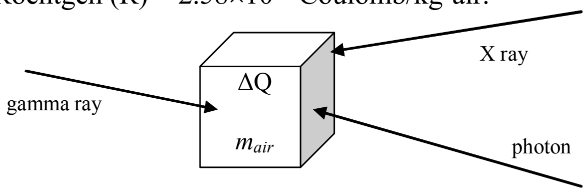
HEALTH PHYSICS

Exposure (X) **(for γ and X rays in air only)**
Exposure (X) is a measure of the charge imparted to (ionization of) air

$$X = \frac{\Delta Q}{m} = \frac{\textit{charge deposition}}{\textit{air mass}} \quad [\mathrm{R}] \tag{1}$$

where ΔQ is the sum of the electrical charges on all the ions of one sign produced in air when all the electrons, liberated by photons in a volume element of air whose mass is m, are completely stopped in air. The unit for exposure is the Roentgen (R) = 2.58×10^{-4} Coulomb/kg-air.



For convenience, we determine the equivalent energy deposition for a Roentgen of charge deposition. Since an energy of about 34 eV is needed to create an ion pair in air, then

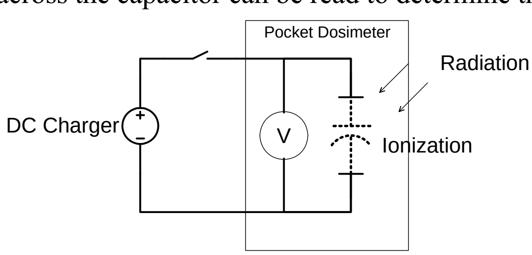
$$1\,\mathrm{R} = \frac{2.58\times10^{-4}\,\mathrm{Coulomb/kg\text{-}air}}{1.6\times10^{-19}\,\mathrm{Coulomb/ion}}\,\frac{34\,\mathrm{eV}}{\mathrm{ion\ pair}} = 54.8\times10^{16}\,\frac{\mathrm{eV}}{\mathrm{kg\text{-}air}} = 5.48\times10^{7}\,\frac{\mathrm{MeV}}{\mathrm{g\text{-}air}} \tag{2}$$

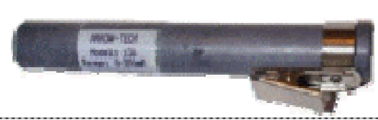
We can determine the charge/energy deposition rate from the interaction rate ($\phi\ \mu\ V$) based upon the source gamma-ray flux (ϕ_γ) and the energy-absorption coefficient for (μ_{en}) air

$$\dot{X} = \frac{\phi_\gamma\ \mu_{en,air}\ V_{air}\ Q_\gamma}{m_{air}} = \phi_\gamma\ E_\gamma \left(\frac{\mu_{en}}{\rho}\right)_{air} \frac{1\,\mathrm{Roentgen}}{5.48\times10^{7}\ \mathrm{MeV/g}} \tag{3}$$

where V_{air} is the air volume, Q_γ is the charge deposition in air, and m_{air} is the air mass. We use a dot above quantities such as exposure (X) and dose (D) to indicate a rate basis, that is, exposure rate ($\dot{X}$) and dose rate ($\dot{D}$). Both of these quantities may well be a function of time. Also noteworthy is that the word 'exposure' is also used in a generic sense—we must consider the context in which the term is being used.

Application:
A pocket dosimeter (PD) is a simple instrument for measuring accumulated photon radiation. An external voltage source initially charges the air chamber capacitor in the PD ($Q = C\,V$). As the PD air chamber is exposed to gamma or X ray radiation, the air is ionized thereby causing the capacitor to discharge. The voltage across the capacitor can be read to determine the radiation exposure ($\Delta V = \Delta Q / C = (X\,m)/C$).





Example:
A pocket dosimeter of volume 1 cm^3 is filled with air at STP. The capacitance of the dosimeter is 2 pF. The voltage across the chamber decreases by 1 V during an exposure. Determine the exposure in mR.
Solution:

Using the definition of exposure from Eq. (1), the cumulative exposure is

$$X = \frac{\Delta Q}{m_{air}} = \frac{C\,\Delta V}{(\rho\, Vol)_{air}} = \frac{(2\times10^{-12}\ \mathrm{F})(1\ \mathrm{V})}{(1.293\times10^{-3}\ \mathrm{g/cm^3})(1\,\mathrm{cm^3})}\left(\frac{1\ \mathrm{R}}{2.58\times10^{-4}\ \mathrm{C/kg}}\right)\frac{10^3\ \mathrm{mR/R}}{10^{-3}\ \mathrm{kg/g}} = 6\ \mathrm{mR}$$

