Chapter 5

- Shielding
- Gamma Constant
- Point Source/Inverse Square
- Line Source, Area Source, Volume Source

SHIELDING

Objectives

- Describe general considerations for shielding
- Describe the considerations for shielding alpha-emitting radioactive material
- Describe the considerations for shielding beta-emitting radioactive material
- Explain the difference in linear and mass attenuation coefficients

Objectives

- Explain how the probability of photon attenuation changes with photon energy and Z of absorber
- Use the photon attenuation equation to determine shielded dose rates, etc.
- Determine dose rate attenuation from shielding using a buildup factor

General Shielding Considerations

- Shielding thickness depends on three things:
  - Energy: The greater the energy of the radiation, the greater the required thickness of shielding
  - Intensity: The higher the radiation intensity, and the more it must be reduced, the thicker the shield
  - Material:
    - For photons, as the atomic number of the shield goes down, the shielding thickness goes up.
    - For neutrons, as the hydrogen content goes down, the shielding thickness goes up.
- The type of shielding also depends, of course, on the type of radiation to be shielded

Alpha Radiation Shielding

- **Most alpha-emitting radionuclides**
  - **have energies between 4 – 7 MeV (>7.5 MeV required to penetrate dead layer of skin)**
    Note: Both radon and thoron decay products include >7.5 MeV alpha particle emitters…
  - **emit low-energy gammas, X-rays and conversion electrons (e.g. U-235: see Isotopes 73, 74)**
  - **decay to daughters that emit betas and gammas**

- **Internal dosimetry issue mainly, but external dosimetry issues arise with large activities**

Beta Radiation Shielding

- Beta-emitters (positive and negative)
  - contribute most of their dose based on ~ 1/3 E_{max}
    - >70 keV – penetrates dead layer of skin
    - >800 keV – lens of eye hazard
    - >2.1 MeV – whole body hazard (e.g., Rb-88)
  - also emit gammas (common "pure" beta-emitters include ^{3}H, ^{14}C, ^{32}P, and ^{35}S)
  - can produce bremsstrahlung (most likely due to high energy beta interacting with high Z material)
  - can produce annihilation radiation after β+ decay

- Common radionuclides primarily represent an external hazard to skin, but other hazards can exist

Shielding Betas

- Low-Z materials, e.g., plastic such as Lucite, can be used to completely shield betas (consider E_{max})

- Since bremsstrahlung production depends on the both the atomic number, Z, of the shielding material and the beta energy, the fraction of beta energy that is converted to photons can be approximated by the following relationship:

$$f = 3.5 \times 10^{-4} Z E_{max}$$

Photon Shielding Coefficients

- The probability that a photon interacts per unit distance traveled in a material is defined as the <u>linear attenuation coefficient</u>, μ.

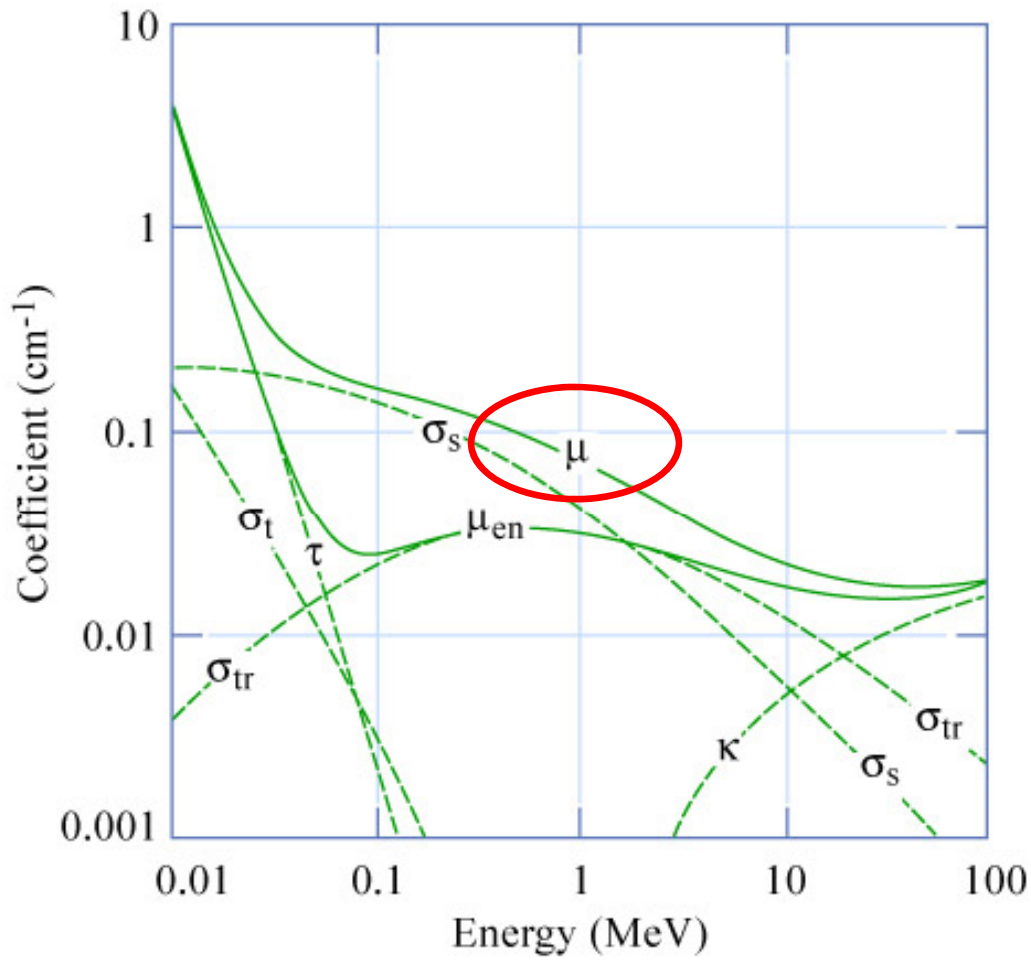
- μ includes the probabilities of the different possible photon interactions:

$$\mu = \mu_{PE} + \mu_{CS} + \mu_{PP}$$

- The contribution of the different interactions depends on the energy of the photon as well as the shielding material

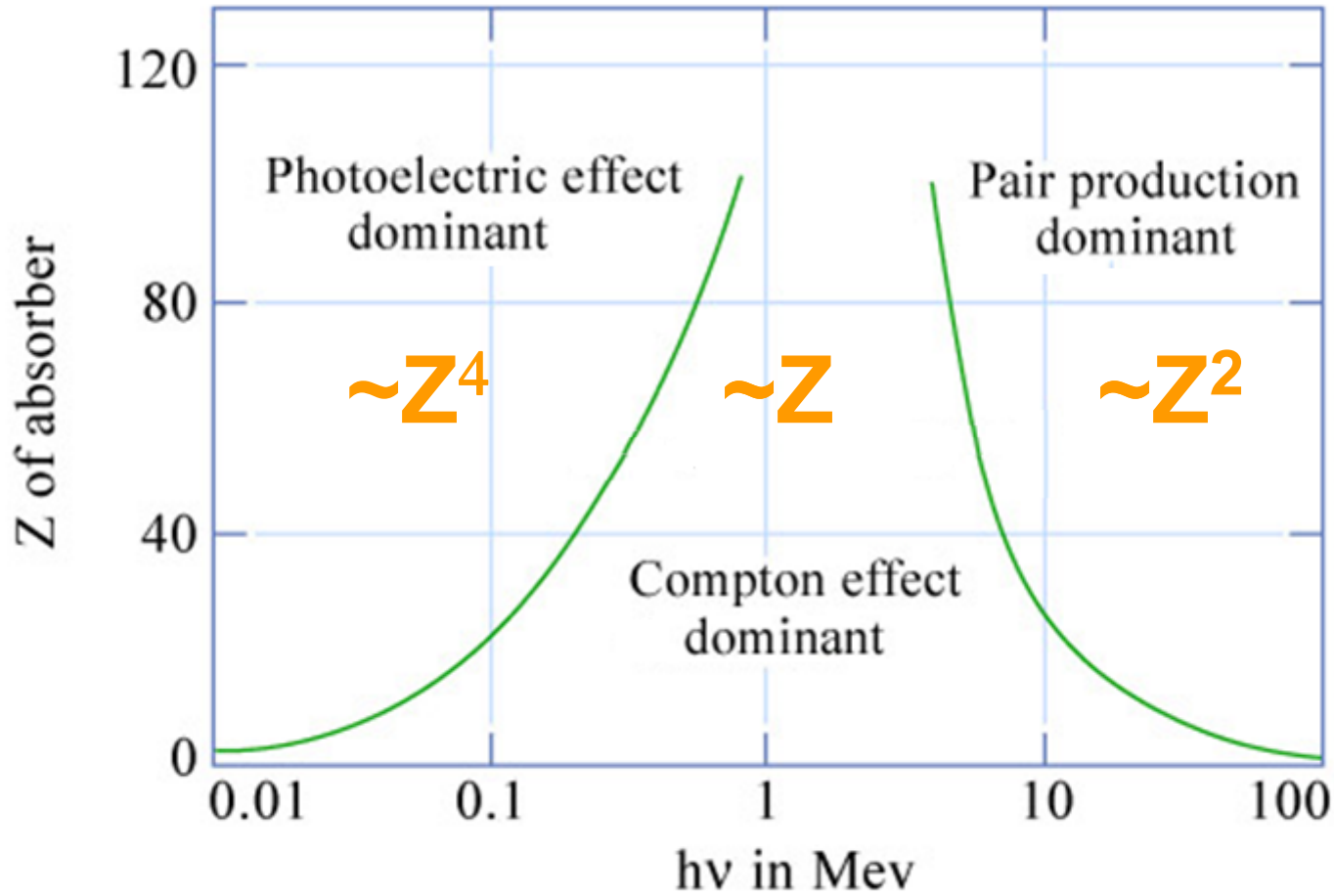
- The dimensions of the linear attenuation coefficient are typically in cm^{-1} (or 1/cm).

Linear Attenuation Coefficient vs. Energy



Linear attenuation and energy-absorption coefficients as functions of energy for photons in water.

Probability of Effect with Z of Absorber



Mass Attenuation Coefficients

- The <u>mass attenuation coefficient</u> (MAC) is a measure of the average number of interactions between incident photons and matter that occur in a given mass-per-unit area thickness of material traversed
- MAC = LAC divided by the density of the material (μ/ρ)
- Since LAC has dimensions of 1/cm and density has dimensions of g/cm^3, the MAC has dimensions of $(1/cm) / (g/cm^3) = cm^2/g$
- MACs are typically given in tables or graphs from which LACs can be determined (see MISC-23 et seq.)

