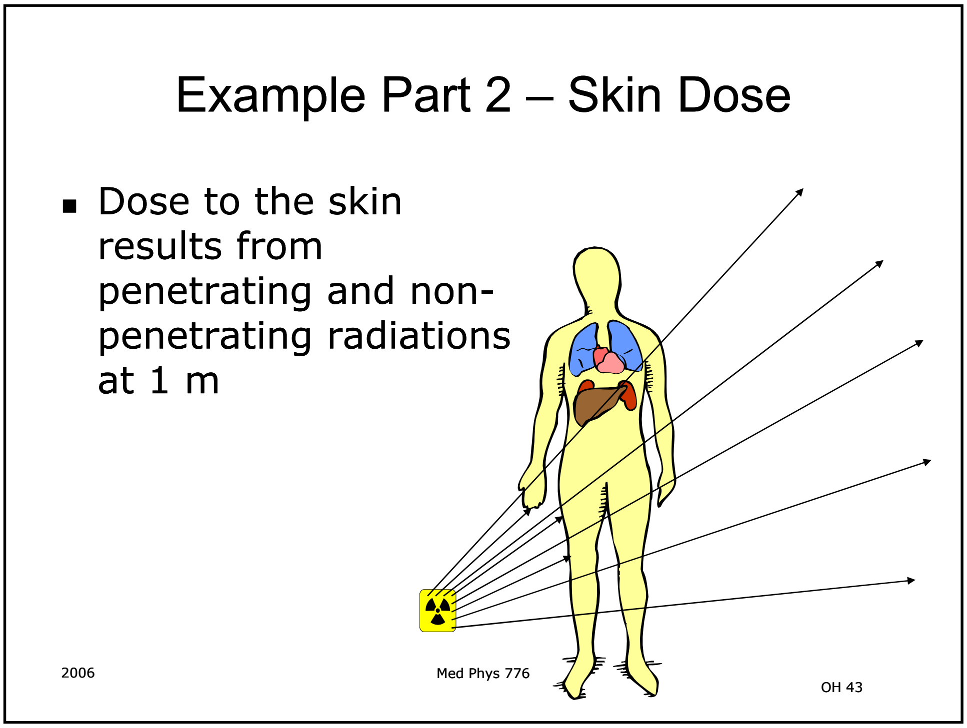
Example Part 1 – Extremity Dose

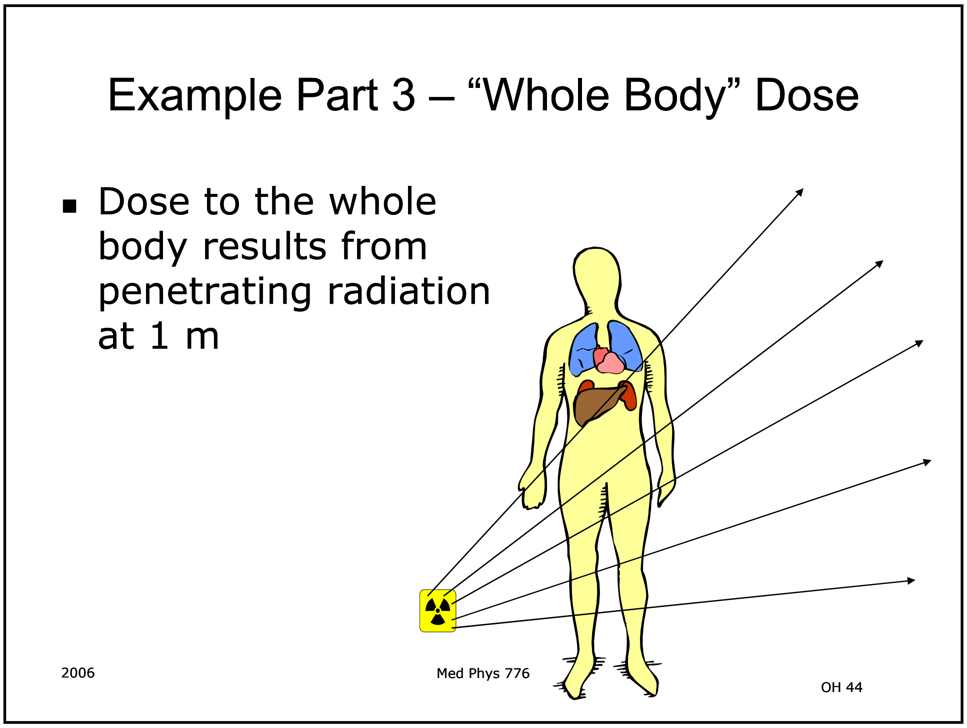
- Dose to the extremity results from penetrating and non-penetrating radiations at 30 cm





Example Part 2 – Skin Dose

- Dose to the skin results from penetrating and non-penetrating radiations at 1 m



Example Part 3 – “Whole Body” Dose

- Dose to the whole body results from penetrating radiation at 1 m

Example B

- An experiment is planned using a PuBe neutron source. The source emits $4x10^6$ fast neutrons per second. If the experimenters will be at 1m from the source, what dose rate will they be exposed to?