Specific Gamma-Ray Constant

Note that if one assumes a point source of activity, $A(t)$, for a given radionuclide, then much of Eq. (3) becomes known values, such that those numbers can be combined into a quantity known as the *specific gamma-ray constant*, Γ:

$$\dot{X}(t) = \frac{A(t)\, f\left[\frac{\gamma-\mathrm{rays}}{\mathrm{disint}}\right] E\left[\frac{\mathrm{MeV}}{\gamma-\mathrm{ray}}\right]\left(1.6\times10^{-13}\ \frac{\mathrm{J}}{\mathrm{MeV}}\right)\left(10^6\ \frac{\mathrm{dps}}{\mathrm{MBq}}\right)\left(3600\frac{\mathrm{sec}}{\mathrm{hr}}\right)\mu_{en}\left[\frac{1}{\mathrm{m}}\right]}{4\pi\, r^2\left[\mathrm{m}^2\right]\rho\left[\mathrm{kg/m^3}\right]\left(34\ \frac{\mathrm{J}}{\mathrm{kg}}\Big/\frac{\mathrm{C}}{\mathrm{kg}}\right)} = \frac{\Gamma\, A(t)}{r^2} \qquad (4)$$

Thus, exposure (rate) in a vacuum (or essentially air) is inversely proportional to distance squared.

Example:
Compute the specific gamma-ray constant for Co-60.
Solution:
Cobalt-60 emits two gamma rays for each decay. The gamma ray energies are 1.173 and 1.332 MeV. For convenience, we use an average gamma ray energy of 1.25 MeV to find the mass energy-absorption coefficient, which for air is 0.02666 $\mathrm{cm^2/g}$.

$$\Gamma = \frac{(1.173+1.332\,\frac{\mathrm{MeV}}{\mathrm{decay}})(1.6\times10^{-13}\,\frac{\mathrm{J}}{\mathrm{MeV}})(0.02666\,\frac{\mathrm{cm^2}}{\mathrm{g}})(3600\,\frac{\mathrm{sec}}{\mathrm{hr}})(3.7\times10^{10}\,\frac{\mathrm{Bq}}{\mathrm{Ci}})}{4\pi(34\,\frac{\mathrm{J}}{\mathrm{kg}}/\frac{\mathrm{C}}{\mathrm{kg}})(100\,\frac{\mathrm{cm}}{\mathrm{m}})^2(2.58\times10^{-4}\,\frac{\mathrm{C}}{\mathrm{kg}}/\mathrm{R})(10^{-3}\,\frac{\mathrm{kg}}{\mathrm{g}})(\mathrm{Bq}/\frac{\mathrm{decay}}{\mathrm{sec}})} = 1.29\,\frac{\mathrm{R\cdot m^2}}{\mathrm{Ci\cdot hr}}$$

Example:
Compute the 10-min exposure today from a 100 mCi Cs-137 source at a distance of 0.5 m.
Solution:
The specific gamma-ray constant for Cs-137 is $\Gamma = 0.35\ \mathrm{R\cdot m^2/Ci\cdot hr}$. Given the fact that the half-life of Cs-137 is 30 yrs, the exposure rate is constant for the brief 10 minute exposure period:

$$\dot{X} = \frac{\Gamma\, A}{r^2} = \frac{(0.35\,\frac{\mathrm{R\cdot m^2}}{\mathrm{Ci\cdot hr}})(100\times10^{-3}\ \mathrm{Ci})}{(0.5\,\mathrm{m})^2} = 0.14\,\frac{\mathrm{R}}{\mathrm{hr}}$$

The total exposure is

$$X = \int \dot{X}\,dt = \dot{X}\,T = (0.14\,\tfrac{\mathrm{R}}{\mathrm{hr}})(10\,\mathrm{min})(1\,\mathrm{hr}/60\,\mathrm{min}) = 0.0233\,\mathrm{R}$$

Kerma (K)

Kerma, originally an acronym for kinetic energy released in matter, describes the amount of charge produced in a given mass (m) in terms of the total initial kinetic energies (E_{tr}) of the all the charged particles liberated by indirectly ionizing (neutral) radiation

$$K = \frac{E_{tr}}{m} \qquad (5)$$

Absorbed Dose (D)