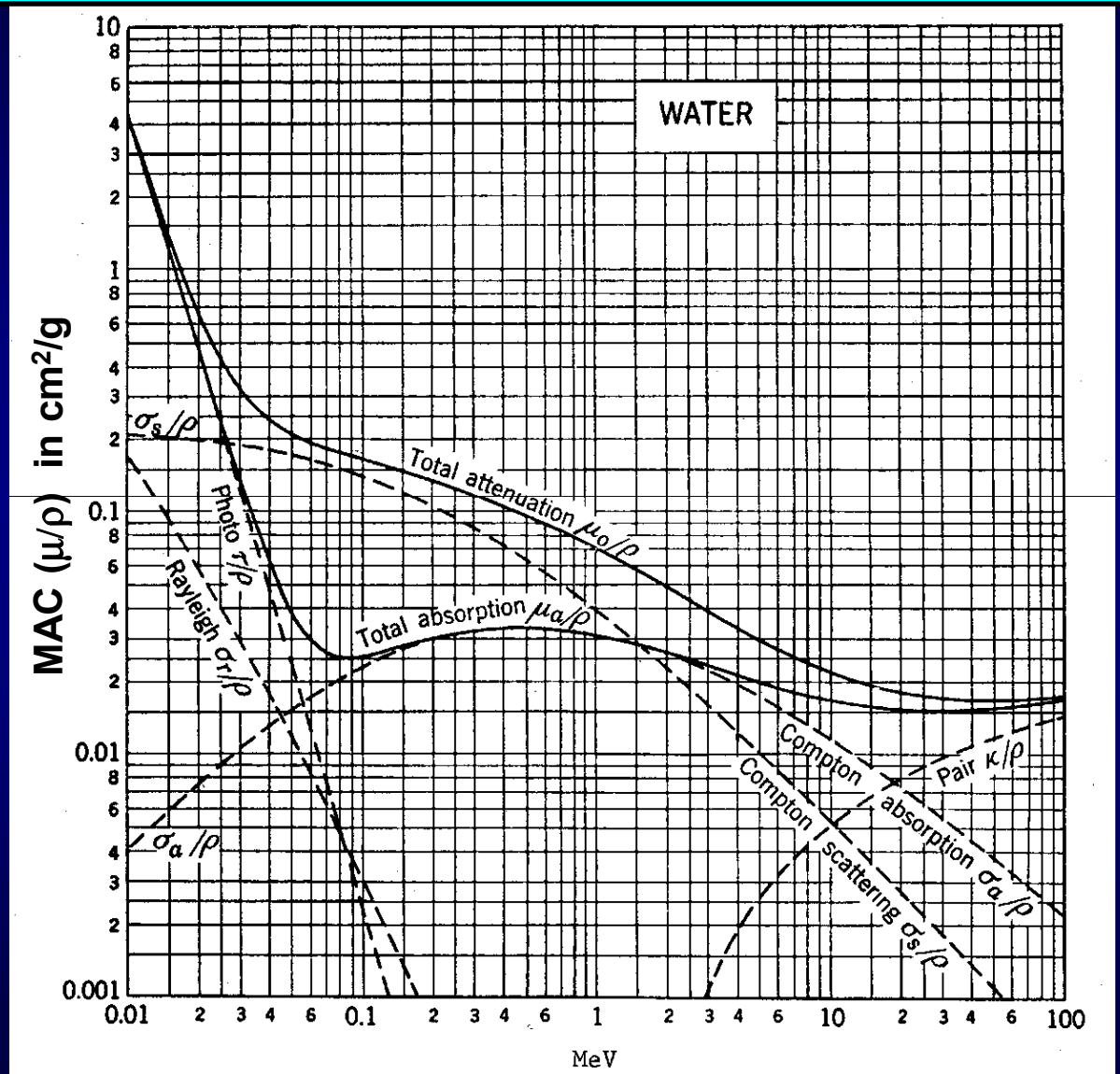
Determining LAC from MAC

- **Multiply the MAC by the density of the material to calculate LAC:**

$$\mu/\rho \times \rho = \mu$$

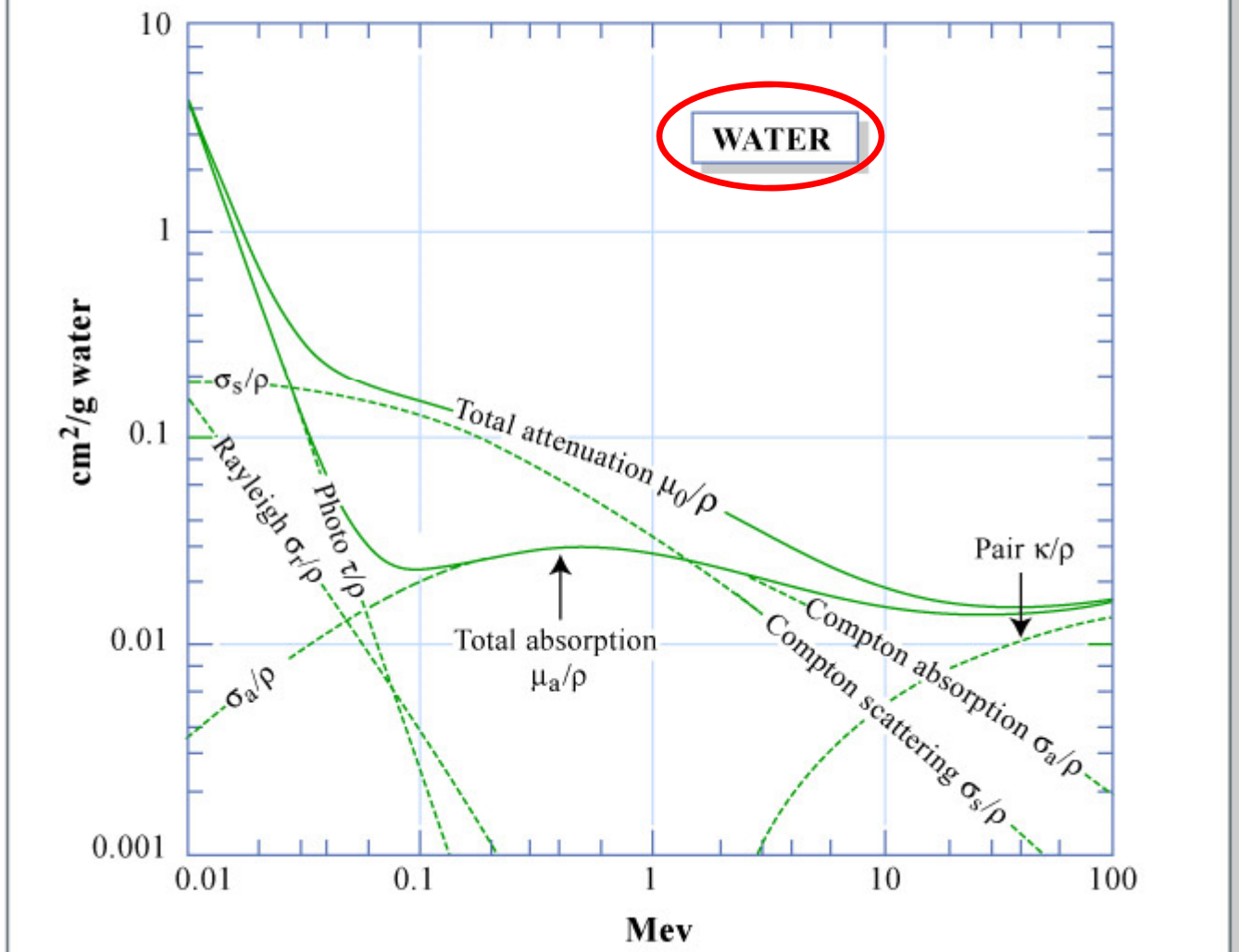
$$(cm^2/g) \times (g/cm^3) = 1/cm$$

Mass Attenuation Coefficient vs. Energy

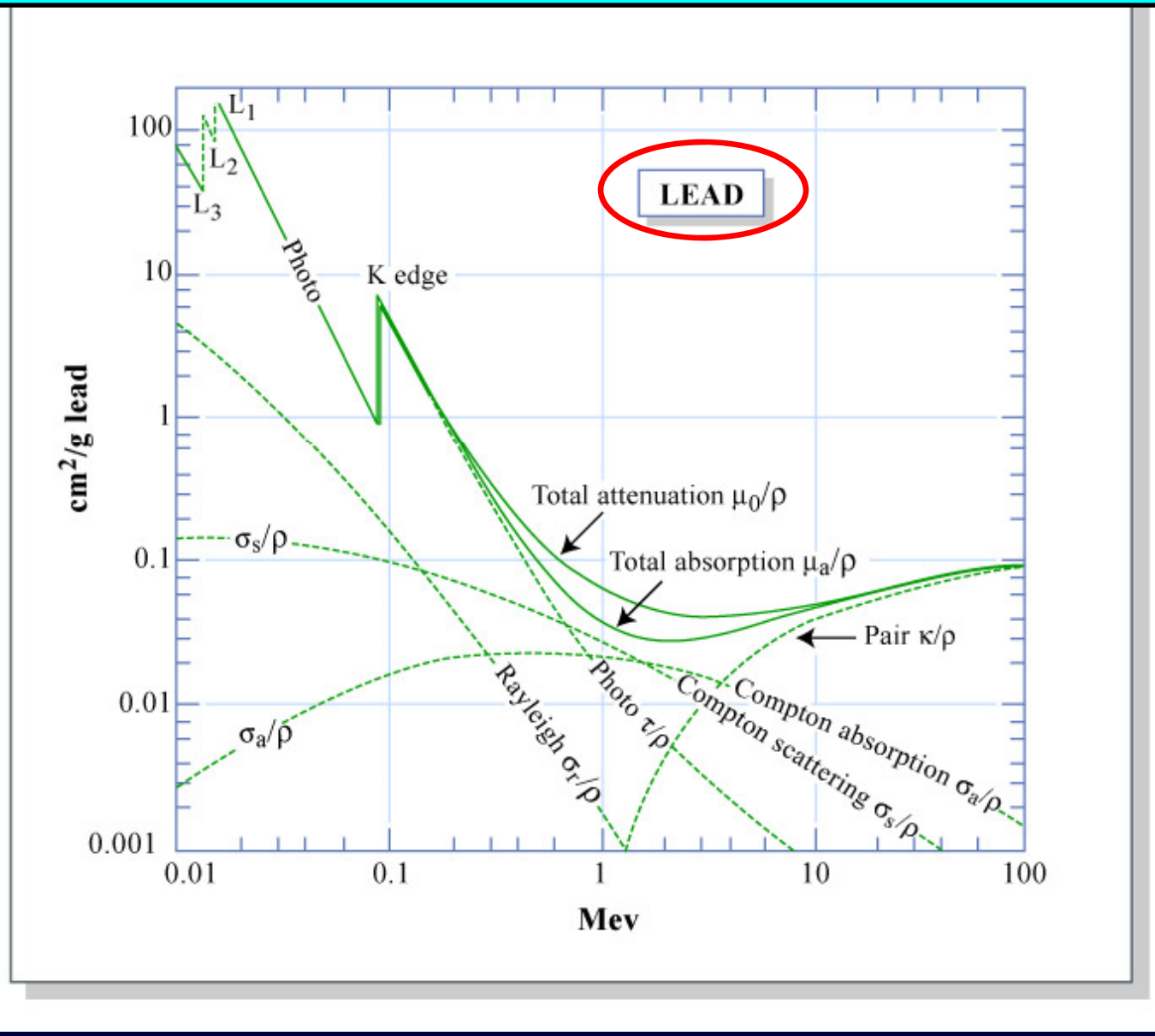


MASS ATTENUATION COEFFICIENTS FOR GAMMA RAYS IN WATER

Mass Attenuation Coefficient vs. Energy



Mass Attenuation Coefficient vs. Energy



Mass Energy-Absorption Coefficient

- The <u>mass energy-absorption coefficient</u> is a measure of the average fractional amount of incident photon energy transferred to kinetic energy of charged particles as a result of photon interactions with matter (μ_{en}/ρ)

- Energy not deposited include losses from bremsstrahlung, positron annihilation, fluorescence photons, etc.

- See MISC-26

Photon Attenuation

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

Where:

- I_0 is the unshielded intensity (or dose rate)
- I is shielded intensity
- μ is the linear attenuation coefficient for the shielding material with units of cm^{-1}
- x is the thickness of the shielding material

Attenuation Example

- What is the dose rate after shielding a source that emits only 1 MeV photons if the unshielded dose rate is 100 mrem/h and the source is shielded by 1/2 inch lead?

  Hint: Determine LAC from MAC to use in the shielding equation

Attenuation Example

- The mass attenuation coefficient for 1 MeV photons for lead is 0.0708 cm^2/g (MISC-24)
- However, we need the LAC. To get this we need the density of the material in which the radiation is interacting (MISC-7)
- The density of lead is 11.35 g/cm^3
- $(\mu/\rho)(\rho) = (0.0708\ cm^2/g)(11.35\ g/cm^3) = 0.8\ cm^{-1} = \mu$

Attenuation Example

- $I = I_0 e^{(-\mu x)}$
- $I = (100 \text{ mrem/h})\ e^{[-(0.8/\text{cm})(0.5 \text{ in})(2.54 \text{ cm/in})]}$
- $I = (100 \text{ mrem/h})(0.36) = 36 \text{ mrem/h}$

Attenuation vs. Absorption

- The linear attenuation coefficient is used to determine the amount of shielding needed
- An absorption coefficient is used to determine the amount of energy that is absorbed, that is, the dose
- The mass energy-absorption coefficient is typically referred to as μ_{en}/ρ
- Turn to MISC-26

HVL and TVL

- The amount of shielding required to reduce the dose rate by 1/2 is called the half-value layer or HVL
- HVLs for given materials are based on photon energy
- The amount of shielding needed to reduce the dose rate by a factor of 10 is called the tenth-value layer or TVL
- Turn to MISC-11

HVL, TVL and μ

The HVL and TVL are mathematically related to μ as follows:

$$HVL = \ln(2)/\mu$$

$$TVL = \ln(10)/\mu$$

HVL Example

Determine the lead HVL for Cs-137 photons using the shielding equation.

Given:

- $I = I_0 e^{(-\mu x)}$
- **Cs-137 has 0.662 MeV photons**
- **To find μ, first turn to MISC-24 to determine the MAC**

HVL Example

Interpolate from MISC-24:

$$[(0.0885 - 0.125) / (800 – 600)] = [(? – 0.125) / (662 – 600)]$$

$$MAC = 0.114\ cm^2/g = \mu/\rho$$

$$(\mu/\rho)(\rho) = (0.114\ cm^2/g)(11.35\ g/cm^3) = 1.29\ cm^{-1} = \mu$$

HVL Example

$I = I_0 e^{(-\mu x)}$ and $I / I_0 = e^{(-\mu x)}$; for HVLs, $I / I_0 = ½$

$½ = e^{(-\mu x)}$; $½ = e^{-(1.29/cm)(X\ cm)}$

$\ln(1/2) = -(1.29/cm)(X\ cm)$

$-(-0.693) = (1.29)(X)$

Why the difference?

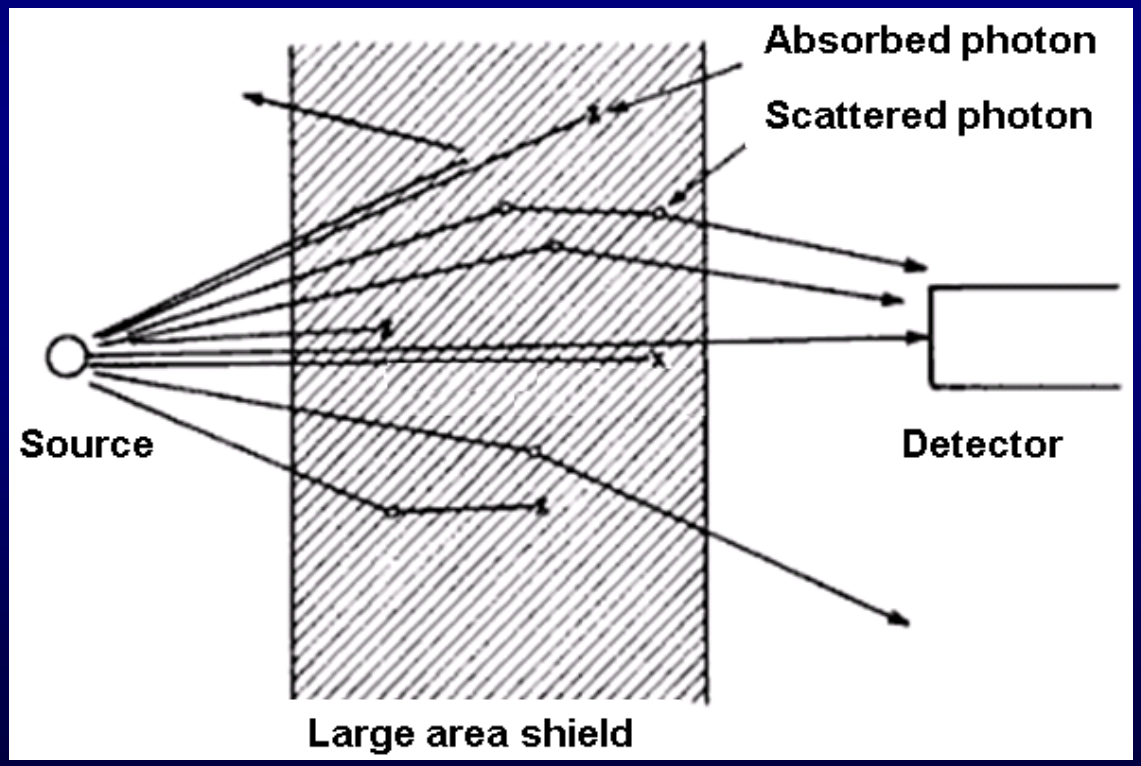
X = 0.54 cm Pb

Also, using HVL = $\ln(2)/\mu$ = 0.54 cm Pb

Note, however, using MISC-11 table, HVL = 0.65 cm Pb

Attenuation & Buildup

The shielding equation does not fully account for photon interactions within shielding materials when you have broad beams or very thick shields. To account for scattered photons and other secondary radiations, we use the buildup factor, B.



Buildup Factor

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

- $B = [1° + 2° / 1°] \geq 1$

  1° = unattenuated radiation
  2° = scattered radiation

- The buildup factor is dependent on the type and amount of shielding material and the energy of the photon.

- Buildup factors have been calculated for many different types of shielding materials and can be found in tables (see MISC-34).