Absorbed dose (D) denotes the quantity of radiation energy absorbed by matter from ionizing radiation, and is defined by

$$D = \frac{\Delta E}{m} = \frac{energy\ deposition}{mass} \quad [\text{rad } or \text{ Gy}] \tag{6}$$

where ΔE is the energy imparted by the ionizing radiation in an elemental volume and m is the mass in that elemental volume. Dose is expressed in gray (Gy), which is the SI unit defined as a joule per kilogram of energy deposition, or the traditional unit is the *rad* where rad is an acronym for radiation absorbed dose. The rad is defined as 100 ergs per gram, such that 1 Gy equals 100 rads, and

$$1\ \text{rad} = \frac{100\ \text{ergs/g}}{1.6\times10^{-6}\ \text{erg/MeV}} = 6.25\times10^{7}\ \text{MeV/g} \tag{7}$$

Referring to Figure 1, the dose (energy deposition) rate from ionizing radiation can be estimated using the linear energy transfer (LET) from the particle flux

$$\dot{D} = \frac{\phi\, LET}{\rho} \tag{8}$$

where ρ is the material density.

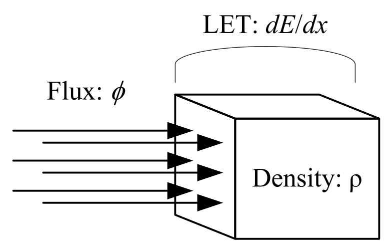
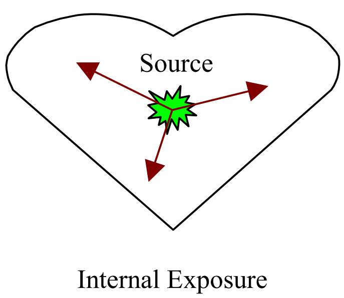


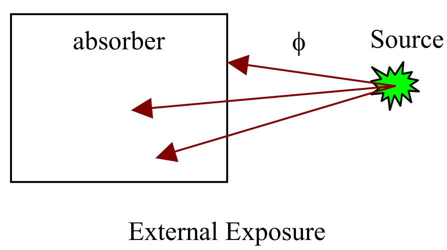
Figure 1. Basis for computing dose using linear energy transfer (LET).

We can integrate the dose rate ($\dot{D}$) expression over time to determine the total absorbed dose.

$$D = \int \dot{D}(t)\, dt \tag{9}$$

Calculation of dose is generally separated into two types: (1) internal and (2) external, based upon where the source is located relative to the material receiving the radiation.





(1) Internal Dose Rate

Internal dose mostly applies to exposure to alpha and beta radiation (*e.g.*, from ingestion or inhalation of the source)

$$\dot{D}(t) = \frac{A(t)\, E}{m_{absorber}} \tag{10}$$

where the source activity at time t is $A(t) = A_0\, e^{-\lambda t}$, E is the average energy per radiation particle, and m_{absorb} is the mass of the absorbing material.

Example:
Determine the initial dose rate to a 250-g stomach if 10 μCi of S-35 is ingested.
Solution:
Sulfur-35 emits beta particles with an average energy of 48.8 keV, such that the initial dose rate is

$$\dot{D}_0 = \frac{A_0\, E_{\beta,avg}}{m_{stomach}} = \frac{(10\times10^{-6}\ \text{Ci})(3.7\times10^{10}\ \text{Bq/Ci})(48.8\times10^{-3}\ \text{MeV/decay})}{250\,\text{g}}\left(\frac{1\,\text{rad}}{6.25\times10^{7}\ \text{MeV/g}}\right)$$

$$= 1.16\,\frac{\mu\text{rads}}{\text{sec}} = 4.18\,\frac{\text{mrads}}{\text{hr}}$$

This dose rate decreases as the S-35 decays.