Determining Buildup Factor

- First use B = 1 and solve for μx
- Then use μx to find B from a table (MISC-34, 35, 36)
- Using this value of B, determine a new value for μx
- Continue this iterative process until B and μx converge to stable values

Buildup Example

What amount of lead shielding is needed to reduce the dose rate from 100 mrem/h to 2 mrem/h for 1 MeV photons? Given $\mu = 0.8\ cm^{-1}$ (previous example)

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

Assume B = 1

Now determine μx:

$$2\ mrem/h = (100\ mrem/h)(1)\ e^{(-\mu x)}$$

Buildup Example

$\ln(2/100) = \ln[e^{(-\mu x)}]$

$\mu x = 3.91$ (Note: $x = 3.91/0.8$ cm-1 = 4.89 cm with B = 1)

Next, find B for $\mu x = 3.91$

Interpolate: for $\mu x = 4$, B = 2.26; for $\mu x = 2$, B = 1.69 so,

(4-2)/(2.26-1.69) = (4-3.91)/(2.26 - ?)

2/0.57 = 0.09/(2.26 - ?)

Buildup Example

$3.51 = 0.09/(2.26 - ?)$

$(2.26 - ?) = 0.09/3.51$

$- ? = (0.09/3.51) - 2.26$

$? = 2.26 - 0.03$

$? = 2.23 = B$

Buildup Example

Now solve for μx using B = 2.23:

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

$2 \text{ mrem/h} = (100 \text{ mrem/h})(2.23) e^{(-\mu x)}$

$\ln(2/223) = \ln[e^{(-\mu x)}]$

$\mu x = 4.71$ (Note: x = 4.71/0.8 cm-1 = 5.89 cm with B = 2.23)

x increased from 4.89 cm to 5.89 cm (17%) due to buildup

Question: Are more iterations needed?

Interpolating Buildup

- A less precise alternative to interpolation is to use the μx that would give the most conservative value of B. In this case you would select B = 2.26.

- When the energy of a photon is not listed, double interpolation is necessary. That is, interpolation for the energy is required prior to interpolation for the value of μx.

Problem

What thickness of lead shielding is required to reduce the dose rate from a ^{137}Cs source from 175 mrem hr^{-1} to 5 mrem hr^{-1}?

Problem

A 1-MeV gamma point source is to be shielded with water. The dose rate is to be reduced from 1 rem hr^{-1} to 10 mrem hr^{-1}. What is the buildup factor for this case (after at least two iterations)? How much water is required?

END OF SHIELDING

GAMMA CONSTANT

Objectives

- Determine attenuation from shielding and calculate buildup
- Explain how each gamma emitting radionuclide has a unique exposure rate constant associated with it
- Use the exposure rate constant correctly in an exposure calculation

Gamma Constant

The gamma constant (Γ) specifies the exposure rate for a radionuclide

Lets see where it comes from

Röentgen vs Rad

$$1\ R = 2.58 \times 10^{-4}\ \frac{C}{kg} \times \frac{1\ kg}{1000\ gm} \times 6.242 \times 10^{18}\ \frac{IP}{C}$$

$$\times\ 34\ \frac{eV}{IP} \times 1.6 \times 10^{-12}\ \frac{ergs}{eV} = 87.6\ \frac{ergs}{gm}$$

Since 1 rad = 100 $\frac{ergs}{gm}$

$$1\ R = 87.6\ \frac{ergs}{gm} \times \frac{1\ rad}{100\ \frac{ergs}{gm}} = 0.876\ rad$$

Röentgen vs Rad

If 1 R = 0.876 rad, then why did NRC (in the previous 10 CFR Part 20) define 1 R as approximately equal to 1 rad? 0.876 is not approximately equal to 1 !

ANSWER:

1 R of exposure equals 0.876 rad of dose in AIR

But 1 R of exposure is approximately equal to 1 rad of dose in TISSUE

Let's see how.

Röentgen vs Rad

To convert from R in air to rad in tissue, we need to compare the mass energy absorption coefficients of these two media and multiply the ratio by the Röentgen to rad conversion factor in air which we just derived

(SEE MISC-26)

TABLE A-4

MASS ENERGY ABSORPTION COEFFICIENTS

(cm^2/gm) and f factor to Convert from Roentgens to Rads.

$$f = 0.869 \frac{(\mu_{en}/\rho)_{med}}{(\mu_{en}/\rho)_{air}}$$

Photon Energy (Mev)	Mass Energy Coefficients: Air	Water	H_2SO_4 .8N	Polystyrene	Compact Bone	Muscle (striated)	f: Water to Air	Compact Bone to Air	Muscle to Air
.01	4.61	4.79	5.36	1.82	19.2	4.87	.903	3.62	.918
.015	1.27	1.28	1.45	.495	5.84	1.32	.876	4.00	.907
.02	.511	.512	.585	.193	2.46	.533	.871	4.18	.903
.03	.148	.149	.169	.0562	.720	.154	.874	4.23	.904
.04	.0668	.0677	.0761	.0300	.304	.0701	.883	3.95	.912
.05	.0406	.0418	.0460	.0236	.161	.0431	.895	3.45	.922
.06	.0305	.0320	.0344	.0218	.0998	.0328	.912	2.84	.933
.08	.0243	.0262	.0271	.0217	.0537	.0264	.937	1.92	.944
.10	.0234	.0256	.0260	.0231	.0387	.0256	.950	1.44	.951
.15	.0250	.0277	.0277	.0263	.0305	.0275	.961	1.06	.955
.2	.0268	.0297	.0296	.0286	.0301	.0294	.964	.976	.957
.3	.0287	.0319	.0319	.0309	.0310	.0317	.966	.939	.958
.4	.0295	.0328	.0327	.0318	.0315	.0325	.967	.931	.959
.5	.0296	.0330	.0330	.0321	.0317	.0328	.968	.927	.959
.6	.0295	.0329	.0328	.0318	.0314	.0325	.968	.924	.959
^{137}Cs .662	.0294	.0327	.0326	.0316	.0312	.0323	.968	.923	.958
.8	.0289	.0321	.0320	.0310	.0306	.0318	.968	.922	.958
1.0	.0278	.0309	.0308	.0300	.0295	.0306	.967	.922	.957
^{60}Co 1.25	.0266	.0295	.0294	.0286	.0281	.0291	.966	.922	.957
1.5	.0254	.0282	.0281	.0275	.0270	.0280	.966	.923	.956
2	.0234	.0260	.0259	.0252	.0249	.0257	.965	.925	.954
3	.0205	.0227	.0227	.0219	.0219	.0225	.962	.928	.951
4	.0186	.0206	.0206	.0198	.0200	.0204	.958	.933	.948
5	.0174	.0191	.0191	.0182	.0187	.0189	.956	.938	.945
6	.0164	.0180	.0180	.0171	.0178	.0178	.954	.943	.943
8	.0152	.0166	.0166	.0155	.0167	.0164	.949	.955	.937
10	.0145	.0157	.0157	.0145	.0159	.0155	.945	.956	.929
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)

Units

The units of the gamma constant are typically given as

$$\frac{R}{hr - mCi} \text{ at 1 cm} = \boxed{\frac{R - cm^2}{hr - mCi}}$$

or

$$\frac{R}{hr - Ci} \text{ at 1 m} = \boxed{\frac{R - m^2}{hr - Ci}}$$

(see MISC-10)

Converting Units

Converting from “cm & mCi” to “m & Ci”

$$\Gamma\left(\frac{R\text{ - cm}^2}{hr\text{ - mCi}}\right) \times \frac{1000\text{ mCi}}{Ci} \times \left(\frac{1\text{ m}}{100\text{ cm}}\right)^2 = \frac{\Gamma}{10}\left(\frac{R\text{ - m}^2}{hr\text{ - Ci}}\right)$$

see MISC-10

Dose Rate vs. Dose

$$\text{Dose rate} = \frac{\Gamma A}{r^2} \qquad \frac{R}{hr} = \Gamma \left(\frac{R - m^2}{hr - Ci} \right) \times \boxed{\frac{Ci}{m^2}}$$

$$\text{Dose, } D = \frac{\Gamma A \ t}{r^2} \qquad R = \Gamma \left(\frac{R - m^2}{hr - Ci} \right) \times \boxed{\frac{Ci}{m^2} \times hr}$$

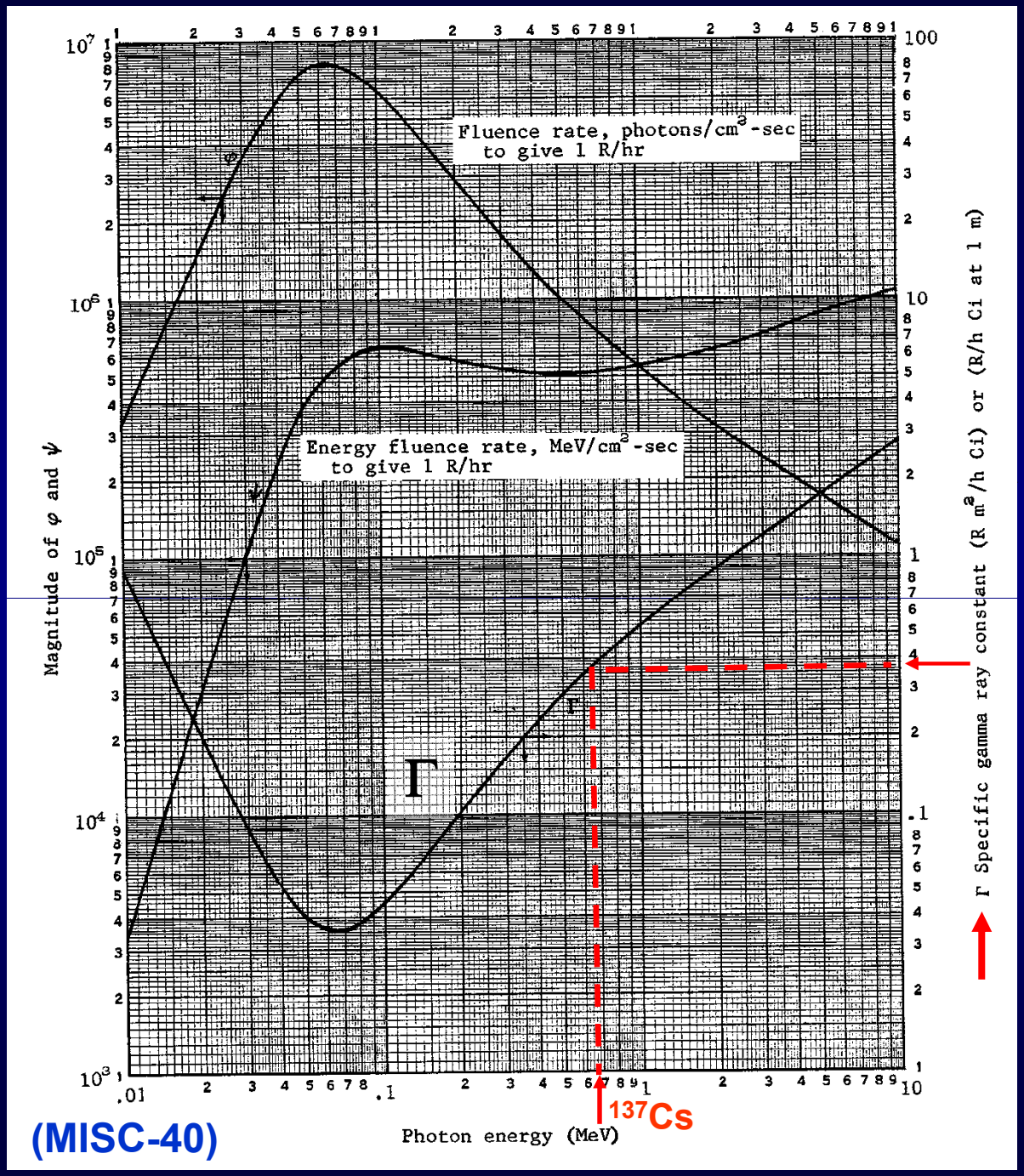
Sample Gamma Constants

$$\Gamma = \left(\frac{R - m^2}{hr - Ci} \right)$$

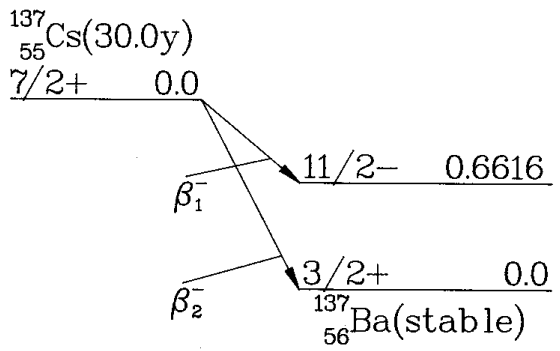
<0.1		0.1 - 0.3		0.3 - 0.5		0.5 - 1		>1	
^{109}Pd	0.003	^{99}Mo	0.18	^{63}Ni	0.31	^{59}Fe	0.64	^{60}Co	1.32
^{133}Xe	0.01	^{131}I	0.22	^{137}Cs	0.33	^{226}Ra	0.83	^{24}Na	1.84
^{125}I	0.07	^{65}Zn	0.27	^{95}Zr	0.41				
				^{54}Mn	0.47				
				^{192}Ir	0.48				

For the same activity (Ci) and the same distance (m):

Co = 3 x Ir or 4 x Cs or 6 x I Ir = 2 x I Cs = 1.5 x I



$$0.38 \frac{\text{R-m}^2}{\text{hr-Ci}}$$



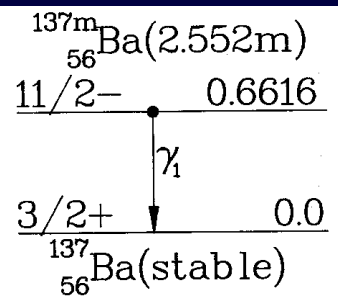
55–CESIUM–137

HALFLIFE = 30 YEARS 04–MAY–77
DECAY MODE(S): β^-

RADIATION	y(i) (Bq–s)$^{-1}$	E(i) (MeV)	y(i)×E(i)
β^- 1	9.46E–01	1.734E–01*	1.64E–01
β^- 2	5.40E–02	4.246E–01*	2.29E–02

LISTED β, ce AND Auger RADIATIONS 1.87E–01
LISTED RADIATIONS 1.87E–01

* AVERAGE ENERGY (MeV)
BARIUM–137M DAUGHTER, YIELD 9.46E–01, IS RADIOACTIVE.
BARIUM–137 DAUGHTER, YIELD 5.40E–02, IS STABLE.