(2) External Dose Rate

External dose generally applies to gamma exposure. Gamma dose is based on the linear (energy) absorption coefficient, μ_{en} (or μ_a), which may be expressed in reference tables as the mass (energy) absorption coefficient, μ_{en}/ρ.

$$\dot{D} = \phi_\gamma\, E_\gamma\, \frac{\mu_{en}}{\rho} \tag{11}$$

Example:
Silicon is exposed to a 1 MeV gamma flux of 5×10^5 γ/cm^2·sec. What is the dose rate in mrad/hr?
Solution:
The mass-energy absorption coefficient for silicon at 1 MeV is 0.02778 cm^2/g. The dose rate is then

$$\dot{D} = \left(5\times10^5\,\frac{\gamma}{\text{cm}^2\cdot\text{sec}}\right)\left(1\,\frac{\text{MeV}}{\gamma}\right)\left(0.02778\,\frac{\text{cm}^2}{\text{g}}\right)\left(\frac{1\,\text{mrad}}{6.25\times10^4\ \text{MeV/g}}\right)\left(3600\,\frac{\text{sec}}{\text{hr}}\right) = 800\,\frac{\text{mrad}}{\text{hr}}$$

Equation (11) is very similar to Eq. (3), which is used to find the exposure. So much so, that in order to obtain a material dose, D, in rads when exposure, X, is given in roentgens, we need only divide Eq. (11) by (3), and utilize the unit conversion from Eq. (7) to find:

$$\frac{\dot{D}_{mat}}{\dot{X}_{air}} = \frac{\phi_\gamma\, E_\gamma\, (\mu_{en}/\rho)_{mat}\left(\frac{1\ \text{rad}}{6.25\times10^7\ \text{MeV/g}}\right)}{\phi_\gamma\, E_\gamma\, (\mu_{en}/\rho)_{air}\left(\frac{1\ \text{R}}{5.48\times10^7\ \text{MeV/g}}\right)} = \frac{(\mu_{en}/\rho)_{mat}}{(\mu_{en}/\rho)_{air}}\left(\frac{5.48\times10^7\ \text{(MeV/g)/R}}{6.25\times10^7\ \text{(MeV/g)/rad}}\right) \tag{12}$$

This relation is applicable for dose–exposure conversions also, and can be reduced to

$$D\,[\text{rad}] = 0.877\,\text{rad/R}\,\frac{(\mu_{en}/\rho)_{mat}}{(\mu_{en}/\rho)_{air}}\,X\,[\text{Roentgen}] \tag{13}$$

For air, we note that 1 rad ≈ 1 Roentgen.

Example:
On April 22, 1983, the dose rate near a Co-60 source is measured as 1.88×10^6 rads/hr. Determine the dose rate at the same location from the Co-60 on April 22, 1992.
Solution:

From Eq. (13) we know that the dose rate is directly proportional to the exposure rate ($\dot{D} \propto \dot{X}$). Further, given that the relative distance between the source and absorber does not change, Eq. (4) shows us that the exposure rate is directly proportional to the source activity ($\dot{X}(t) \propto A(t)$). Therefore, $\dot{D}(t) \propto A(t)$. The half-life of Co-60 is 5.271 yrs, and as 9 years have elapsed since the measurement, thus

$$\dot{D}(t) = D(0)\, e^{-\lambda t} = D(0)\left(\tfrac{1}{2}\right)^{t/t_{1/2}} = (1.88 \times 10^6 \ \tfrac{\text{rads}}{\text{hr}})\left(\tfrac{1}{2}\right)^{9\,\text{yrs}/5.271\,\text{yrs}} = 5.755 \times 10^5 \ \text{rads/hr}$$

From Equation (11), the relative dose rate to two differing materials is

$$\dot{D}_1 = \dot{D}_2 \, \frac{(\mu_{en}/\rho)_1}{(\mu_{en}/\rho)_2} \tag{14}$$

Therefore, it is proper to indicate with a given dose (rate), the particular material for which that dose corresponds, for example, rads(SiO_2). The mass-energy coefficient values for tissue and air are very similar, which allows health physicists[‡‡] to more easily use instruments employing air to accurately measure radiation doses to humans.

Example:
Determine the relative dose received by a gallium arsenide (GaAs) device versus that of silicon (Si) for the same gamma flux at an energy of 1.25 MeV.
Solution:
The mass energy-absorption coefficient (μ_{en}/ρ) obtained for GaAs and Si at 1.25 MeV is 0.02361 cm^2/g and 0.02652 cm^2/g, respectively. From Eq. (14), the dose (or dose rate) ratio is

$$\frac{D_{\text{GaAs}}}{D_{\text{Si}}} = \frac{\dot{D}_{\text{GaAs}}}{\dot{D}_{\text{Si}}} = \frac{(\mu_{en}/\rho)_{\text{GaAs}}}{(\mu_{en}/\rho)_{\text{Si}}} = \frac{0.02361\,\text{cm}^2/\text{g}}{0.02652\,\text{cm}^2/\text{g}} = 0.890$$

Hence, the dose to GaAs is about 11% less than that to Si for the same exposure.