56–BARIUM–137M

HALFLIFE = 2.552 MINUTES 04–MAY–77
DECAY MODE(S): IT

RADIATION	y(i) (Bq–s)$^{-1}$	E(i) (MeV)	y(i)×E(i)
γ 1	8.98E–01	6.616E–01	5.94E–01
ce–K, γ 1	8.32E–02	6.242E–01	5.19E–02
ce–L_1, γ 1	1.19E–02	6.557E–01	7.80E–03
ce–L_2, γ 1	1.69E–03	6.560E–01	1.11E–03
ce–L_3, γ 1	1.39E–03	6.564E–01	9.10E–04
ce–M, γ 1	3.18E–03	6.606E–01*	2.10E–03
ce–N^+, γ 1	9.02E–04	6.616E–01*	5.97E–04
$K\alpha_1$ X–ray	3.92E–02	3.219E–02	1.26E–03
$K\alpha_2$ X–ray	2.13E–02	3.182E–02	6.78E–04
Auger–KLL	5.35E–03	2.618E–02*	1.40E–04
Auger–KLX	2.53E–03	3.075E–02*	7.79E–05
Auger–LMM	4.76E–02	3.577E–03*	1.70E–04
Auger–LMX	2.78E–02	4.531E–03*	1.26E–04
Auger–MXY	1.49E–01	9.276E–04*	1.38E–04

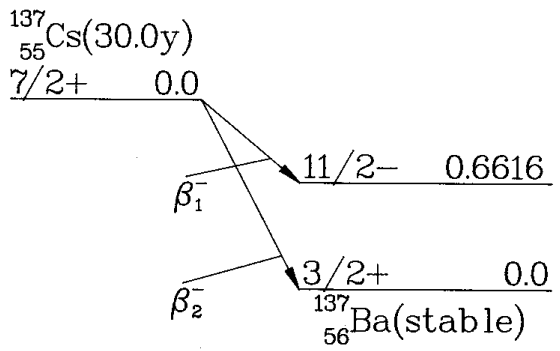
LISTED X, γ AND $\gamma\pm$ RADIATIONS 5.96E–01
OMITTED X, γ AND $\gamma\pm$ RADIATIONS** 5.68E–04
LISTED β, ce AND Auger RADIATIONS 6.51E–02
OMITTED β, ce AND Auger RADIATIONS** 3.96E–05
LISTED RADIATIONS 6.61E–01
OMITTED RADIATIONS** 6.07E–04

* AVERAGE ENERGY (MeV)
** EACH OMITTED TRANSITION CONTRIBUTES <0.100% TO $\Sigma y(i)\times E(i)$ IN ITS CATEGORY.
BARIUM–137 DAUGHTER IS STABLE.

Why is γ emitted 89.8% instead of 100% ?
Photon Energy = 0.6616 MeV
Conversion Electron Energy = 0.6242 MeV
Difference = 0.6616 - 0.6242 = 0.037 MeV
K-Shell Binding Energy (next page)

Atomic Number	Element	K series					L series							
		K_{ab}	$K\beta_2$	$K\beta_1$	$K\alpha_1$	$K\alpha_2$	L_{Iab}	L_{IIab}	L_{IIIab}	$L\gamma_1$	$L\beta_2$	$L\beta_1$	$L\alpha_1$	$L\alpha_2$
31	Gallium	10.368	10.365	10.263	9.251	9.234	1.30	1.134	1.117			1.122	1.096	
32	Germanium	11.103	11.100	10.981	9.885	9.854	1.42	1.248	1.217			1.216	1.186	
33	Arsenic	11.863	11.863	11.725	10.543	10.507	1.529	1.359	1.323			1.317	1.282	
34	Selenium	12.652	12.651	12.495	11.221	11.181	1.652	1.473	1.434			1.419	1.379	
35	Bromine	13.475	13.465	13.290	11.923	11.877	1.794	1.599	1.552			1.526	1.480	
36	Krypton	14.323	14.313	14.112	12.648	12.597	1.931	1.727	1.675			1.638	1.587	
37	Rubidium	15.201	15.184	14.960	13.394	13.335	2.067	1.866	1.806			1.752	1.694	1.692
38	Strontium	16.106	16.083	15.834	14.164	14.097	2.221	2.008	1.941			1.872	1.806	1.805
39	Yttrium	17.037	17.011	16.736	14.957	14.882	2.369	2.154	2.079			1.996	1.922	1.920
40	Zirconium	17.998	17.969	17.666	15.774	15.690	2.547	2.305	2.220	2.302	2.219	2.124	2.042	2.040
41	Niobium	18.987	18.951	18.621	16.614	16.520	2.706	2.467	2.374	2.462	2.367	2.257	2.166	2.163
42	Molybdenum	20.002	19.964	19.607	17.478	17.373	2.884	2.627	2.523	2.623	2.518	2.395	2.293	2.290
43	Technetium	21.054	21.012	20.585	18.410	18.328	3.054	2.795	2.677	2.792	2.674	2.538	2.424	2.420
44	Ruthenium	22.118	22.072	21.655	19.278	19.149	3.236	2.966	2.837	2.964	2.836	2.683	2.558	2.554
45	Rhodium	23.224	23.169	22.721	20.214	20.072	3.419	3.145	3.002	3.144	3.001	2.834	2.696	2.692
46	Palladium	24.347	24.297	23.816	21.175	21.018	3.617	3.329	3.172	3.328	3.172	2.990	2.838	2.833
47	Silver	25.517	25.454	24.942	22.162	21.988	3.810	3.528	3.352	3.519	3.348	3.151	2.984	2.978
48	Cadmium	26.712	26.641	26.093	23.172	22.982	4.019	3.727	3.538	3.716	3.528	3.316	3.133	3.127
49	Indium	27.928	27.859	27.274	24.207	24.000	4.237	3.939	3.729	3.920	3.713	3.487	3.287	3.279
50	Tin	29.190	29.106	28.483	25.270	25.042	4.464	4.157	3.928	4.131	3.904	3.662	3.444	3.435
51	Antimony	30.486	30.387	29.723	26.357	26.109	4.697	4.381	4.132	4.347	4.100	3.843	3.605	3.595
52	Tellurium	31.809	31.698	30.993	27.471	27.200	4.938	4.613	4.341	4.570	4.301	4.029	3.769	3.758
53	Iodine	33.164	33.016	32.292	28.610	28.315	5.190	4.856	4.559	4.800	4.507	4.220	3.937	3.926
54	Xenon	34.579	34.446	33.644	29.802	29.485	5.452	5.104	4.782	5.036	4.720	4.422	4.111	4.098
55	Cesium	35.959	35.819	34.984	30.970	30.623	5.720	5.358	5.011	5.280	4.936	4.620	4.286	4.272
56	Barium	37.410	37.255	36.376	32.191	31.815	5.995	5.623	5.247	5.531	5.156	4.828	4.467	4.451
57	Lanthanum	38.931	38.728	37.799	33.440	33.033	6.283	5.894	5.489	5.789	5.384	5.043	4.651	4.635
58	Cerium	40.449	40.231	39.255	34.717	34.276	6.561	6.165	5.729	6.052	5.613	5.262	4.840	4.823
59	Praseodymium	41.998	41.772	40.746	36.023	35.548	6.846	6.443	5.968	6.322	5.850	5.489	5.034	5.014
60	Neodymium	43.571	43.298	42.269	37.359	36.845	7.144	6.727	6.215	6.602	6.090	5.722	5.230	5.208
61	Promethium	45.207	44.955	43.945	38.649	38.160	7.448	7.018	6.466	6.891	6.336	5.956	5.431	5.408
62	Samarium	46.846	46.553	45.400	40.124	39.523	7.754	7.281	6.721	7.180	6.587	6.206	5.636	5.609
63	Europium	48.515	48.241	47.027	41.529	40.877	8.069	7.624	6.983	7.478	6.842	6.456	5.846	5.816
64	Gadolinium	50.229	49.961	48.718	42.983	42.280	8.393	7.940	7.252	7.788	7.102	6.714	6.059	6.027
65	Terbium	51.998	51.737	50.391	44.470	43.737	8.724	8.258	7.519	8.104	7.368	6.979	6.275	6.241
66	Dysprosium	53.789	53.491	52.178	45.985	45.193	9.083	8.621	7.850	8.418	7.638	7.249	6.495	6.457
67	Holmium	55.615	55.292	53.934	47.528	46.686	9.411	8.920	8.074	8.748	7.912	7.528	6.720	6.680
68	Erbium	57.483	57.088	55.690	49.099	48.205	9.776	9.263	8.364	9.069	8.188	7.810	6.948	6.904
69	Thulium	59.335	58.969	57.576	50.730	49.762	10.144	9.628	8.652	9.424	8.472	8.103	7.181	7.135
70	Ytterbium	61.303	60.959	59.352	52.360	51.326	10.486	9.977	8.943	9.779	8.758	8.401	7.414	7.367
71	Lutecium	63.304	62.946	61.282	54.063	52.959	10.867	10.345	9.241	10.142	9.048	8.708	7.654	7.604
72	Hafnium	65.313	64.936	63.209	55.757	54.579	11.264	10.734	9.556	10.514	9.346	9.021	7.898	7.843
73	Tantalum	67.400	66.999	65.210	57.524	56.270	11.676	11.130	9.876	10.892	9.649	9.341	8.145	8.087
74	Tungsten	69.508	69.090	67.233	59.310	57.973	12.090	11.535	10.198	11.283	9.959	9.670	8.396	8.333
75	Rhenium	71.662	71.220	69.298	61.131	59.707	12.522	11.955	10.531	11.684	10.273	10.008	8.651	8.584
76	Osmium	73.860	73.393	71.404	62.991	61.477	12.965	12.383	10.869	12.094	10.596	10.354	8.910	8.840
77	Iridium	76.097	75.605	73.549	64.886	63.278	13.413	12.819	11.211	12.509	10.918	10.706	9.173	9.098
78	Platinum	78.379	77.866	75.736	66.820	65.111	13.873	13.268	11.559	12.939	11.249	11.069	9.441	9.360
79	Gold	80.713	80.165	77.968	68.794	66.980	14.353	13.733	11.919	13.379	11.582	11.439	9.711	9.625
80	Mercury	83.106	82.526	80.258	70.821	68.894	14.841	14.212	12.285	13.828	11.923	11.823	9.987	9.896
81	Thallium	85.517	84.904	82.558	72.860	70.820	15.346	14.697	12.657	14.288	12.268	12.210	10.266	10.170
82	Lead	88.001	87.343	84.922	74.957	72.794	15.870	15.207	13.044	14.762	12.620	12.611	10.549	10.448
83	Bismuth	90.521	89.833	87.335	77.097	74.805	16.393	15.716	13.424	15.244	12.977	13.021	10.836	10.729
84	Polonium	93.112	92.386	89.809	79.296	76.868	16.935	16.244	13.817	15.740	13.338	13.441	11.128	11.014
85	Astatine	95.740	94.976	92.319	81.525	78.956	17.490	16.784	14.215	16.248	13.705	13.873	11.424	11.304
86	Radon	98.418	97.616	94.877	83.800	81.080	18.058	17.387	14.618	16.768	14.077	14.316	11.724	11.597
87	Francium	101.147	100.305	97.483	86.119	83.243	18.638	17.904	15.028	17.301	14.459	14.770	12.029	11.894
88	Radium	103.927	103.048	100.136	88.485	85.446	19.233	18.481	15.442	17.845	14.839	15.233	12.338	12.194
89	Actinium	106.759	105.838	102.846	90.894	87.681	19.842	19.078	15.865	18.405	15.227	15.712	12.650	12.499
90	Thorium	109.630	108.671	105.592	93.334	89.942	20.460	19.688	16.296	18.977	15.620	16.200	12.966	12.808
91	Protactinium	112.581	111.575	108.408	95.851	92.271	21.102	20.311	16.731	19.559	16.022	16.700	13.291	13.120
92	Uranium	115.591	114.549	111.289	98.428	94.648	21.753	20.943	17.163	20.163	16.425	17.218	13.613	13.438
93	Neptunium	118.619	117.533	114.181	101.005	97.023	22.417	21.596	17.614	20.774	16.837	17.740	13.945	13.758
94	Plutonium	121.720	120.592	117.146	103.653	99.457	23.097	22.262	18.066	21.401	17.254	18.278	14.279	14.082
95	Americium	124.876	123.706	120.163	106.351	101.932	23.793	22.944	18.525	22.042	17.677	18.829	14.618	14.411
96	Curium	128.088	126.875	123.235	109.098	104.448	24.503	23.640	18.990	22.699	18.106	19.393	14.961	14.743
97	Berkelium	131.357	130.101	126.362	111.896	107.023	25.230	24.352	19.461	23.370	18.540	19.971	15.309	15.079
98	Californium	134.683	133.383	129.544	114.745	109.603	25.971	25.080	19.938	24.056	18.980	20.562	15.661	15.420
99		138.067	136.724	132.781	117.646	112.244	26.729	25.824	20.422	24.758	19.426	21.166	16.018	15.764
100		141.510	140.122	136.075	120.598	114.926	27.503	26.584	20.912	25.475	19.879	21.785	16.379	16.113

(MISC-28)



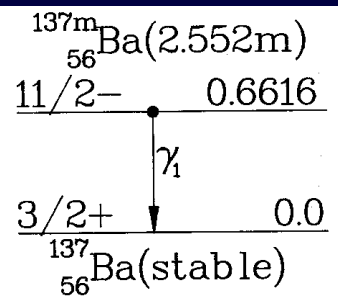
55–CESIUM–137

HALFLIFE = 30 YEARS 04–MAY–77
DECAY MODE(S): β^-

RADIATION	y(i) (Bq–s)$^{-1}$	E(i) (MeV)	y(i)×E(i)
β^- 1	9.46E–01	1.734E–01*	1.64E–01
β^- 2	5.40E–02	4.246E–01*	2.29E–02

LISTED β, ce AND Auger RADIATIONS 1.87E–01
LISTED RADIATIONS 1.87E–01

* AVERAGE ENERGY (MeV)
BARIUM–137M DAUGHTER, YIELD 9.46E–01,
IS RADIOACTIVE.
BARIUM–137 DAUGHTER, YIELD 5.40E–02,
IS STABLE.



56–BARIUM–137M

HALFLIFE = 2.552 MINUTES 04–MAY–77
DECAY MODE(S): IT

RADIATION	y(i) (Bq–s)$^{-1}$	E(i) (MeV)	y(i)×E(i)
γ 1	8.98E–01	6.616E–01	5.94E–01
ce–K, γ 1	8.32E–02	6.242E–01	5.19E–02
ce–L_1, γ 1	1.19E–02	6.557E–01	7.80E–03
ce–L_2, γ 1	1.69E–03	6.560E–01	1.11E–03
ce–L_3, γ 1	1.39E–03	6.564E–01	9.10E–04
ce–M, γ 1	3.18E–03	6.606E–01*	2.10E–03
ce–N^+, γ 1	9.02E–04	6.616E–01*	5.97E–04
$K\alpha_1$ X–ray	3.92E–02	3.219E–02	1.26E–03
$K\alpha_2$ X–ray	2.13E–02	3.182E–02	6.78E–04
Auger–KLL	5.35E–03	2.618E–02*	1.40E–04
Auger–KLX	2.53E–03	3.075E–02*	7.79E–05
Auger–LMM	4.76E–02	3.577E–03*	1.70E–04
Auger–LMX	2.78E–02	4.531E–03*	1.26E–04
Auger–MXY	1.49E–01	9.276E–04*	1.38E–04

LISTED X, γ AND $\gamma\pm$ RADIATIONS 5.96E–01
OMITTED X, γ AND $\gamma\pm$ RADIATIONS** 5.68E–04
LISTED β, ce AND Auger RADIATIONS 6.51E–02
OMITTED β, ce AND Auger RADIATIONS** 3.96E–05
LISTED RADIATIONS 6.61E–01
OMITTED RADIATIONS** 6.07E–04

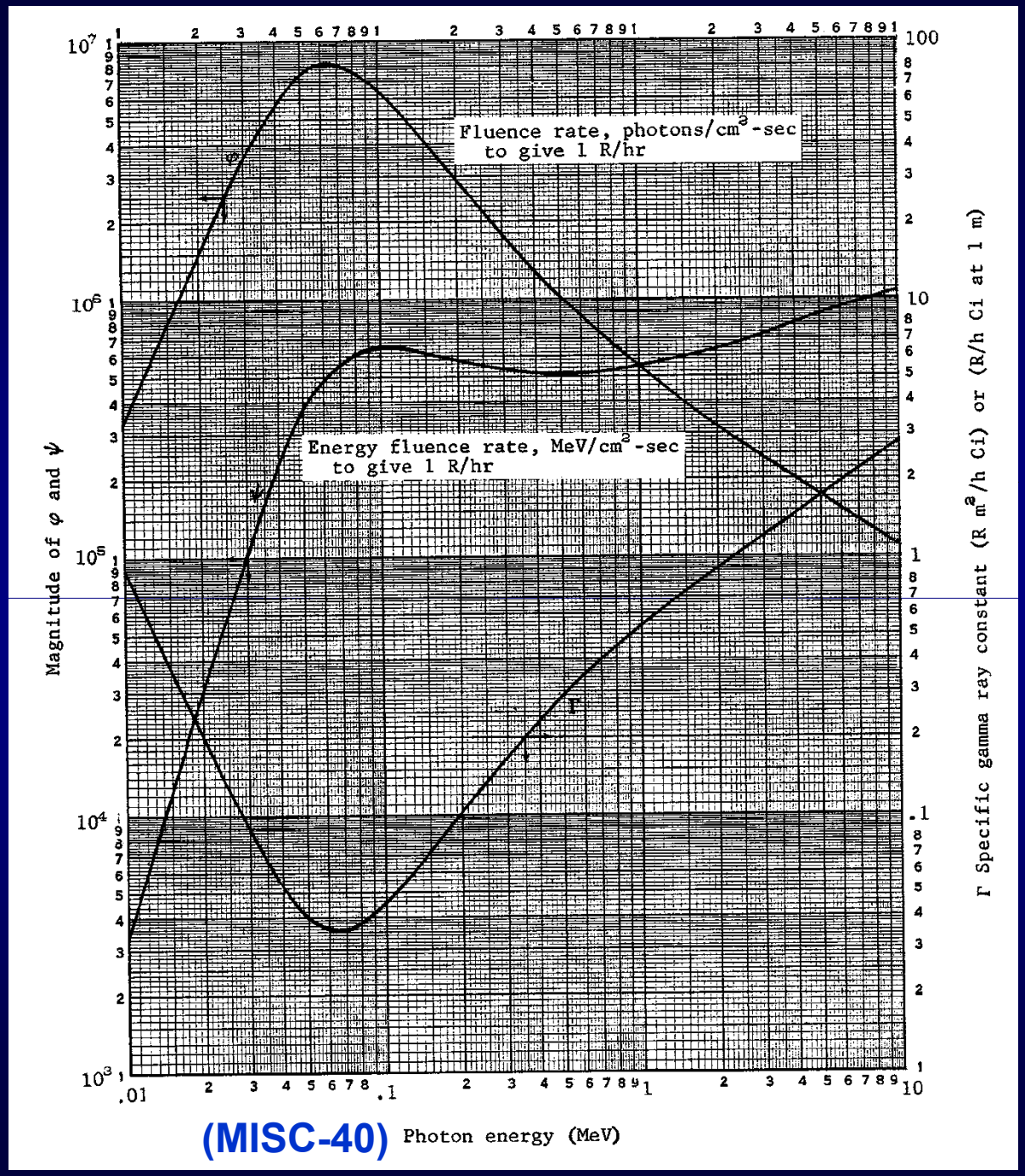
* AVERAGE ENERGY (MeV)
** EACH OMITTED TRANSITION CONTRIBUTES
<0.100% TO $\Sigma y(i)\times E(i)$ IN ITS CATEGORY.
BARIUM–137 DAUGHTER IS STABLE.

0.946 * 0.898 = 0.85

See MISC-45

Page Isotopes-20

Page Isotopes-8



(MISC-40)

$$\begin{array}{r} 0.38 \\ \times\ 0.85 \\ \hline 0.32 \end{array} \quad \frac{\text{R-m}^2}{\text{hr-Ci}}$$

Gamma Constant Rule of Thumb

$$\Gamma \approx 0.5\ E\ \ Y\ \frac{R}{hr}\ @\ 1\ \text{meter}$$

$$\Gamma \approx 6\ E\ Y\ \frac{R}{hr}\ @\ 1\ \text{foot}$$

E = energy of the photon (MeV)
Y = yield of the photon (fraction emitted per transformation, e.g., 0.85 for ^{137}Cs). Also known as "n"

If more than one photon, sum the products of E and n

$$\Gamma \approx 6\ \Sigma\ E_i\ Y_i\ \frac{R}{hr}\ @\ 1\ \text{foot}$$

Problem

An individual walks into a room containing a 500-curie ^{60}Co beam-type irradiator. All indications are that the beam exit port is closed. The individual stands in the path of the beam and performs work on a piece of medical equipment located approximately one meter from the source. The individual works for about 5 minutes and then exits the room. Upon exiting, the individual discovers that the beam port was open the entire time. You are the resident expert. You are called at home and asked to estimate the dose received. You have no reference material with you.

a. What is the individual's estimated dose?

b. Is this an overexposure?

END OF GAMMA CONSTANT

POINT SOURCE AND INVERSE SQUARE

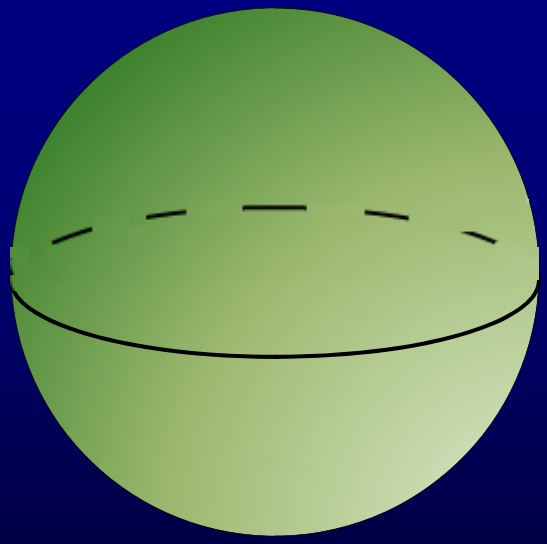
Objectives

- Understand how radiation is affected by distance from a point source
- Calculate the dose from a point source

Point Source

Surface Area of a Sphere is:

$$4 \pi r^2$$



Point Source

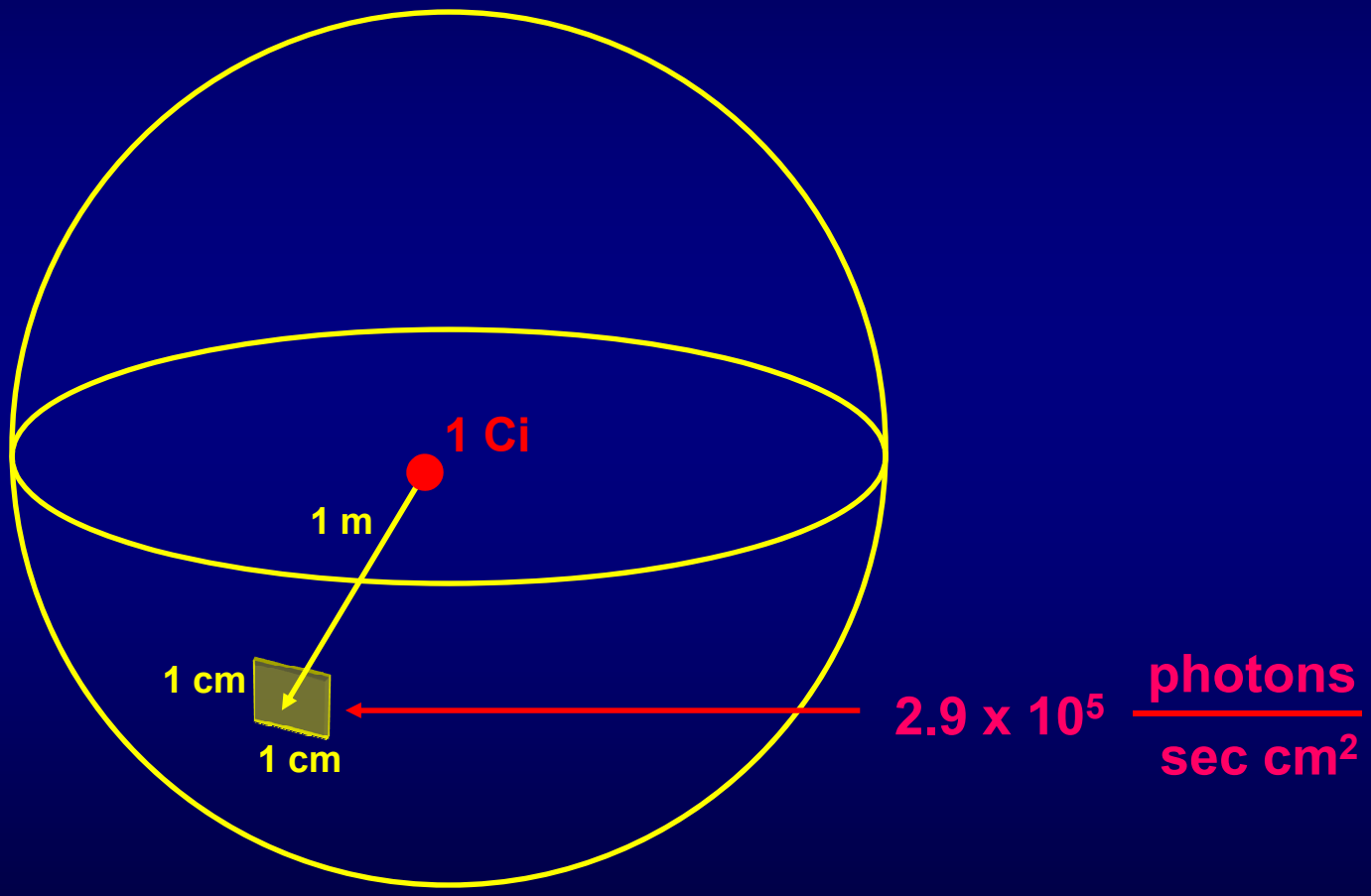
For a photon emitter located at the center of a sphere, the fluence rate, or intensity, I, can be related to the photon emission rate, S, as follows:

$$I = \frac{S}{4 \pi r^2}$$

Therefore, a 1-curie point source in a sphere with a radius of 1 meter (100 cm):

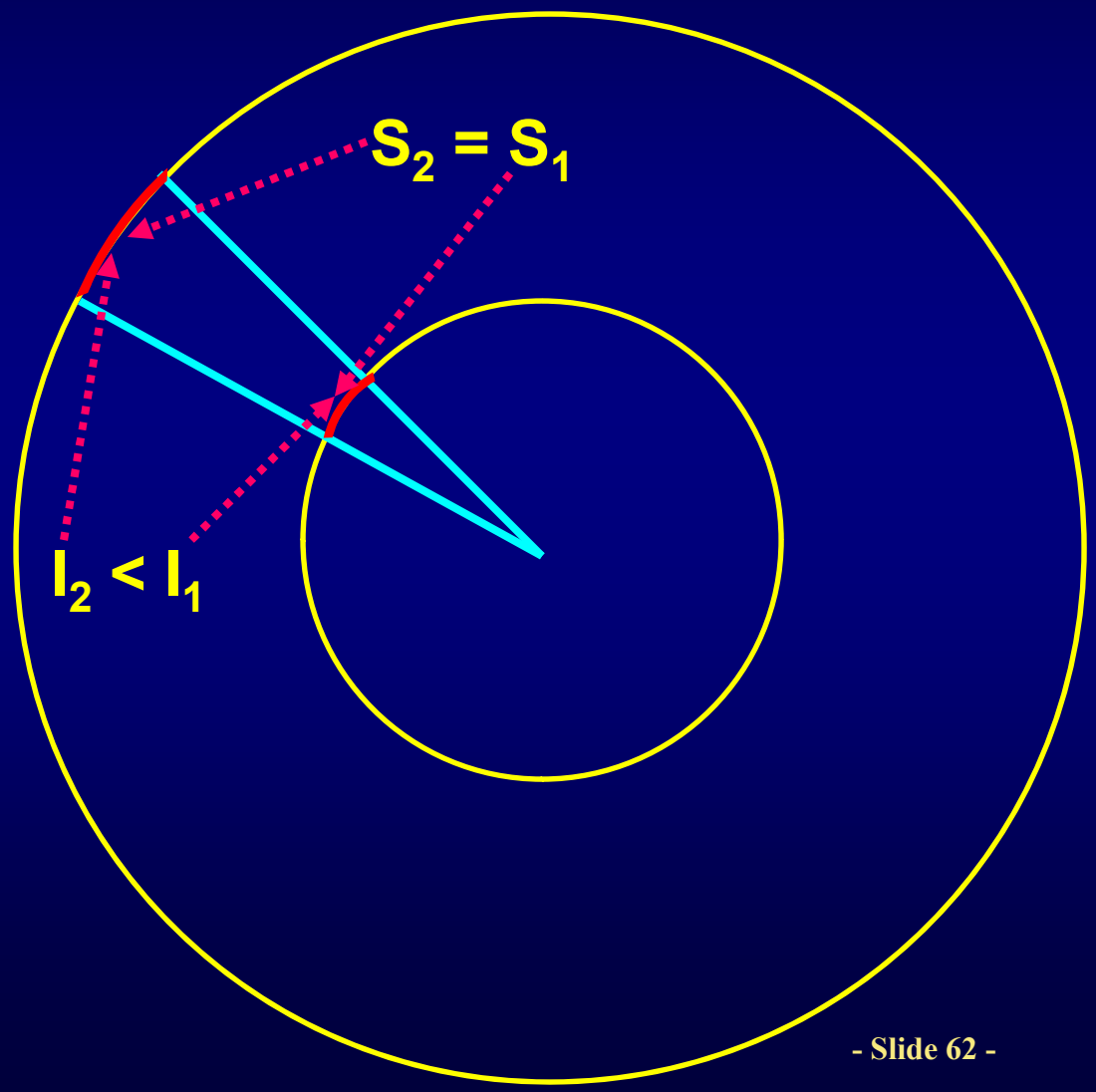
$$I = \frac{3.7 \times 10^{10} \frac{\text{photons}}{\text{sec - Ci}}}{4 \pi \times 10^4 \text{ cm}^2} = 2.9 \times 10^5 \frac{\text{photons}}{\text{cm}^2 \text{ - sec - Ci}}$$