Biological Dose Equivalent (*H*)
The (biological) dose equivalent expresses all radiations on a common scale for calculating the effective absorbed dose, *H*. The biological dose *H* is measured in sievert (Sv) or *rem* with 1 Sv equal to 100 rem. Due to an unfortunate historical definition, rem is an acronym for Roentgen Equivalent Man, but we can see from Eqs. (2) and (7) that 1 rem does not equal 1 Roentgen.

$$\begin{aligned} \dot{H} &= \dot{D}\, QF \\ [\text{rem}] &= [\text{rad}] * QF \\ [\text{Sv}] &= [\text{Gy}] * QF \end{aligned} \tag{15}$$

The above formula is valid for either the dose rate or the integrated dose. The *quality factor* (*QF*) is a measure of the relative effects of the radiation in producing damage for a given energy deposition, and hence, *QF* is closely related to the *relative biological effectiveness*, RBE. Higher LET radiation produces more biological damage, and is hence given a larger quality factor according to[§§]

$$QF = \begin{cases} 1 & LET < 10 \ \text{keV}/\mu\text{m} \\ 0.32\, LET - 2.2 & 10 \le LET \le 100 \ \text{keV}/\mu\text{m} \\ 300/\sqrt{LET} & LET > 100 \ \text{keV}/\mu\text{m} \end{cases} \tag{16}$$

[‡‡] The term "health physics" originated in 1942, and is said by some to have been coined in an effort to maintain secrecy regarding such activities during the Manhattan Project of World War II.
[§§] International Commission on Radiological Protection, ICRP Publ. 60, 1991.

In 1991, ICRP Publication 60 the quality factor was superseded by the *radiation weighting factor* (W_R). The U.S. Nuclear Regulatory Commission (NRC) assigned quality factors and ICRP radiation weighting factors for various radiations are compared in Table 1. Note that the heat energy causing such biological damage is extremely small.

Table 1. Comparison of NRC quality factor values*** and ICRP radiation weighting factors†††

Radiation	QF	W_R
Photons and electrons (betas)	1	1
High-energy protons	10	5
Neutrons (energy dependent)	2–11	5–20
Alpha particles, fission fragments, heavy ions	20	20

Example:
Why can the units rad and rem be used interchangeably for X-rays?
Solution:
The quality factor for photons is unity ($QF = 1$); therefore

$$\dot{H} = \dot{D} \qquad and \qquad H = D$$

Example:
The dose rate from Po-210 is 5 rad/hr. What is the biological dose rate in rem/hr and Sv/hr?
Solution:
Polonium-210 is a natural alpha emitter, which means that the quality factor is twenty according to Table 1.

$$\dot{H} = \dot{D}\, QF = (5\text{ rad/hr})(20) = 100\text{ rem/hr}\left(\frac{1\,\text{Sv}}{100\,\text{rem}}\right) = 1\,\text{Sv/hr}$$

Example:
Various radiopharmaceuticals can be administered to a patient. Determine a general formula for determining the total equivalent dose.
Solution:
The biological dose rate for such an internal source can be determined from combining Eqs. (15) and (10):

$$\dot{H}(t) = \dot{D}(t)\, QF = \frac{A(t)\, E}{m}\, QF$$

The instantaneous activity in the body (or organ) is a function of both the radioactive decay and the ability of the body to expunge the material from the body (or organ); hence

$$A(t) = A_0\, e^{-\lambda_{eff}\, t}$$

where the effective decay constant is the sum of the radioactive and biological decay constants

$$\lambda_{eff} = \lambda_{rad} + \lambda_{bio}$$

Combining the above expressions, and integrating over the remaining lifetime (T) of the person gives

$$H = \int_0^T \dot{H}(t)\, dt = \int_0^T \frac{A_0\, e^{-\lambda_{eff}\, t}\, E\, QF}{m}\, dt = \frac{A_0\, E\, QF}{m} \left.\frac{e^{-\lambda_{eff}\, t}}{-\lambda_{eff}}\right|_0^T = \frac{A_0\, E\, QF}{m\, \lambda_{eff}}\left(1 - e^{-\lambda_{eff}\, T}\right)$$

*** 10 CFR 20.1004, Standards for Protection Against Radiation.
††† International Commission on Radiological Protection, ICRP Publ. 60, 1991.