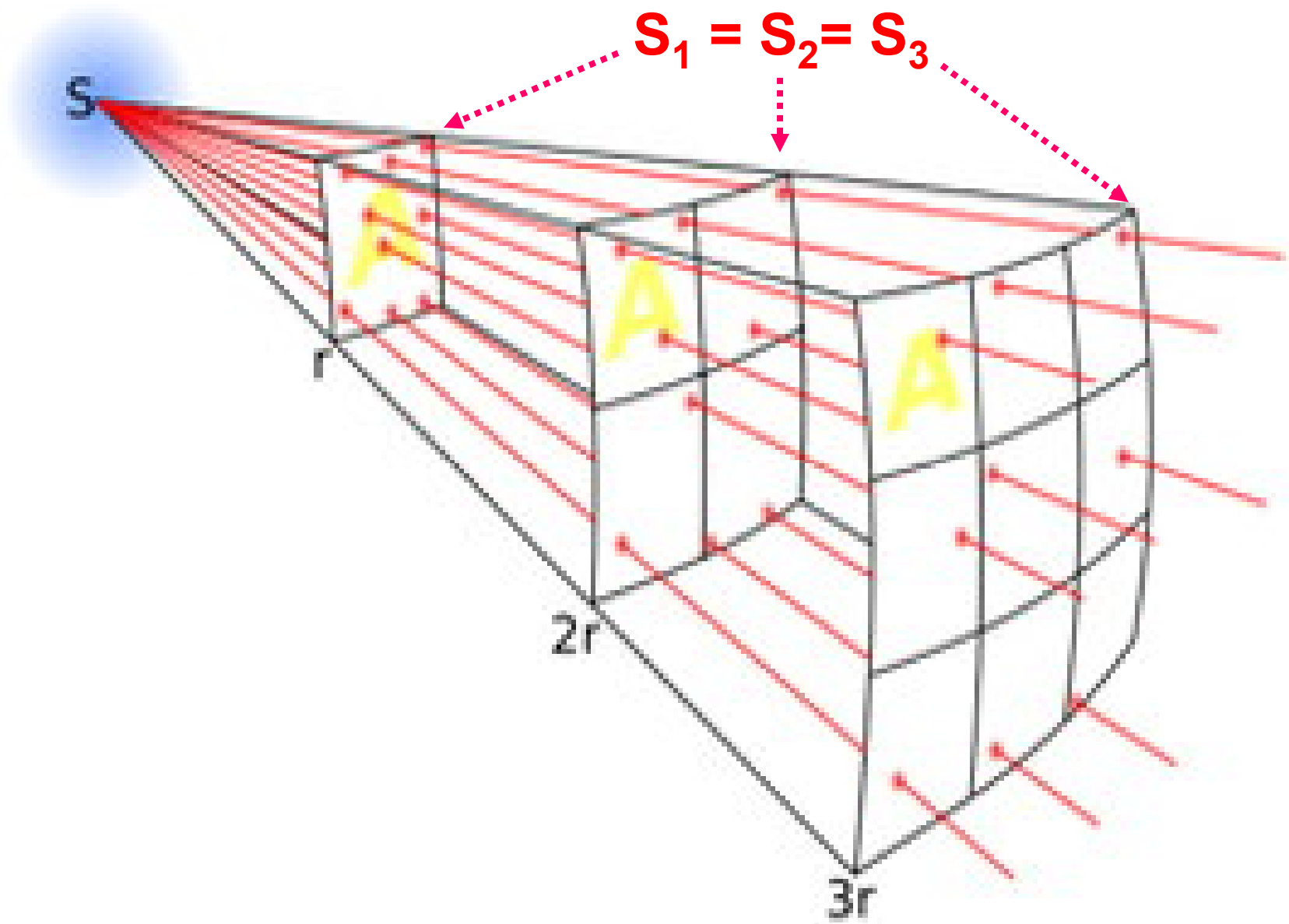
Point Source



Point Source

For a given point source, changing the radius of the sphere changes the intensity, I, (i.e., the larger sphere has less photons per square cm) but the photon emission rate, S, doesn't change.




$S_1 = S_2 = S_3$
S
A
A
A
r
2r
3r

Inverse Square

$$I = \frac{S}{4\pi r^2}$$

$$S = I(4\pi r^2) = 4\pi(Ir^2)$$

$$S_1 = 4\pi I_1(r_1)^2$$

$$S_2 = 4\pi I_2(r_2)^2$$

$$4\pi I_1(r_1)^2 = 4\pi I_2(r_2)^2$$

$$\boxed{I_1(r_1)^2 = I_2(r_2)^2}$$

Inverse Square Example 1

A measurement made at 1 m yields 100 mR/hr. What would the exposure rate be at 4.5 m?

$$I_1(r_1)^2 = I_2(r_2)^2$$

where I_2 is unknown, $I_1 = 100$, $r_1 = 1$ and $r_2 = 4.5$

$$I \times (4.5\ m)^2 = 100\ mR/hr \times (1\ m)^2$$

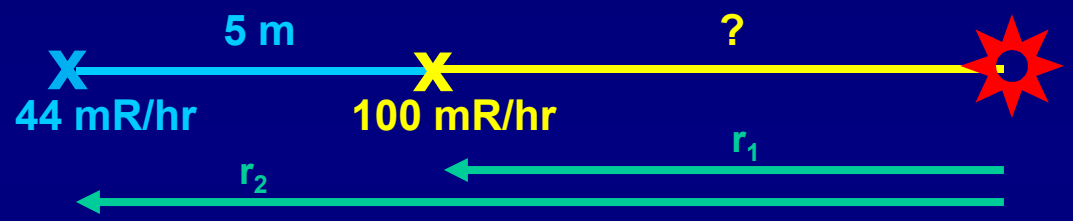
$$I = \frac{100 \times 1^2}{4.5^2} = \frac{100\ mR/hr \times 1\ m^2}{20.25\ m^2} = 4.94\ mR/hr$$

(Sanity Check)

Inverse Square Example 2

A measurement yields 100 mR/hr. A second measurement 5 m farther from the source yields 44 mR/hr. What is the original distance from the source?

$$I_1(r_1)^2 = I_2(r_2)^2$$



We know I_1 and I_2, but we don't know r_1 and r_2

We do know that $r_2 = r_1 + 5$ m. Solve for r_1 and then r_2

Inverse Square Example 2

$$I_1(r_1)^2 = I_2(r_2)^2 = I_2\,(r_1 + 5\text{ m})^2$$

If you have "squares" on both sides of an equation, DON'T EXPAND. Instead, get rid of the "squares."

$$\frac{I_1}{I_2}(r_1)^2 = (r_1 + 5\text{ m})^2$$

$$\sqrt{\frac{I_1}{I_2}(r_1)^2} = \sqrt{(r_1 + 5\text{ m})^2}$$

$$\sqrt{\frac{I_1}{I_2}}\,r_1 = (r_1 + 5\text{ m})$$

$$\left(\sqrt{\frac{I_1}{I_2}}\,r_1\right) - r_1 = 5\text{ m}$$

$$\left(\sqrt{\frac{I_1}{I_2}} - 1\right) r_1 = 5\text{ m}$$

Inverse Square Example 2

Since we know I, I_0 and d, let's solve for r

$$r_1 = \frac{5\ m}{\left(\sqrt{\frac{I_1}{I_2}} - 1\right)} = \frac{5\ m}{\left(\sqrt{\frac{100}{44}} - 1\right)}$$

$$r_1 = \frac{5\ m}{\sqrt{2.273} - 1} = \frac{5\ m}{1.51 - 1} = \frac{5\ m}{0.51}$$

$$r_1 = 9.8\ m$$

Inverse Square Example 2

So r_1 is 9.8 m and $r_2 = r_1 + 5$ m = 14.8 m

According to the equation: $I_1(r_1)^2 = I_2(r_2)^2$

$$100 \frac{mR}{hr} \times (9.8\ m)^2 = 44 \frac{mR}{hr} \times (14.8\ m)^2$$

If you actually do the math the two sides are only approximately equal due to roundoff

Dose vs. Dose Rate

Remember also that there are two point source equations in which the inverse square is used:

$$D_{rate} = \frac{\Gamma \ A}{r^2} = \frac{mR}{hr}$$

$$D_{dose} = \frac{\Gamma \ A \ t}{r^2} = mR$$

Very Small Distances

Approximate gamma dose rate to the hand from a 1 Ci Sealed Source

Isotope	Γ $\frac{\text{R-cm}^2}{\text{hr-mCi}}$	Surface Dose Rate (R/min)	Dose Rate at 1 cm* (R/min)	Dose Rate at 3 cm* (R/min)
^{137}Cs	3.26	513	28	3.7
^{60}Co	13.0	2075	114	16.0
^{192}Ir	4.8	813	43	5.5
^{226}Ra	8.25	1310	72	9.7

(* depth in tissue)

(Table 6, NCRP Report No. 40)

Problem

What is the exposure received by an individual who spends one minute at 3 m from an unshielded 100 Ci ^{192}Ir source?

Problem

An individual is involved in an exposure incident. She states that she was about 4 m from an unshielded 100 Ci ^{137}Cs source for about 10 min. The dosimeter (TLD) worn by the individual is processed and registers 2.24 rem. What is your conclusion about the individual's statement?

Problem

Tech A measures 5 mR/hr at 6 m from a point source. Tech B measures 45 mR/hr. How far from the source is Tech B?

Problem

A radiation source is located in a room. The licensee has previously made a measurement which indicates 25 mrem/hr. You measure 20 mrem/hr. What are some possible explanations for this discrepancy?

Problem

You are told that the exposure rate at 5 m from an unshielded ^{192}Ir source is 10 mR/hr. What is your estimate of the activity of the source?

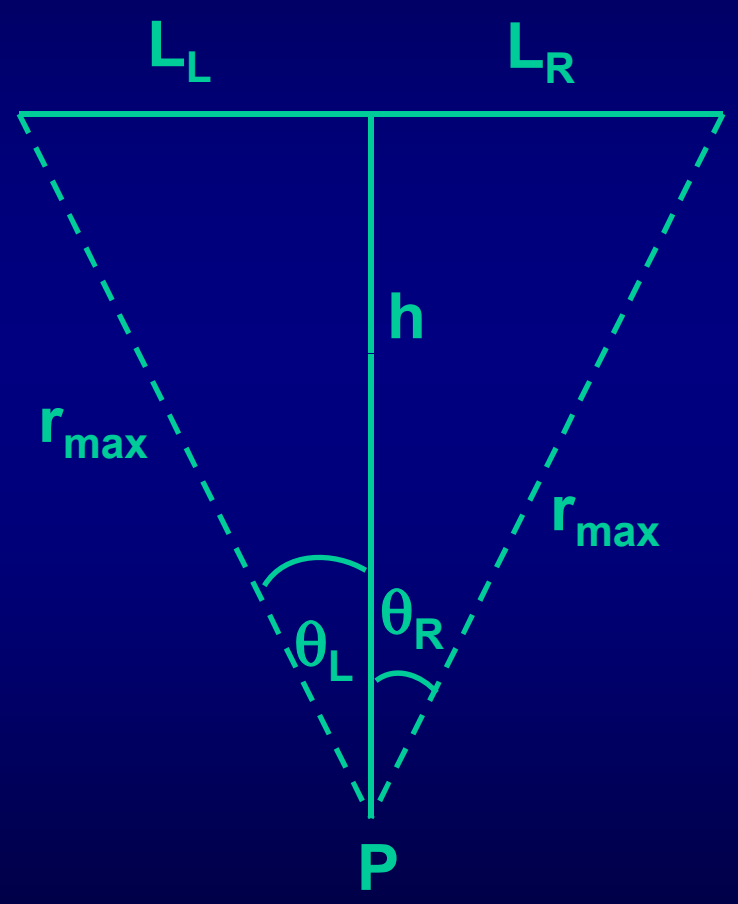
END OF POINT SOURCE AND INVERSE SQUARE

LINE SOURCE

Objectives

- Understand how radiation is affected by distance from a line source
- Calculate the dose from a line source

Line Source



$L_L + L_R = L$

L = length of source

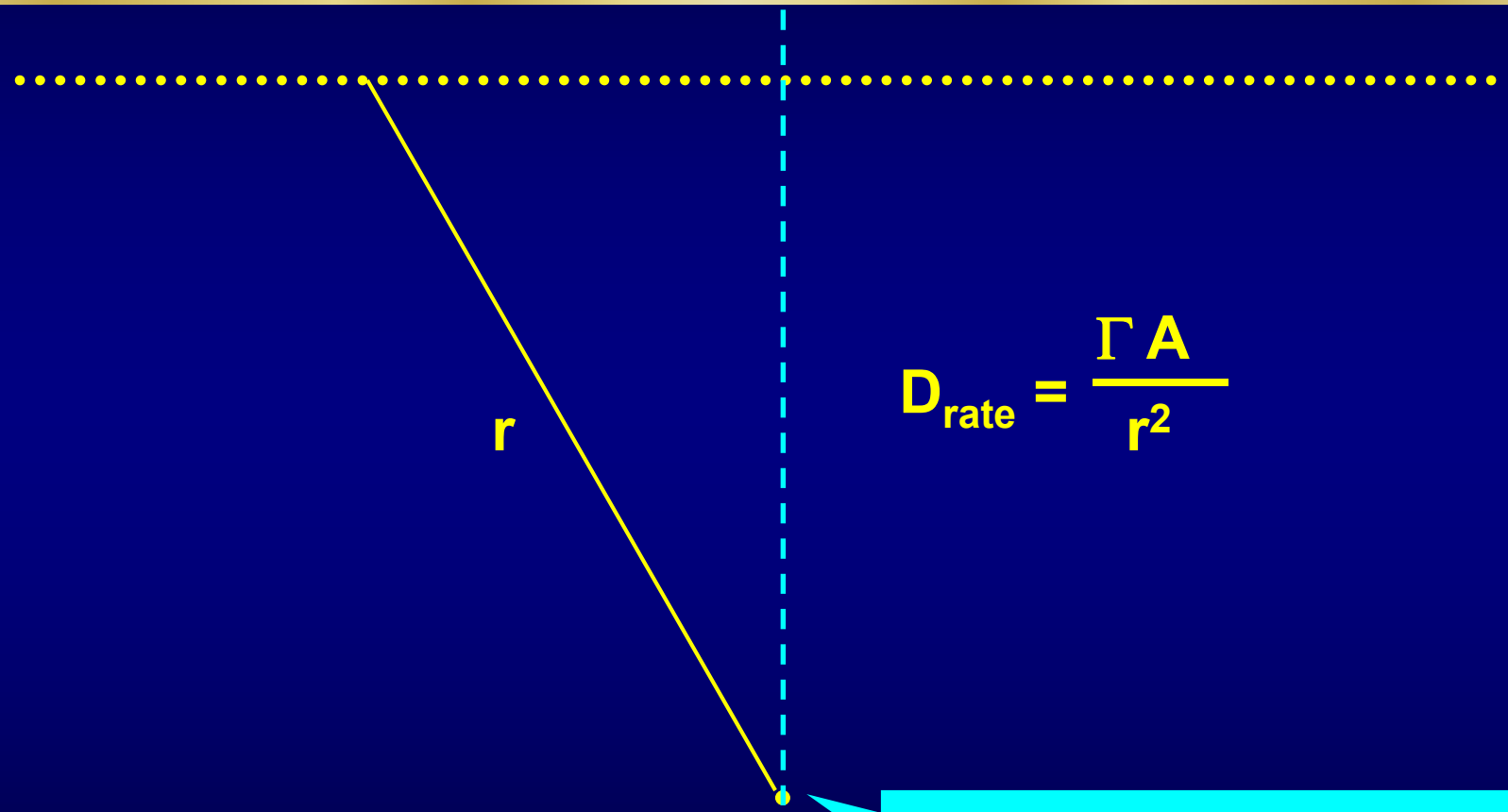
h = perpendicular distance from source

r = actual distance from any point on the source

"L" & "h" are constants

"r" is a variable

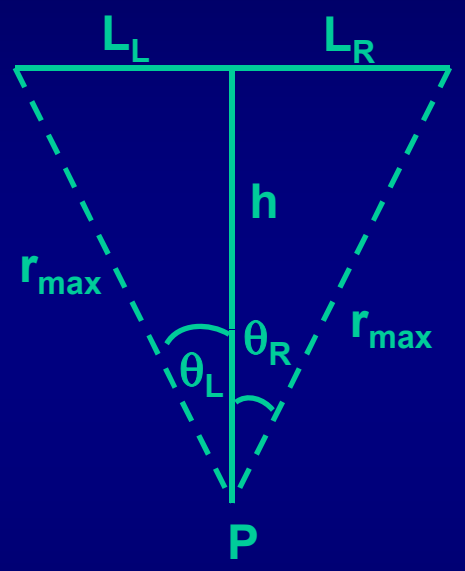
A "Line" is Just a Series of Points



$$D_{rate} = \frac{\Gamma A}{r^2}$$

You are here !

Integration or Adding Up Point Source Contributions

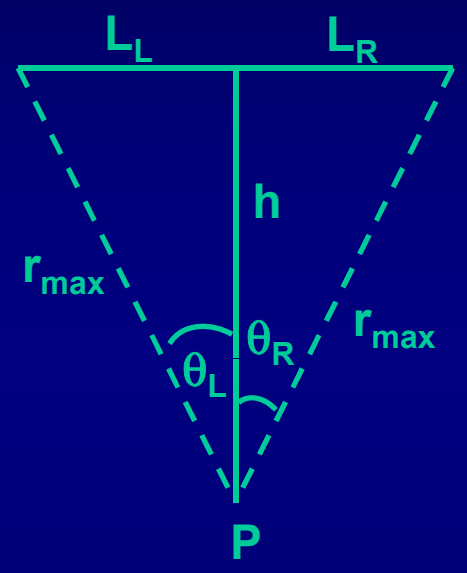


$$D = \frac{\Gamma A}{r^2} = \frac{\Gamma C_L L}{r^2}$$

$$\delta D = \frac{\Gamma C_L \delta L}{r^2}$$

where $A = C_L \times L = (\mu Ci/cm) \times cm = \mu Ci$

Integration or Adding Up Point Source Contributions



$$D_{rate} = \frac{\Gamma C_L}{h} \left\{ \arctan\left[\frac{L_L}{h}\right] + \arctan\left[\frac{L_R}{h}\right] \right\}$$

OR

$$D_{rate} = \frac{\Gamma C_L}{h} \left(\theta_L + \theta_R \right)$$

$$\frac{\Gamma C_L}{h} = \frac{\Gamma A}{hL}$$

If L goes to ∞, then arctan (L_i/h) goes to 1.57 radians = $\pi/2$

so that,

$$D_{rate} = \frac{\pi \Gamma C_L}{h}$$

for a VERY LONG line !

Converting from Degrees to Radians

$\pi = 3.14$

360°	$= 2\pi$ radians	= 6.28
180°	$= \pi$ radians	= 3.14
90°	$= \pi/2$ radians	= 1.57
45°	$= \pi/4$ radians	= 0.79
30°	$= \pi/6$ radians	= 0.52

tan 30° = 0.58 and arctan 0.58 = 0.52 radians = 30°

Page Misc-15 has a Table of Degrees, Radians, Tangents and ArcTangents

Problem

An individual stands 4 m from a pipe carrying a Co^{60} solution. The concentration is 10 mCi/cm^3. The pipe penetrates a very thick concrete wall at either end. The walls are 6 m apart. The individual is 2 m from one of the walls. The radius of the pipe is 10 cm. What is the dose rate?

Problem

What would the dose rate be in the previous problem if all the activity in the pipe were concentrated at a point 4 m from the individual?

Problem

What would the dose rate be in the first problem if the pipe had an infinite length?

Problem

How would the dose rates from the point source in the second problem and the line source in the first problem compare if the individual was 8 m away?

Comparison of Point and Line Source

	Ratio of distance from line to length of line (h/L)	% difference between point & line equations {[(Point-Line)/Line]x100}
	0.1	264.060
	0.5	27.324
10% →	1.0	7.841
	1.5	3.600
	2.0	2.050
	2.5	1.319
1% →	3.0	0.919
	3.5	0.677
	4.0	0.519
	4.5	0.410
	5.0	0.332

Problem

A one foot section of straight iridium brachytherapy wire with a total activity of 32 mCi is accidentally dropped on the floor. An individual not familiar with such sources sees the wire, picks it up and places it on a table in someone's office. Not realizing the source is there, the occupant of the office sits at her desk for 3 hours. She is about 6 feet from the wire directly centered on it.

a) determine her dose
b) explain why you used the method you did

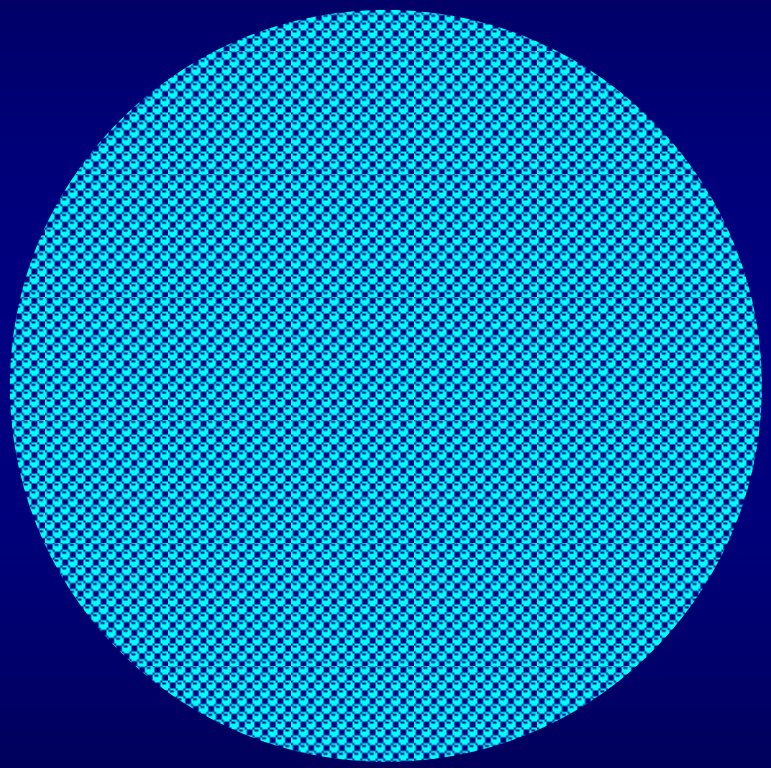
END OF LINE SOURCE

AREA SOURCE

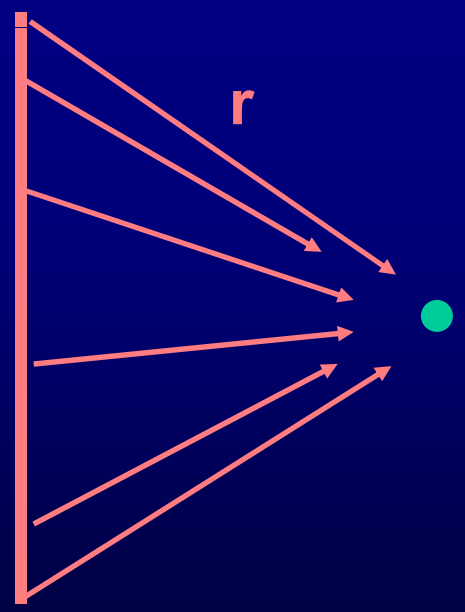
Objectives

- Understand how radiation is affected by distance from an area source
- Calculate the dose from an area source

An Area Source is Just a Round Pizza



Each point on the surface of the pizza contributes to the dose via the point source equation.

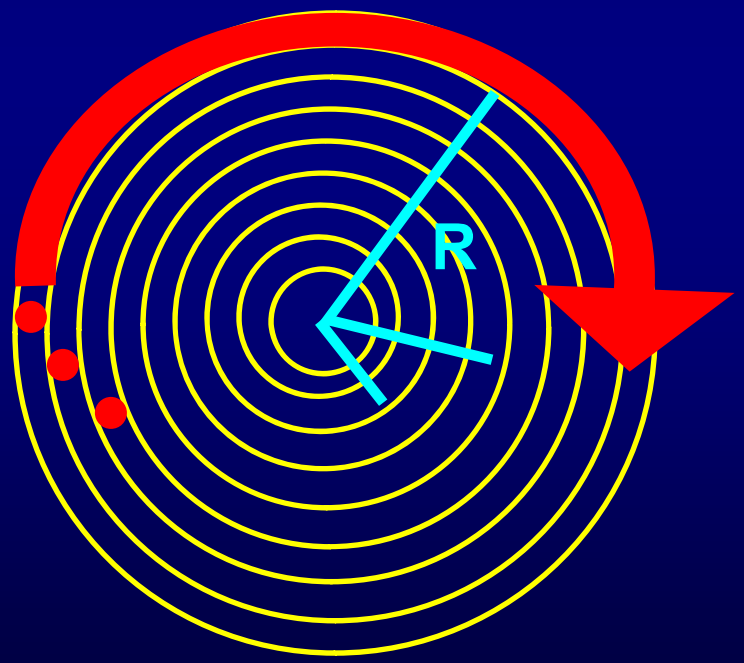


side view

Integration or Adding Up Point Source Contributions

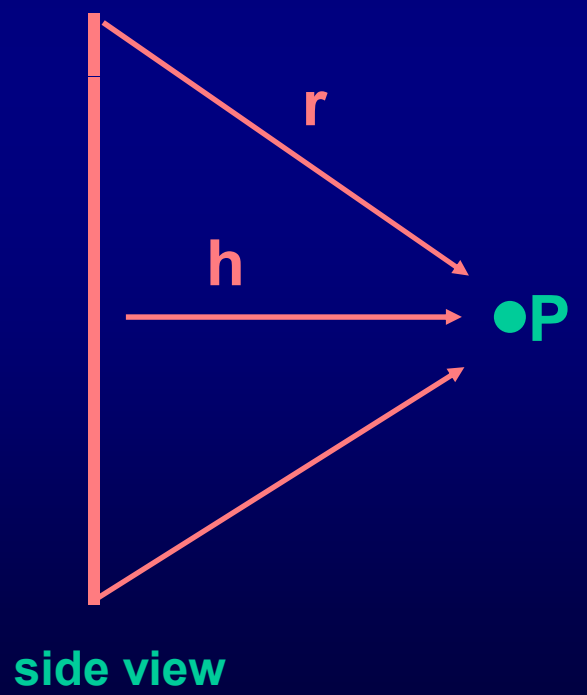
Rather than repeat the point source equation thousands of times we can slice the pizza into rings (not wedges) and take a small piece of the outermost ring. We integrate (add up) all the doses from each point on that ring.

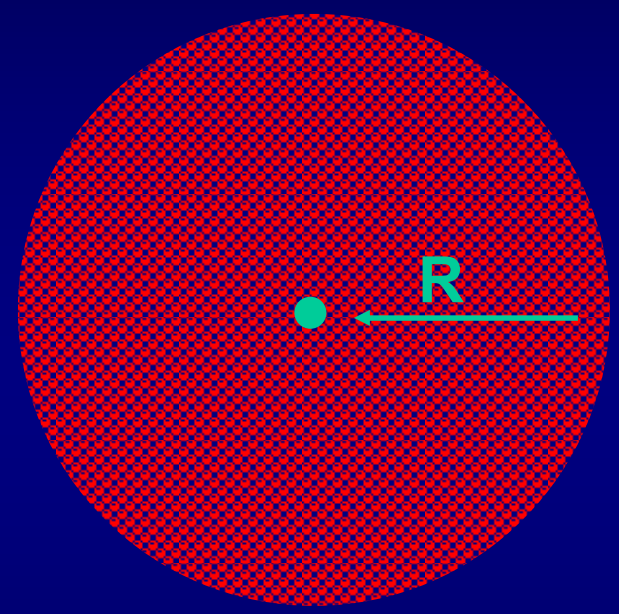
We then move in towards the center to the next ring and repeat the process. Effectively we are integrating (adding up) the contribution from each ring as the radius varies from R (which is the radius of the whole pizza) to 0.



Integration or Adding Up Point Source Contributions

If the point at which we are calculating the dose is centered, then the dose from each point on a given ring is the same.





The dose contribution increases as we approach the center of the rings since the center is closest to the point of interest "P"

The Result of the Double Integral

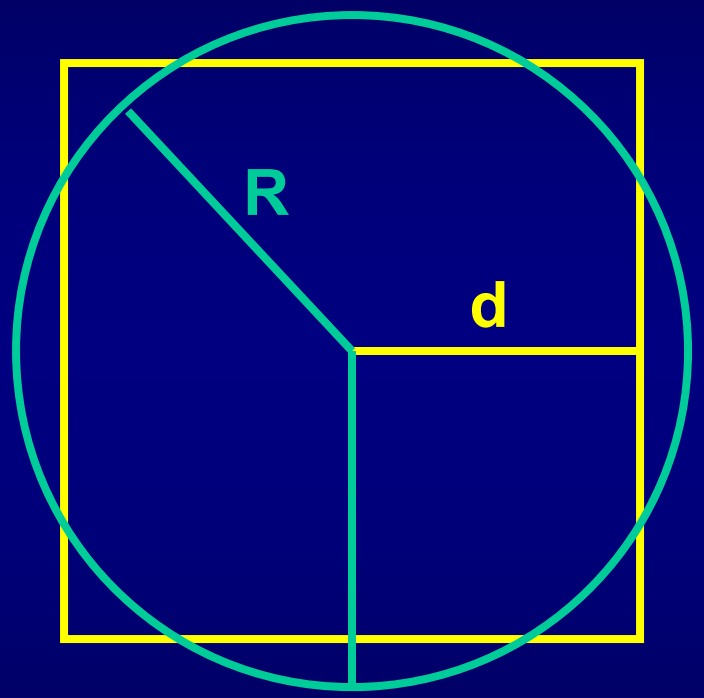
$$D_{rate} = \pi \, \Gamma \, C_A \ln\left[\frac{R^2 + h^2}{h^2}\right]$$

$$C_A = \frac{A}{\pi R^2}$$

$$D_{rate} = \frac{\Gamma A}{R^2} \ln\left[\frac{R^2 + h^2}{h^2}\right]$$

Similar to $D = \dfrac{\Gamma A}{r^2}$

Equivalent Areas



Area of square = 2d x 2d = $4d^2$

Area of Equivalent Circle = πR^2

To make them equal:

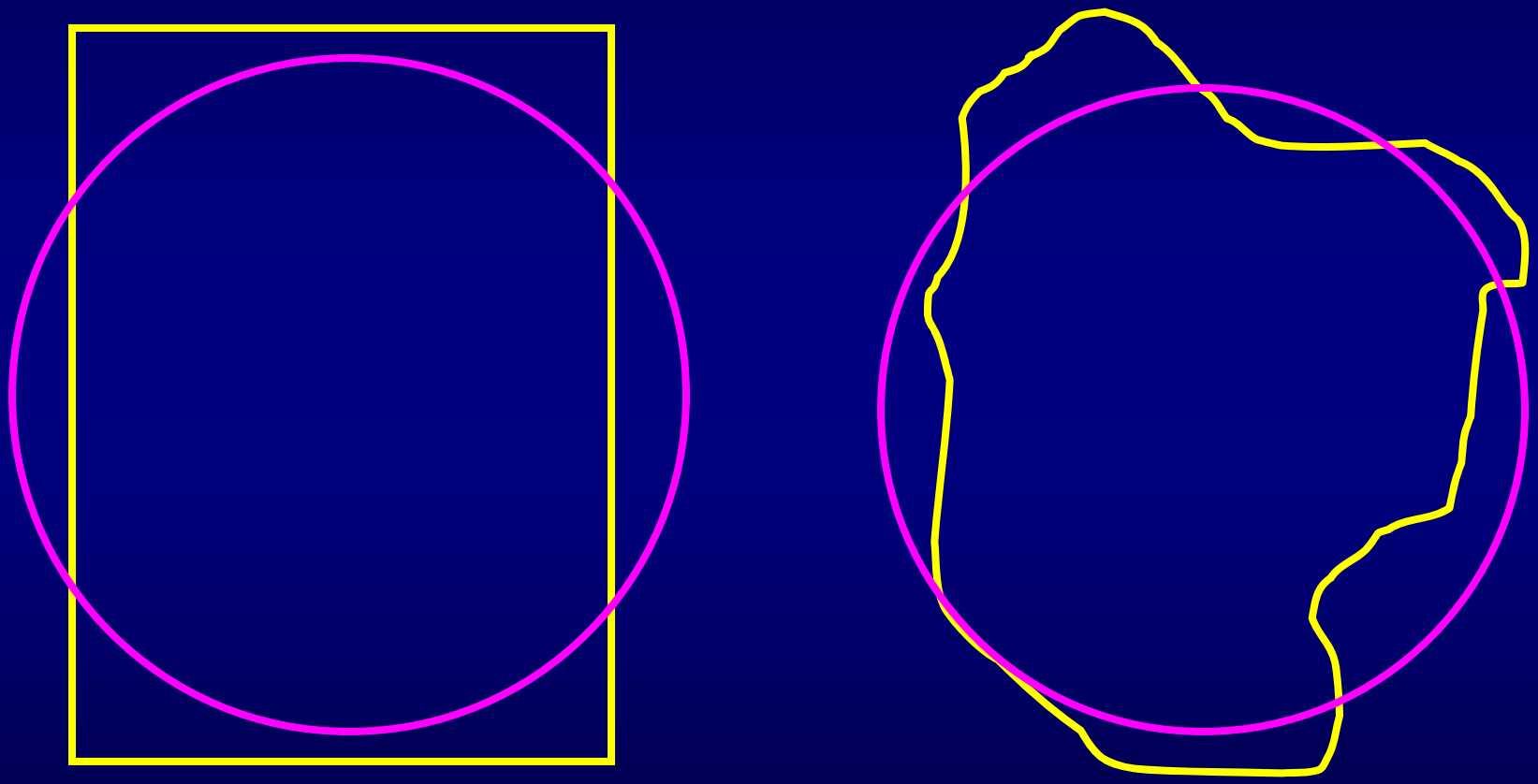
$\pi R^2 = 4d^2$

$R^2 = 4d^2/\pi$

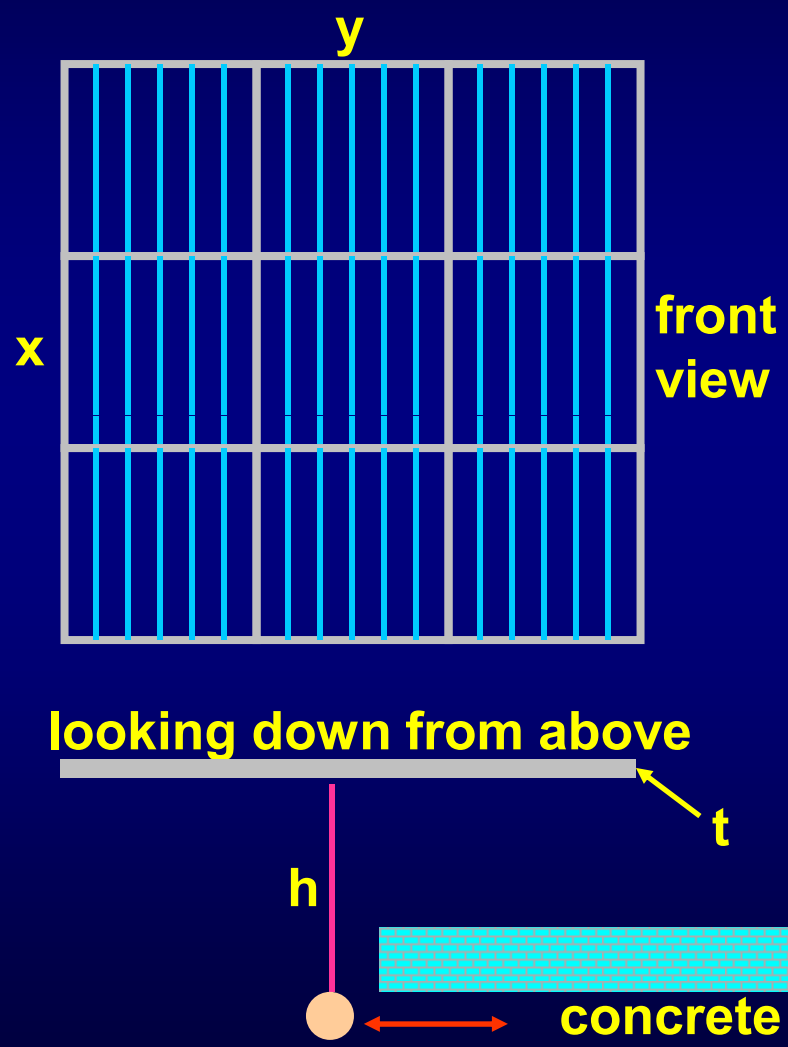
$R = \sqrt{4d^2/\pi} = 2d/\sqrt{\pi}$

$R = 1.13\ d$

Equivalent Areas



Problem



A radiation worker walks into the room where a large pool type irradiator source is exposed. Upon rounding a concrete wall and seeing the source out of the pool, the worker turns and runs out of the room.

source = ^{60}Co
activity = 10^6 Ci
distance from source (h) = 1 m
source dimensions:
source length (x) = width (y) = 3 m
source thickness (t) = 0.02 m

Problem

- estimate the worker's dose
- if the entire source activity were concentrated at a single point at the center of the actual source, what would your dose estimate be
- how far from the source would the worker have to stand so that the doses from the actual planar source and the hypothetical point source would be approximately equal (less than a 1% difference)

Comparison of Point and Area Source

	Ratio of distance from circle to diameter of circle (h/2R)	% difference between point & area equations {[(Point-Area)/Area] x 100}
	0.1	667.319
	0.5	44.270
10% →	1.0	12.036
	1.5	5.458
	2.0	3.093
	2.5	1.987
	3.0	1.383
1% →	3.5	1.017
	4.0	0.779
	4.5	0.616
	5.0	0.499

Problem

A source manufacturing facility has a spill of radioactive Mn^{54} in powdered form. As the initial responder you visually scan the spill area and note that although the edges of the spill are irregular, the extent of the spill appears to be about 1.5 meters in diameter. You take a small dose rate meter and attach it to a pole. From a safe distance, holding the meter over the approximate center of the spill you obtain a reading of about 22 mrem/hr. The instrument is about 1.5 meters above the floor. Calculate the amount of activity deposited in the spill.

Problem

The floor of a large storage room is contaminated with about 10 Ci of ^{106}Ru. The contamination is spread over an area about 10 meters in diameter. How high above the center of the floor would you expect to find an exposure rate of 100 mR/hr?

END OF AREA SOURCE

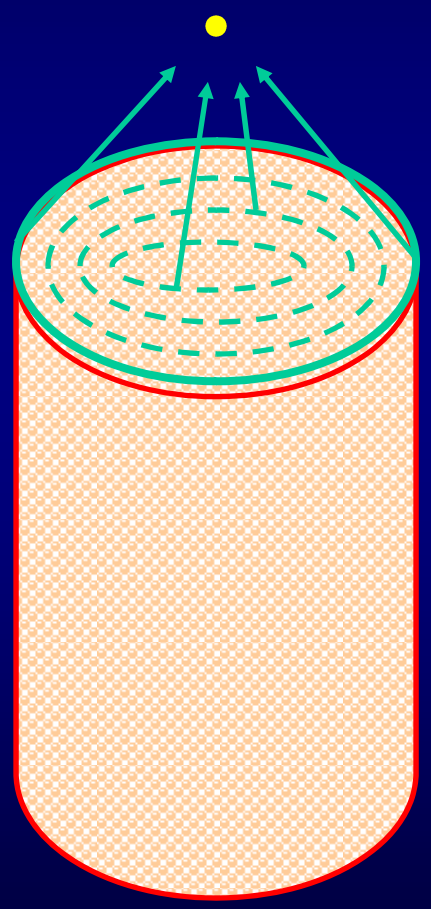
VOLUME SOURCE

Objectives

- Understand how radiation is affected by distance from a volume source
- Calculate the dose from a simple volume source

A Drum is a Volume Source

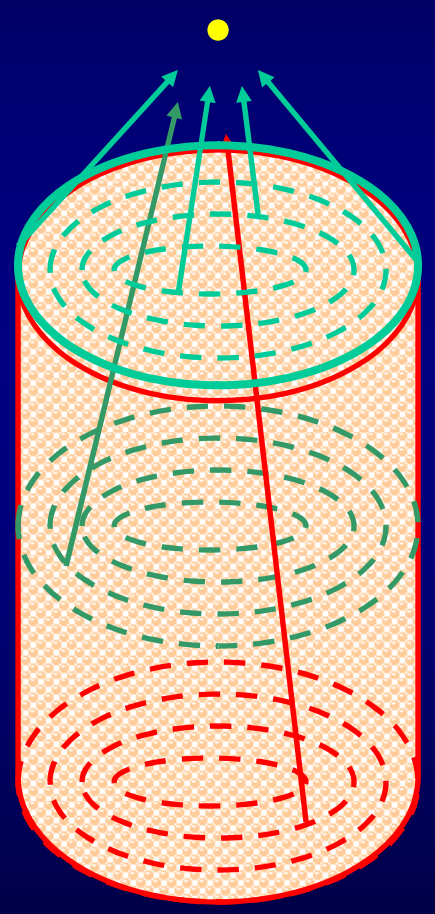
Each point on the top surface of the drum is just an area source and each point on that surface contributes to the dose via the point source equation. We can solve for the total dose from the top of the drum by simply using the area source equation.



A Drum is a Volume Source

Now we can slice the drum into many stacked area sources (a stack of pizzas).

We can calculate the dose from each level using the area source equation. The only difference is that the photons emitted from all the levels except the top one have to penetrate the slices above them. This results in a correction factor that includes the exponential attenuation equation.



Integration or Adding Up Point Source Contributions

$$D_{rate} = \pi \Gamma \frac{C_V}{\mu} (1 - e^{-\mu T}) \ln \left[\frac{R^2 + h^2}{h^2} \right] \qquad C_V = \frac{A}{\pi R^2 T}$$

T is the height of the drum, h is the distance from the top of the drum to the point of interest & R is the radius of the drum

$$D_{rate} = \frac{\Gamma A}{\mu R^2 T} (1 - e^{-\mu T}) \ln \left[\frac{R^2 + h^2}{h^2} \right]$$

[units of μ (cm^{-1}) & T (cm) cancel]

Integration or Adding Up Point Source Contributions

If μT is small such as for a very thin drum then:

$$e^{-\mu T} \approx 1 - \mu T$$

$$D_{rate} = \frac{\Gamma A}{\mu R^2 T} (1 - [1 - \mu T]) \ln \left[\frac{R^2 + h^2}{h^2} \right]$$

$$D_{rate} = \frac{\Gamma A}{\mu R^2 T} (\mu T) \ln \left[\frac{R^2 + h^2}{h^2} \right]$$

$$D_{rate} = \frac{\Gamma A}{R^2} \ln \left[\frac{R^2 + h^2}{h^2} \right]$$

This is just the area source equation.

END OF VOLUME SOURCE

END OF CHAPTER 5